5G Deterministic Networks for Industries

How 5G networks can deliver the reliable and predictable connectivity required to support key industrial processes

February 2024

GSMA

The GSMA is a global organisation unifying the mobile ecosystem to discover, develop and deliver innovation foundational to positive business environments and societal change. Our vision is to unlock the full power of connectivity so that people, industry and society thrive. Representing mobile operators and organisations across the mobile ecosystem and adjacent industries, the GSMA delivers for its members across three broad pillars: Connectivity for Good, Industry Services and Solutions, and Outreach. This activity includes advancing policy, tackling today's biggest societal challenges, underpinning the technology and interoperability that make mobile work, and providing the world's largest platform to convene the mobile ecosystem at the MWC and M360 series of events.

GSMA Digital Industries

GSMA Digital Industries is a community of network operators, industrial organisations and the wider ecosystem working together to advance the adoption of mobile technologies in the industrial and manufacturing sector. As the industrial revolution continues towards digitalisation and connected intelligence, the community explores all aspects of the industrial value chain from raw material extraction, to refining, supply chain, component production, assembly, and smart warehousing.

Find our more and how to get involved at:
gsma.com/iot/digital-industries

China Telecom

China Telecom is a large state-owned communication backbone enterprise. With a registered capital of 213.1 billion yuan, an asset scale of more than 800 billion yuan and an annual income scale of more than 520 billion yuan, it has been ranked among the Fortune Global 500 for many consecutive years.

China Telecom owns the technology-leading mobile communication network. It provides global customers with comprehensive information services and customer service channel system covering all regions and services. At present, it has become the world's largest 5G SA RAN sharing network, NB-IoT network, and gigabit optical fiber network.

For more information, please visit the China Telecom website at **www.chinatelecomglobal.com**

GSMA 5G IN

GSMA 5G IN (5G Innovation and Investment Group) is a GSMA Foundry project, aiming to help grow and leverage the rapidly expanding 5G start-up community. It was created by GSMA with 12 co-founding members: China Mobile Capital, China Telecom Investment, China Unicom Capital, China Mobile State Investment, China Broadband Capital, Chenshan Capital, Huawei, ZTE, Orient Securities Capital, CSDN, Shenzhen Valley Ventures and Deloitte China.

During this key window phase of 5G development, the group will fully leverage the global resources of GSMA mobile industries; aggregate key leadership opinions from leading investment organizations and communities in the mobile industry, and discover high-quality start-ups in the fields of AI, IoT, edge computing, cloud computing, big data, 5G network, security, chipset, AR/VR/XR, Fintech and vertical applications to match the innovation and investment and drive the commercialization of 5G applications.

To better serve the needs of the start-up community, the GSMA has established 5G IN Sector Membership where members can gain insights from leading investment organisations and academic communities in the mobile industry; connect with other high-quality start-ups in the fields of AI, IoT, edge computing, cloud computing, big data, 5G network, security, chipset, AR/VR/XR, Fintech & vertical applications; and foster innovation and investment to drive the commercialisation of 5G applications.

GSMA 5G IN:
https://www.gsma.com/greater-china/5g-in-2/

Contents

Executive Summary

5G networks are beginning to enable the digital transformation of various industries, such as manufacturing, logistics and other sectors. As many use cases in these sectors place high demands on network capabilities, telecoms operators are developing 5G networks with deterministic capabilities for latency, reliability, jitter, availability and other key parameters. These networks are designed to meet the requirements of demanding use cases, such as high uplink capacity for artificial intelligence (AI)-based visual inspections, 99.99% availability for operations monitoring, and meter-level positioning data for the control of automated guided vehicles (AGVs).

Pilots in steel automobile manufacturing, warehouse logistics and port operations in China have demonstrated the potential of various 5G deterministic technologies working in tandem to realise major business benefits. For example, the combination of time division duplex (TDD) spectrum, 5G LAN, network and service collaboration (NSC) and frame replication and elimination for reliability (FRER) has enabled a 5G deterministic network to deliver 586 Mbps uplink bandwidth and a latency of 4ms at 99.999% reliability to support key processes in a steel rolling plant. By utilising the 5G network to remotely control overhead cranes and automated guided vehicles (AGVs), the number of on-site personnel can be lowered by 65%. With the 5G network transmitting the 4K video required to support AI-based quality inspections of steel surfaces, the defect detection rate reaches 90%, and production capacity loss is reduced by 92%, helping to achieve greenhouse gas emissions goals, as well as lower costs.

However, at present, the integration of 5G deterministic networks into vertical industries is still at the exploration stage. Key challenges include the diversity of requirements, protocol compatibility issues, 5G technology and industry maturity, and business model maturity. Moreover, the selection of key deterministic technologies must consider the trilemma of reliability, latency and radio resource trade-offs.

5G network utilisation

results in **65%** **reduction** of on-site personnel

\+ **90%** **increase** in defect detection rate

\+ **92%** **reduction** in production capacity loss

This paper proposes the merger of the protocols and mechanisms of 5G and industrial sectors to realise the integration of communication technology (CT) with information technology (IT) and operational technology (OT). As a result, 5G deterministic networks will further deepen the core production links of vertical industries to build successful models that can be copied and generalised to other industries, promoting the digital transformation process.

Acknowledgements

The document has been created thanks to the following contributing GSMA Digital Industries Members

Lead GSMA member:

Supporting GSMA members:

Digital Industries Ecosystem Contributors:

1.0 Introduction

1.0

Introduction

In the information age, industrial enterprises are exploring how digital transformation can increase the efficiency and quality of their operations, and build new business models. The commercialisation and deployment of 5G aerw accelerating this digital transformation: The technology has gradually been adopted for core production links, such as asset management, industrial control and product testing. However, many vertical industries have increasingly high requirements that traditional networks can't necessarily meet. Therefore, the mobile industry has developed 5G deterministic technologies that ensure network latency, reliability, jitter and availability are predictable.

The component technologies of 5G deterministic networks are being studied in standardisation organisations, academic institutions and alliances. In the 3rd Generation Partnership Project (3GPP) standards body, the discussion of 5G deterministic networks started from time-sensitive networking (TSN) over 5G, and gradually attracted wide attention in the community. 3GPP Rel-16 proposed the integration of 5G and TSN to deliver the latency, jitter and reliability required for typical industrial control scenarios. 3GPP Rel-16 to Rel-18 also enhance the capabilities of ultra reliable and low latency communication (URLLC), industrial Internet of things (IIoT), multi-access edge computing (MEC) and network slicing. The International Telecommunication Union-Telecommunication Standardization Sector (ITU-T) has also defined some test models to evaluate the capabilities of 5G deterministic networks[1].

Various international alliances are conducting 5G deterministic network research. For instance, the 5G Alliance for Connected Industries and Automation (5G ACIA)[2] is developing a 5G deterministic network URLLC industrial automation test-bed. The Alliance of Industrial Internet (AII)[3] has released a series of 5G deterministic network white papers and built joint laboratories. The Stic5G consortium[4] is developing a unified solution to realise more efficient and flexible production processes. As a result, 5G deterministic network technologies continue to evolve and innovate to provide better network capabilities and create a digital production mode for various vertical industries.

This white paper analyses the challenges of integrating 5G into vertical industries. It then describes the service and network architecture of a 5G deterministic network, and briefly introduces key technologies within a 5G deterministic network. The paper also includes several case studies that demonstrate the effectiveness of service level agreement (SLA) grading and the capabilities of a 5G deterministic network. Finally, it outlines the prospects for the development of 5G deterministic networks in vertical industries.

---

1 ITU-T G.1051: Latency measurement and interactivity scoring under real application data traffic patterns
2 https://5g-acia.org/.
3 http://www.aii-alliance.org/.
4 https://franco-german-5g-ecosystem.eu/stic5g/.

2.0 Challenges

2.0

Challenges of 5G Integration into Vertical Industries

Although 3GPP 5G usage scenarios define URLLC and massive machine type of communication (mMTC) for vertical industries, there are various challenges that need to be overcome to successfully integrate 5G into vertical industries to provide deterministic services.

2.1 Diverse Vertical Industry Demands

Vertical industries typically employ networks to drive the operation of machinery. Different sectors have different network requirements in terms of speed, bandwidth, etc. In the manufacturing sector, for example, the need for precise motion control requires low latency and low jitter connectivity. Industrial park management use cases, such as information monitoring and automated transportation, require large uplink bandwidth and precise positioning.

In complex end-to-end scenarios, there are also many challenges in handling deterministic concurrent services at scale. For example, material management processes need collaborative cooperation between a range of equipment, such as AGVs, stackers, shuttle cars, circular shuttle cars, etc. Each node action needs to be completed within a determined time. Therefore, a 5G deterministic network needs to provide flexible concurrent URLLC services and have multiple capabilities.

