工业互联网产业联盟
Alliance of Industrial Internet

5GACIA

5G-ACIA - All Joint Publication

Technical Evolution and Application of *5G-Advanced* in Industrial Scenarios

5G Alliance for Connected Industries and Automation

Executive Summary

With the advent of 5G-Advanced technology and its enhanced capabilities, it is expected to provide critical support for the evolution of the Industrial Internet. However, there is currently a lack of systematic analysis of the convergence value and implementation pathways of 5G-Advanced in industrial sector. This publication aims to translate technological potential into tangible value and accelerate the innovative development of 5G-Advanced for industrial use cases.

Structured around the framework of "Trends, Technology, Scenarios, and Outlook," this publication first analyzes the emerging network requirements driven by industrial digital transformation, including low latency, high reliability, flexible deployment, adaptability to diverse application scenarios, security, and energy efficiency. It then outlines the key technical characteristics of 5G-Advanced that are relevant to the industrial domain, including deterministic capabilities, positioning and integrated sensing and communication, enhanced RedCap (eRedCap), Ambient IoT, and enhanced uplink bandwidth. The publication then demonstrates how 5G-Advanced enables transformation across key industrial segments, including production operations, inspection and monitoring, warehousing and logistics, and operations management. Representative commercial deployments and pilot cases are examined to illustrate how 5G-Advanced addresses the pain points of the respective industrial applications and delivers tangible benefits.

To address the challenges and accelerate the adoption of 5G-Advanced in the industrial sector, the following recommendations are proposed:

- **Deepen collaborative innovation and enhance product adaptability:** Strengthen multi-stakeholder collaborative innovation across industry, academia, research institutions, and application sectors to address technical bottlenecks, while accelerating the validation of key 5G-Advanced technologies in industrial scenarios.

- **Consolidate product supply and establish benchmarks for promotion:** Establish a comprehensive, full-stack supply ecosystem for industrial-grade products and leverage the exemplary role of benchmark projects that integrate 5G-Advanced with industrial applications.

- **Deepen technological convergence to establish a new paradigm of "Communication, Sensing, Computing, and Artificial Intelligence":** Promote the integration of 5G-Advanced with the Industrial Internet, artificial intelligence, and digital twins.

- **Improve standard systems to eliminate cross-domain collaboration barriers:** Establish closer coordination mechanisms among 3GPP, ITU, and authoritative industry organizations.

- **Innovate business models to lower the barriers to industrial adoption:** Explore flexible service models, such as private network operations and slice-based subscriptions, particularly for Small and Medium-sized Enterprises (SMEs).

- **Strengthen regional adaptation to advance localized implementation:** Promote the localized customization and adaptation of 5G-Advanced industrial application solutions, ensuring the compliance and applicability of technical solutions in global markets.

- **Deepen industry-education integration and strengthen talent cultivation through multiple channels:** Optimize interdisciplinary curriculum design and promote cross-domain internal training within enterprises.

About 5G-ACIA

The 5G Alliance for Connected Industries and Automation (5G-ACIA) was established to serve as the central and global forum for addressing, discussing, and evaluating relevant technical, regulatory, and business aspects with respect to 5G for the industrial domain. It reflects the entire ecosystem and all relevant stakeholder groups, including the operational technology (OT) industry (industrial automation companies, engineering companies, production system manufacturers, end users, etc.), the ICT industry (chip manufacturers, network infrastructure vendors, mobile network operators, etc.), academia, research institutes, and other relevant players. The paramount objective of 5G-ACIA is to ensure the best

possible applicability of 5G technology and 5G networks to the industrial domain. 5G-ACIA's mission is to make sure the interests and needs of the industrial domain are adequately considered in 5G standardization and regulation and that ongoing 5G developments are understood by and effectively transferred to the industrial domain.

About AII

Alliance Industrial Internet (AII) was established by China Academy of Information and Communications Technology (CAICT) with 143 founding member organizations worldwide in 2016. Currently, AII has over 2,800 member organizations, covering industrial internet-related fields such as industrial manufacturing, industrial solutions, ICT, and security. AII has collaborated with its members to promote the development and scale-up application of the industrial internet in all aspects, including top-level design, technology research, standardization, testbeds, industrial practice, international cooperation, talent cultivation, and industry-finance integration. By now, AII has published a series of achievements, including 308 technical reports, 595 application cases and solutions, and 101 testbeds.

https://aii-alliance.org/

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1 Introduction

The enhanced evolution phase of fifth-generation mobile communication technology (5G), known as 5G-Advanced (5G-A), is driving the transformation of 5G from a mere "capability provider" toward "intelligent convergence." By introducing key enhancements such as ultra-low latency, ultra-high reliability, initial integrated sensing and communication capabilities, and built-in artificial intelligence (AI), 5G-A provides a new network foundation for the digital transformation and intelligent upgrading of the industrial sector. Emerging industrial trends, including flexible manufacturing, ubiquitous IoT, digital twins, and AI integration, are placing demands on communication networks that go beyond the capabilities of existing 5G, requiring more extreme performance and highly converged application capabilities.

This publication aims to provide an in-depth exploration of how 5G-A meets the requirements of and drives the development of the next-generation Industrial Internet. It not only analyzes the key technical capabilities of 5G-A but also examines its convergence with industrial applications and its development trajectory across industrial scenarios. The publication provides forward-looking technical insights and practical references for industrial enterprises, telecom operators, equipment manufacturers, and system integrators.

The structure of this publication is as follows: Chapter 2 first analyzes key emerging trends in the current industrial sector and the corresponding requirements these trends impose on communication networks. Chapter 3 elaborates on the key technical capabilities and features of 5G-A that can empower Industrial 5G. Chapter 4 demonstrates, through a series of specific application scenarios, how 5G-A technology addresses real-world industrial pain points and creates new value. Chapter 5 presents representative commercial deployments and pilot case studies where 5G-A technology has been applied. Finally, Chapter 6 summarizes the development trends and challenges of 5G-A applications in the industrial sector and proposes strategic recommendations to promote further adoption and development.

2 Key Trends and Network Requirements of the Industrial Sector

The global industrial landscape is undergoing a profound transformation driven by digitalization and intelligentization. The combined forces of evolving demands and emerging technologies are reshaping production models and operational management practices. This chapter explores key trends emerging across the industrial sector. Together, these trends define the core characteristics of future factories and establish expectations and requirements for the continued advancement of wireless communication technologies.

2.1 Integration of Intelligence and Digitalization to Unleash New Core Industrial Productivity

The industrial sector has evolved from traditional automation toward a new era characterized by the comprehensive integration of data and artificial intelligence. Full-process connectivity, digitalization, and intelligent transformation have become major development trends in the manufacturing industry. Industries such as automotive, electronics, and high-end equipment manufacturing have integrated their entire value chains, spanning R&D, production, quality inspection, logistics, and sales. Digital factories and intelligent production systems have become industry benchmarks, placing higher demands on the overall performance of under-

lying network infrastructure. Locally deployed cellular private networks can effectively address industrial requirements for network stability, low latency, and high security. Deterministic communication, characterized by ultra-low latency, high reliability, and controllable latency, has emerged as a key direction for the commercial deployment of digital and intelligent factories.

2.2 Flexible Manufacturing and Mass Customization for a New Paradigm of Efficient Collaborative Production

Diversified and personalized market demands are driving the manufacturing industry to transition from mass standardized production toward flexible, customized production characterized by small batches and multiple product categories. This shift introduces new challenges for the flexibility and agility of production lines. Mixed-model production has been widely adopted in automotive, new energy equipment, consumer electronics, and other industries. Production lines are required to rapidly adjust process parameters, support the manufacturing of multiple product models, and enable real-time scheduling of intelligent logistics.

Flexible manufacturing and mass customization require underlying networks to provide dynamic adaptability and enable seamless interconnection with Manufacturing Execution Systems (MES) and Industrial Control Systems (ICS). Millisecond-level end-to-end latency and ultra-high communication reliability provide the foundation for equipment collaboration, remote operations, visual quality inspection, and distributed production. Wireless networks equipped with dynamic resource scheduling and Quality of Service (QoS) assurance capabilities serve as a core foundation for flexible production systems.

2.3 Transparent Supervision of Supply Chains to Enhance Industrial Operational Resilience

Against the backdrop of a complex and volatile global environment and economic landscape, building resilient and highly transparent supply chains has become critical for enterprises to maintain stable operations. Real-time collaboration and risk management across regions and business entities remain significant challenges for industrial development, creating strong demands for collaborative networks and information systems.

By leveraging wireless communications, the Internet of Things (IoT), big data, and artificial intelligence, enterprises can build end-to-end transparent supply chain architectures. These architectures enable full lifecycle traceability, in-transit monitoring, early risk warning, and dynamic resource allocation for critical components and production materials, thereby significantly enhancing supply chain resilience.

In key sectors such as power batteries, electronic components, and high-end equipment components, supply chain stability is essential to ensuring uninterrupted production. High-performance communication networks provide a fundamental foundation for intelligent supply chain management.

2.4 Security and Reliability as Primary Prerequisite

As industrial systems become increasingly connected to external networks, cybersecurity and functional safety have become fundamental requirements. Industrial environments require the integration of cybersecurity and physical safety to ensure reliable and secure operations. Any network attack could result in production disruptions, equipment damage, or even safety incidents. An integrated, defense-in-depth cybersecurity system spanning the cloud, network, edge, and devices is essential to ensure the confidentiality, integrity, and availability of production data. Modern wireless technologies provide enhanced security capabilities, establishing a trusted wireless foundation for industrial automation.

2.5 Advancement of Green and Low-carbon Transition to Underpin Enterprises' Long-term Sustainable Strategies

With the comprehensive advancement of carbon neutrality strategies, energy efficiency optimization and green manufacturing have evolved beyond conventional cost control measures and become essential components of enterprises' core competitiveness. Enterprises are deploying extensive sensor networks based on wireless communications to collect real-time energy consumption data from equipment, production lines, and entire facilities. Combined with intelligent algorithms, these networks enable optimized energy utilization and refined carbon footprint management.

Wireless networks offer low power consumption, while their massive machine-type communication capabilities support large-scale energy consumption monitoring across factories. Meanwhile, wireless networking reduces cabling complexity, optimizes production workflows, and enables applications such as remote maintenance and unmanned operations. These capabilities facilitate energy conservation and emission reduction throughout manufacturing processes, providing strong technical support for enterprises to achieve long-term sustainability goals.

3 Key Technical Capabilities and Features of 5G-Advanced for Industrial 5G

3.1 Introduction to 5G-Advanced

5G-Advanced (5G-A), specified from 3GPP Rel-18 onward, represents the enhancement and evolution of fifth-generation mobile communication technology (5G), marking a transition from the "Internet of Everything" to the "Intelligent Internet of Everything" [1]. 5G-A is not merely an incremental improvement in 5G performance metrics; rather, it represents a systematic innovation designed to better address the complex requirements of vertical industries, including the Industrial Internet, smart cities, and autonomous driving. Compared with initial 5G deployments, the core advancement of 5G-A lies in its enhancement of key technological capabilities for industrial scenarios, further driving the evolution of wireless networks from "best-effort" connectivity services toward "assured, measurable, and guaranteed" intelligent infrastructure. It represents a step forward from a single communication function toward the initial realization of integrated capabilities encompassing "Communication, Sensing, and Computing."

In the field of industrial control, 5G-A provides millisecond-level, low-jitter, reliable connections for critical processes, such as high-precision mechanical collaborative control and closed-loop production, by enabling deterministic latency capabilities. This strongly supports the wireless and flexible transformation of industrial systems [2]. Its ultra-high reliability, achieved through air interface enhancements and multi-path redundancy, enables transmission success rates exceeding 99.999%, providing robust support for demanding applications such as smart grid differential protection and industrial automation. At the same time, 5G-A elevates high-precision positioning to a core service capability, achieving centimeter-level accuracy [3] and enabling precise spatial awareness for applications such as terminal equipment tracking.

Furthermore, 5G-A introduces integrated communication and sensing capabilities, enabling communication networks to simultaneously provide environmental perception and target detection capabilities. These capabilities can be widely applied in critical factory scenarios, such as human-machine safety coexistence and trajectory tracking. To reduce IoT

deployment costs, eRedCap and Ambient IoT technologies provide lightweight, low-power, and passive connectivity solutions, respectively, supporting the large-scale deployment of massive sensors and tags and helping build a wide-coverage, sustainable IoT ecosystem. To address the demand for high-definition video surveillance and real-time data uploading in industrial environments, uplink enhancement technologies significantly improve uplink bandwidth through carrier aggregation and supplemental uplink, ensuring smooth transmission of industrial services.

Through multi-dimensional technological innovation, 5G-A provides a robust information and communication foundation for the digital, networked, and intelligent transformation of the industrial sector and broader key industries [4].

Please note that the implementation and availability of 5G-A features in devices and networks will only occur after the relevant 3GPP specifications have been finalized. These features typically span multiple 3GPP Releases and will have different deployment timelines depending on the specific feature.

3.2 Deterministic Capability

In scenarios such as industrial automation and smart grids, where machines communicate with each other, traditional "best-effort" networks can no longer meet stringent requirements for latency, packet loss, jitter, and reliability. To address this challenge, the IETF standardized Deterministic Networking (DetNet) at the IP/MPLS layer, while 3GPP introduced support for DetNet in Rel-18. Building on these developments, 5G-A further leverages 5G radio resources to enable predictable, plannable, and verifiable mobile private networks with end-to-end Change this to: service quality assurance [5].

Among these deterministic capabilities, deterministic latency and ultra-high reliability are particularly critical. Deterministic latency ensures that end-to-end latency remains within strict bounds with controlled jitter, enabling predictable and repeatable transmission performance. Ultra-high reliability bolsters this, by delivering more than 99.999% service availability for industrial control and remote operations. Together, these capabilities support the transition from "communication reachability" to "control reliability," enabling the digital transformation of industrial manufacturing, smart grids, and V2X applications.

A selection of relevant 3GPP documents related to deterministic capability is listed in Table 1.

3.2.1 Key Features

Deterministic capability underpins real-time industrial control and machine collaboration, serving as a key enabler for industrial digital transformation. Its key characteristics are reflected as follows:

(1) Ultra-low and bounded latency:
5G-A reduces end-to-end latency through flexible scheduling and reduced subcarrier spacing, ensuring that the end-to-end transmission delay of data packets remains within a predefined upper limit, even under network congestion scenarios.

(2) Zero/low jitter:
The variation range of transmission latency is strictly controlled within a narrow interval, ensuring consistent and predictable communication performance.

(3) Latency-bound reliability criteria:
It is important to note that reliability must be measured within a specified latency boundary. Data packets exceeding the latency limit are also considered transmission failures. The key performance indicator is a packet loss rate below 10^{-5}, corresponding to packet reliability above 99.999%.

(4) Air interface enhancements:
5G-A leverages mechanisms such as PUSCH retransmission, micro-slot transmission, and robust low-rate MCS/CQI schemes to improve transmission stability while balancing throughput performance.

(5) Multipath redundancy protection:
Through mechanisms such as resource reservation, redundant paths, and multi-link transmission, including PDCP

Table 1: 3GPP Documents Related to Deterministic Capability

3GPP Document	Title	Relevant Content
TS 22.104	Service requirements for cyber-physical control applications in vertical domains	Demands and performance metrics for end-to-end ultra-high reliability services toward vertical industries.
TR 28.865	Study on Deterministic Communication Service Assurance (DCSA)	Study on Deterministic Communication Service Assurance (DCSA)
TR 38.913	Study on scenarios and requirements for next generation access technologies	Evaluated the key performance metrics of ultra-high reliability and the corresponding deployment scenarios
TR 38.824	Study on physical layer enhancements for NR ultra-reliable and low latency case (URLLC)	Physical layer enhancements for NR ultra-reliable and low latency case (URLLC)
TS 28.554	Management and orchestration; 5G end to end Key Performance Indicators (KPI)	Management and orchestration; 5G end to end Key Performance Indicators (KPI)
TR 28.832	Study on management aspects of Ultra-Reliable and Low Latency Communications (URLLC)	Study on management aspects of Ultra-Reliable and Low Latency Communications (URLLC)
TR 22.874	5G System (5GS); Study on traffic characteristics and performance requirements for AI/ML model transfer	Traffic characteristics of AI/ML model transmission services in 5G and its requirements for performance metrics including delay and reliability.
TR 23.700-80	Study on 5G system support for AI/ML-based services	Architectural enhancements supporting ultra-high reliability services in 5G systems
TS 22.261	Service requirements for the 5G system	Defines the general requirements, key performance indicators, and application scenarios for ultra-high reliability services supported in 5G systems.

