GTI White Paper of Value of 5G High Uplink in Industrial Digitalization

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01 Introduction

5G has been initiated to build a fully connected, intelligent world.

ITU has prioritized three use cases for 5G: enhanced Mobile Broadband (eMBB), ultra-reliable low-latency communication (URLLC), and Massive Machine-Type Communications (mMTC). The first version of 3GPP 5G specifications is Release 15, which was completed at the end of 2018, and it paved the way for the commercial implementation of eMBB. 3GPP Release 16 was unveiled in early July of 2020, and is expected to complete the URLLC technical specifications by the end of September 2020. The 3GPP 5G mMTC technical specifications will be finalized in 2021 as well. With the specifications continuing to be enhanced for the three use cases, 5G will continue to diversify industry-oriented capabilities well into the next decade.

Along with the global commercial rollout and exploration of industrial applications, 5G is being increasingly converged with industries, healthcare, transportation, and education, as well as many other fields, as a promising platform of digital connections. 5G is enabling automated and intelligent operations for businesses, with high uplink bandwidth, low latency, and high-precision positioning as the first round of pressing application demands. Based on the characteristics and development processes of mobile networks, high uplink bandwidth will be among the first commercial functionalities available for empowering automated and intelligent businesses.

This white paper analyzes the requirements of service processes and connections for 5G as well as 5G's value in the first-batch demonstration industries, including port, steel, and mining, based on China Mobile's and Huawei's exploration. Suggestions are also provided on how to improve the uplink bandwidth capabilities of current networks.

02 Industrial Digital Transformation Is Inevitable

2.1 Digital Economy Is Expanding Rapidly

The way data flows determines how people interact economically. Currently, digital economy has grown into the world's most important industry, emerging as a new engine to bolster global economic recovery. Going digital is essential for countries to inject new momentum for economic development, address competitiveness, and seize strategic advantages.

Digital economy has become a vital composition of national economy. The World Bank's report found a growing contribution of digital economy to GDP. In the 47 countries surveyed in 2018, digital economy contributed more than 60% to the GDP in the UK, the USA, and Germany. This proportion exceeded 40% in the South Korea and Japan, and 30% in Singapore, China, and Finland, while reaching 15% to 30% in the other 25 countries. Digital economy grew faster than overall GDP in 2018 in 80% of countries, as indicated in a report on the global digital economy released by the China Academy of Information and Communications Technology (CAICT).

In China, digital economy is scaling up significantly, taking an increasingly prominent position in national economy. In the six years from 2014 to 2019, China's digital economy has steadily contributed more than 50% to the GDP growth, and has become a key driving force behind economic growth.

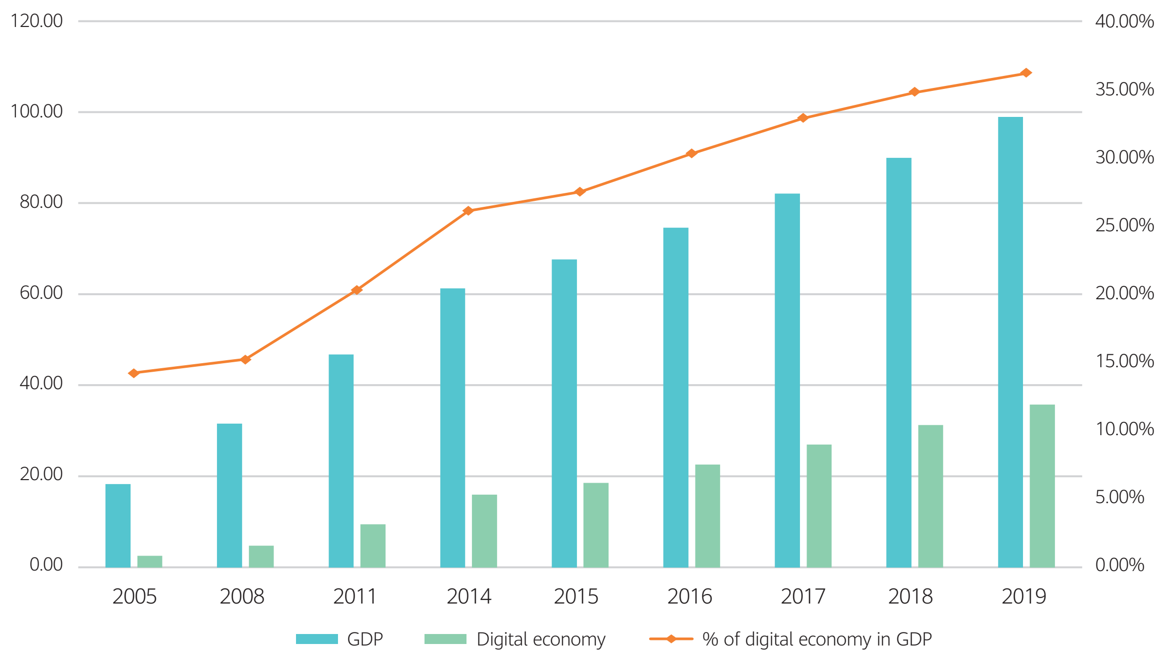


Figure 1: Percent of digital economy in GDP, Digital Economy Development in China (2020)