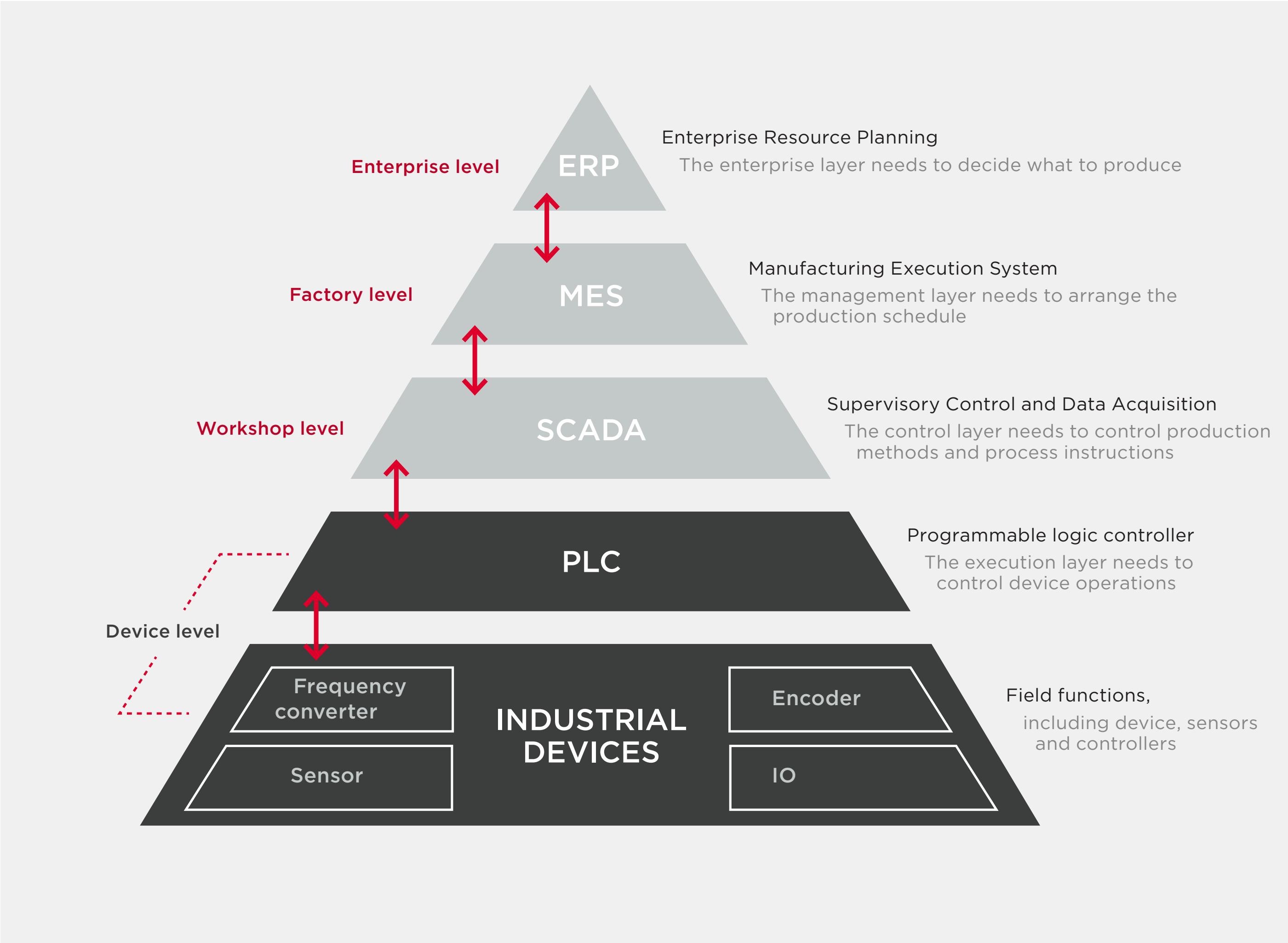
2.2 Industrial Protocol Integration Challenges

Introducing a 5G deterministic network into factories will raise protocol compatibility issues. Today, industrial enterprises' networks primarily employ industrial control protocols including:

- Industrial Ethernet, such as process field net (PROFINET), and Ethernet control automation technology (EtherCAT)
- Industrial bus, such as process field bus (PROFIBUS) and controller area network open (CANopen).

The ISA-95 architecture, which includes equipment, workshop, factory and enterprise layers (as shown in the Figure 1), can be used to analyse and process the real-time and reliability requirements of industrial applications. 5G can be integrated with information technology (IT) to assist production from manufacturing execution system (MES) to enterprise resource planning (ERP). At the equipment level, communication between programmable logic controllers (PLCs) and on-site devices needs the 5G deterministic network to integrate seamlessly into the operational technology (OT) network. The key application scenarios involve real time communication (RTC) for on-site networks and isochronous real time communication (IRT) for motion control synchronisation.

Figure 1
The ISA-95 architecture used in vertical industries



2.3 5G Technology and Industry Maturity

5G's business capabilities began to be standardised with 3GPP Rel-15 and were gradually enhanced in Rel-16 and Rel-17. The URLLC functionality introduced in Rel-15 and Rel-16 is now enabling the development of corresponding commercial capabilities. Currently, global 5G deployments are mainly focused on supporting enhanced mobile broadband (eMBB) scenarios. The maturity of the end-to-end 5G's industry chain still falls short, mainly constrained by the network infrastructure and terminal chips.

The gradual deployment of 5G in key production processes is highlighting gaps between 5G trial capabilities and industrial requirements, as outlined in Table 1.

Table 1: The gaps between 5G trial capability and industrial requirements.

TYPE	5G THEORETICAL CAPABILITY [5]	5G TRIAL CAPABILITY*	INDUSTRIAL REQUIREMENTS [7]
Latency	1 ms	4 ms [6]	0.5 ms to 500ms
Reliability	99.9999%	99.999% [6]	99.9% to 99.999999%
Communication service reliability	/	1 day and more	1 day to 10 years
Jitter	/	4 ms	8 ms to 50μs
Uplink data rate	10 Gbps	1.3 Gbps	Several Gbps
Downlink data rate	20 Gbps	2.6 Gbps	Several Gbps
Positioning	Several decimetres	Several meters	Between 0.2 m and 10 m

*This table shows the peak capabilities exhibited in 5G trials conducted by multiple mobile operators in China at the end of 2023 using 100 MHz of bandwidth in frequency range 1. More information about some of these trials is available **here**. Note, some of these capabilities are being commercialised.

2.4 Unclear Collaborative Business Models

Whereas consumer 5G services are underpinned by a clear business model, mobile operators have not yet sufficiently differentiated their services for vertical industry users. Therefore, operators urgently need to establish network classification and grading capabilities for vertical industries. In this process, OT requirements need to be precisely translated into the network capabilities criteria of communication technology (CT), to create a robust SLA framework. Distinct from the consumer market, this strategic shift would enable the implementation of diversified market strategies.

[5] R-REC-M.2083-0-201509, "Framework and overall objectives of the future development of IMT for 2020 and beyond"
[6] China Telecom, Huawei, Baoshan Iron and Steel Co., Ltd., and Beijing University of Posts and Telecommunications: 5G deterministic private network helps Baoshan Iron and steel plate lead the smart production of green steel - Mobile World Live
[7] GSMA Private 5G Industrial Networks: https://www.gsma.com/iot/resources/private-5g-industrial-networks-2023/

3.0 Architecture

3.0

Architecture of 5G Deterministic Network

3.1 Service Requirements

The extension of 5G networks from auxiliary production processes to core production processes places higher demands on their deterministic service capabilities. There are many types of vertical industries, and different application scenarios and services have different demands for the deterministic capabilities of the network. An analysis of the main capability requirements of industry networks points to the following five key aspects and the hierarchical classification of service requirements shown in Table II.

Latency and reliability:

The latency denotes the end-to-end round trip time (RTT) of the user plane, which refers to the total time it takes from the source point to the successful receipt of destination confirmation information. In general, cumulative probability distribution Xms@Y% is used to evaluate the latency that a service demands. For example, the latency requirement for a fully automated service in PLC factories can reach 5ms@99.99%, which denotes that the RTT for 99.99% of samples is equal to or less than 5ms.

Jitter:

Jitter refers to the degree of deviation between the actual transmission latency and the latency demanded by the service. Generally, interval probability distribution Ams@B% is used to evaluate jitter. Ams@B% denotes that the latency of samples greater than or equal to B% is within the interval of [service demanded latency minus Ams, service demanded latency]. The jitter requirement for controller to IO (C2IO) southern interface of PLC can be as low as 1ms@99.99%. .

Uplink bandwidth:

For mobile communication systems, insufficient uplink capacity often becomes the main bottleneck. The uplink bandwidth can be represented by the uplink cell capacity, which refers to the uplink throughput that a cell can provide per unit of time under certain coverage, terminal quantity, terminal distribution and service models. The uplink bandwidth requirement for industrial use cases that employ image recognition systems can reach 600 Mbps.

Availability:

Availability refers to the degree to which a system is in a working or usable state at any random time when requested to perform a task. For example, if the system is interrupted for 1 minute within a week, then the availability is (7*24*60-1)/(7*24*60)=99.99%. The availability requirement for safety-related use cases in coal mining, for example, can reach 99.999%.

Positioning:

Positioning accuracy describes the difference between the calculated position and the actual position. The definition of positioning accuracy is Xm@90%, which denotes that over 90% samples fall into a circle with the target position as the centre and a radius of Xm. The positioning requirement for the operation of automated assembly lines can be as low as 10 cm or less.