Source: 5G-ACIA / ZVEI e. V.

packet duplication over dual wireless links, Rel-18 enhances carrier aggregation and dual connectivity capabilities for high-reliability industrial scenarios. Beyond the scope of 3GPP standardization, end-to-end redundancy can be further supported by the FRER protocol defined in TSN (Time-Sensitive Networking).

(6) Deterministic network architecture:
The integration of network slicing and TSN, combined with AI/ML-driven intelligent network management, enables predictable and guaranteed QoS for the Industrial Internet and other critical applications with stringent service requirements.

3.2.2 KPI/Performance Metrics[1]

Deterministic capability refers to the ability of a network to provide predictable and guaranteed communication performance in terms of both latency and reliability for critical services. The end-to-end latency requirement typically ranges from 1 ms to 1 s. The data rate required for user experience may be relatively low, as each transaction typically contains less than 256 bytes. In factory automation scenarios, including motion control, control-to-control communication within motion control systems, mobile robotics, the transition from wired to wireless connections, and cooperative load handling, the control-plane latency target should be at the millisecond level.

1 KPI and performance metrics that are cited throughout Chapter 3 are those as specified in 3GPP specifications

Table 2: Periodic deterministic communication service performance requirements for different typical scenarios (based on TS 22.104 [8])

Scenes	Communication service availability	Communication service reliability: mean time between failures	End-to-end latency: maximum	Service bit rate: user-experienced data rate
Motion Control	99.999 % to 99.999 999 %	~10 years	< 0.5 ms to < 2 ms	
Wired-to-wireless 100 Mbit/s link replacement	99.999 9 % to 99.999 999 %	~ 10 years	< 1 ms	50 Mbit/s
Mobile Operation Panel: Emergency stop	99.999 999 %	1 day	< 8 ms	250 kbit/s
Mobile Operation Panel: Safety data stream	99.999 99 %	1 day	< 10 ms	< 1 Mbit/s

Source: 3GPP

For URLLC, the target user-plane latency for the radio access network (RAN) should be 0.5 ms for uplink (UL) and 0.5 ms for downlink (DL) [6] with a corresponding latency jitter of 1 µs [7]. For the transmission of a single data packet, the general reliability requirement for URLLC is 99.999%.

In Rel-18, 3GPP further advanced research on ultra-high reliability, focusing on feature management, including configuration management and performance measurement, to support future commercial deployment. Rel-19, completed at the end of December 2025, defines more stringent performance targets. The reliability requirement for successfully transmitting a 32-byte packet within 1 ms of user-plane latency is $1–10^{-5}$. Rel-19 also expands the application scope of ultra-high reliability to emerging scenarios, including AI/ML model transmission, by providing a defined performance framework for new critical services. It further investigates time synchronization optimization, intra-system multipath redundancy, user-plane replication, and collaboration with industrial Ethernet and distributed TSN [8]. These enhancements address the urgent need of vertical industries to transition from best-effort services toward deterministic services. Table 2 illustrates the communication service availability requirements for different typical scenarios.

3.2.3 Application to Industrial Scenarios

As industrial digital transformation advances in depth, communication determinism and stability have become core metrics for evaluating the capabilities of industrial networks. With its "committable, measurable, and guaranteed" communication performance, the deterministic capability of 5G-A networks provides a critical wireless technology capability for core industrial production processes, enabling a range of advanced scenarios that were previously difficult to achieve. Key industrial applications include:

(1) High-precision collaborative manufacturing, enabling "wireless" flexible reconfiguration of production lines:
In scenarios such as automotive assembly and consumer electronics manufacturing, multiple robots must perform millisecond-level synchronized collaborative operations within highly constrained spaces.

(2) Closed-loop process control, enabling "wireless" optimization of complex processes:
In continuous production environments, such as precision chemical engineering and semiconductor wafer processing, parameters including temperature, pressure, and flow rate require rapid closed-loop control. Deterministic latency and

Table 3: 3GPP Documents Related to Positioning and ISAC

3GPP Document	Title	Relevant Content
TR 22.837	Study on Integrated Sensing and Communication	Feasibility Study on Integrated Sensing and Communication
TS 22.137	Integrated Sensing and Communication	Service requirements for Integrated Sensing and Communication
TR 38.901	Study on channel model for frequencies from 0.5 to 100 GHz	Study on channel model for frequencies from 0.5 to 100 GHz
TS 22.261	Service requirements for the 5G system	Positioning service levels and KPIs for high-precision positioning
TS 22.104	Service requirements for cyber-physical control applications in vertical domains	Refined requirements for low power high-accuracy positioning for industrial internet scenarios
TR 23.700-86	Study on Architecture Enhancement to support Ranging based services and sidelink positioning	Research on architectural enhancements supporting ranging-based services and sidelink positioning
TR 38.859	Study on expanded and improved NR positioning	Evaluates and quantifies key technologies in high-precision and low-power positioning, including carrier phase positioning, carrier aggregation, RedCap positioning, and side-chain positioning/ranging.
TS 38.305	NG Radio Access Network (NG-RAN); Stage 2 functional specification of User Equipment (UE) positioning in NG-RAN	Introduced and updated advanced measurements and workflows for Release 18 in the NG-RAN UE positioning.
TS 38.355	NR; Sidelink Positioning Protocol (SLPP); Protocol Specification	Defines the NR Sidelink Positioning Protocol, providing the air interface protocol foundation for high-precision relative positioning.
TS 33.533	NR; User Equipment (UE) conformance specification; Radio Resource Management (RRM)	Defines the security mechanism for the ranging/ sidelinking positioning service

Source: 5G-ACIA / ZVEI e. V.

ultra-high reliability together ensure that control commands and feedback data are delivered within strict latency and reliability boundaries, supporting stable and precise process optimization.

(3) Large-scale mobile device scheduling, building a "non-interrupted" intelligent logistics system:

In large warehouse logistics centers, modern ports, factories, and open-pit or underground mines, hundreds or thousands of autonomous vehicles, unmanned transport trucks, loading equipment, and mobile robots need to be simultaneously scheduled and operated. The deterministic capability of 5G-A provides a stable and predictable communication foundation for these complex mobile systems.

3.3 Positioning and Integrated Sensing and Communication

Integrated Sensing and Communication (ISAC) in a 3GPP 5G system refers to the integration of sensing capabilities into the same wireless infrastructure used for communication, enabling the convergence of communication, sensing, and computing capabilities. The high-precision positioning technology of 5G-A achieves higher-resolution time, spatial, and beam measurements through the air interface, thereby enabling precise terminal location awareness.

By combining positioning and ISAC capabilities and coordinating with Global Navigation Satellite System (GNSS) and local networks, 5G-A delivers more refined positioning ser-

vices than traditional cellular networks and standalone GNSS solutions. More broadly, ISAC extends beyond positioning by enabling communication-assisted sensing and sensing-assisted communication, creating a bidirectional enhancement capability that represents the key distinction of ISAC compared with standalone positioning or radar systems.

A selection of relevant 3GPP documents related to positioning and ISAC is listed in Table 3.

3.3.1 Key Features

5G wireless sensing is a technology enabler for acquiring information about environmental characteristics and/or objects within an environment [9]. It uses radio waves to determine parameters such as the distance (range), angle, and instantaneous linear velocity of objects. The 5G wireless sensing service relies on analyzing the transmission, reflection, and scattering of wireless sensing signals.

(1) Wireless sensing technology:
Wireless sensing aims to acquire information about remote objects and their characteristics without requiring direct communication with the objects. It leverages sensing data to extract meaningful insights about the surrounding environment.

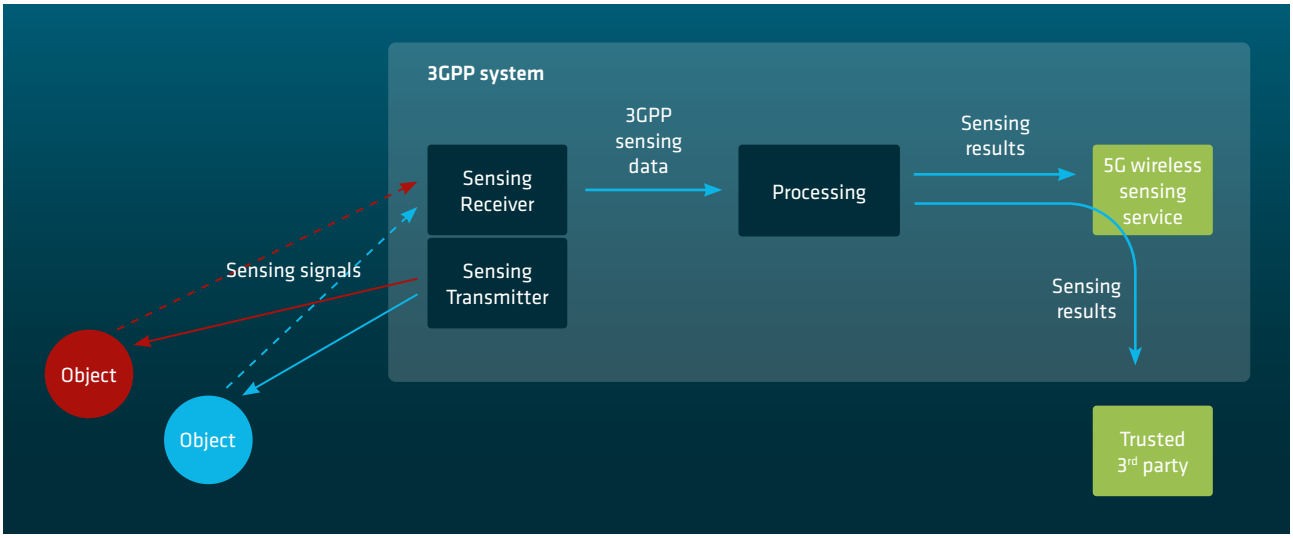
(2) High-precision sensing and positioning:
With sub-meter or even centimeter-level positioning and tracking accuracy, the technology can detect target attributes such as speed and posture, providing critical environmental information for a wide range of integrated applications.

(3) Integrated communication and sensing design:
Featuring native integration across air interface signals, frame structures, and network architectures, this design enables coordinated scheduling of sensing and communication tasks, as well as real-time processing of multi-dimensional data. It delivers unified services to upper-layer applications. An example of sensing with co-located sensing receiver and sensing transmitter is shown in Figure 1.

3.3.2 KPI/Performance Metrics

Radio frequency sensing functionality enables device-free object localization, eliminating the need for objects to be connected through devices within the network. By leveraging NR radio frequency signals, parameters such as signal strength,

Figure 1: Example of sensing with co-located sensing receiver and sensing transmitter [10]



Source: 3GPP

delay, Doppler, and angle spectrum information can be estimated from scattered and/or reflected radio frequency signals transmitted and received by RAN nodes or UEs. Through the processing of these radio frequency signals, object-related features, including location, velocity, and geometric information, can be extracted and further exposed to different applications together with contextual information.

The capability to obtain range, velocity, and angle information from radio frequency signals enables a broad range of new functionalities, including object detection, object recognition (e. g., vehicles, humans, AGVs), high-accuracy localization, tracking, and activity recognition. The performance requirements for 5G wireless sensing are shown in Table 4.

3.3.3 Application to Industrial scenarios

5G-A ISAC technology enables real-time sensing of objects, spaces, and movements in the surrounding environment. In industrial applications, it primarily addresses two key challenges: safety and efficiency. The applications in industrial scenarios are described below.

(1) High-precision positioning and AGV control:
ISAC enables real-time measurement of AGV speed, posture, and location. Multiple base stations can perceive road conditions and obstacles along planned routes, enabling dynamic control of speed and direction at intersections and in safe operating areas. High-precision positioning further supports applications such as tool tracking, mobile control panel positioning, navigation for monitoring systems, production process optimization, personnel safety, and equipment coordination.

(2) Intelligent quality inspection:
With its high-resolution sensing capabilities, ISAC can support non-contact defect detection. By analyzing reflected signals to construct a digital twin of a component's surface, ISAC can achieve micron-level detection accuracy.

(3) Vibration monitoring and predictive maintenance:
Vibration monitoring is essential in industrial environments to maintain machinery health and operational efficiency. In factories equipped with ISAC-enabled mobile networks, RF signals can measure vibrations, transmit data, and provide actionable insights for operators. For example, 5G-A base stations can detect micro-deformations in mechanical bearings, enabling failure prediction and proactive maintenance to reduce downtime.

In addition, 5G-A ISAC technology can support micro-deformation monitoring in critical areas such as large-scale industrial plants and heavy machinery workshops. By capturing RF signal scattering and phase variations, the technology enables real-time, contactless monitoring of millimeter-level subsidence, micro-tilting, and micro-cracks. This capability provides precise support for ensuring production safety and optimizing operations and maintenance.

(4) Port and ship management:
The application of 5G-A ISAC in port and ship monitoring can improve ship berthing efficiency and reduce collision risks through collaborative perception.

3.4 eRedCap

With increasing demands for "lower power consumption, improved cost efficiency, and more precise rate adaptation" in scenarios such as industrial wireless sensor data collection and smart grid load control, the performance limitations of RedCap have become increasingly apparent. Against this backdrop, eRedCap, which can be regarded as a further simplified evolution of RedCap, has emerged [11].

Building on the core advantages of RedCap, such as "low complexity and low cost," eRedCap further optimizes terminal power consumption, hardware costs, and scenario adaptability through multi-dimensional technological enhancements, including bandwidth compression, extended eDRX periods, and precise peak rate control. These improvements address the industrial sector's requirements for wireless connectivity with "low cost, low power consumption, and high reliability," making eRedCap a lightweight technology foundation for enabling the digital transformation of vertical industries through 5G-A.

Table 4: Performance requirements for 5G wireless sensing (based on TS 22.137 [10])

Scenario	Sensing service category	Confidence level [%]	Accuracy of positioning estimate by sensing (for a target confidence level)		Accuracy of velocity estimate by sensing (for a target confidence level)		Sensing resolution		Max sensing service latency[ms]	Missed detection [%]	Sensing service description in a target sensing service area
			Horizontal [m]	Vertical [m]	Horizontal [m/s]	Vertical [m/s]	Range resolution[m]	Velocity resolution (horizontal/ vertical)[m/s x m/s]			
Object detection and tracking	1	95	10	10	N/A	N/A	10	5	1000	5	Indoor/outdoor (e. g., detection of human, UAV)
	2	95	2	5	1	N/A	1	1	1000	0.1 to 5	Outdoor (e. g., detection of human, UAV)
	3	95	1	1	1	1	1	1 x 1	100 , or 1000; 5000 for detection in highway	2	Indoor/outdoor (e. g., detection and tracking of human, animal, UAV)
	4	99 for public safety, otherwise, 95	0.5	0.5	1.5 for pedestrian, 15 for vehicle, otherwise, 0.1	1.5 for pedestrian	0.5	0.5 x 0.5 for factories	100 to 5000	1	Indoor/outdoor (e. g., detection and tracking of human, animal, UAV, AGV, vehicle)
Environment monitoring	5	95	10	0.2	N/A	N/A	N/A	N/A	60000	0.1 to 5	Nature of environments monitored by sensing (e. g. rainfall, flooding monitoring)
Motion monitoring	6	95	N/A	N/A	N/A	N/A	N/A	N/A	60000	5	Human motions and activities obtained by sensing
	7	95	0.2	0.2	0.1	0.1	0.375	0.3	5 to 50	5	Human hand gestures obtained by sensing

Source: 3GPP

eRedCap provides a smooth migration path for existing 4G medium-to-low-speed IoT scenarios toward 5G-A. In terms of 3GPP IoT device capabilities and complexity, eRedCap is positioned as follows (from low to high capability and complexity; see also Figure 2):

NB-IoT/LTE-M (mMTC) < eRedCap < RedCap < eMBB/URLLC

eRedCap fills the gap between "medium-low-end, medium-rate, and low-cost" IoT connectivity, enabling operators to support a broad range of IoT requirements—from ultra-low-speed to ultra-high-speed applications—within a single 5G-A network.