2.2 5G Is a Core Driving Force of Digital Economy

In 2020, new infrastructure becomes a buzzword in China, broadly hailed as a key measure to vitalize China's economy. According to the National Development and Reform Commission (NDRC), new infrastructure mainly includes information infrastructure, converged infrastructure, and innovative infrastructure. The information infrastructure includes communications network infrastructure represented by 5G, the Internet of Things (IoT), the industrial Internet, the satellite Internet, new technology infrastructure represented by artificial intelligence (AI), cloud computing, and blockchain, and computing infrastructure represented by data centers and intelligent computing centers.

5G is the foundation of new infrastructure and promotes industrial digitalization. It has been fully integrated with production in many industries to streamline design, manufacturing, and services, creating positive business cycles. It enables enterprises to leverage data assets to explore opportunities of services and increase revenue, realizing the value of 5G digital production.

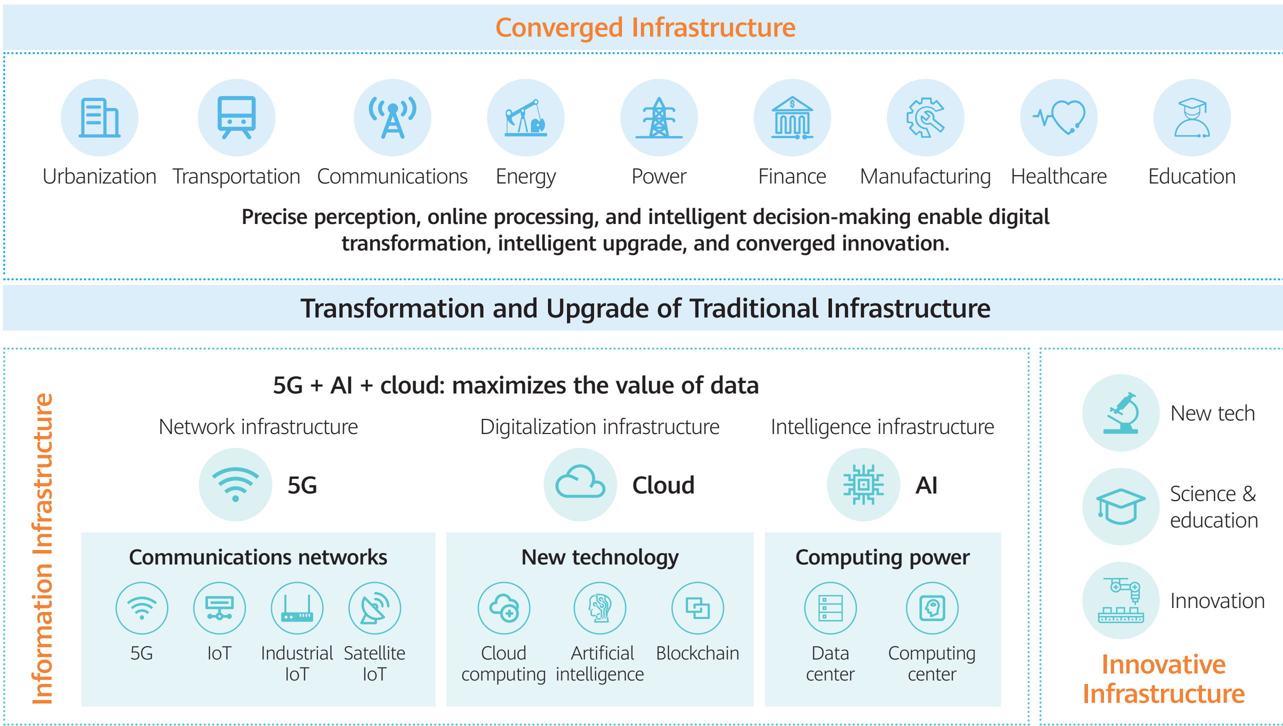


Figure 2: Definition of new infrastructure by the NDRC

2.3 High Uplink Is Compulsory for Digital Transformation

The digital exploration in steel, mining, port, manufacturing, and education shows that video surveillance, remote control, and machine vision are typical industrial applications. These applications have high requirements on uplink single-point rates and uplink single-cell capacity. With the advent of high definition (HD) and ultra-high definition (UHD) services and increasing precision on machine vision, uplink requirements will become even higher.