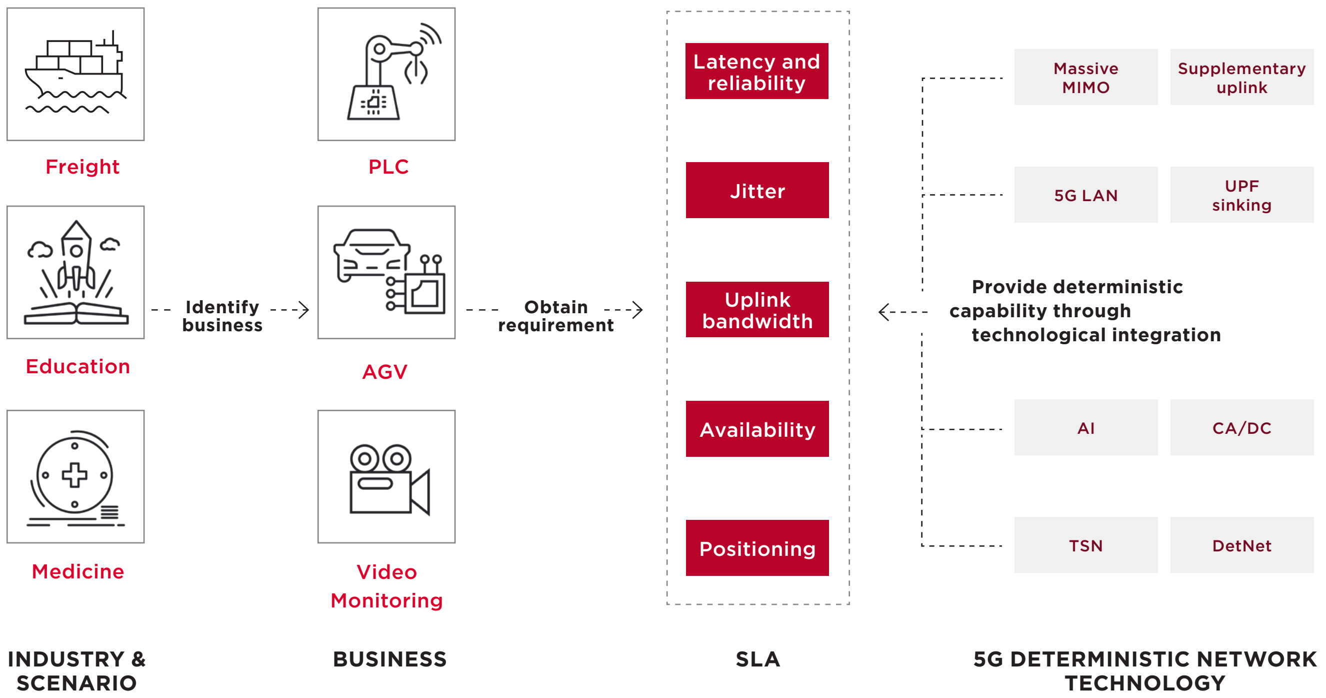
Table II: The hierarchical classification of service requirements

DETERMINISTIC ABILITY	LEVEL 1	LEVEL 2	LEVEL 3	LEVEL 4	LEVEL 5
Latency and reliability (L)	100ms@99.99%	50ms@99.99%	20ms@99.99%	10ms@99.99%	5ms@99.99%
Jitter (J)	8ms@99.99%	4ms@99.99%	2ms@99.99%	1ms@99.99%	50µs@99.99%
Uplink bandwidth (U)	<200Mbps	200-400Mbps	400-600Mbps	600-800Mbps	>800Mbps
Availability (A)	99%	99.9%	99.99%	99.999%	99.9999%
Positioning (P)	100-meter	10-meter	Meter	Decimetre	Centimetre

3.2 Service Architecture

The service architecture of a 5G deterministic network primarily consists of the three stages shown in Figure 2. The first stage identifies the industry application and scenario. Extracting and analysing the characteristics of the service can reveal its distinct statistical indicators and requirements. The second stage flexibly combines and applies various 5G deterministic technologies and exclusive network resources to create an integrated solution to provide end-to-end deterministic services. The third stage divides the service into levels to form the network SLA - the promise made by the service providers to the customers, as listed in Table II. Customers can then order services-on-demand based on the SLA list.

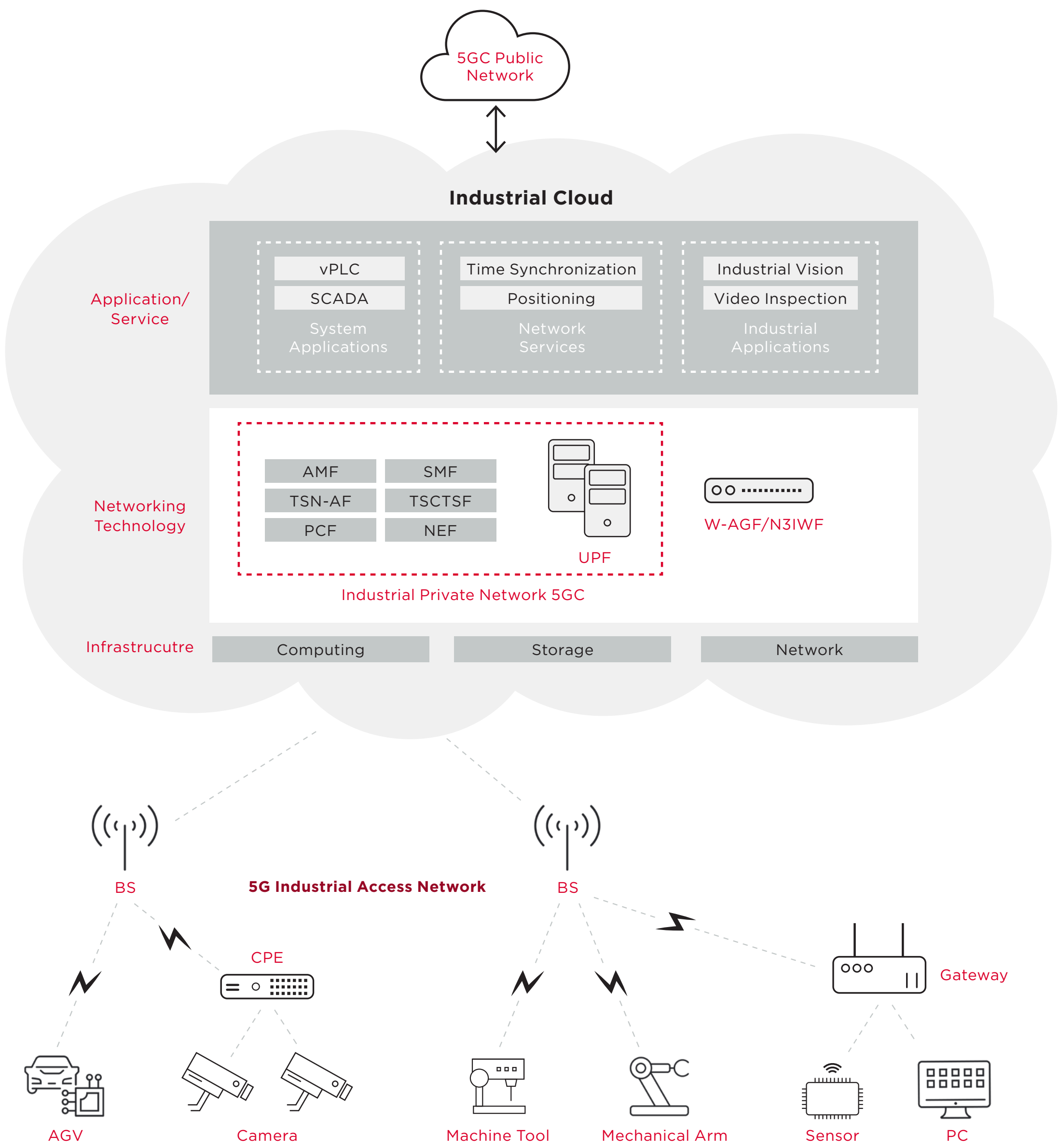
Figure 2
Service architecture of 5G deterministic network



3.3 Cloud-network Integrated Architecture

A 5G deterministic network can employ a cloud-network integrated architecture, including an industrial cloud and 5G industrial access network, as shown in Figure 3.

Figure 3
5G cloud-network integrated deterministic network architecture



Depending on the available infrastructure, the networking technology and application/service can be deployed in an industrial edge cloud, which can provide computing power for different applications/services. Cloud-based industrial system applications, such as virtual PLC (vPLC) and supervisory control and data acquisition (SCADA), can achieve intelligent and reliable data analysis and industrial control, while cloud-based network services can achieve accurate synchronisation and positioning. Running in the cloud, industrial applications, such as artificial intelligence (AI)-based industrial vision and video inspection, can achieve high processing performance.

A 5G local area network (LAN) can be employed to interconnect different industrial equipment. An industrial private network 5G core includes the access and mobility management function (AMF), the session management function (SMF), the TSN-application function (TSN-AF), the user plane function (UPF) and other functions. These elements enable the network to meet the strict requirements for latency and jitter required for industrial automation. In addition, a wireline access gateway function/non-3GPP interworking function (W-AGF/N3IWF) can support the integration of fixed and mobile access networks, allowing for efficient integration between 5G networks and vertical industry networks, solving the problem of multiple networks coexisting within the industry.