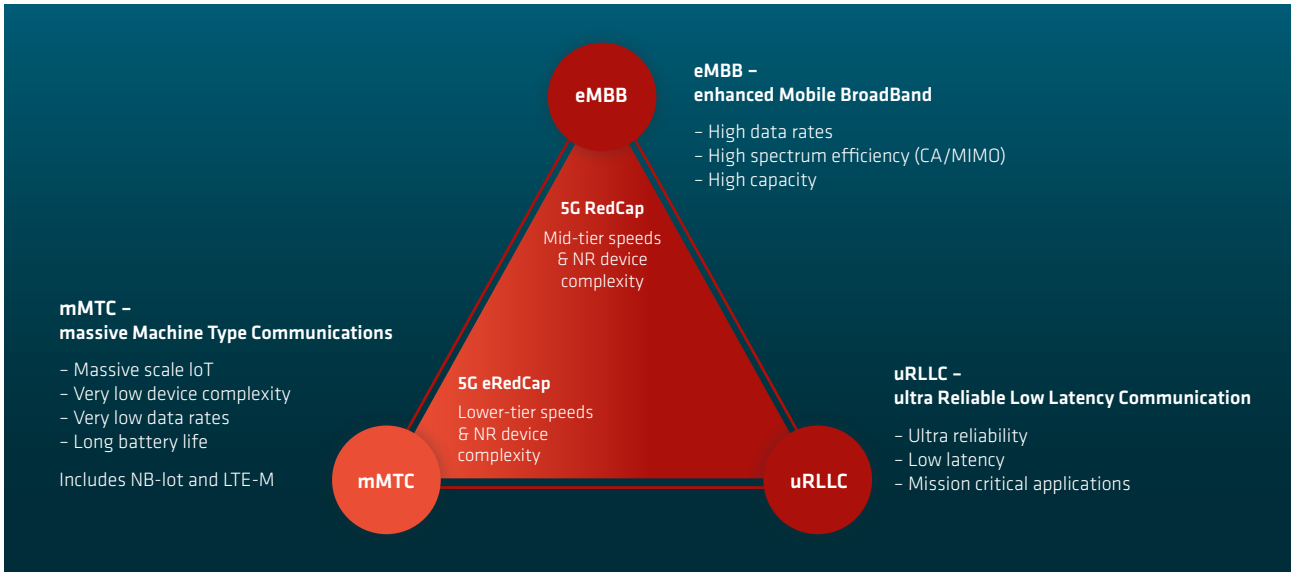
A selection of relevant 3GPP documents for eRedCap is listed in Table 5.

Table 5: 3GPP Documents Related to eRedcap

3GPP Document	Title	Relevant Content
TR 38.865	Study on further NR RedCap UE complexity reduction	Further NR RedCap UE complexity reduction for Rel-18 low-tier NR devices.
TR 23.700-68	Study on support for reduced capability NR devices; Phase 2	Study on enhancements supporting reduced capability NR devices (eRedCap)
TS 38.101-1	NR; User Equipment (UE) radio transmission and reception; Part 1: Range 1 Standalone	User Equipment (UE) radio transmission and reception; Range 1 Standalone
TS 38.306	NR; User Equipment (UE) radio access capabilities	User Equipment (UE) radio access capabilities
TS 38.331	NR; Radio Resource Control (RRC); Protocol specification	Radio Resource Control (RRC) protocol specification

Source: 5G-ACIA / ZVEI e. V.

Figure 2: RedCap/eRedCap in relation to 5G key scenario technology capabilities [12]



Source: GSMA

3.4.1 Key Features

The key features of eRedCap are centered on cost reduction, improved efficiency, and adaptability across different scenarios. These features include both the baseline capabilities inherited from 5G RedCap [13] and the new or enhanced capabilities introduced exclusively for 5G-A. eRedCap retains the core capabilities of 5G RedCap, including native compatibility with the 5G SA network architecture and support for network slicing. In addition, eRedCap introduces the following targeted optimizations and new features:

1. **Optional narrower transmission bandwidth:** For eRedCap UEs that support this optional capability, the PDSCH and PUSCH bandwidth used for data transmission can be reduced to 5 MHz, enabling lower device complexity and cost.

2. **Peak rate adjustment:** By relaxing the peak rate limit and restricting the maximum transport block size and the number of physical resource blocks allocated to the data channel, the peak data rate is reduced to 10 Mbit/s for both the uplink and downlink. This better aligns with low-data-rate industrial scenarios while avoiding unnecessary resource consumption.

3. **Enhanced power optimization:** Initially introduced as part of the Rel-17 RedCap work item and further enhanced in the Rel-18 eRedCap work item, support for an extended eDRX cycle in the non-active state is available for NR UEs, including both RedCap and eRedCap UEs. The eDRX cycle can be extended to as long as 10,485.76 seconds, allowing the terminal to remain in a low-power sleep state for the majority of the time. Through coordination between the core network and the RAN during the UE sleep period, data transmission can be managed more efficiently, balancing communication performance with optimized energy consumption.

3.4.2 KPI /Performance Metrics

Compared with RedCap [14], eRedCap further reduces non-essential capabilities, lowering terminal complexity and cost while maintaining the inherent low-latency and high-reliability advantages of the 5G network.

A summary of the differences between RedCap and the further simplified eRedCap features is provided in Table 6.

3.4.3 Application to Industrial scenarios

Specifically designed for large-scale industrial IoT scenarios, eRedCap achieves an effective balance between performance and complexity by streamlining 5G NR functionality. It meets the communication requirements of a wide range of "lightweight" yet "critical" industrial applications. In practical deployments, the value of eRedCap extends across the entire industrial value chain:

1. **Wireless sensor networks:** Vibration, temperature, pressure, and flow sensors distributed throughout industrial sites provide the data foundation for predictive maintenance and process optimization. eRedCap enables high-frequency, high-precision sensor data to be transmitted reliably and in real time to cloud or edge platforms for analysis.

2. **Flexible manufacturing and mobile devices:** Automated warehouses and flexible production lines rely on large numbers of AGVs and AMRs that require stable mobility management and seamless handover capabilities. eRedCap supports precise navigation, collaborative scheduling, and real-time control of mobile robots in complex industrial environments, ensuring production continuity and operational efficiency.

3. **Predictive maintenance:** The rate-optimized design of eRedCap supports the wireless transmission of high-frequency equipment waveform data, partial discharge detection data, and other high-volume operational information. Combined with AI algorithms

Table 6: Summary of Technical Differences between RedCap and eRedCap

Key Metrics	RedCap (R17)	eRedCap (R18)
Peak Rate	DL 150-220 Mbit/s UL 50-120 Mbit/s	DL/UL ≈10 Mbit/s
Max Channel Bandwidth	20 MHz (FR1) / 100 MHz (FR2)	5 or 20 MHz (FR1 only)
Antenna Configuration	1R*1T or 2R*1T optional MIMO	1R*1T or 2R*1T optional MIMO
Duplex Mode	Half-duplex FDD / Full-duplex FDD / TDD	Half-duplex FDD / Full-duplex FDD / TDD
Modulation	64 QAM mandatory 256 QAM optional	64 QAM mandatory 256 QAM optional
Power Saving	RRC-Idle eDRX up to ~3 h RRC-Inactive eDRX up to ~10 s in R17 and up to ~3 h in R18	RRC-Idle eDRX up to ~3 h RRC-Inactive eDRX up to ~3 h
Voice/Slicing	VoNR, network slicing	VoNR, network slicing
Module Cost	Medium (like LTE Cat-4)	Low (like LTE Cat-1)

Source: 5G-ACIA / ZVEI e. V.

deployed at the edge, this enables enterprises to predict equipment failures more accurately, shifting from scheduled maintenance to predictive maintenance while significantly reducing unplanned downtime and extending equipment lifecycles.

3.5 Ambient IoT

Ambient IoT, a technology introduced as part of 5G-A, differs from traditional cellular standards by focusing on end-device innovation rather than core network optimization. Conventional cellular networks primarily aim to maximize bandwidth, minimize latency, and ensure reliable communications. Their primary objective is to support the transmission of large volumes of data, while the convenience of end devices is often a secondary consideration. In contrast, Ambient IoT leverages ambient energy harvesting to replace conventional power sources. Combined with a highly simplified backscatter architecture, this enables ultra-low-power data transmission while eliminating the need for wired power or batteries.

This approach offers two key advantages. First, the significantly simplified architecture and batteryless design eliminate the operational burden associated with battery replacement and disposal. Second, these characteristics enable maintenance-free operation in large-scale and hard-to-access industrial manufacturing and logistics environments. A selection of relevant 3GPP documents for Ambient IoT is listed in the Table 7.

3GPP introduced the conceptual framework for Ambient IoT in Rel-18. Rel-19, finalized by the end of 2025 with commercial deployment anticipated in 2026, established backscatter communication as the primary operating mechanism and defined the integration framework for cellular networks.

Table 7: 3GPP Documents Related to Ambient IoT

3GPP Document	Title	Relevant Content
TR 22.840	Study on Ambient power-enabled Internet of Things	Study on Ambient IoT application requirements.
TR 38.848	Study on Ambient IoT (Internet of Things) in RAN	Study on Ambient IoT in RAN
TR 38.769	Study on solutions for Ambient IoT (Internet of Things) in NR	Study on solutions for Ambient IoT in NR
TS 38.291	NR; Ambient IoT Physical layer	Specifies the physical layer for Ambient IoT
TS 38.391	NR; Ambient IoT Medium Access Control (MAC) protocol	Specifies the Medium Access Control (MAC) protocol for Ambient IoT
TS 38.191	NR; Ambient IoT device radio transmission and reception	Ambient IoT device radio transmission and reception
TS 38.194	NR; Ambient IoT Base Station (BS) and Carrier-Wave (CW) node radio transmission and reception	Ambient IoT Base Station (BS) and Carrier-Wave (CW) node radio transmission and reception
TS 23.369	Architecture support for Ambient power-enabled Internet of Things; Stage 2	Architecture support for Ambient power-enabled Internet of Things
TS 33.369	Security for Ambient IoT (Internet of Things)	Security aspects of ambient IoT services in 5G

Source: 5G-ACIA / ZVEI e. V.

3.5.1 Key Features

Ambient IoT is built on enhancements to the communication network. To support Ambient IoT tag reading, the 5G cellular network must be upgraded accordingly. Compared with conventional cellular networks, the key changes are reflected in two areas:

1. **More diverse air-interface topology:** Rel-19 supports direct UE-to-base-station communication, while Rel-20 introduces relay functionality to enable indirect communication and extended coverage. This provides greater networking flexibility for large-scale deployments.

2. **Simplified core network architecture:** Conventional 5G procedures are too complex for Ambient IoT devices, making a lightweight architectural approach necessary. As shown in [15][16], the base station acts as the reader/writer, while the Ambient IoT Function (AIoTF) is responsible for managing device-related information, processing signaling messages, and integrating operational results [17]. AIoTF can communicate directly with the Radio Access Network (RAN) or forward and exchange signaling messages and service data through the Access and Mobility Management Function (AMF). Based on this architecture, Ambient IoT devices do not require complex functions such as session management or policy management, simplifying interactions between the devices and the network and effectively reducing device complexity.

The key features of Ambient IoT include:

1. **Technical performance:** Ambient IoT relies on short-range communication (10–50 m indoors, as defined in 3GPP TR 38.848) between Ambient IoT devices and reader nodes. It can share spectrum resources with 5G and reuse parts of the existing 5G network infrastructure.

2. **Service capabilities:** Ambient IoT enables scalable and unified management of massive numbers of devices, with built-in support for interoperability and security. By leveraging the 5G core network, it provides end-to-end service integration across industry value chains, supporting both Business-to-Business (ToB) and Business-to-Consumer (ToC) scenarios.

3. **Deployment:** Ambient IoT supports co-deployment with existing cellular infrastructure, minimizing additional hardware requirements and network upgrade costs. This enables efficient infrastructure reuse and delivers "multiple functions within a single network."

3.5.2 KPI/Performance Metrics

To address diverse deployment requirements, 3GPP Rel-19 defines two distinct Ambient IoT device types based on their energy consumption and functional capabilities. These device types are primarily differentiated by their power profiles and supported functionality:

1. Device Type 1
   - Power: Basic device type, with peak power consumption of 1–10 microwatts (μW).
   - Mechanism: Operates entirely on RF energy harvesting. For the uplink (UL), it uses an external carrier for backscatter modulation.
2. Device Type 2a
   - Power: Enhanced device type, with peak power consumption of approximately 100 μW.
   - Mechanism: Can be powered by either RF energy harvesting or other external energy harvesting sources. Signal amplification for the uplink (UL) and/or downlink (DL) is optional. The UL signal can be generated either independently or through an external backscatter carrier.

The technical performance requirements for Ambient IoT devices are summarized in Table 8.

Because Ambient IoT differs fundamentally from traditional cellular networks, a new set of network KPI metrics should be defined based on its unique characteristics and the requirements of specific application scenarios.

1. **Inventory Accuracy:** Inventory accuracy is defined as the percentage of Ambient IoT devices that are successfully read or recognized relative to the total number of devices to be read or recognized during the system inventory process. This is one of the most critical performance metrics for Ambient IoT networks, as high reading accuracy is essential for reliable operation.

2. **Read Rate:** Read rate typically refers to the group read rate of Ambient IoT devices, defined as the number of devices successfully read per unit of time. This metric directly reflects overall system efficiency, particularly in

Table 8: Technical performance requirements of Ambient IoT devices

Type	Communication Mode	Frequency Band	Tag Transmit Power (dBm)	Communication Distance (m)	Power Consumption	Energy Harvesting/ Power Method
Type 1	Backscatter Communication	Sub-1 GHz	-30	30-50	1 μW	RF Energy
Type 2a	Backscatter Communication	Sub-1 GHz	-45	150-200	500 μW	RF Energy

Source: 5G-ACIA / ZVEI e. V.

high-density deployment scenarios such as warehouse inventory management, where it has a direct impact on application performance and operational efficiency.

3. **Positioning Accuracy:** Positioning accuracy refers to the precision with which the location of an Ambient IoT device can be estimated based on its signal (for example, the positioning error range). The importance of this metric depends on the specific industry application. For example, in warehouse environments, high positioning accuracy enables pallets or goods to be located quickly within designated storage areas during inventory operations, improving search efficiency and overall warehouse management.

3.5.3 Application to Industrial Scenarios

Ambient IoT is creating a new ecosystem for intelligent connectivity through its low-power operation, ease of deployment, and maintenance-free design.

1. **Smart industrial parks:** Ambient IoT connects personnel, materials, and vehicles while supporting flexible indoor and outdoor deployment. It enables real-time inventory visibility and precise scheduling, ensuring that goods are delivered to the right place at the right time. As a result, it optimizes space utilization and improves overall supply chain efficiency.

2. **Smart logistics:** Ambient IoT enables full lifecycle management of parcels and goods, from production through delivery. It supports real-time inventory monitoring and dynamic inventory updates, improving decision-making for replenishment and production planning. In addition, it provides accurate asset positioning, enabling rapid retrieval of goods and reducing operational delays, thereby enhancing overall logistics efficiency.