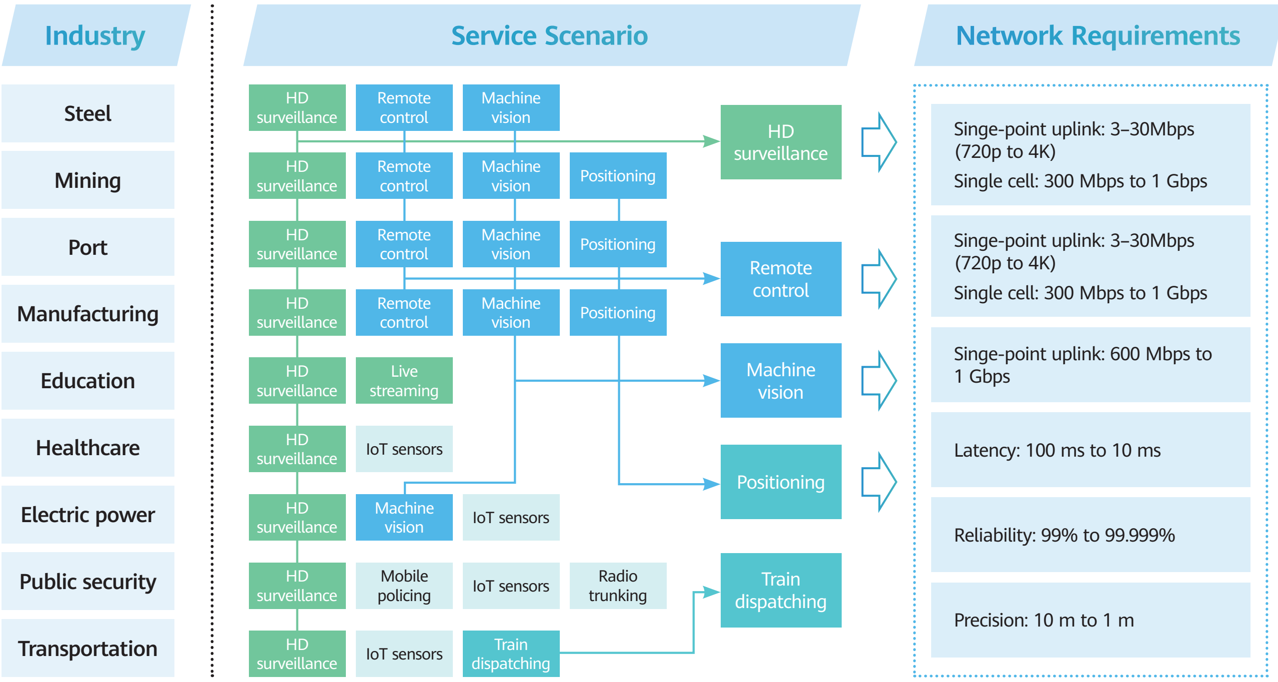


Figure 3: Typical uplink-demanding industries and scenarios, and their capability requirements

To meet requirements for video upload of HD surveillance and remote operations, the current resolution of 720p to 1080p will be definitely increased to 2K, 4K, and 8K. This means that the current uplink single-point rate of 3 Mbps will increase to 20 Mbps and even 60 Mbps. Given that concurrent video upload is required in most scenarios, the uplink single-cell capacity must be increased exponentially.

The high precision of machine vision requires single-frame image transfer to be completed with an exacting latency and free of any quality loss. To recognize images with a higher precision and frame rates in one second, uplink capabilities must be remarkably improved.

Currently, with a timeslot configuration of 8:2 or 7:3, a single 5G TDD system allows a peak rate of 250–370 Mbps as demonstrated in tests. This level of capabilities can only fulfill the uplink requirements in some scenarios. As industrial digitalization continues to gain pace, there will be even higher uplink requirements. To adapt to these trends, 5G networks must further improve uplink capabilities in line with digital transformation across industries.

03 Typical Cases of Digital Transformation

China Mobile and Huawei in partnership with industry partners have carried out a large number of explorations into 5G-driven industrial digitalization. This section analyzes the requirements for and the value of 5G in advancing business digitalization in port, steel, mining, and other industries.

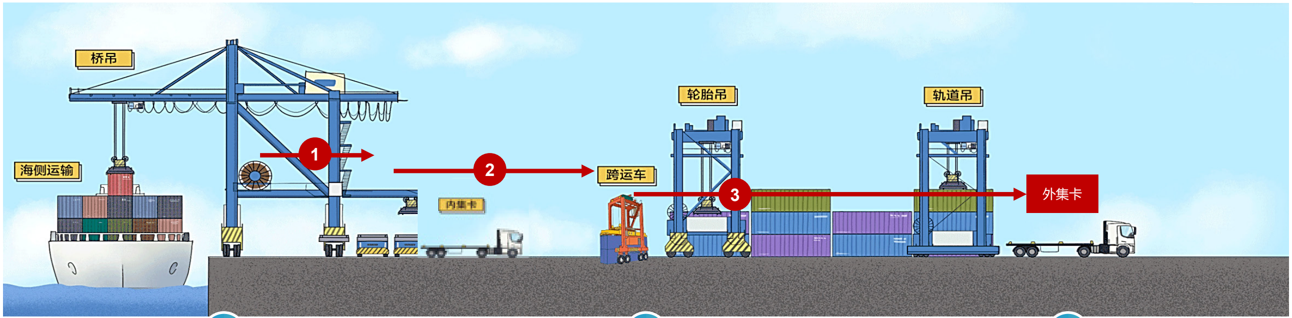
3.1 Application and Value of 5G in Smart Port