A 5G industrial access network can support high-quality broadband connectivity for various vertical industry equipment, including AGVs, customer premise equipment (CPE), machine tools and gateways. It can also offer refined and dedicated resource reservation technology to provide enterprises with very precise deterministic solutions.

Running in the cloud, industrial applications, such as artificial intelligence (AI)-based industrial vision and video inspection, can achieve high processing performance

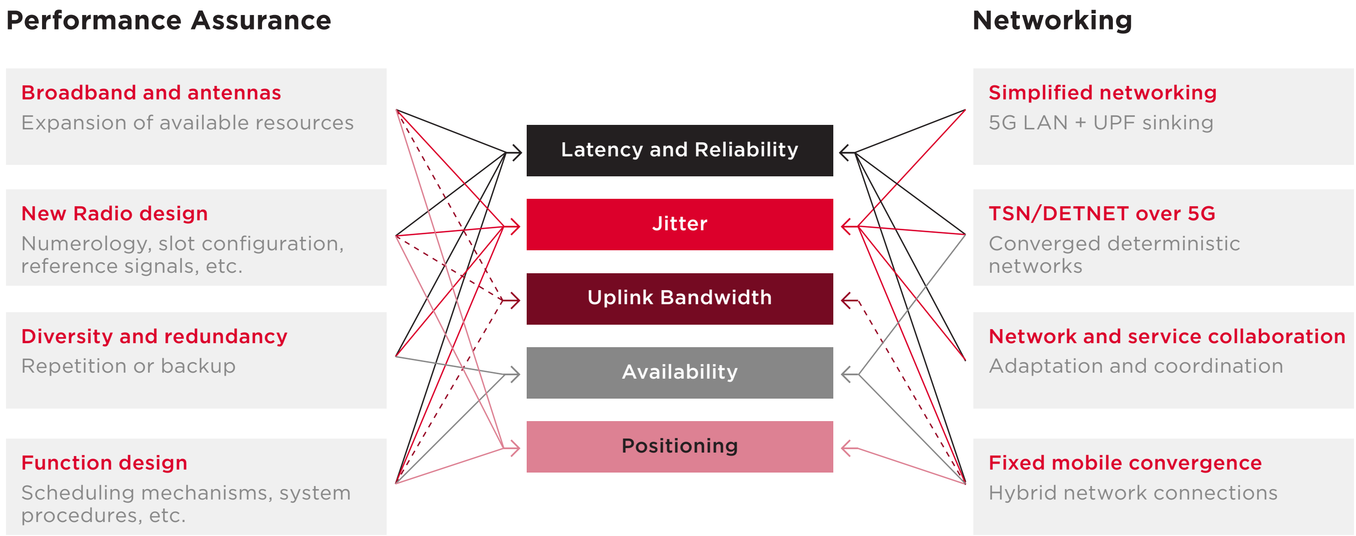
4.0 Key Technologies

4.0

Key Technologies of a 5G Deterministic Network

The technical architecture of a 5G deterministic network focuses on two aspects: performance assurance and networking, as shown in Figure 4. New technologies are being developed to support deterministic services: More refined and flexible technology combinations are set to provide multi-dimensional service level guarantees, including ultra reliability and bounded latency, low jitter, enhanced uplink bandwidth, high availability, and accurate positioning.

Figure 4
Technical architecture for 5G deterministic network



4.1 Performance Assurance Technologies

A. Latency, Reliability and Jitter

End-to-end ultra-reliable, low-latency and low-jitter communication is critical to support real-time feedback and precise control applications in industry. For example, the control of AGVs and mechanical arms (see also 5.2) requires deterministic control signal transmission.

Most enhancements for reliable communication employ diversity: Time, frequency and spatial diversities are adopted to boost radio link reliability. At the same time, redundant transmission on N3/N9 interfaces in a 5G system, and the frame replication and elimination for reliability (FRER) protocol, support multiple separate data forwarding paths.

To enable timely transmission, TSN provides shaper, pre-emption, and queuing mechanisms that guarantee bounded latency and jitter. Time-frequency resource allocation, which determines the transmission duration, is the key to low latency in the air interface. Scalable numerology, mini-slot, and flexible slot patterns can shorten frame alignment and transmission delay. Pre-scheduling, grant-free scheduling, pre-emption, and enhanced hybrid automatic repeat request (HARQ) can further lower latency in the mechanism design.

B. Uplink Bandwidt

In order to support demanding applications, such as machine vision systems for quality control (see also 5.1), the network should be capable of handling very large volumes of traffic, particularly in the uplink.

The available bandwidth determines the capacity and data rate. The bandwidth of a 5G new radio (NR) carrier has expanded to 100 MHz, while a FR2 carrier supports bandwidth up to 400 MHz. Furthermore, carrier aggregation (CA), dual connectivity (DC), and supplementary uplink (SUL) mechanisms can be used to combine multiple frequency bands to accommodate wider bandwidth. In time division duplex (TDD) mode, the ratio of uplink and downlink slots can be configured to provide a higher uplink data rate, while 5G NR also allows spatial multiplexing to multiply capacity. Enhancements to terminal antennas, such as uplink transmitter switching, can ensure the user can access the full capacity available.

C. Availability

Manufacturers need consistent service availability to avoid costly pauses in production. As well as using high-quality components, building redundancy into the 5G system is important to improve availability. Critical components can be backed up to ensure continuity of operation in the case of a single point failure. For example, redundant UPFs, working in “hot backup” mode, can maintain network services when some of them break down.

It is also important to be able to tolerate failures. When signalling connection failures occur, resilient network functions can retain established sessions and configuration, maintaining service continuity for users.

D. Positioning

The development of location-based services, such as shuttle car navigation (see also 5.3), has elevated the importance of positioning capabilities.

3GPP. Rel-16 calls for vertical positioning accuracy of 3 meters, as well as horizontal positioning accuracy of 3 meters (indoor) and 10 meters (outdoor). The location management function (LMF) in the 5G system computes the position of the user equipment (UE) based on positioning measurements and assistance information. Positioning in 5G NR is mainly based on observed time difference, angle of radio signals or signal strength. Enhancements, such as timing delay correction at the transmitter and receiver sides, have been proposed to obtain more precise measurements. Integrated positioning solutions, such as 5G+WLAN, 5G+Bluetooth, and 5G+ultra wide band (UWB), are designed to further enhance accuracy.

4.2 Networking Technologies

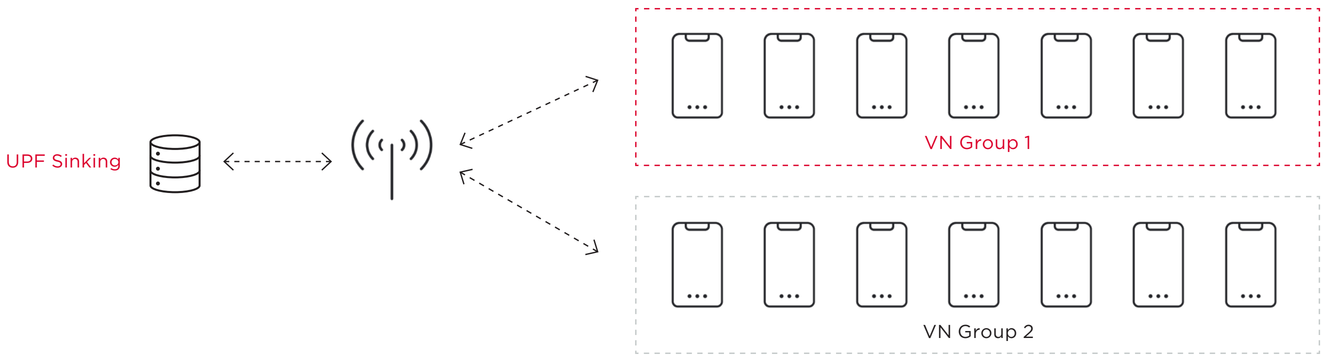
A. Simplified Networking

A simplified network structure based on 5G LAN + UPF sinking can satisfy the needs of industrial control communications based on Ethernet protocols, as shown in Figure 5. Various operations, such as an automated logistics warehouses (see also 5.3), can benefit from it. The deployment of 5G LAN makes it easier for industrial control devices to communicate directly and efficiently: a 5G LAN significantly optimises the user plane transfer path and facilitates sessions of Ethernet type.

A 5G virtual network (VN) group consists of a set of UEs with 5G LAN-type services. Unicast, broadcast, and multicast communication can also be provided within a 5G VN.

A UPF located close to the RAN can offload user traffic so that data can be processed locally. Processing data at the network edge improves performance by reducing network hops and relieves core network traffic efficiently. UPF sinking also enables MEC, which can provide an IT service environment and cloud-computing capabilities. The UPF in charge of traffic steering can also be part of the MEC implementation.

Figure 5
5G LAN + UPF sinking



B. TSN/DetNet over 5G

TSN over 5G is designed to support bounded latency and jitter to meet the stringent requirements of some applications, such as industrial automation. TSN brings valuable tools to enable traffic shaping, resource management, time synchronisation and reliability[8]. The 5G system is integrated transparently with the external TSN as a logical TSN bridge. The device-side TSN translator (DS-TT) and the network-side TSN translator (NW-TT) in the 5G system enable interoperability between the TSN and 5G.