3.6 Enhanced Uplink Bandwidth

Enhanced Uplink Bandwidth in 5G-A is a key set of technologies designed to address the uplink rate limitations of traditional 5G systems, which have historically prioritized downlink performance to support mainstream content consumption requirements.

To meet the increasing uplink capacity demands of applications such as industrial automation, intelligent surveillance, ultra-high-definition live streaming, and immersive XR interactions, 5G-A dynamically allocates additional spectrum and time-frequency resources to the uplink. This is achieved through technologies including Uplink Carrier Aggregation (Uplink CA), Supplementary Uplink (SUL), and Dual Connectivity, significantly improving peak uplink rates, spectral efficiency, and network capacity while enabling a more balanced evolution of uplink and downlink user experiences.

A selection of relevant 3GPP documents for enhanced uplink bandwidth is listed in Table 9.

3.6.1 Key Features

5G-A supports various combinations of Supplementary Uplink, Carrier Aggregation, Dual Connectivity, and multi-band operation. These technologies are essential for achieving higher uplink throughput, broader coverage, and improved cell-edge user throughput.

1. **Supplementary Uplink:** A UE can be configured with an additional Supplementary Uplink (SUL) paired with FDD UL/DL or TDD bidirectional carriers. Unlike aggregated uplink transmission, SUL uses time-division transmission rather than simultaneous transmission, significantly improving uplink coverage, transmission speed, and cell-edge connection reliability.

Table 9: 3GPP Documents Related to Enhanced Uplink Bandwidth

3GPP Document	Title	Relevant Content
TR 38.719-01-01	Rel-19 NR intra-band CA combinations	Specifies the baseline system configuration, channel model, and core parameter specifications for Enhanced Uplink in FR1 (sub-6GHz).
TR 38.719-02-01	Rel-19 NR inter-band CA/DC configurations including inter band CA for 2 different bands DL with up to 2 different bands UL	Provides system-level and link-level performance evaluation results of FR1 Enhanced Uplink technologies
TR 38.719-03-01	Rel-19 NR inter-band CA/DC configurations including inter band CA for 3 different bands DL with x different bands UL(x=1,2)	Evaluates the performance of Enhanced Uplink technologies in FR2 (millimeter wave).
TR 38.719-00-00	Rel-19 SUL configurations and CA band combinations with SUL(s)	Defines the overall scope, core objectives, and technical framework of NR Enhanced Uplink.
TS 38.101-1	NR; User Equipment (UE) radio transmission and reception; Part 1: Range 1 Standalone	Specifies the mandatory RF transmission and reception performance requirements for FR1 standalone UEs supporting Enhanced Uplink.
TS 38.101-2	NR; User Equipment (UE) radio transmission and reception; Part 2: Range 2 Standalone	Defines the RF performance specifications for FR2 standalone UEs with Enhanced Uplink capabilities.
TS 38.101-3	NR; User Equipment (UE) radio transmission and reception; Part 3: Range 1 and Range 2 Interworking operation with other radios	Specifies the RF and interworking requirements for UEs supporting both FR1 and FR2 Enhanced Uplink.

Source: 5G-ACIA / ZVEI e. V.

2. **Carrier Aggregation:** As a core technology for bandwidth expansion and rate enhancement, Carrier Aggregation enables UEs to simultaneously transmit and receive over multiple component carriers, aggregating bandwidth of up to hundreds of MHz (continuous/non-continuous, intra/inter-band). This significantly improves uplink and downlink peak data rates, enhances spectrum utilization, and increases overall network capacity.

3. **Dual Connectivity and multi-band operation:** A UE maintains simultaneous connections to two base stations to utilize uplink resources across different frequency bands. This provides more robust coverage and higher uplink throughput while improving network reliability and the cell-edge user experience.

3.6.2 KPI/Performance Metrics

5G-A enhances uplink throughput through technologies such as Supplementary Uplink (SUL), Carrier Aggregation (CA), and Dual Connectivity (DC), supporting various combinations of these technologies.

Key performance metrics include band combination configurations, uplink Resource Block (UL RB) limits for Reference Sensitivity (REFSENS) testing, and core RF requirements, including additional maximum power reduction, maximum output power, and reference sensitivity.

For inter-band Carrier Aggregation with uplink transmission configured on two NR bands, the occupied bandwidth is defined for each component carrier. Occupied bandwidth is defined as the bandwidth containing 99% of the total integrated mean power of the transmitted spectrum within the assigned channel bandwidth of the component carrier [18].

For intra-band contiguous Carrier Aggregation, the throughput of each component carrier shall be ≥95% of the maximum throughput of the reference measurement channels [18].

3.6.3 Application to Industrial Scenarios

5G-A significantly enhances uplink data rates, which is critical for industrial applications requiring real-time transmission of large volumes of data. Key use cases include high-definition video upload, advanced industrial control, and large-scale Internet of Things (IoT) deployments.

1. **Machine vision quality inspection systems:** Enhanced uplink bandwidth enables real-time upload of HD production-line video streams for AI-based defect detection, reducing inspection failure rates and lowering manual inspection labor costs for enterprises.
2. **Mining and energy:** These industries often operate in large-scale and harsh environments, requiring reliable high-bandwidth uplink capabilities to ensure safety and operational efficiency. In open-pit coal mining, unmanned mining trucks equipped with multiple cameras require high uplink capacity to support simultaneous remote control, HD video retrieval, and autonomous driving operations.
3. **Smart grid monitoring:** Smart meters, phasor measurement units (PMUs), and grid sensors transmit high-frequency (100+ Hz) data for power flow monitoring and fault detection. These capabilities improve grid stability, reduce outages, and enable demand response optimization.

4 Application Scenarios of 5G-Advanced for Industrial 5G

As an evolution of 5G, 5G-Advanced leverages capabilities such as multi-gigabit speeds, millisecond-level latency, massive connectivity, and high-precision positioning to enable critical value creation across the industrial sector [19]. The application framework of 5G-A in industry is illustrated in Figure 3, which is structured into four layers: the terminal layer, network layer, platform layer, and application layer.

5G-A accelerates transformation across key industrial domains, including production operations, inspection and monitoring, warehousing and logistics, and operations management, enabling the following typical application scenarios.

4.1 Application Scenarios in Production Operations

Typical applications of 5G-A in industrial production environments primarily include on-site assisted assembly, industrial production process management, industrial-grade embodied intelligence systems, new industrial control systems, and remote equipment control.

4.1.1 On-site Assisted Assembly

4.1.1.1 Scenario Description

On-site assisted assembly leverages devices such as AR/VR glasses and smart terminals to capture real-time production data. The collected data is transmitted through the network

to an auxiliary system for processing. The system then generates operational guidance information, such as overlaid augmented images or visualized assembly instructions, and delivers it back to the terminal device. This enables workers to accurately assemble complex equipment while supporting functions such as real-time remote expert guidance and synchronized blueprint delivery.

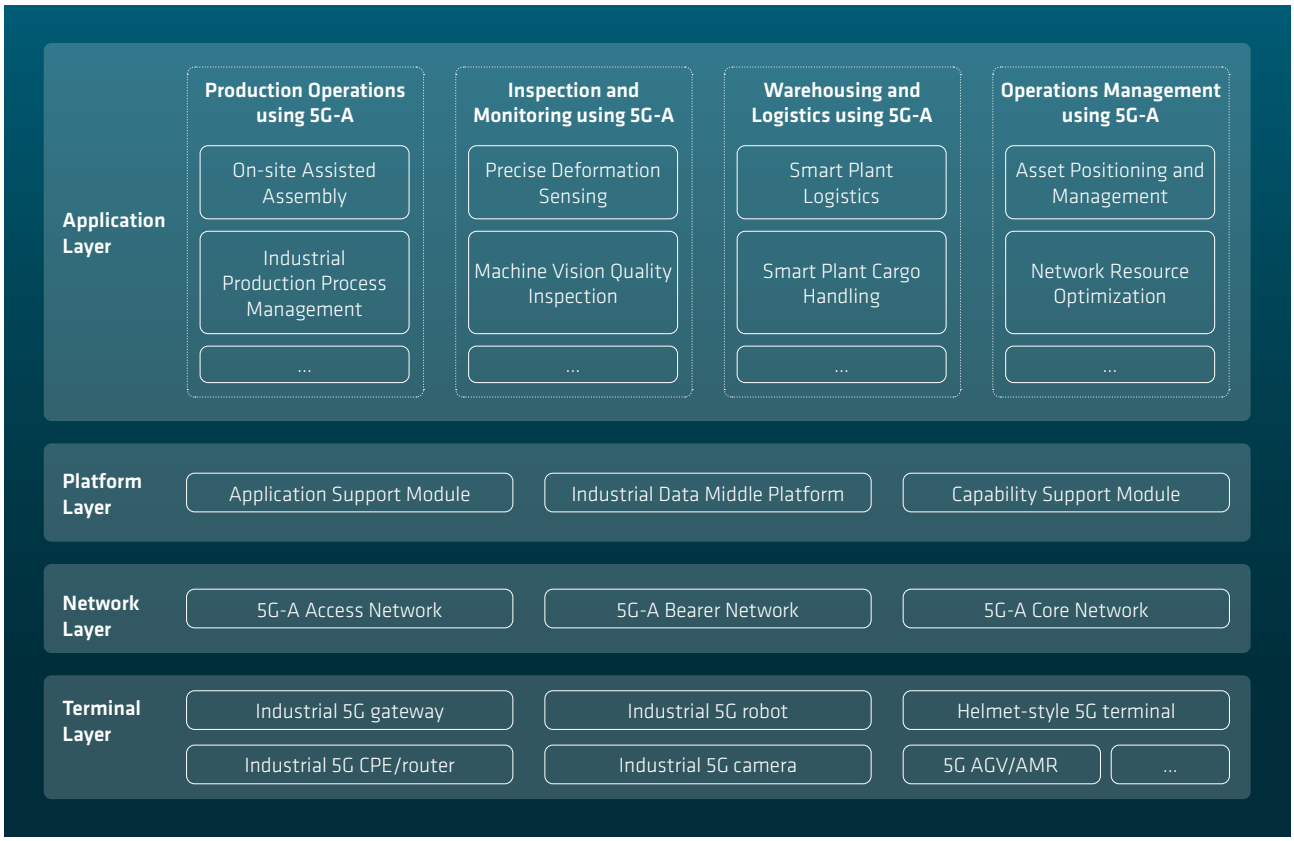
This application scenario presents significant challenges in network transmission bandwidth, latency, and reliability:

1. **High bandwidth requirements:** High-resolution models, blueprints, and real-time video streams require substantial network bandwidth. Transmitting single-stream XR content at 8K resolution and 120 FPS requires bandwidth exceeding 100 Mbit/s. Higher resolutions, such as 16K and 24K, impose exponentially greater bandwidth requirements, exceeding 1 Gbit/s.

2. **Low latency requirements:** Latency exceeding 20 ms can cause motion sickness or discomfort. To ensure a seamless real-time interactive experience, millisecond-level latency is essential.

3. **Transmission reliability:** The loss of critical intra-coded frames within an XR video stream can lead to cascading decoding failures for subsequent predictive-coded frames and bi-directionally predicted frames. Intra-coded frames serve as independent key frames that provide complete images and decoding references. Predictive-coded frames achieve data compression by recording differences relative to preceding frames, while bi-directionally

Figure 3: 5G-A in industrial applications



Source: All

predicted frames leverage differences from both preceding and succeeding frames to achieve the highest compression efficiency. Such frame losses can result in prolonged screen freezing or video stuttering.

4.1.1.2 Capability Enhancements Brought by 5G-A

1. **Ultra-high data rates:** By leveraging technologies such as Uplink/Downlink Ultra-Wideband and Extended Reality Enhancement, 5G-A achieves peak downlink rates of 10 Gbit/s and peak uplink rates of 1 Gbit/s per user. These capabilities enable smooth transmission of ultra-HD video streams and AR/VR models.

2. **Extremely low latency:** Through technologies such as Complementary Time Division Duplex (Complementary TDD) and L4S (Low Latency, Low Loss, Scalable throughput) traffic control, 5G-A reduces end-to-end latency to the millisecond level. This enables near-instantaneous synchronization of remote guidance information, helping prevent assembly errors.

3. **Highly reliable transmission:** 5G-A implements QoS handling based on PDU sets specifically designed for XR data streams. Combined with deterministic technologies that provide frame-level latency guarantees, these capabilities ensure stable and complete data transmission while eliminating freezing and stuttering caused by frame loss.

4.1.2 Industrial Production Process Management

4.1.2.1 Scenario Description

Industrial production management faces critical challenges in efficiency and scalability, requiring a fundamental transformation of network capabilities. This scenario involves multiple concurrent operational requirements. For example, high-precision machinery and robotic arms require ultra-low latency for real-time synchronization; material tracking systems and automated vehicles require massive connectivity to monitor material flows across workstations; and advanced applications such as machine vision require high bandwidth to support quality inspection and predictive maintenance. This complex environment requires a unified network capable of supporting diverse performance requirements simultaneously, preventing operational fragmentation and enabling intelligent automation.

Key challenges include:

1. **Conflicting performance requirements for real-time control and massive connectivity:** Previous generations of networking technologies cannot simultaneously satisfy the ultra-low latency (<10 ms) and high reliability requirements of critical systems such as PLCs, while also supporting massive-scale, low-power (<1 W) connectivity for widespread IIoT sensor networks.

2. **Limited manufacturing flexibility and high operational costs:** Traditional fixed resource allocation approaches result in prolonged production line changeovers, significantly limiting flexibility in multi-variety, small-batch manufacturing. They also contribute to resource underutilization and increased operational costs.

3. **Insufficient support for edge intelligence and data security:** Centralized computing models limit real-time data processing at the source for advanced applications such as digital twins. Meanwhile, the increasing deployment of IIoT devices introduces additional security risks, requiring stronger security and privacy protection mechanisms for critical industrial data.

4.1.2.2 Capability Enhancements Brought by 5G-A

1. **Enhanced network slicing for agility:** 5G-A enables precise partitioning of physical network resources to provide customized QoS levels for specific applications. It supports the coexistence of multiple access technologies (e. g., eRedCap, Massive MIMO) within a single slice,

simplifying system deployment while meeting diverse application requirements.

2. **Dynamic resource optimization:** Leveraging AI/ML, 5G-A dynamically adjusts resource allocation based on real-time traffic conditions, maximizing data throughput and optimizing resource orchestration across network slices. This reduces resource idling, improves utilization efficiency, and lowers overall network costs.

3. **Localized edge computing:** 5G-A enables the integrated deployment of MES, SCADA, and ERP systems at edge nodes, supporting efficient real-time processing and analysis for IIoT, and empowering complex applicationssuch as digital twins and intelligent monitoring.

4. **Robust security and reliability:** 5G-A introduces enhanced security and privacy protection mechanisms for IIoT device access. For example, multi-layer encryption and stricter authentication protocols help ensure data security during transmission and storage.

4.1.3 Industrial-Grade Embodied Intelligence System

4.1.3.1 Scenario Description

Automated production lines that rely on vision-guided industrial robotic arms face two critical constraints when using existing networks, particularly for complex operations such as electronic component assembly and welding. These robotic systems must perform high-precision tasks, including identifying small components and executing rapid, accurate movements. Such operations require the transmission of multiple high-definition video streams for real-time analysis, along with the delivery of immediate control commands back to the robots. However, current network limitations often create data bottlenecks and response delays, preventing these systems from achieving the high-speed performance and real-time visual feedback required by modern industrial standards.

Key challenges include:

1. **Insufficient bandwidth for high-resolution vision:** High-precision applications require robotic arms to be equipped with multiple high-definition cameras, often supporting 4K or 8K resolution. The data rate of a single camera can reach up to 500 Mbit/s, meaning that the aggregate demand for multiple synchronized video streams frequently exceeds 1 Gbit/s. Some applications may require up to 3 Gbit/s to support six 4K video streams. Standard 5G networks operating in the Sub-6 GHz band typically provide actual single-device rates below 500 Mbit/s due to signal interference and multi-user resource sharing, making reliable transmission of multiple high-definition video streams challenging.