Port hubs, linking water and land transportation, play an important role in industrial and agricultural import and export. Nearly 90% of global trade is carried by water transportation, highlighting the importance of ports. According to a report released by the APEC Port Services Network (APSN) in 2019, global ports saw a 2.3% throughput increase in 2019, reaching 800 million TEU.

Globally, there are more than 4,300 ports, 200 of which are operated in China. Automated ports account only for an insignificant number, 34 in total and 4 in China. This means that more than 90% of ports still depend on manual operations of container cranes in harsh working conditions, leading to high labor intensity and costs. In the context of growing demands for global water transportation, information-based, intelligent port development is essential to improve core competitiveness, reduce logistics costs, and increase logistics efficiency.

3.1.1 Port Service Processes and Digitalization Requirements

Based on the direction of cargo flows, the service processes in a port include unloading with bridge cranes, container tally, in-yard horizontal transportation, and in-yard loading and unloading.



1 Quay crane: ship -> container trucks

- Containers are unloaded from ships to horizontal transport vehicles (AGVs, internal container trucks, and straddle trucks).
- Loading and unloading information is collected and recorded.

2 In-port transfer: container trucks -> container yards

- Containers are transferred from the unloading areas to container yards.

3 Outbound transfer: container yards -> external container trucks

- Containers are unloaded from horizontal transport vehicles and kept in the container yards where they are relayed to their destinations.

Figure 4: Typical service processes in a port

Efficiency is of uttermost importance to port services. Renting a large vessel is costly and paid for by the day, meaning that an extra hour of delay or operations would ensue a huge waste in costs and even direct economic loss to cargo owners. A long loading or unloading time indicates a low transfer efficiency, which will force cargo owners to choose other ports. Therefore, efficient cargo transfer is a core component of port operations. With cargo transfer mainly implemented in quay crane loading areas and container yard areas, wireless connections are mostly required in bridge crane operations, container truck transportation, rubber tyred gantry (RTG) crane operations, and rail-mounted gantry (RMG) crane operations. The typical applications involve HD video surveillance, remote driving, unmanned driving, and machine vision. 5G can well fulfill the bandwidth and latency requirements of these applications.

Process	Current Challenges	Connection Requirements	Network Requirements
Unloading (bridge crane)	• Onsite attendance at heights • Costly and difficult fiber deployment in some ports	• Remote and unmanned operations	• Singe-point uplink bandwidth: ≥ 30 Mbps • Latency: < 18 ms on average, ≤ 30 ms at maximum
Container tallying	• Various information: time-consuming, labor-intensive recording • Limited 4G bandwidth: low-quality video transfer, inefficient recognition	• Machine vision detection • HD video/image transfer	• Uplink bandwidth: ≥ 30 Mbps • Latency: < 20 ms
Horizontal container transportation	• Manual driving, leading to high labor costs • Fixed routes, lack of flexibility, difficult O&M	• Unmanned truck driving • Truck-route and truck-truck coordination	• Uplink bandwidth: > 20 Mbps • Maximum latency: ≤ 20 ms
Unloading/ loading in container yards	• Harsh working conditions, health risks • Communication interruptions	• Remote operations of RTG cranes • Remote unloading and loading	• Single-crane uplink bandwidth: > 20 Mbps • Latency: < 18 ms on average, ≤ 30 ms at maximum

Table 1: Challenges and connection requirements of port services

3.1.2 Application Scenarios and Value of 5G High Uplink in Smart Port

Remote RTG crane operations are essential for port efficiency. 90% of the operations can be automatically performed through technological upgrades. This section describes the application of 5G in the remote RTG crane operations.

Traditional RTG crane operations are typically faced with three major pain points. The operator has to look down in the cabin 30 m above the ground, so that the operator is easily fatigued, posing high safety and health risks. Operating an RTG crane 24-hour uninterruptedly requires three operators to work on a rotation and an extra one to stand by, leading to a huge labor cost. Furthermore, resource sharing is not supported, leaving some operators unassigned as not all RTG cranes work at the same time.

With remote operations, RTG cranes are operated in offices, rather than in cabins high above the ground. 90% of operations are completed automatically. One operator is able to work on multiple RTG cranes (more than four), significantly improving the efficiency. Additionally, operators do not have to work onsite, greatly reducing safety risks.