Time synchronisation and QoS handling in TSN over 5G are the basis of time-critical communications. The 5G grand master system clock (5G GM) time can be different from the TSN master clock (TSN GM) time. As the DS-TT

[8] 5G-TSN integration meets networking requirements for industrial automation https://www.ericsson.com/en/reports-and-papers/ericsson-technology-review/articles/5g-tsn-integration-for-industrial-automation

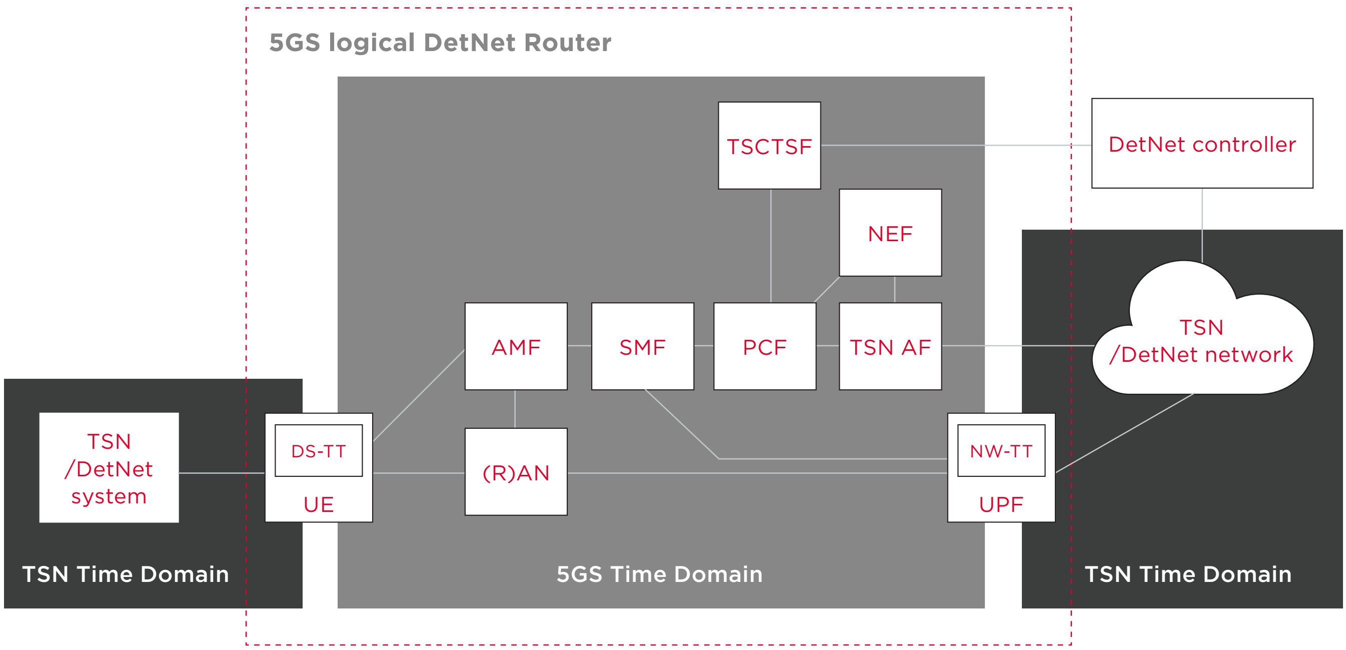
and NW-TT are aware of the time in both the 5G and TSN domains, they play key roles in time synchronisation.

Likewise, TSN and 5G have independent QoS mechanisms, meaning QoS alignment between the two domains is necessary. The different TSN traffic classes are mapped to different 5G QoS indicators (5QIs) in the application function (AF) and the policy control function (PCF). The 5G system then performs end-to-end QoS treatment with the help of QoS requirements provided by the AF[9].

Collaborating with TSN, deterministic networking (DetNet) will address Layer 3 aspects, such as time synchronisation, resource reservation, guaranteed latency and packet loss, as well as convergence of critical and best-effort data streams. For these purposes, DetNet has introduced mechanisms for resource allocation, service protection and explicit routes.

DetNet over 5G is making progress. 3GPP Rel-18 has studied interworking between 5G and DetNet[10]. The 5G system acts as a DetNet node and does not impact the 5G RAN and UE. Solutions for 5G system DetNet node reporting and DetNet configuration provisioning have been proposed. 3GPP is also working on specifying extensions to the time sensitive communication (TSC) framework to support DetNet, as shown in Figure 6[11].

Figure 6
TSN/DetNet over 5G



TSN/DetNet over 5G

[9] Understanding 5G & Time Critical Services https://www.thefastmode.com/img/images/5gamericas/2022_campaign_1_wp_Understanding_5G_Time_Critical_Services.pdf
[10] TS 28.530 Aspects; Management and orchestration; Concepts, use cases and requirements
[11] SP-220801 New WID: Extensions to the TSC Framework to support DetNet

C. Network and Service Collaboration

Network and service collaboration (NSC) refers to the mutual adaptation of network and service requirements, enhancing the air interface resource scheduling to meet diverse SLA demands from multiple terminals on the production line. The realisation of NSC involves two phases:

Firstly, the network adapts to the service. The 5G system captures the message features of the service, including time-sensitive communication assistance information (TSCAI), such as maximum burst size, flow direction, periodicity, burst arrival time (BAT), etc. The 5G system then adjusts the uplink and downlink air interface resource scheduling, ensuring the stable operation of the production line. 3GPP has defined the core network and radio access network collaboration mechanism to support NSC in TS 22.261[12].

Secondly, the service adapts to the network. The 5G system provides feedback on uplink and downlink information to the application layer. The industrial equipment adjusts the timing of message transmission and reception by selecting the corresponding sub-frame. Note, industrial protocols should be redefined in this phase.

D. Fixed and Mobile Convergence

Fixed and mobile convergence (FMC) refers to the combination of 5G mobile communication technology with industrial passive optical network (PON), Ethernet, Wi-Fi and other fixed access technologies used in industrial settings to provide convenient, fast and appropriate network access. In many deployments, the 5G network is added to the existing fixed network. After introducing FMC, customers can select the access technology according to the service requirements. At the same time, FMC allows for the use of dual links to ensure greater availability of the network connection.

FMC can be implemented in two stages. The first stage is the integration of application platforms. In this stage, the 5G and fixed network are relatively independent. MEC provides an open network capability to users, enabling the flexible arrangement and loading of network resources through the application platform. The second stage is the integration of access networks. In this stage, the deployment of a W-AGF or N3IWF access gateway can enable wireless and wireline convergence for the 5G system (5WWC)[13]. Wireless and wireline access technologies are integrated into the 5G core directly. Through unified planning of the network and control of terminal services, the network construction cost can be effectively reduced and the application deployment efficiency can be improved.

[12] TS 22.261 Service requirements for the 5G system
[13] TS 23.316 Wireless and wireline convergence access support for the 5G System

4.3 Technology Selection

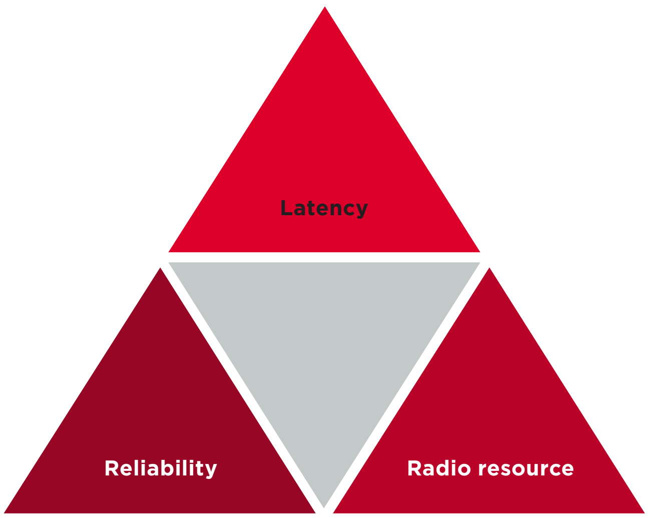
The simple superposition of technologies can directly enhance network performance. However, techniques and tactics used to reduce latency or enhance reliability often consume radio resources in access network. For example, resources are reserved in pre-scheduling to lower latency, or multiple copies of packets are transmitted in packet data convergence protocol (PDCP) duplication to increase reliability. The relationship between reliability, latency, and radio resource can be summed up as a trilemma in network performance (see Figure 7). Notably, radio resources are fundamental to network capacity, which affects key parameters, such as the number of concurrent terminals or data rates.

In practice, a thorough understanding of the demands of industrial enterprises is critical to technology selection. In a multipurpose network, the performance of various concurrent services can be guaranteed through network slicing and QoS mechanisms. When the all-round demands cannot be met as expected, trade-offs must be made. Service demands can be categorised as core and non-core. The network solution should give the highest priority to the core demands that determine the key indicators of network performance.

Technologies should be selected based on the demand for customised network solutions. Prioritising demands can simplify the selection of the technology combination. For example, it is difficult for a large number of terminals to achieve low-latency transmission simultaneously. If support for a high number of connections is more important than latency, it may not be appropriate to pre-schedule for each terminal, as that would consume excess radio resources. In this situation, it may be better to employ other technologies to enable low latency.