2. **Latency requirements not met for real-time control:** Industrial robotic operations, including precise identification, grasping, and assembly, require ultra-low and deterministic latency of 1 to 5 ms. However, typical latency in current 5G networks is approximately 10 to 20 ms. This delay is insufficient to meet the real-time precision and safety requirements of critical robotic operations on the production floor.

4.1.3.2 Capability Enhancements Brought by 5G-A

1. **Ultra-high capacity and low latency:** 5G-A significantly enhances performance through mmWave advancements, including support for the 60 GHz band, cross-band Carrier Aggregation between Sub-6 GHz and mmWave, and ultra-short frame structures. By utilizing the 26–28 GHz band with 400 MHz bandwidth, it can achieve 2 Gbit/s per camera, combined with 2 ms latency and 99.99999% reliability, enabling 7×24 continuous operation.

2. **Massive robotics support:** The combination of enhanced mmWave capabilities and localized data processing through Edge Computing enables a single 5G-A deployment to support 30 simultaneous robotic arms, with theoretical capacity exceeding 100 devices. This significantly improves the scalability and efficiency of automated production lines.

4.1.4 New Industrial Control System

4.1.4.1 Scenario Description

Assembly production lines, which are essential for high-volume manufacturing in industries such as automotive and mobile phones, are fundamentally constrained by rigid wired infrastructure. The current architecture, consisting of a main PLC and numerous distributed sub-PLCs (projected to reach 400 units), faces two major challenges:

1. **Prohibitive wiring and maintenance costs:** Industrial wired networks require significant upfront investment in infrastructure, including Ethernet interfaces, switches, cables, cabinets, and power supply lines. As production lines expand, these cabling costs increase substantially, even within a relatively small 1,000 m^2 area. In addition, the existing distributed control architecture requires continuous labor and investment for cable wear management and time-consuming maintenance activities, such as production line modifications, resulting in high operational expenses.

2. **Limited flexibility and scalability:** Wired infrastructure fundamentally restricts the implementation of flexible production models, such as the C2M model, for small-batch and multi-variety manufacturing. Adding, removing, or relocating I/O devices and sub-PLCs requires extensive network reconfiguration, preventing rapid adaptation to changing production requirements. Supporting a projected 400 devices requires a scalable and highly flexible network solution capable of accommodating future growth without major infrastructure upgrades. To enable the transition to flexible, C2M-ready production, the system requires a wireless network that supports a 10 ms business cycle for real-time control, full mobility support, data rates exceeding 10 Mbit/s, and near-perfect stability with a target of zero downtime over a period of 1–3 years.

4.1.4.2 Capability Enhancements Brought by 5G-A

5G-A's deterministic capabilities, which provide performance comparable to URLLC, enable a fundamental architectural transformation. This allows a transition from complex distributed wired control systems to efficient centralized wireless control architectures. The transformation delivers significant value through both cost reduction and enhanced operational agility:

1. **Centralized control and significant cost reduction:** 5G-A supports control system transformation by migrating the functions of on-site sub-PLCs to a centralized architecture and enabling centralized PLC management. The control functions of the entire assembly line are consolidated into a single central PLC, eliminating the need for distributed sub-PLC stations at individual workstations. This integration significantly reduces infrastructure investment by minimizing cabling requirements and associated hardware costs, including switches and interface devices. It also reduces ongoing labor costs related to cable maintenance and wear management while lowering software costs per workshop by reducing the need for customized development for multi-protocol integration.

2. **Enhanced flexibility and intelligent deployment:** By leveraging the wireless flexibility and deterministic performance of 5G-A, production systems can quickly adapt to changing requirements through the seamless addition, removal, or relocation of I/O devices and automated equipment, such as robots, without network disruption. Because the central PLC uniformly manages control of all on-site equipment, eliminating local sub-PLCs further improves deployment flexibility and reduces deployment costs for each workshop. This supports expansion to 400 devices and enables the realization of C2M flexible production.

4.1.5 Remote Equipment Control

4.1.5.1 Scenario Description

Remote equipment control is a cornerstone of smart manufacturing and unmanned operations in high-risk environments. It enables high-precision, real-time synchronized control and collaborative operation of multiple on-site devices (e.g., robotic arms and welding robots) from a remote location. This application requires rapid and accurate delivery of control commands, combined with real-time, lossless transmission of ultra-high-definition (UHD) video streams and multi-dimensional sensor data from the site. Together, these capabilities form a closed-loop system that enables "real-time visualization and immediate control."

This application scenario faces the following key challenges:

1. **High uplink bandwidth requirements:** Immersive remote operation and precise decision-making rely on the real-time, lossless transmission of multi-channel UHD video streams and large volumes of sensor data. The peak uplink bandwidth requirement can reach hundreds or even thousands of Mbit/s.

2. **Low latency and jitter requirements:** High-precision synchronized control of multiple devices is a fundamental requirement, necessitating ultra-low network latency (<10 ms) and stable performance with jitter below 1 ms.

3. **High reliability requirements:** The loss or disorder of control commands and critical perception data may cause incorrect actions by remote equipment, potentially resulting in severe safety incidents.

4.1.5.2 Capability Enhancements Brought by 5G-A

1. **Uplink capacity enhancement:** 5G-A enables full-slot uplink transmission by aggregating multiple component carriers (CCs) and combining dual-carrier complementary aggregation. It introduces uplink ultra-large-scale MIMO multi-TRP collaborative reception and upgrades modulation technology to 1024-QAM. In addition, refined UL-TPC parameters are introduced at the uplink control layer to support higher transmit power and more precise power regulation. These enhancements improve the uplink signal quality of remote User Equipment (UE) and support the real-time transmission of large volumes of data.

2. **Deterministic low latency:** 5G-A adopts Complementary TDD technology to achieve "zero waiting" for air interface frame transmission, eliminating delays caused by static frame structures. Meanwhile, XSO (Cross-layer Scheduling Orchestration) technology enables cross-layer interaction and service collaboration between 5G-A and industrial protocols, supporting dynamic low-latency guarantees for remote control operations.

3. **End-to-end high reliability:** 5G-A integrates TSN/DetNet technologies, enabling the 5GC to function as a DetNet node that supports resource reservation and explicit routing. At the same time, 5G-A enables coordinated operation between TSCTSF and PCF to map the core Quality of Service (QoS) requirements of DetNet streams to executable QoS parameters within the 5G network. The DetNet controller delivers precise path constraints and resource reservation instructions to the 5G-A network through the standardized YANG model.

By combining mechanisms such as grant-free scheduling, packet retransmission, and DetNet Frame Replication and Elimination for Reliability (FRER) on the air interface side, together with deep collaboration with TSN networks for time synchronization and explicit routing, 5G-A achieves deterministic transmission with sub-millisecond latency, extremely low jitter, and near-zero packet loss.

4.2 Application Scenarios in Inspection and Monitoring

Typical applications of 5G-A in inspection and monitoring primarily include precise deformation sensing, machine vision quality inspection, and on-site production monitoring.

4.2.1 Precise Deformation Sensing

4.2.1.1 Scenario Description

In environments such as power plant pipe racks and industrial buildings, the installation of heavy-duty equipment can introduce additional stress on load-bearing structures. Through 5G-A Communication-Sensing Integration Technology, deformation parameters such as settlement, inclination, and verticality of columns and buildings can be measured accurately, providing reliable data support for structural safety assessment and maintenance. This application scenario faces the following major challenges:

1. **Time synchronization accuracy requirements:** Micro-deformation monitoring places extremely high requirements on the time synchronization accuracy of multi-source sensing data. Long-term static deformation monitoring (e. g., building settlement and dam displacement) requires an error margin of no more than 1 second, while dynamic deformation monitoring (e. g., modal analysis and vibration monitoring) requires stricter accuracy, with an allowable error of no more than 10 milliseconds. Without sufficient synchronization accuracy, overall deflection and deformation trends cannot be calculated accurately.

2. **Multi-dimensional sensing data fusion:** In complex building environments, structural micro-deformation is influenced by dynamic factors such as wind and temperature. Single-dimensional sensing is insufficient to achieve the required accuracy, making it necessary to integrate multi-dimensional data, including distance, angle, speed, and environmental parameters, to improve measurement accuracy.

4.2.1.2 Capability Enhancements Brought by 5G-A

1. **High-precision time synchronization:** To meet the stringent time consistency requirements of multi-source sensing data in building micro-deformation monitoring, 5G-A deeply integrates IEEE 1588v2/TSN protocols and enhances its time synchronization capabilities, establishing a multi-level high-precision clock distribution system covering the internal 5GS, UEs, and TSN networks. Through multi-point coordination and high-precision delay measurement mechanisms, it dynamically compensates for wireless link delays and jitter, effectively reducing time errors in the air interface segment. This ultimately enables time synchronization between the base station side and the terminal side in micro-deformation monitoring scenarios.

   Building on this capability, 5G-A leverages network slicing and URLLC technologies to associate multi-source sensing data services with QoS Flows, establishing a synchronization mechanism for sensing service data that is observable, guaranteed, and monitorable. The achieved time accuracy significantly exceeds the requirements of 1 s for static monitoring and 10 ms for dynamic monitoring in micro-deformation scenarios, providing a robust foundation for accurate analysis of multi-source sensing data.

2. **Multi-dimensional integrated sensing and communication data fusion:** Building micro-deformation monitoring requires a multi-dimensional monitoring system that integrates structural characteristics, environmental factors, and deformation evolution patterns. Such a system enables the perception and integration of multi-dimensional data, including distance, angle, speed, and environmental parameters, to achieve accurate measurement of minor building deformations.

   5G-A addresses this requirement by standardizing and preprocessing heterogeneous data at the base station, enabling real-time data fusion. The processed data is uploaded to the core network for AI-based analysis, creating an “edge + cloud” hierarchical fusion model. Built-in AI capabilities adapt to environmental variations by dynamically adjusting fusion parameters, optimizing monitoring results, and achieving adaptive precision for micro-deformation tracking.

4.2.2 Machine Vision Quality Inspection

4.2.2.1 Scenario Description

Machine Vision Quality Inspection (for more details, refer to Section 4.2.5 of [20]) uses industrial cameras to capture real-time HD images for product quality assessment. Through 5G networks, captured images are transmitted to an AI expert system platform deployed in MEC or the cloud. The expert system performs real-time analysis using AI algorithm models, compares the results against predefined rules or model requirements, determines whether materials or products meet quality standards, enables real-time defect detection and automatic alarms, and records defect information for quality traceability.

After processing, inspection results are transmitted back through the same network to qualified or unqualified product removal devices for automated batch processing. This application scenario faces the following key challenges:

1. **High bandwidth demand:** The overall uplink bandwidth requirement of a single application exceeds 100 Mbit/s, depending on the number of cameras, original image size, and image upload interval. Machine vision quality inspection systems are typically deployed with 4–8 industrial cameras. The original image size is determined by factors such as resolution, pixel count, color depth, and image compression ratio. The upload interval is constrained by the production cycle. Therefore, machine vision inspection applications with more cameras, higher resolutions, faster production cycles, and higher levels of concurrency may require uplink bandwidth of 500 Mbit/s to 1 Gbit/s.

4.2.2.2 Capability Enhancements Brought by 5G-A

1. **Ultra-high data rates:** Leveraging technologies such as Uplink/Downlink Carrier Aggregation (UL/DL CA) and millimeter wave (mmWave) spectrum, 5G-A achieves peak downlink rates of up to 10 Gbit/s and peak uplink rates of up to 1 Gbit/s per user. This enables smooth, real-time transmission and interactive feedback of ultra-high-definition images and inspection results. As a result, machine vision quality inspection can replace manual visual inspection, reducing labor requirements while improving inspection efficiency and defect detection rates.

4.2.3 On-site Production Monitoring

4.2.3.1 Scenario Description

On-site production monitoring targets industrial environments such as factories, offshore oil and gas platforms, and remote mining sites. By deploying various sensors and video monitoring terminals across critical production equipment, key process nodes, and plant environments, multi-dimensional data—including equipment status, process parameters, and environmental safety information—is collected in real time. This data is transmitted to a centralized monitoring center through the network, enabling comprehensive awareness of production operations, early fault detection, and efficient remote maintenance.

Key challenges in network transmission include:

1. **Insufficient deep coverage:** In challenging environments such as offshore platforms and remote mining areas, the deployment and coverage costs of traditional terrestrial 5G networks are extremely high, resulting in signal blind spots.

2. **High bandwidth requirements:** To achieve precise monitoring, a single high-definition infrared thermal imaging or machine vision video stream requires stable uplink bandwidth of tens of Mbit/s. When multiple monitoring points transmit data simultaneously, the total uplink bandwidth requirement can reach the Gbit/s level.

3. **Low latency requirements:** For control applications such as precision operations and collaborative tasks, end-to-end latency—from monitoring data feedback to control

command delivery—must be maintained below tens of milliseconds. Failure to meet this requirement can result in delayed control responses, reducing production efficiency.

4.2.3.2 Capability Enhancements Brought by 5G-A

1. **Seamless wide-area deep coverage:** 5G-A integrates Non-Terrestrial Networks (NTN) with terrestrial networks to establish an integrated three-dimensional coverage architecture. Combined with enhanced wireless relay technologies, it provides reliable, "dead-zone-free" connectivity for offshore and remote areas.

2. **Ultra-high data rates:** 5G-A introduces more flexible spectrum aggregation solutions and enhanced uplink multi-antenna technologies, such as uplink Carrier Aggregation and Supplementary Uplink (SUL) enhancements. By leveraging broader spectrum resources and more efficient air-interface technologies, it significantly improves uplink throughput, supporting the real-time, concurrent, and reliable transmission of massive sensor data and high-definition video streams.

3. **Low latency guarantee:** 5G-A further strengthens integration with TSN and DetNet while optimizing frame structures and scheduling mechanisms. Through deterministic forwarding paths with guaranteed performance, end-to-end user-plane latency can be consistently controlled at the millisecond level, enabling latency-sensitive monitoring applications such as collaborative operations.

4.3 Application Scenarios in Warehousing and Logistics

Typical applications of 5G-A in warehousing and logistics primarily include smart plant logistics and smart plant cargo handling.

4.3.1 Smart Plant Logistics

4.3.1.2 Scenario Description

AGV trolleys are widely used in manufacturing workshops to replace material transportation operations traditionally performed by battery-powered trucks, forklifts, and other industrial vehicles. This reduces potential safety hazards and improves operational intelligence. AGV trolley and push-puller trolley networks typically use traditional AC+AP wireless networking to enable AGVs to follow predefined target trajectories and seamlessly connect with various production processes.

This application scenario faces the following key challenge:

1. **High-precision positioning requirements:** AGVs execute commands to transport materials to designated locations, requiring high-precision navigation with a typical positioning error tolerance of ≤20 mm. Positioning accuracy directly affects production efficiency and product quality and may also increase safety risks if requirements are not met.

4.3.1.2 Capability Enhancements Brought by 5G-A

To address the challenges of high-precision positioning and latency in cross-workshop AGV scheduling scenarios, 5G-A enhances positioning capabilities and reduces latency to overcome key limitations in this application scenario.

1. **High-precision positioning:** 5G-A introduces carrier phase positioning technology, which achieves significantly higher measurement accuracy than code-based measurement methods by measuring the phase of carrier signals. By integrating carrier phase measurements with AOA/AoD and other positioning information, 5G-A effectively mitigates challenges caused by non-line-of-sight transmission and multipath effects. It also addresses full-cycle ambiguity, enabling centimeter-level positioning accuracy in AGV scheduling scenarios.

In addition, 5G-A optimizes the signal structures and resource allocation of downlink PRS and uplink SRS. By increasing bandwidth, it improves delay resolution, while massive MIMO technology generates narrower and more accurate beams to enhance angle measurement accuracy. For AGV scheduling scenarios involving the INACTIVE state, 5G-A can maintain high positioning accuracy by using configured PRS/SRS in combination with eDRX.