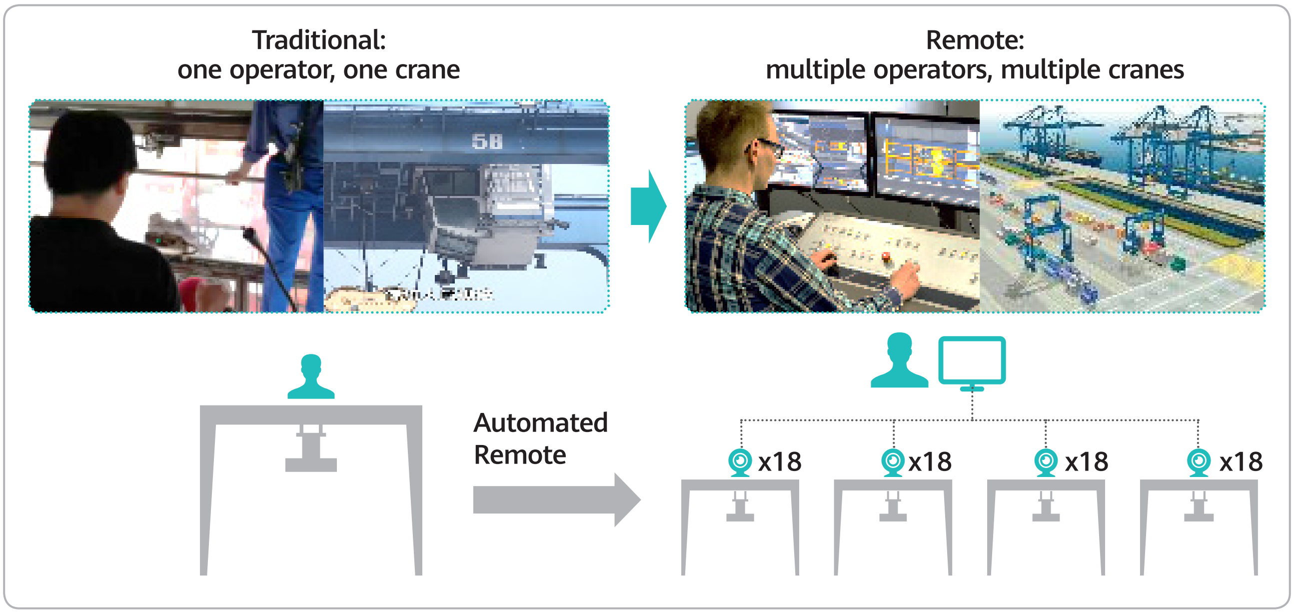


Figure 5: Comparison between traditional and remote RTG crane operations

5G Network Requirements

The 5G port operation requires outdoor LAN networking, which has the following requirements on uplink capabilities.

- **5G remote control of RTG cranes:**

  A common RTG crane is equipped with 18 to 21 cameras of 480p to 1080p resolution. For 1080p videos, the uplink rate of each channel should be 2 to 4 Mbps, and 8 to 10 channels of videos will be uploaded simultaneously for remote control. Therefore, a single RTG crane requires an average uplink rate of 20 to 40 Mbps. Each container yard is divided into 14 areas. During peak hours, two RTG cranes in an area, or 20 RTG cranes in a container yard, work at the same time. Therefore, the uplink bandwidth of a container yard must reach 400 to 800 Mbps.

- **5G unmanned container truck transportation:**

  Unmanned container truck transportation is also required in container yards. Each truck requires at least 20 Mbps uplink bandwidth for real-time video upload. During peak hours, up to 20 trucks will work in a yard, requiring 400 Mbps uplink bandwidth.

Overall, these two services require an uplink bandwidth of 800 Mbps to 1.2 Gbps in 5G cells. Considering the requirement of reliable transmission of I frames for industrial purposes, 3 to 6 times of redundancy will be needed in the future, which requires higher uplink bandwidth.

Ningbo Zhoushan Port is an important container trunk line port and the largest coal and crude oil transfer hub in China. It has ranked the world's No.1for 11 consecutive years in terms of cargo throughput, which hit 1.119 billion tons in 2019. Its container throughput ranks the world's No. 3, exceeding 27.53 million in 2019. At present, the port has more than 620 berths.

Currently, the port has realized 5G remote control of RTG cranes. More than 90% of operations are completed by machines, except for grabbing and unloading containers which require manual intervention at the control room. One operator can control multiple RTG cranes, significantly improving efficiency.

Take Meishan Area of Zhoushan Port as an example, which has an annual throughput of 5 million TEU. The largest cost of traditional ports lies in labor force, accounting for more than 30% of the total. The automated operations of bridge cranes and RTG cranes through 5G reduce labor costs significantly, improves work efficiency by 20%, lowers operation risks, and shortens the time for interruption and troubleshooting.