Technologies should be selected based on the demand for customised network solutions. Prioritising demands can simplify the selection of the technology combination.

Figure 7
The trilemma in network performance



The trilemma in network performance

5.0 Exploration

5.0

Exploration and Practice of 5G Deterministic Networks

The section outlines use cases in steel manufacturing, automobile manufacturing, warehouse logistics, and port operations, based on actual pilots in China. These deployments demonstrate how 5G deterministic networks can deliver multiple business benefits in industrial settings.

5.1 Steel Manufacturing

Typical steel manufacturing includes four stages: iron making, steel making, continuous casting and rolling. For the rolling stage, in which billets are transformed into rolled materials to meet technical requirements, AI-based steel surface quality inspection needs 4K video from two line scanning colour cameras. To support this high-speed photography with instant capture and transmission characteristics requires a total uplink bandwidth of 586 Mbps. A 5G deterministic network can also be used to remotely control cranes, meaning operators don't need to work in hazardous areas and be exposed to potential safety risks. At the same time, heavy-duty AGVs can be used to transfer goods seamlessly to the next factory.

As shown in Table III, a 5G deterministic network will need different SLA grades to meet the different requirements of overhead crane remote control, AI-based steel surface quality inspection, and operating heavy-duty AGVs.

Table III: SLA grading for steel rolling scenario

	OVERHEAD CRANE REMOTE CONTROL	AI-BASED STEEL SURFACE QUALITY INSPECTION	HEAVY-LOAD AGV
Latency and rereliability (L)	L3	L4	L1
Uplink bandwidth (U)	U1	U3	U1
Availability (A)	A3	A3	A3
Simplified networking	✓	✓	✓
Network and service collaboration	/	✓	/

As Table III shows, simultaneous fulfilment of the L4 and the U1+U3+U1 is required within the same cellular network. By utilising complementary TDD, 5G LAN, and NSC, the latency and reliability can achieve 4ms@99.999%. FRER ensures uninterrupted continuous operation of the overhead crane remote control and seamless transportation of heavy-load AGVs. MEC can provide the AI computing power needed to ensure high-quality inspection of steel surfaces.

The implementation of a 5G deterministic network delivers a number of business benefits. Through the implementation of remote control for overhead cranes, quality inspection and AGVs, the number of on-site personnel can be lowered by 65%. With AI-based quality inspection, the defect detection rate reaches 90%, and production capacity loss is reduced by 92%, helping to achieve greenhouse gas emissions goals, as well as lower costs.

5.2 Automobile Manufacturing

The automotive manufacturing industry includes four major processes: pressing, welding, painting and final assembly. In the welding process, the robotic arms at the valve island need to exchange different types of welding guns, causing circuit wear and tear. Meanwhile, between 50-60 sensors are required to monitor the real-time production parameters, such as operational status and material consumption, requiring network availability of 99.99%. Additionally, real-time control of AGVs requires meter-level positioning to achieve safe and convenient product transportation. Automating the welding point quality inspection needs ten 4K industrial cameras, which requires a total uplink bandwidth of 250 Mbps.

As shown in Table IV, a 5G deterministic network will need different SLA grades to meet the different requirements of the flexible valve island, production data acquisition, and logistics AGVs.

As Table IV shows, simultaneous fulfilment of the L4, U1+U1+U1+U2, J1, and P3 is required within the same cellular network. Employing pre-scheduling, TSN, 5G LAN, and UPF sinking can deliver latency and reliability of 10ms@99.99%, and jitter of 8ms@99.99%. Resilient network functions ensure the flexible valve island is available and reliable, meeting the connection needs of PLCs.

The business benefits include a reduction in the production line valve island wireless transformation time of 85.7%, and a reduction in the annual downtime of this production line of 98%.

The business benefits include a reduction in the production line valve island wireless transformation time of 85.7%, and a reduction in the annual downtime of this production line of 98%.

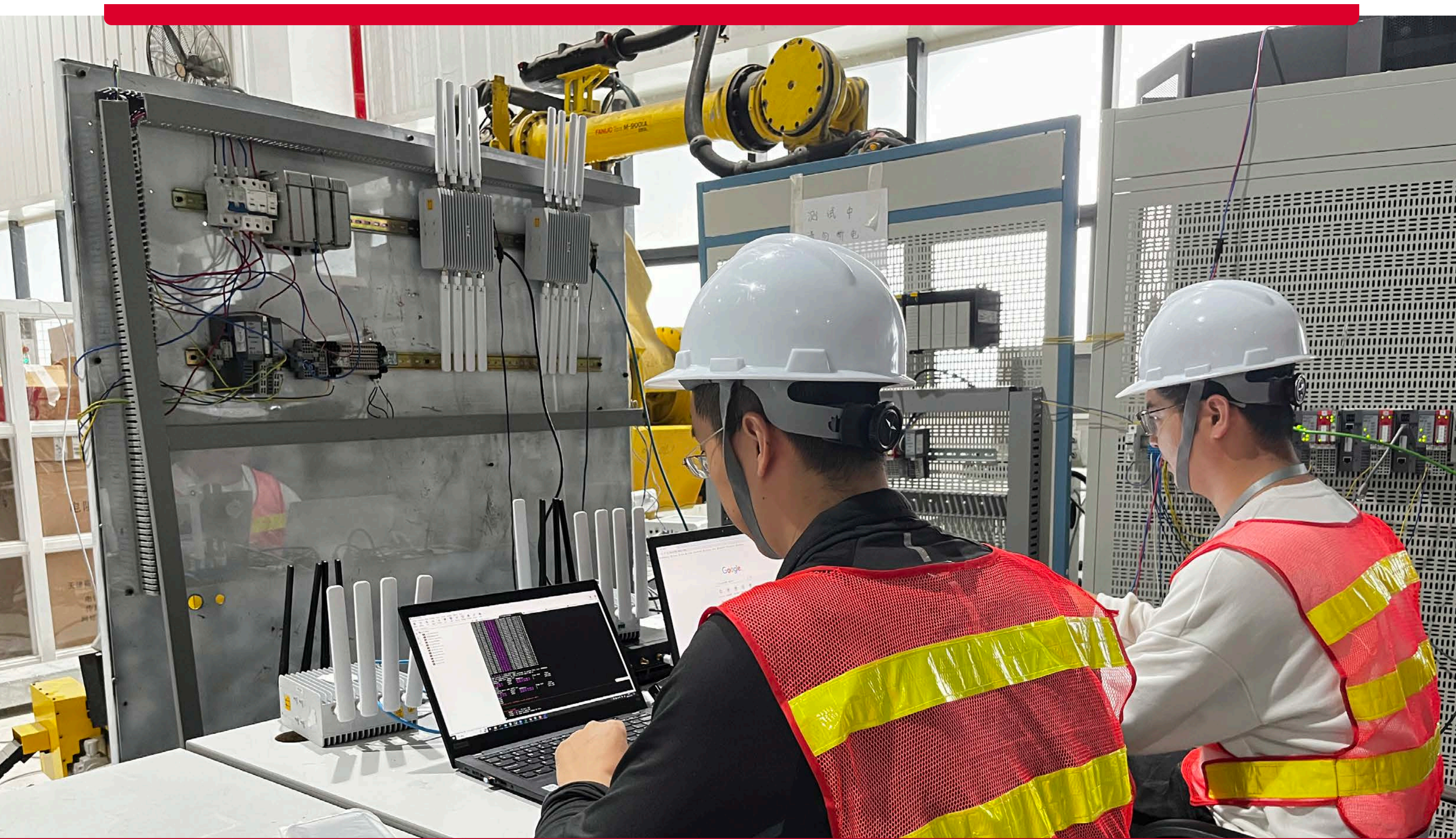
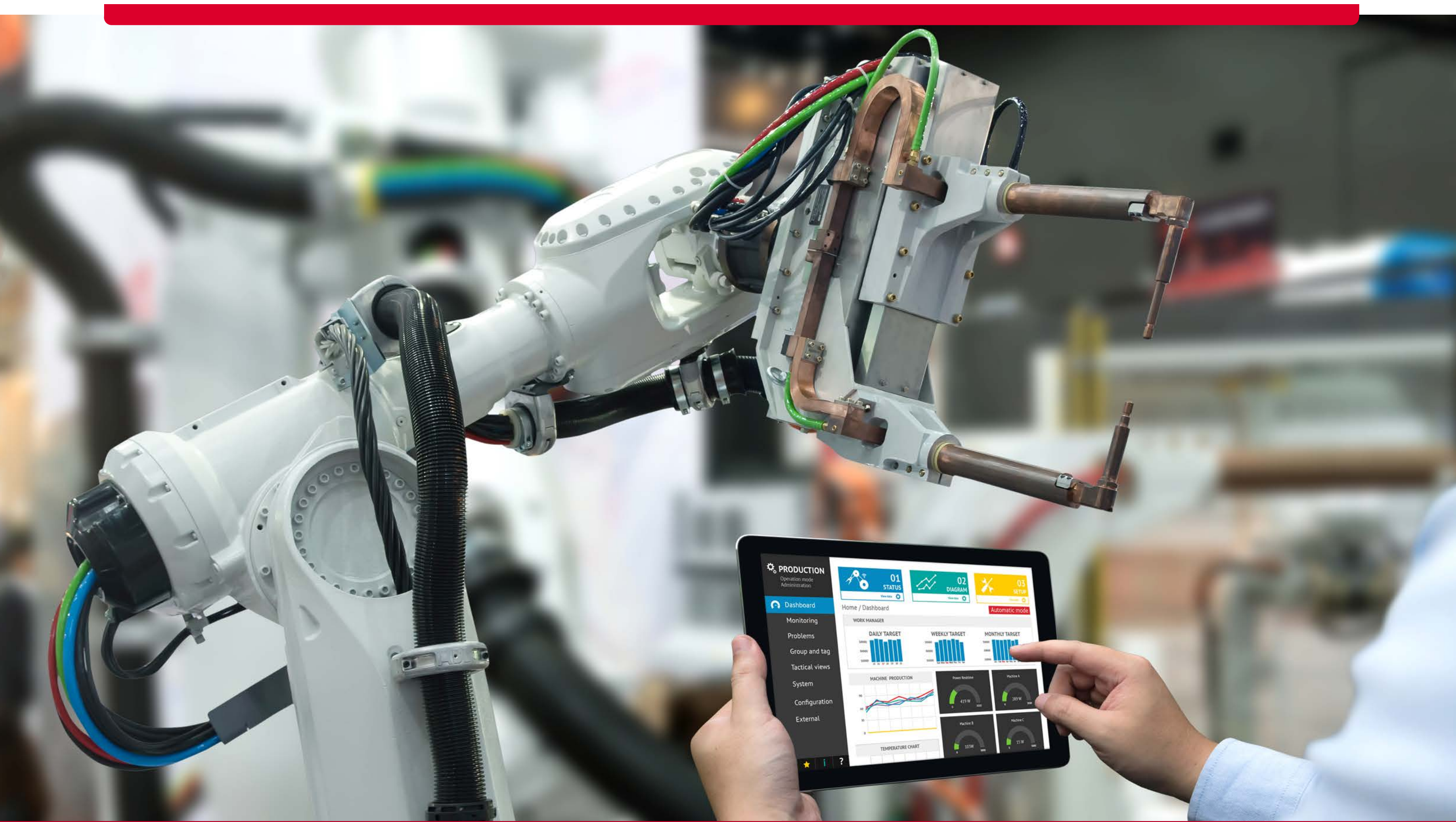