4.3.2 Smart Plant Cargo Handling

4.3.2.1 Scenario Description

Industrial cargo handling relies heavily on manual operations for inbound logistics, outbound logistics, and inventory inspection. Traditional passive RFID systems are limited by meter-level communication ranges and low concurrency capabilities, typically recognizing only hundreds of tags per second. As a result, manual handling remains necessary, increasing the risk of errors and failing to meet the real-time accuracy requirements of intelligent, high-volume logistics operations.

Key challenges include:

1. **Inaccurate inventory management and low search efficiency:** Component inventory data is often inaccurate and not updated in real time, leading to production delays caused by material shortages or increased costs due to overstocking. In global supply chains, locating components can be time-consuming, while manual verification in high-rise automated warehouses is challenging, increasing error rates and disrupting production plans.

2. **High risk and workload in reusable box tracking:** Managing thousands of reusable boxes from multiple suppliers is complex. Traditional tracking methods rely on manual processes that are slow, labor-intensive, and prone to errors, often requiring physical scanning. Although some automation has been introduced through passive RFID technology, its effectiveness remains limited by significant technical constraints.

4.3.2.2 Capability Enhancements Brought by 5G-A

1. **Massive connectivity:** Ambient IoT enables a single base station to power and read tens of thousands of passive tags simultaneously. It extends identification distances from meters to hundreds of meters, allowing ceiling-mounted stations to automatically perform instant and continuous inventory operations without human intervention. This overcomes the concurrency limitations and labor bottlenecks of traditional RFID systems.

2. **Real-time automated inventory:** The system provides a continuous and dynamic view of all materials. It enables one-click, fully automated site-wide inventory counting to be completed within minutes, replacing traditional processes that require hours or days. By continuously updating inventory levels, it achieves near-100% accuracy, eliminates manual verification, and ensures that decision-makers have access to real-time inventory data.

4.4 Application Scenarios in Operations Management

Typical applications of 5G-A in operations management primarily include asset positioning and management, as well as network resource optimization.

4.4.1 Asset Positioning and Management

4.4.1.1 Scenario Description

Asset positioning and management focuses on the dynamic movement and utilization of resources during production. The workflow includes tracking work-in-progress materials as they move between workstations, monitoring equipment status in real time, and managing reusable assets such as tools and containers. Unlike static warehouse inventory management, this process emphasizes operational flow, ensuring that the right components arrive at the correct assembly line at the right time.

Key challenges include:

1. **Inefficient manual labor and idle materials in production:** Traditional in-factory management relies heavily on manual processes to track and move work-in-progress materials between workstations. Without real-time visibility into production flows, workers often stockpile materials near assembly lines to prevent potential line stoppages, resulting in significant accumulation of idle inventory. Manual tracking is also slow and error-prone, creating bottlenecks that disrupt manufacturing operations.

2. **Lack of seamless connectivity for internal digitalization:** A major barrier to digital transformation is the lack of seamless connectivity between production assets, mobile containers, and logistics systems. Traditional RFID solutions suffer from high latency, as multi-step wake-up and authentication procedures can take tens to hundreds of milliseconds. In high-speed scenarios such as conveyors and AGVs, this delay may cause tags to move out of the identification range before recognition, resulting in data loss.

4.4.1.2 Capability Enhancements Brought by 5G-A

1. **Automated material flow and optimized resource utilization:** Ambient IoT eliminates manual scanning by providing continuous, automated visibility of materials from the warehouse to the production line. Real-time tracking of work-in-progress materials and reusable assets ensures that resources reach workstations precisely when needed, reducing idle material accumulation and minimizing manual handling to optimize production costs.

2. **Seamless connectivity and enhanced operational transparency:** Leveraging 5G-A, thousands of battery-free tags can connect simultaneously without manual intervention. This creates a unified digital thread across the factory, transforming isolated assets into a transparent, real-time data network. It enables instant, site-wide inventory and asset tracking, providing decision-makers with accurate, up-to-date information to identify bottlenecks, optimize logistics, and accelerate fully digitized intelligent manufacturing.

4.4.2 Network Resource Optimization

4.4.2.1 Scenario Description

AI-driven network resource optimization refers to the use of AI models embedded in 5G-A base stations to analyze network data and service flow characteristics in real time. This enables dynamic optimization of radio resource allocation, load scheduling, and energy efficiency management. It provides flexible and intelligent resource scheduling capabilities with strong scalability, adapting to the dynamically changing connectivity requirements of services deployed on flexible production lines.

The core challenges of this application scenario include:

1. **Difficulty predicting dynamic service traffic:** Traditional networks that rely on manual static configuration struggle to adapt to order-driven production line reconfiguration, traffic fluctuations, and interference variations caused by equipment mobility. These limitations can result in excessive latency for critical control commands.

2. **Difficulty balancing energy efficiency and performance:** To ensure low latency, base stations often keep high-power modules continuously active, resulting in significant energy consumption during non-production periods (e. g., at night) and relatively low energy efficiency.

3. **Frequent interference in complex industrial environments:** Electromagnetic interference generated by equipment such as frequency converters and motors can cause signal attenuation and increased bit error rates, threatening the reliability of critical control commands.

4.4.2.2 Capability Enhancements Brought by 5G-A

1. **Service-aware dynamic load balancing:** Base stations with built-in AI models analyze historical traffic patterns and real-time measurement reports to predict service load fluctuations, such as burst uplink traffic generated by AR-based quality inspection videos. Based on the R18-defined "Predicted Resource State Information" and "UE Performance Feedback" mechanisms, the system dynamically adjusts frequency band priorities.
2. **Precise energy saving based on Energy Cost metrics:** Rel-18 introduces an AI/ML-based network energy-saving framework and defines a standardized Energy Cost (EC) indicator. Based on production line schedules and service load predictions, base stations use AI models to determine sleep and activation strategies for selected cells or radio frequency modules.
3. **AI-enhanced interference identification and avoidance:** Using the Rel-18 CSI feedback enhancement technology, AI models analyze channel state information to identify periodic industrial interference and generate interference maps to guide resource scheduling, prioritizing clean spectrum resources for critical services.

5 Application Cases of 5G-Advanced in Industry

Currently, some companies have begun exploring trial application of 5G-A in industrial environments and have achieved positive results, providing preliminary validation of the feasibility for on-site deployment of key 5G-A technologies across various application scenarios, thought large-scale roll-out is yet to be confirmed. The following section presents several representative cases.

5.1 Application Case of 5G-A in Electronics Manufacturing Industry

(1) Application scenario

A commercial deployment of a 5G-A native private network and three application scenarios has been implemented at an electrical appliance factory in Zhuhai, Guangdong Province, China, enabling a "lights-out factory" for flexible, intelligent, and green manufacturing[2].

The deployment integrates three application scenarios:

- On-site Assisted Assembly
- Industrial-Grade Embodied Intelligence System
- Smart Plant Cargo Handling

(2) Objectives

Through the deep integration of 5G-A technologies with smart manufacturing, the deployment aims to enable end-to-end applications of 5G-A across quality inspection, logistics, and industrial control. This supports the factory's transition from traditional automation toward flexible and intelligent manufacturing.

(3) Key 5G-A technologies used and outcomes

Built on a dedicated 5G private network foundation, the deployment leverages 5G industrial base stations to enable flexible and highly reliable networking, compatibility with multiple industrial protocols, and intelligent scheduling for massive concurrent device connections. It integrates millimeter-wave and large language model technologies to implement high-precision, 3D, multi-modal, cloud-based quality

2 Source: https://www.gd.chinanews.com.cn/2025/2025-03-07/440717.shtml

inspection. By leveraging low-power positioning and embedded digital twins, the deployment establishes a visualized management system for smart logistics.

These capabilities have resulted in threefold improvements in management efficiency, manufacturing efficiency, and resource utilization efficiency.

The outcomes are primarily reflected in two aspects:

- In terms of production efficiency improvement, the 5G-A smart lights-out factory has achieved more than ten thousand intelligent mobile connections across the entire production process. Production efficiency has increased by 86%, with annual output exceeding ten million split-type air conditioners and zero-defect production achieved.

- The system has achieved full equipment connectivity, fully intelligent logistics, and fully online quality inspection. Through applications such as 5G+AI visual inspection, on-site assisted assembly, industrial robotics, and visual guidance, it enables intelligent decision-making and precise production control. This has established a data-driven, fully connected 5G smart factory, which received two international awards at the 2025 GSMA GLOMO Awards: "Best Private Network Solution" and "Best Mobile Innovation for Connected Economy."

5.2 Application Case of 5G-A in Steel Industry

5.2.1 Case 1

(1) Application scenario

A commercial 5G-A application deployment was conducted at a steel factory in China to transform a traditional PLC-IO wired control architecture into a 5G-based wireless network. The deployment focused on validating deterministic wireless communication capabilities for steel manufacturing scenarios.

The deployment focused on the following application scenario:

- New Industrial Control System

(2) Objectives

- To evaluate the feasibility of replacing conventional wired PLC-IO control networks with a 5G-A deterministic transmission architecture in real production environments.

Figure 4: 5G glasses and 5G camera (both with 5G-A capability) deployed in the electrical appliance factory

Source: China Unicom

- To simplify industrial network deployment while maintaining ultra-high reliability and low-latency performance.

(3) Key 5G-A technologies used and outcomes

The core technical solution is based on 5G-A deterministic TAN (Time Accuracy Networking) transmission technology, combined with a self-developed deterministic gateway. This architecture enables seamless migration from the original wired topology to a 5G dual-transmission, selective-reception wireless network architecture, providing highly reliable remote 5G communication services for on-site industrial equipment.

The effectiveness of this pilot deployment is primarily reflected in two aspects:

- In this solution, the deterministic gateway replaces the traditional "5G CPE + router" combination as the northbound communication node for I/O. The I/O module and deterministic gateway are connected through a LAN port, while the terminal side enables dual-path 5G wireless access. This approach simplifies network deployment while ensuring reliable industrial communication.

- The system achieved 20 ms latency with 99.99% reliability during continuous 7×24-hour testing, validating its deterministic communication capability for industrial control applications.

5.2.2 Case 2

(1) Application scenario

A commercial implementation and large-scale deployment of 5G-A featuring technical capabilities such as ultra-low latency, ultra-high reliability, and high bandwidth has been conducted at the heavy plate production line of a steel factory in Shanghai, China[3].

Figure 5: 5G-A deterministic communication for steel manufacturing scenario

Source: China Mobile

3 Source: https://www.chinatelecom.com.cn/ct/news/xydxxtx/154420.html?CT6T=306960&CT6TS=1cWpWGisp_1NgGVL11JPL2Go5LNjX6CIFV0oEaT3X8OH8gD8T68Hglbb5d62Iy4F

The application scenario of this deployment is:

- Industrial Production Process Management

(2) Objectives

- To verify the feasibility and industrial value of 5G-A deterministic networks in core steel production processes. The deployment achieves this objective by establishing an automated dynamic collaborative control architecture, enabling the decoupling of PLC hardware and software in steel rolling production lines and supporting precise multi-process collaborative control. This promotes autonomous control, intelligent operation, and green transformation in steel manufacturing.

(3) Key 5G-A technologies used and outcomes

This deployment utilizes the core technologies of a 5G-A deterministic private network, namely "native 5G LAN in the core network + Dual Fed and Selective Receiving (DFSR)", to meet the requirements of ultra-low latency, ultra-high reliability, and high bandwidth in industrial control networks.

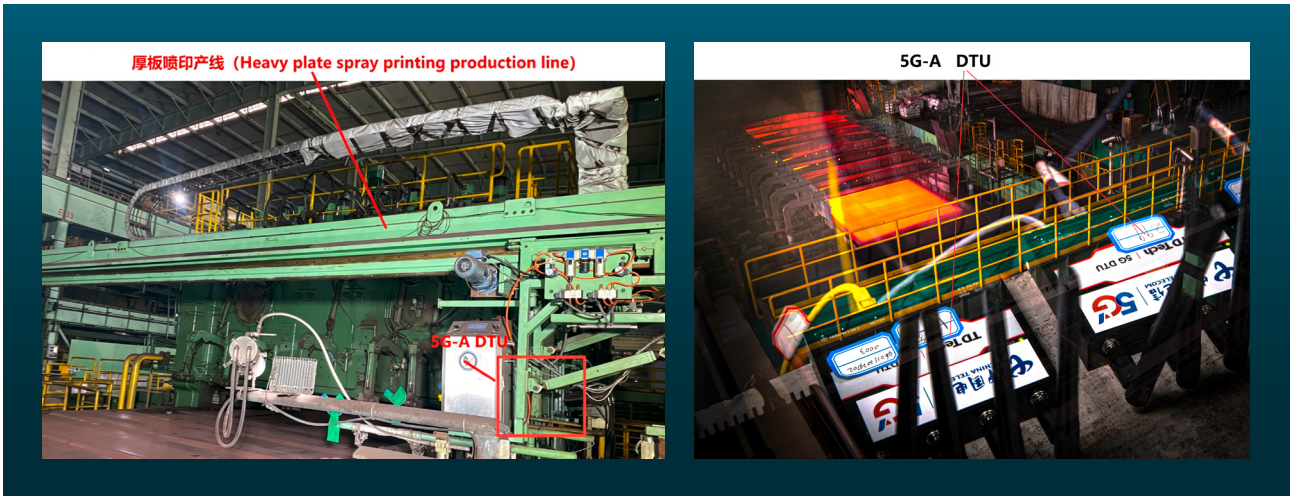
The solution enables cross-layer interaction and service collaboration between 5G-A communication protocols and steel industry protocols, including Profinet and OPC UA. It achieves precise and rapid matching between remote control requirements and network resources, enabling dynamic low-latency scheduling for steel rolling processes. Through coordination between the central dynamic collaborative control center and multiple production processes—including continuous casting, heating, rolling, and cooling—the system controls vPLC (virtual PLC) and distributed IO systems to execute precise operations.

The application outcomes of this deployment are as follows:

- The system supports real-time transmission of massive process data, equipment sensor data, and high-definition monitoring videos from the steel rolling production line. Network deterministic performance reaches 4 ms@99.999%, enabling long-term, stable industrial operation with a 16 ms sampling cycle and significantly improving collaborative efficiency across multiple steel rolling processes.

- The deployment achieves autonomous and controllable production operations and has been applied to core processes such as the shearing line in the heavy plate department. To date, 10 industrial application scenarios have been deployed, with approximately 100 terminals installed.

Figure 6: 5G-A steel smart factory; Application of the new control architecture based on 5G-A



Source: Esurfing IoT Technology

5.3 Application Case of 5G-A in Automotive Manufacturing Industry

5.3.1 Case 1

(1) Application scenario

A commercial deployment of 5G-A URLLC for core industrial control processes has been conducted at an automotive manufacturing factory in Baoding, Hebei Province, China[4].