Arguably, 5G will play a significant role in the port's various operational processes. The high bandwidth and low latency of 5G meet the requirements of remote control, HD surveillance, and machine vision, improving operation efficiency. In addition, multiple services can be implemented over a single 5G network, simplifying O&M and reducing the operation costs for ports. In the future, with the continuous enhancement of low-latency, high-reliability, and mMTC technologies, 5G will ensure the performance improvement, reduce cost of the entire port, and accelerate the adoption of automated and intelligent port operations, creating new space for port development.

3.2 Application and Value of 5G in Smart Steel

With the development of automated and information-based infrastructure, China's steel industry has built a relatively complete system and achieved scaled production. At present, China's steel industry has ushered in a critical stage of technical development confronting with numerous difficulties. Faced with the transformation of traditional manufacturing and requirements of flexible manufacturing and intelligent manufacturing, the steel industry needs to rethink the management mode of production equipment and how to obtain the maximum value from it. In addition, steel enterprises need to improve their digital manufacturing capabilities to cope with the challenges.

The next-generation information technology represented by 5G continuously accelerates the intelligent transformation of steel enterprises and deepens the application in production and operation, featuring intelligent process, production line control, and production and operation. It also promotes timely and accurate data acquisition, information transfer, data modeling and analysis, scientific decision-making, and implementation control in the production process.

Xiangtan Iron and Steel Company (XISC) is a high-quality steel production base in southern China with an annual output of 12 million tons. It utilizes advanced technical equipment and production techniques throughout the entire production process. However, it encounters bottlenecks in efficiency improvement and energy consumption reduction. In addition, the high-temperature and high-risk environment is not appealing to young labor forces. To further raise productivity, reduce energy consumption, and improve working environment as well as employees' happiness and fulfillment at work, XISC is determined to leverage ICT technologies including 5G, AI, big data, and cloud computing to implement digital upgrade of the entire process and all services, and build an intelligent industrial Internet platform in the steel industry. This will not only promote XISC's high-quality development, but also drive an industry-wide development towards smart and green steel.

3.2.1 Steel Service Processes and Digitalization Requirements

Automation is widely adopted in major production lines of leading steel enterprises in China. However, the next-stage development of smart steel factories is restricted by high packet loss rate during Wi-Fi transmission due to large production areas, harsh production environment, and severe electromagnetic shielding. This means that the current requirements for network bandwidth and real-time performance cannot be met and many operations need to be performed manually. Therefore, it is urgent to promote 5G smart manufacturing in smart steel factories.

Network connection is the prerequisite for factory digitalization and in-depth interconnection of all elements in each process. This requires transitions from wired to wireless access, and from the integration of multiple RATs to the coexistence of 5G and optical fiber, jointly building a foundation network with low latency and high reliability. Factory connection has six elements: production environment, materials, logistics vehicles, production equipment, manufacturing execution and management system, and labor force.

Figure 6: Production line process and production elements of steel enterprises

Production environment	Indicates elements such as temperature, humidity, dust, hazardous gases, cyclic wind speed, and lighting. Sensors are used for monitoring and data collection in real time.
Materials	Indicates raw materials and material storage in warehouses.
Logistics vehicles	Indicates vehicles that transfer materials, including cranes, automated guided vehicles (AGVs), and trucks.
Production equipment	Indicates blast furnaces, rolling mills, mechanical arms, machine tools, bridge cranes, as well as tools, instruments, monitoring devices, and fire fighting devices. The production equipment can be connected to the Internet through IoT SIM cards or remotely controlled through PLC. PLC is located between manufacturing execution system (MES) and production equipment. The MES schedules and controls PLCs of several production lines. The production line PLC is a general automatic control module that controls the PLCs of several sites simultaneously. A site PLC controls the equipment of an operation unit, and is directly connected to the valves, I/O modules, conveyors, and robots of the production equipment.
Manufacturing execution and management system	It is a top-level execution and management system in a workshop. It consists of MES in a traditional workshop and is used for the management of manufacturing data, plan scheduling, production scheduling, inventory, and tools and fixtures. MES generally integrates traditional manufacturing execution information systems such as supervisory control and data acquisition (SCADA) system. With the development of the IoT, some new management systems, such as environment detection management, AGV scheduling control, and preventive maintenance of production equipment, complement MES to form a more intelligent manufacturing execution and management system.