Table IV: SLA grading for automobile welding scenario

	FLEXIBLE VALVE ISLAND	PRODUCTION DATA ACQUISITION	LOGISTICS AGV	WELDING POINT QUALITY INSPECTION
Latency and rereliability (L)	L4	L1	L1	L1
Jitter (J)	J1	/	/	/
Uplink bandwidth (U)	U1	U1	U1	U2
Availability (A)	A3	A3	A3	A3
Positioning (P)	/	/	P3	/
Simplified networking	✓	✓	✓	✓
TSN/DetNet over 5G	✓	/	/	/



5.3 Warehouse Logistics

Warehouse logistics includes six processes: tracking, loading and unloading, handling, receiving, storage, and dispatch. In the loading and unloading processes, remotely coordinating various transportation machinery, such as AGVs, stacker cranes and shuttle cars, requires network latency and reliability of 20ms@99.99%. These processes can be managed by a warehouse management system (WMS) and warehouse control system (WCS) deployed on MEC. The machine vision systems used in warehouses require six parallel cameras with an uplink rate of 30 Mbps to precisely detect damage to packaging, while automated inventory checks require 10 high-definition cameras with an uplink rate of 20 Mbps. The total uplink capacity reaches 380 Mbps.

As shown in Table V, a 5G deterministic network will need different SLA grades to meet the different requirements of stacker cranes, shuttle cars, unmanned inventory, and packaging damage detection.

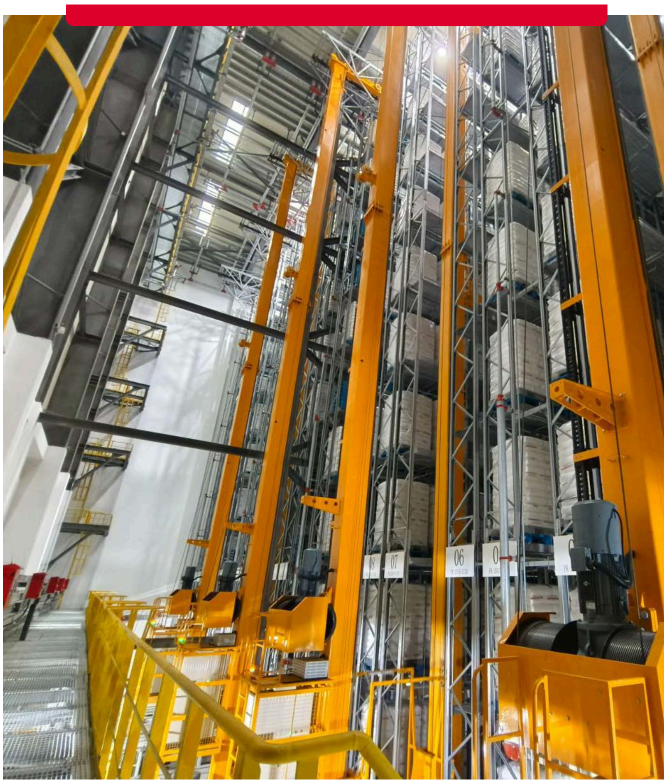


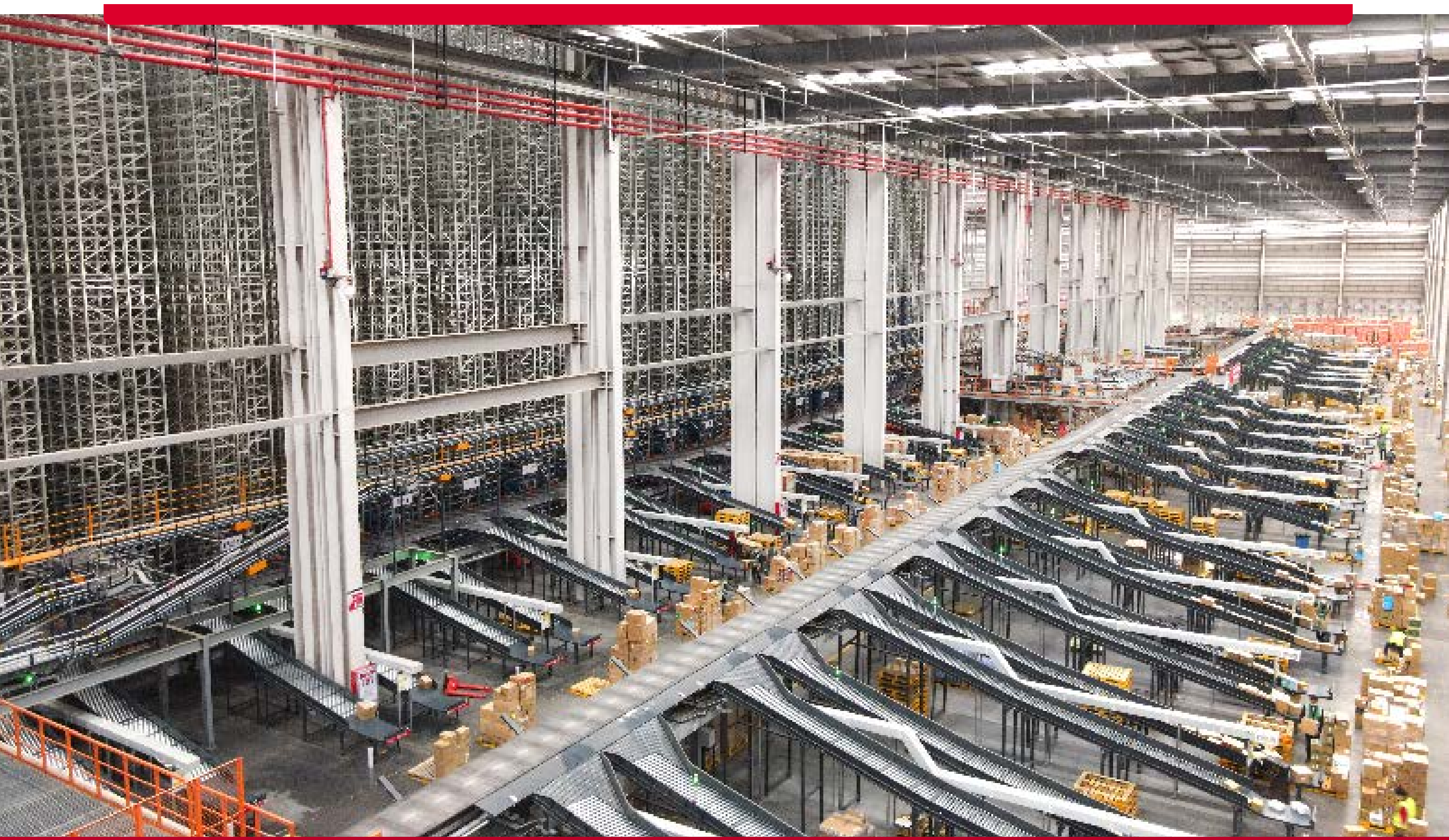
Table V: SLA grading for warehouse scenario

	STACKER CRANES	SHUTTLE CARS	UNMANNED INVENTORY	PACKAGING DAMAGE DETECTION
Latency and rereliability (L)	L3	L3	L1	L1
Uplink bandwidth (U)	U1	U1	U2	U1
Availability (A)	A2	A2	A3	A3
Positioning (P)	P3	P3	/	/
Simplified networking	✓	✓	✓	✓
Network and service collaboration	✓	✓	/	/
Fixed and mobile convergence	✓	/	✓	/

As Table V shows, simultaneous fulfilment of the L3, U1+U1+U2+U1, and P3 is required within the same cellular network. By employing URLLC, 5G LAN, and complementary TDD, the latency and reliability can be 20ms@99.99%. 5G+UWB achieves positioning accuracy of 1-3 meters, enabling efficient and accurate stacking of goods by stacker cranes and shuttle cars. FMC can also help meet the connectivity requirements of stacker cranes and unmanned inventory checks.