The application scenario of this deployment is:

- Industrial Production Process Management

(2) Objectives

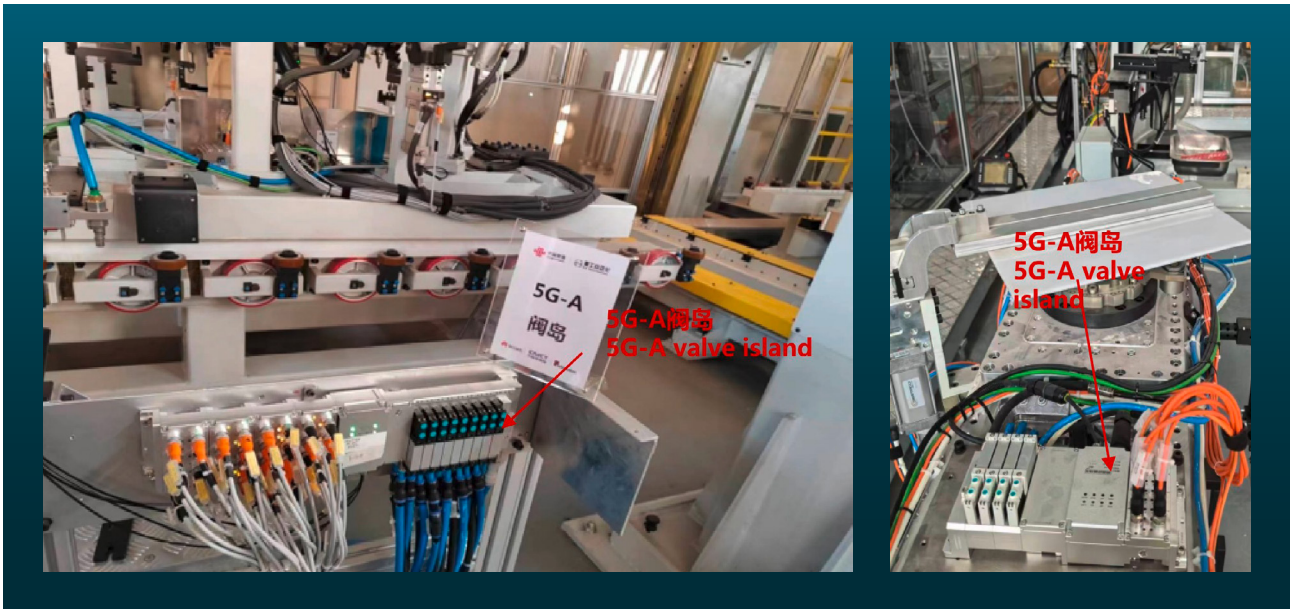
- The deployment aims to verify the feasibility and commercial value of enhanced 5G-A URLLC networks in core industrial control scenarios for automotive manufacturing. By overcoming latency and reliability bottlenecks in industrial communications, removing the constraints of wired networks, and addressing challenges related to device interconnection and real-time data synchronization, the initiative promotes the expansion of 5G applications from peripheral auxiliary processes to core industrial control operations. This supports the transition toward flexible and digitally transformed automotive manufacturing.

(3) Key 5G-A technologies used and outcomes

The core technical implementation is based on enhanced 5G-A URLLC technologies, optimized through complementary TDD and cross-carrier HARQ techniques. By integrating industrial modules supporting 5G-A URLLC capabilities into production line I/O devices, valve island, and other industrial control units, the deployment enables cross-layer coordination between communication protocols and industrial protocols, supporting the wireless transformation of industrial control equipment.

The pilot application and commercial outcomes are primarily reflected in two aspects:

Figure 7: 5G-A valve island deployed in the automotive manufacturing factory



Source: China Unicom

4 Source: https://gxt.hebei.gov.cn/hbgyhxxht/xwzx32/mtzb/20250419191714755755/index.html

- In terms of industrial control performance improvement, the 5G-A network achieved end-to-end latency of 4 ms and reliability of 99.999%, successfully supporting high-precision industrial control applications such as robotic arm welding and roof assembly. This ensures stable operation of the production line.

- In enhancing production line flexibility, the integration of 5G-A with industrial systems accelerates the adoption of remote I/O for robots and cloud-based/centralized PLC implementations. This reduces network deployment costs, while cloud computing capabilities and real-time network connectivity provide a foundation for intelligent and flexible manufacturing.

5.3.2 Case 2

(1) Application scenario

A commercial deployment leveraging 5G-A technical capabilities, including high-precision positioning, has been conducted at an automotive factory in Qingdao, Shandong Province, China.

This deployment focuses on the following application scenario:

- Smart Plant Logistics

(2) Objectives

- The purpose of this deployment is to evaluate the feasibility and application value of 5G-A high-precision positioning capabilities in real production environments. It aims to replace battery-powered vehicles and forklifts with autonomous navigation AGVs, enabling unmanned material transportation.

(3) Key 5G-A technologies used and outcomes

This deployment leverages the high-precision positioning capability of 5G-A to meet the centimeter-level positioning requirements of autonomous AGV navigation. It incorporates carrier phase positioning technology, which achieves higher measurement accuracy than traditional code-based methods by measuring the phase of carrier signals.

Figure 8: Smart Plant Logistics

Source: Esurfing IoT Technology

The application outcomes of this deployment are primarily reflected in the following aspect:

- This deployment leverages 5G-A high-precision positioning technology and carrier phase positioning to achieve centimeter-level accuracy, fully meeting the requirements for Automated Guided Vehicle (AGV) autonomous navigation. In addition, by utilizing 5G-A cross-layer scheduling orchestration technology, the system provides low latency and high reliability, ensuring real-time and stable transmission of operational data. As a result, the average positioning error of AGVs is maintained within 20 mm, while overall material handling efficiency is doubled compared with traditional methods. This significantly improves equipment utilization and reduces production line stoppages, material handling errors, and labor requirements.

5.4 Application Case of 5G-A in Shipbuilding Industry

(1) Application scenario

A commercial deployment leveraging 5G-A capabilities, including high reliability, low latency, and high transmission rates, has been conducted at a shipyard in Wuxi City, Jiangsu Province, China.

This deployment focuses on the following application scenario:

- Remote Equipment Control

(2) Objectives

- The objective is to evaluate the feasibility and application value of 5G-A capabilities, including high reliability, low latency, and high transmission rates, in real production environments. The deployment aims to enable unmanned welding operations through intelligent remote control of multiple industrial control computers and welding machines.

Figure 9: 5G-A shipyard smart factory; Interconnection and intercommunication of welding machine equipment

Source: Esurfing IoT Technology

(3) Key 5G-A technologies used and outcomes

This deployment leverages 5G-A technology through a deterministic 5G private network to meet the requirements of industrial control networks for high reliability, low latency, and high transmission rates. It introduces XSO technology to enable cross-layer interaction and service collaboration between 5G-A communication protocols and shipbuilding industry protocols, achieving precise and rapid matching between remote control requirements and network resources, as well as dynamic low-latency scheduling.

Through a central control system, multiple machines are coordinated for welding operations, enabling multiple welding robots to simultaneously execute precise tasks.

The application outcomes of this deployment are primarily reflected in the following aspect:

- The system supports real-time transmission of massive welding data and high-definition monitoring videos. It uploads 24 frames of 30 MB images per second, together with data from more than one hundred welding sensors, achieving an uplink bandwidth of 764 Mbit/s. Meanwhile, deterministic performance in terms of latency, jitter, and reliability reaches 10 ms ± 1 ms @ 99.99%. This has significantly improved welding efficiency while ensuring that each weld seam achieves millimeter-level precision and consistency.

5.5 Application Case of 5G-A in Energy Industry

5.5.1 Case 1

(1) Application scenario

A large-scale commercial deployment of 5G-A Carrier Aggregation and Ambient IoT technologies for new energy intelligent manufacturing scenarios has been conducted with a battery manufacturer in Ningde, Fujian Province, China[5,6] and Changzhou, Jiangsu Province, China.

The deployment focuses on two major application scenarios:
- Machine Vision Quality Inspection
- Asset Positioning and Management

(2) Objectives

- To comprehensively verify the feasibility and application value of 5G-A Carrier Aggregation and Ambient IoT technologies in new energy battery factories. The ultra-high bandwidth capability of 5G-A networks meets the concurrent data transmission requirements of numerous 5G industrial quality inspection cameras deployed in processes such as battery coating and battery pack assembly. Meanwhile, Ambient IoT technology enables the sensing and application of identity and location information for personnel and equipment, helping factories achieve digitalized production and further enhance lean management capabilities.

(3) Key 5G-A technologies used and outcomes

The Carrier Aggregation capability of 5G-A base stations provides the high uplink bandwidth required for 5G industrial quality inspection cameras to transmit ultra-high-definition images. Based on these 5G-A base stations, Ambient IoT devices are connected to form a two-level network architecture. Ambient IoT antennas detect direction, distance, and other feedback signals triggered by passive IoT tags attached to personnel and equipment. The collected data is transmitted through the 5G network to the positioning platform in the enterprise data center for intelligent processing, enabling positioning and tracking of personnel and equipment with an accuracy of 1 to 3 meters.

The outcomes of this deployment are primarily reflected in three aspects:

- Machine Vision Quality Inspection: 5G-A base stations support Carrier Aggregation across the 2.6 GHz and 4.9 GHz bands. Industrial 5G quality inspection cameras

5 Source: https://finance.sina.com.cn/roll/2026-01-07/doc-inhfmppz5021394.shtml

6 Source: https://gxt.fujian.gov.cn/zwgk/xw/hydt/snhydt/202604/t20260409_7120808.htm

deployed in processes such as coating and battery pack assembly transmit 8K ultra-high-definition images to on-site quality inspection workstations in real time. Through end-to-end machine vision quality inspection across the entire production process, the product defect rate has been reduced from 1 part per million (ppm) to 1 part per billion (ppb).

- Personnel Management: Ambient IoT technology uses dual tags to enhance positioning and sensing capabilities for worker safety helmets. Combined with AI algorithms, it addresses technical challenges including dynamic sensing, environmental adaptation, and helmet-separation detection. This has enabled zero safety risks for personnel working in oven areas.

- Equipment Management: The passive wireless management system deploys passive tags, 5G thermo-hygrometers, and door magnetic sensors on material transfer cabinets. AI algorithms intelligently analyze temperature variations and regional dwell times to accurately identify and warn of material damage risks. As a result, temperature fluctuations during material transfer have been reduced by 45%, with zero abnormal incidents reported.

5.5.2 Case 2

(1) Application scenario

A technical performance verification of 5G-A for intelligent oilfield operations has been conducted at an oilfield in Dongying, Shandong Province, China[7].

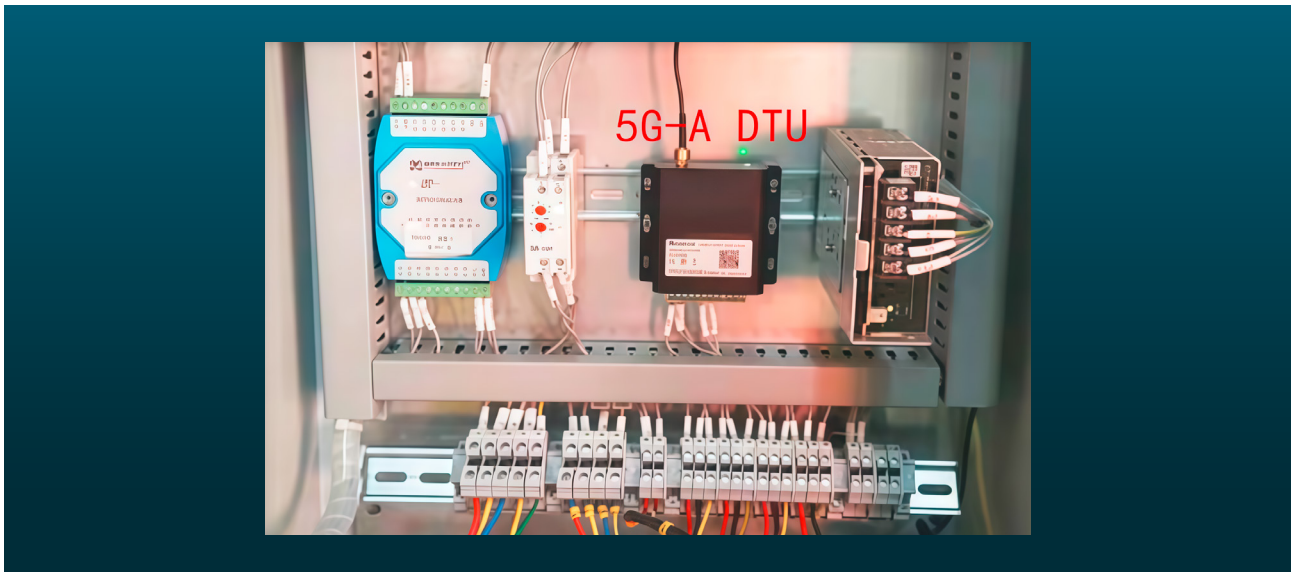
This project integrates two application scenarios:

- On-site Production Monitoring
- Industrial Production Process Management

(2) Objectives

- To assess the feasibility and application value of 5G-A private networks in offshore and onshore oilfield production environments, enabling full-process digitalization and intelligent operation of oilfields.

Figure 10: 5G-A carrier aggregation enabled high-bandwidth visual quality inspection; 5G-A access terminal



Source: China Mobile

7 Source: https://www.cnii.com.cn/rmydb/202408/t20240826_596078.html

- To promote the transformation of the traditional oil and gas industry toward safer, more efficient, and greener operations.

(3) Key 5G-A technologies used and outcomes

The core technical implementation is based on 5G-A triple-carrier aggregation base stations, which provide high-speed and low-latency network capabilities. This enables ultra-high-speed and highly reliable connectivity for offshore and onshore production operations, high-definition video surveillance, mobile office applications, and employee services.

The pilot application outcomes are primarily reflected in two aspects:

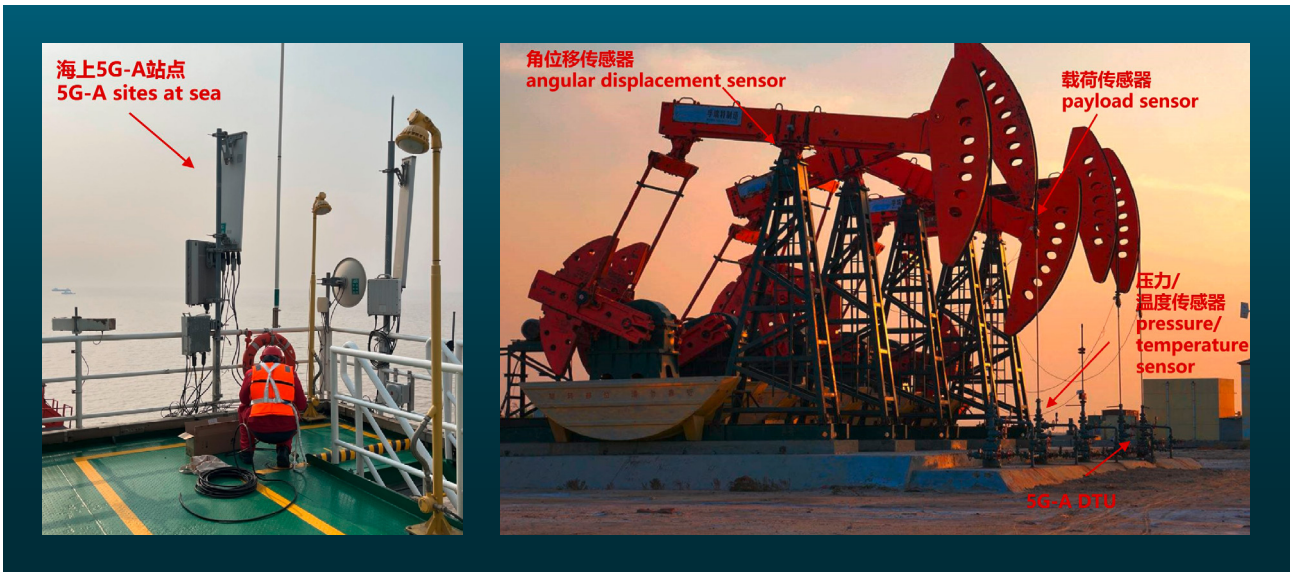
- In terms of offshore platform emergency drills, the 5G-A network enabled full-process live streaming, real-time monitoring, and assessment during emergency drills. Field tests achieved a downlink rate of 2.2 Gbit/s, supporting simultaneous real-time transmission of multiple ultra-high-definition video streams, remote equipment control, AR remote collaboration, and massive IoT device access. This significantly advances the digitalization and intelligent operation of offshore oil and gas production. In addition, laboratory simulation verification of NTN low-Earth-orbit satellite technology has been completed, with future plans to promote its application on offshore platforms.
- In onshore well management, the system enabled remote start/stop control and unmanned inspection operations. It achieved real-time and accurate monitoring of production conditions, effectively improving production efficiency and operational performance while accelerating the transformation of production management toward refined operations, intelligent operation, and energy conservation.