3.2.2 Application Scenarios and Value of 5G High Uplink in Steel Digitalization

The production and technological process of the steel is complex. Based on customer surveys, 5G technical features, and performance evaluation, the following typical scenarios are selected for smart reconstruction in the initial phase:

5G + Smart Bridge Crane

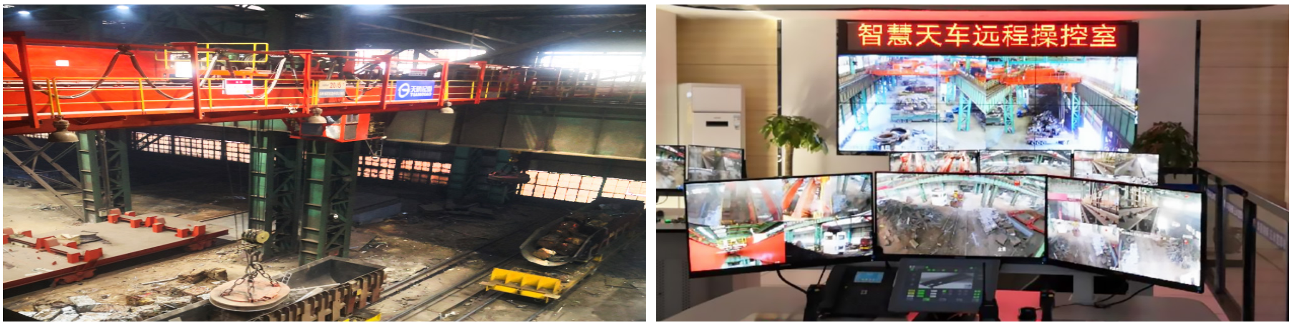


Figure 7: 5G smart bridge crane control site of steel enterprises

The bridge crane is used for loading and unloading, handling, and transportation. It is one of the most important devices in steel production and a key factor to determining highly-efficient operation of steel factories. The bridge crane operates at heights in factories. In the past, it had to be operated manually in the crane cabin, which was inefficient and dangerous with harsh working environment. For the purpose of improving efficiency and eliminating operation risks, it is an inevitable trend to develop unmanned bridge crane systems.

In the remote control of unmanned bridge cranes, the 3D scanner, ranger, codec, and multiple HD cameras installed on bridge cranes are used together with the laser 3D contour scanning technology to obtain information about surrounding materials, vehicles, and car hopper height as well as loading and unloading positions. The 5G network with ultra-high bandwidth, ultra-high rate, and ultra-low latency transmits data to the server in real time, processes the data, establishes a three-dimensional model, calculates the action instruction set, and delivers the instruction set to bridge cranes for execution, implementing unmanned loading and transportation. The remote control of 5G bridge cranes solves problems such as insufficient coverage and capacity, and poor anti-interference capability of industrial Wi-Fi, as well as difficult routing, high costs, and complex maintenance of optical fibers, while significantly improving working environment and labor efficiency.

5G + AI Machine Vision

Developing technologies and ever-increasing quality demands have made the steel surface quality inspection a mandatory process. For example, the number of surface defects of automobile panels cannot be greater than two, and the number of surface defects of home appliance steel plates must be zero.

At present, the quality inspection of industrial products is based on traditional manual inspection methods. A slightly advanced inspection method is to compare the product to be detected with the preset defect type library. However, the inspection precision and efficiency of the preceding method cannot meet the current requirements of high-quality production. The learning capability and inspection flexibility are insufficient, resulting in low inspection precision and efficiency. Furthermore, due to weak computing capability as well as 4G's high latency and low bandwidth, data association is impossible within the system and all data is processed offline, entailing high labor costs.

Micrometer-level observation of objects is enabled by the integration of 5G, AI, and machine vision based on 5G's high bandwidth and low latency. As a result, the acquired information is comprehensive and traceable, with convenient information collection and requirement of faster transmission rate. 5G can completely solve the transmission problem of visual inspection, enabling machine vision for manufacturing.

5G Network Requirements

Bridge crane remote control and machine vision are typical indoor scenarios of steel factories. The network requirements are as follows:

- **5G smart bridge cranes:**

  Sufficient uplink bandwidth is required to enable remote control and video upload of 5G smart bridge cranes.

  For remote control and video upload, each bridge crane is equipped with five cameras (1080p) and one panoramic camera (4K), with uplink bandwidth requirements of 2–4 Mbps and 8–16 Mbps, respectively. The bandwidth requirement of each bridge crane is 18–36 Mbps, with the total bandwidth of 90–180 Mbps for five bridge cranes in a single area. The remote control of bridge cranes has high requirements on the video quality and smoothness. Considering the I-frame peak rate and frame collision probability, three to six times of redundancy is reserved. In this case, the bandwidth requirement of each bridge crane is 54–216 Mbps, with the total bandwidth of 270–1080 Mbps for five bridge cranes in a single area.

  If unmanned operation of bridge cranes is further developed, laser ranging and 3D scanners are required, with the uplink bandwidth to be increased by 10 Mbps and the PLC control latency to be within 20 ms.

  Therefore, the total 5G uplink capacity required in a single area is 140–230 Mbps without any redundancy, or 320–1130 Mbps with reserved redundancy.