Employing a real-time 5G deterministic network in warehousing logistics can decrease the fault handling time by 80%. By replacing complex and expensive wired communications with 5G deterministic communications, the cost of implementing an intelligent warehousing logistics system can fall by approximately US$150,000.

By replacing complex and expensive wired communications with 5G deterministic communications, the cost of implementing an intelligent warehousing logistics system can fall by approximately US$150,000



5.4 Port Operations

In a port, typical use cases for a 5G network include bridge remote control, unpiloted container trucks and automated cargo tallies. The transmission of instructions for bridge remote control and unpiloted container processes requires a network latency and reliability of 20ms@99.99%. The automated cargo tally process requires 50 parallel 2K HD video streams, each of whose uplink bandwidth should be greater than 6 Mbps. To minimise capital expenditure (CAPEX), the existing transport networks of the bridge remote control and Wi-Fi for automated cargo tally need to cooperate with newly built 5G networks.

As shown in Table VI, a 5G deterministic network will need different SLA grades to meet the different requirements of bridge remote control, unpiloted container truck and automated cargo tally.

As Table VI shows, simultaneous fulfilment of the L3 and the U1+U1+U2 is required within the same cellular network. Employing complementary TDD and 5G LAN can achieve latency and reliability of 20ms@99.99%. FRER and redundant UPFs ensure continuous operation of the bridge remote control and unpiloted container truck without interruption. MEC deployed on site provides the AI computing power to ensure high-quality recognition of characters.

The deployment of a 5G deterministic network in port operations can increase the overall operating efficiency by 30% to 30 cycles per hour, and the number of on-site personnel can be lowered by 70%. The capital investment cost of the bridge remote control based on a 5G solution is only about one-tenth of that of optical fibre.

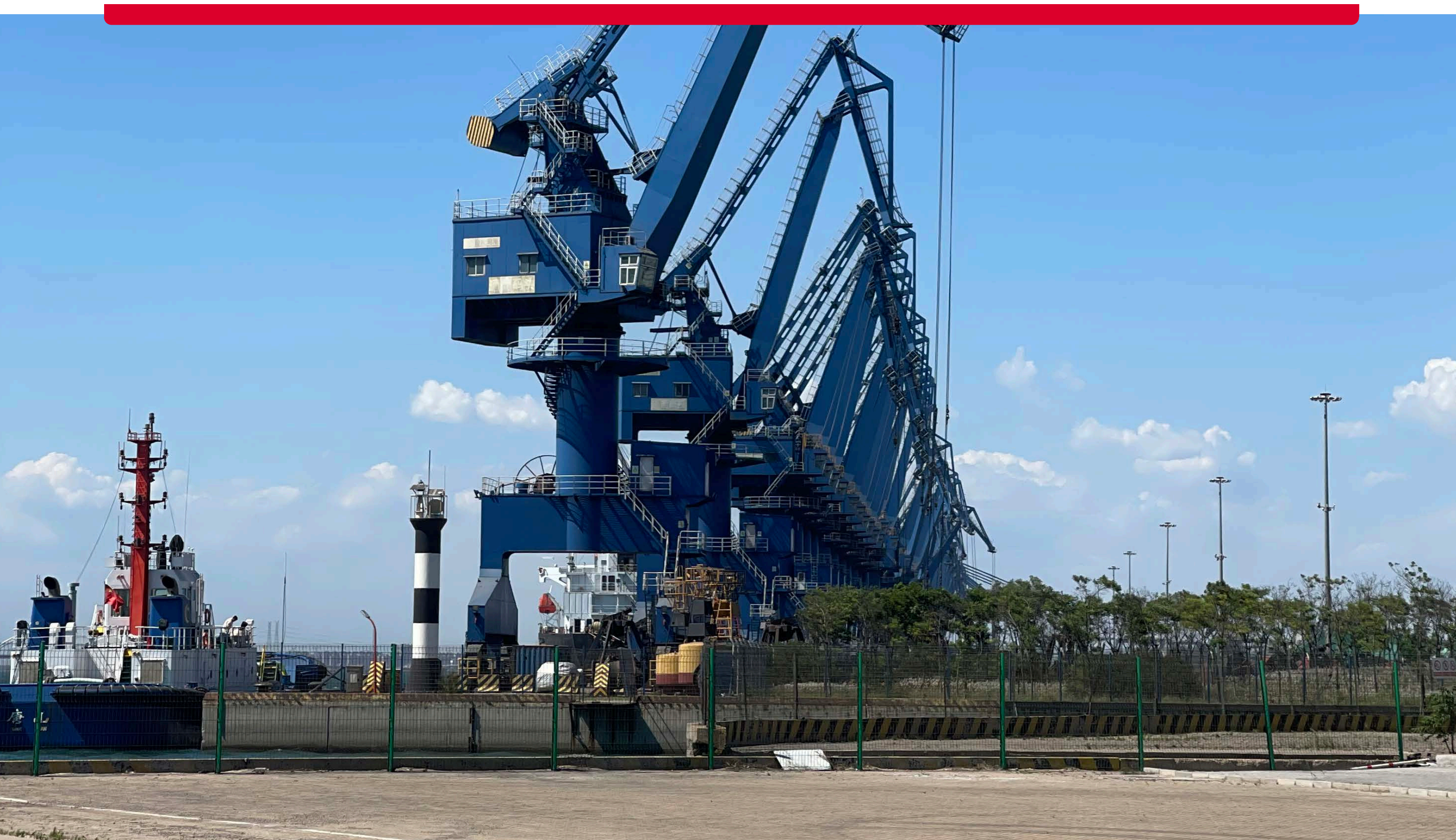


Table VI: SLA grading for port operation scenario

	BRIDGE REMOTE CONTROL	UNPILOTED CONTAINER TRUCK	AUTOMATED CARGO TALLY
Latency and rereliability (L)	L3	L3	L1
Uplink bandwidth (U)	U1	U1	U2
Availability (A)	A3	A3	A2
Simplified networking	✓	✓	✓
Network and service collaboration	✓	✓	/
Fixed and mobile convergence	✓	/	✓

6.0 Conclusions

6.0

Conclusions

5G deterministic network technology is evolving with the needs of industrial applications, as the capabilities of 5G deterministic networks are gradually enhanced and commercialised. However, at present, the integration of 5G deterministic networks into vertical industries is still at the exploration stage.

The protocols and mechanisms of 5G and industries need to be merged to realise the integration of CT with IT and OT. As a result, 5G deterministic networks will continue to deepen the core production links of vertical industries to build successful models that can be copied and generalised to other industries, promoting the digital transformation process.

To meet the growing requirements of different industries, the 6G standardisation process should begin by introducing network native deterministic capabilities.

Abbreviations:

TERM	DESCRIPTION
3GPP	3rd Generation Partnership Project
5G ACIA	5G Alliance for Connected Industries and Automation
5G LAN	5G local area network
5GS	5G System
AGV	automated guided vehicle
AI	artificial intelligence
AII	Alliance of Industrial Internet
BAT	burst arrival time
BS	base station
C2IO	controller to IO
CA	carrier aggregation
CANopen	controller area network open
CT	communication technology
DC	dual connectivity
eMBB	enhanced mobile broadband
ERP	enterprise resource planning
EtherCAT	EtherNet control automation technology
FRER	frame replication and elimination for reliability
IIOT	industrial Internet of things
IRT	isochronous real time communication

TERM	DESCRIPTION
IT	information technology
ITU-T	International Telecommunication Union-Telecommunication Standardization Sector
LMF	location management function
MEC	multi-access edge computing
MES	manufacturing execution system
mMTC	massive machine type of communication
MTBF	mean time between failure
MTTR	mean time to repair
NR	new radio
OT	operational technology
PDCP	packet data convergence protocol
PLC	programmable logic controller
PON	passive optical network
PROFIBUS	process field bus
PROFINET	process field net
pRRU	pico remote radio units
RAN	radio access network
RTC	real time communication
RTT	round trip time

TERM	DESCRIPTION
SCADA	supervisory control and data acquisition
SLA	service level agreement
SUL	supplementary uplink
TDD	time division duplex
TSCAI	time sensitive communication assistance information
TSN	time-sensitive networking
UPF	user plane function
URLLC	ultra reliable and low latency communication

GSMA Head Office
1 Angel Lane
London
EC4R 3AB
United Kingdom
Tel: +44 (0)20 7356 0600
Fax: +44 (0)20 7356 0601