5.6 Application Case of 5G-A in Home Appliance Industry

(1) Application scenario

A feasibility study and technical performance verification of 5G-A Ambient IoT for industrial automation has been con-

Figure 11: 5G-A sites at sea; remote control of beam pumping units using 5G-A



Source: China Unicom

ducted at a home appliance factory in Qingdao, Shandong Province, China[8].

The project combines two application scenarios:

- Smart Plant Cargo Handling
- Asset Positioning and Management

(2) Objectives

- To assess the feasibility and application value of 5G-A Ambient IoT in real production environments, with the goal of achieving comprehensive industrial digitalization by enabling connectivity among assets, materials, and logistics systems.

(3) Key 5G-A technologies used and outcomes

The core technical implementation is based on 5G pRRU technology, which activates Ambient IoT devices by transmitting power and subsequently receives backscattered information for device identification, inventory management, and antenna-level positioning.

The pilot application outcomes are primarily reflected in two aspects:

- For real-time regional material inventory, the Ambient IoT system enables one-click, fully automated inventory operations. The process covers key areas such as unloading zones, warehouses, and production lines, completing inventory tasks within five minutes with 100% accuracy.
- The system enabled unmanned in-plant material handover. It supports simultaneous delivery by multiple tool carts and rapid detection of zone changes, effectively replacing manual handover processes and FIFO-based management across the facility.

Figure 12: 5G-A Ambient IoT for asset tracking in industrial automation

Source: China Mobile

8 https://5g-acia.org/testbeds/ambient-iot-for-industrial-automation-in-haier-factory/

6 Development Trends and Path Suggestions for the Industrial Application of 5G-Advanced

6.1 Development Trends of 5G-Advanced Features in Industry

6.1.1 The Trend of 5G-Advanced in Different Regions

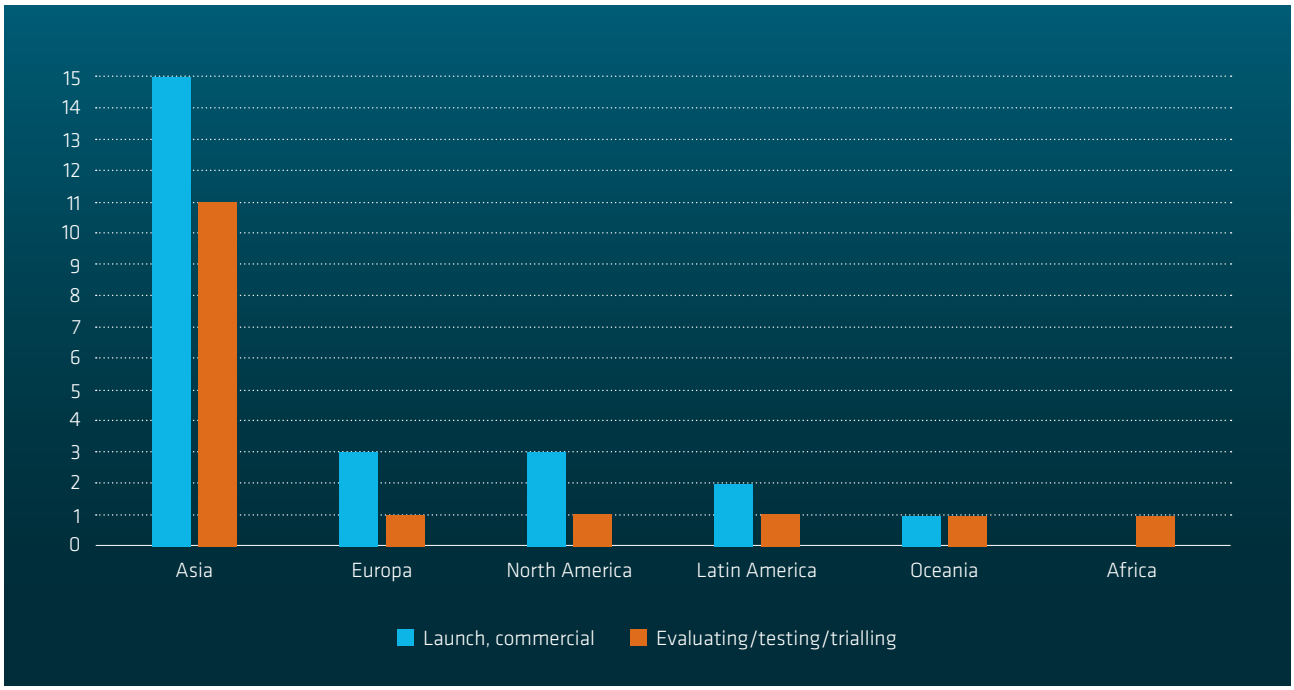
With the continuous advancement of 5G-A technologies and standards [21], regions worldwide are accelerating the construction and deployment of 5G-A networks. According to statistics from GSA [22] and GSMA [23], as of April 2026, a total of 24 operators worldwide had launched commercial 5G-A networks, while 16 operators were conducting assessments, testing, or trials of 5G-A networks.

The regional distribution of commercially deployed 5G-A networks is shown in Figure 13. Specifically, in Asia, 15 telecom operators across six countries have achieved 5G-A commercialization. In Europe, three operators across three countries have launched commercial services, while North America has seen three operators across two countries roll out similar services. In addition, two operators in one Latin American country and one operator in one Oceanian country have commenced commercial 5G-A operations.

6.1.2 The trend of 5G-Advanced Features in Industry

As 5G-A technology continues to evolve, its applications in the industrial sector will become increasingly extensive and deeply integrated. Collaboration across the entire industry chain will also evolve from single-point cooperation toward cross-domain, comprehensive synergy. Technology, appli-

Figure 13: Global Telecom Operators' Deployment Status of 5G-A Networks



Source: All

cations, and ecosystems will develop along the following trends.

The technological trend centers on the deep integration of "connectivity + sensing + AI," driving industrial networks to evolve from simple data transmission infrastructures into multifunctional intelligent platforms [24][25]. At the connectivity layer, highly reliable and low-latency capabilities will provide a foundation for industrial operations. The sensing layer will expand the boundaries of dynamic management through integrated communication and sensing capabilities. The intelligence layer will enable native integration of AI with networks, facilitating collaborative intelligent decision-making.

In the coming years, 5G-A will accelerate its penetration from production assistance scenarios into core industrial control processes. It will overcome the limitations of wired network dependence, integrate more deeply with industrial control systems, and support critical production processes. Application scenarios will expand from auxiliary functions to core operational functions, establishing mature deployment pathways, reshaping production coordination models, and driving digital transformation across industries.

The ecosystem trend will be driven by collaborative development among multiple stakeholders across the industry chain, forming a virtuous cycle of "technology R&D - product supply - scenario application - standard evolution." Different stakeholders will complement each other's capabilities, transitioning from individual cooperation to full-chain collaboration. This will accelerate technology commercialization, promote scenario replication, and drive the ecosystem toward large-scale development.

6.2 Challenges and Suggestions for the Converged Application of 5G-A and Industry

6.2.1 Challenges Ahead

Currently, the convergence of 5G-A and industrial applications faces three primary challenges:

(1) Technological Integration

At the technological integration level, technical adaptation capabilities and the degree of standard convergence are not yet fully aligned with the requirements of large-scale industrial deployment. As 5G-A remains in an evolutionary stage, the stability of key technologies, including deterministic networking and integrated sensing and communication, requires further large-scale validation in complex industrial environments characterized by metal obstructions and multipath reflections. In addition, the depth of integration between 5G-A and industrial fieldbus standards, such as Profinet and EtherCAT, remains insufficient. Technical challenges related to cross-protocol interoperability and time synchronization still require further resolution.

(2) Business Models

From a business model perspective, cost control mechanisms, value quantification frameworks, and diversified service models remain under exploration and refinement. The high costs of industrial-grade 5G-A chips, modules, and terminals, combined with significant capital expenditures associated with private network deployment and production line upgrades, create substantial investment pressure for enterprises, particularly small and medium-sized enterprises (SMEs). The value generated by 5G-A enablement is often reflected through indirect benefits, such as reduced equipment failures and improved product quality, which are difficult to quantify over the short term. Currently, 5G-A industrial applications are primarily delivered through project-based deployments, while scalable, diversified, and replicable business models are still being actively explored.

(3) Ecosystem and Talent

Regarding ecosystem development and talent availability, further improvements are required in industrial chain collaboration and the supply of interdisciplinary professionals. The convergence of 5G-A and industrial applications spans multiple domains, including terminals, networks, platforms, and applications. Differences in equipment and software protocols among vendors create significant barriers to system integration and increase the complexity of collaborative optimization. Large-scale industrial adoption of 5G-A requires interdisciplinary professionals with expertise in both 5G-A technologies and industrial production processes. At present,

the shortage of such talent has become a key constraint limiting technology implementation and solution optimization.

6.2.2 Development Suggestions

To accelerate the adoption of 5G-A integration in the industrial sector and further enable industrial digital transformation, the following targeted development recommendations are proposed:

(1) Technological Aspect: Align with Industrial Requirements and Establish a Precisely Adapted Technical Foundation

With the practical needs of the industrial sector as the primary driver and 5G-A technology evolution as the foundation, it is essential to promote deeper integration between 5G-A capabilities and the entire industrial production chain. This will provide strong underlying support for industrial digital transformation.

Deepen Collaborative Innovation and Improve Product Adaptability.

It is recommended to strengthen collaborative innovation among industry, academia, research institutions, and application stakeholders. Efforts should focus on enhancing 5G-A deterministic networking capabilities and deepening integration with industrial protocols. Resources should be directed toward addressing technical challenges related to cross-protocol interoperability, microsecond-level synchronization, and ultra-high reliability. In addition, validation of key 5G-A technologies in industrial environments should be accelerated to address challenges related to product adaptability, stability, and compatibility under complex and demanding operating conditions.

Strengthen Product Supply and Establish Industry Promotion Benchmarks.

It is essential to establish a comprehensive industrial-grade product supply system covering chips, modules, terminals, networks, platforms, and applications. At the same time, collaborative optimization among equipment, platforms, and software from different vendors should be promoted. A portfolio of practical and replicable benchmark projects demonstrating 5G-A and industrial integration should be established to facilitate large-scale replication and global adoption of successful solutions.

Advance Technological Convergence and Build a New Paradigm of "Communication, Sensing, Computing, and AI."

It is recommended to accelerate cross-domain integration between 5G-A and emerging technologies, including the Industrial Internet, AI, and digital twins. A comprehensive capability framework integrating communication, sensing, computing, and AI should be developed to maximize the value of industrial applications through technological synergy.

(2) Ecosystem Construction: Enhance Collaboration Mechanisms and Build a Sustainable Development Ecosystem

To address the practical requirements of 5G-A and industrial integration, coordinated efforts across multiple areas—including standards development, supply chain collaboration, and innovation partnerships—are required to establish an open, collaborative, and sustainable ecosystem.

Improve Standard Systems and Remove Barriers to Cross-Domain Collaboration.

It is recommended to strengthen coordination among 3GPP, ITU, and authoritative industry organizations. The development of unified 5G-A interfaces and interoperability standards tailored for complex industrial scenarios should be accelerated. Priority should be given to eliminating technical barriers across vendors and industries to enable seamless interoperability.

Innovate Business Models and Reduce Barriers to Industrial Adoption.

Flexible service models, including private network operations and slice subscription models, should be actively explored to better align with the cost structures and operational practices of industrial enterprises. The adoption pathway for enterprises, particularly SMEs, should be optimized through approaches such as lightweight deployment and phased implementation. Priority should be given to scenarios with lower investment requirements and faster returns. These efforts will reduce barriers to technology adoption, establish measurable return on investment (ROI) models, and increase enterprise willingness to deploy 5G-A solutions.

Strengthen Regional Adaptation and Promote Localized Implementation.
It is recommended to consider differences in industrial development levels and regulatory requirements across global regions. A localized adaptation strategy should be adopted to support the customization and transformation of 5G-A industrial application solutions, ensuring compliance, effectiveness, and market applicability across different regions.

Deepen Industry-Education Collaboration and Strengthen Multi-Channel Talent Development.
Schools and enterprises should be encouraged to enhance cooperation, optimize interdisciplinary academic programs, and jointly establish practical training platforms to cultivate composite talent. Enterprises should also strengthen internal cross-domain training to promote collaboration between OT and ICT professionals. In parallel, efforts to attract high-level talent should be increased, with improved compensation and incentive mechanisms to enhance talent retention.

7 Conclusion

This publication has systematically examined the innovation and convergence between 5G-A—as a new phase of ICT evolution—and the intelligent transformation and upgrading of the industrial sector. It covers key technologies, application scenarios, practical implementations, and future development trends. The core contents of the publication are summarized as follows:

- Demand-Driven Evolution: As the industrial sector advances toward greater flexibility, intelligent operations, and green development, communication networks must evolve beyond basic connectivity toward intelligent convergence. This demand serves as a fundamental driver for the development of 5G-A, representing the next evolutionary stage of 5G technology.

- Foundational Capabilities: Through key enhancements such as enhanced URLLC, deterministic networking, enhanced RedCap, Ambient IoT, integrated sensing and communication, and native intelligence, 5G-A establishes a comprehensive technical foundation for industrial applications. These capabilities address stringent industrial requirements, including ultra-low latency, ultra-high reliability, high-precision synchronization and positioning, and massive connectivity. It should be noted that some capabilities, such as native intelligence and integrated sensing and communication, remain in the early stages of development and will continue to evolve toward the 6G era.

- Value Creation and Realization: The true value of technology is realized through scenario-based applications. This publication demonstrates that the capability portfolio of 5G-A can effectively empower key industrial scenarios, including high-precision motion control, large-scale collaborative scheduling, machine vision quality inspection, and intelligent warehousing and logistics. These applications generate commercial value by improving production efficiency and enabling flexible manufacturing.

- Development Path: The large-scale industrial adoption of 5G-A is not simply a matter of technology deployment; it is a complex system engineering endeavor. Successful implementation requires coordinated advancement through technology and scenario-driven innovation, seamless integration with existing OT/IT/CT systems, and ecosystem collaboration across the entire industry chain.

Looking ahead, the convergence of 5G-A and industry will continue to expand in both depth and scope. It will evolve from "single-point applications" toward "system-level integration," and from "technology-driven development" toward "value co-creation." This transformation will accelerate the evolution of the Industrial Internet from "Internet of Everything" toward "Intelligent Connectivity of Everything."

8 Abbreviations

5G	5th Generation mobile communication technology
5G-A	5G-Advanced
5G-ACIA	5G Alliance for Connected Industries and Automation
5GS	5G System
AGV	Automated Guided Vehicle
AI	Artificial Intelligence
AII	Alliance of Industrial Internet
AIoTF	Ambient IoT Function
AMF	Access and Mobility Management Function
CQI	Channel Quality Indicator
eDRX	Extended Discontinuous Reception
FRER	Frame Replication and Elimination for Reliability
GNSS	Global Navigation Satellite System
ICS	Industrial Control Systems
ICT	Information and Communication Technology
ISAC	Integrated Sensing and Communication
L4S	Low Latency, Low Loss, Scalable throughput
MCS	Modulation and Coding Scheme
MES	Manufacturing Execution Systems
ML	Machine Learning
PDA	Personal Digital Assistant
PDCP	Packet Data Convergence Protocol
PDU	Protocol Data Unit
PRS	Positioning Reference Signal
PUSCH	Physical Uplink Shared Channel
RAT	Radio access technology
SRS	Sounding Reference Signal
TDD	Time Division Duplex
UE	User Equipment
URLLC	Ultra-reliable low latency communication
V2X	Vehicle to Everything

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