- **5G + AI machine vision for quality inspection:**

  Quality inspection has the following requirements on the uplink bandwidth: pixel (expected inspection precision: 5, 10, and 20 megapixels for industrial cameras), image format (1, 8, 16, 24, and 32 bits for rich display content), and frame per second (application requirement, that is, the duration of image collection allowed in a specified time period). Therefore, the bandwidth requirement of quality inspection is not a fixed value, but depends on the specific application requirements. Take the 3D structured light SPI visual inspection as an example. Eight 5-megapixel 8-bit grayscale images are required within 500 ms. The latency for processing a single image is 62.5 ms. The size of a single image is 5 MB, the size of eight images is 40 MB, and the transmission frequency is 500 ms. Therefore, the uplink rate requirement of each inspection node is 640 Mbps.

5G-enabled smart bridge cranes have improved operation efficiency, decreased fault rate, and reduced energy consumption, in addition to lessened labor intensity and enhanced safety. In terms of labor cost saving, a traditional bridge crane requires three to four operators to work in shifts, while only one operator is required for two unmanned bridge cranes.

Compared with traditional manual inspection, the sampling rate of 5G + AI steel surface inspection is up to 45%. Machine vision not only implements real-time inspection, but also increases the sampling rate to 91%. In addition, the μm-level machine inspection precision enables machine vision for tasks beyond human capabilities.

3.3 Application and Value of 5G in Smart Mining

Coal is a fundamental energy source and a key basic industry, and coal mine exploitation develops from mechanization to automation, digitization, and intelligence. In China, the proportion of mechanized coal mining reached 78.5% by 2018. Automation technologies (such as drum-type mining machines) have also seen widespread application in coal mining enterprises. At present, intelligent coal mining is still in the demonstration phase and is applicable only to the working face with good conditions. With the improvement of the engineering level, large-scale application of intelligent coal mining will come out in the next 10 to 20 years. There are about 5,300 coal mines in China. Currently, the mining working face requires on-site manual operation of mining machines and a large number of staff for inspection of on-site sensing devices. In addition, harsh working environment, intensive labor, and high labor cost pose risks of major accidents that will attract attention from municipal or provincial government. Smart mining can be applied to non-coal mines (such as metal mining). Due to harsh underground environment and explosion-proof requirements, smart mining is applicable to production fields with harsh environments, such as oil and gas and petrochemical industries. There are more than 30,000 non-coal mines in China, presenting a huge demand for intelligent development.

3.3.1 Mining Service Processes and Digitalization Requirements

Coal mining is implemented either above or under the ground. In underground mining, coal is excavated from the fully mechanized mining face, and then transported from underground laneways to ground areas.

Smart mining achieves intelligent control, comprehensive sensing, and real-time interconnection. Intelligent control includes remote precise control, and in the future, it will implement automated delivery of instructions based on machine vision. Comprehensive sensing collects data such as status, videos, and locations and sends them to the surveillance center. Real-time interconnection predominantly achieves communication anytime and anywhere aside from simple remote diagnosis.

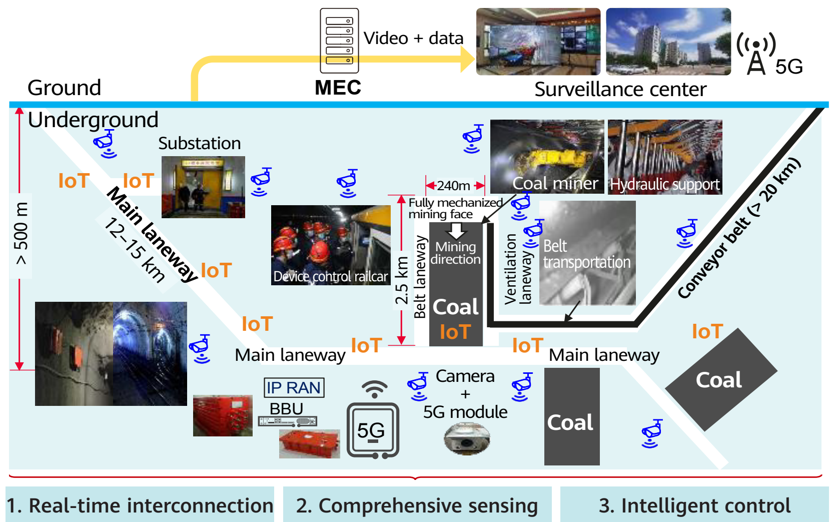


Figure 8: Digital reconstruction of a common coal mine

Scenario	Sub-scenario	Description	RTT(ms)	Number of Connected Devices/Cell	Uplink		
					Peak Rate per User (Mbps)	Avg. Capacity per Cell (Gbps)	Cell-edge Rate per User (Mbps)
Intelligent control	Remote precise control	Centralized control of tunneller and coal miner on fully mechanized mining face	<100	50	Low requirements		
	Machine vision	HD video upload for remote control and automated delivery of instructions	<100	30–40 4K cameras (on 240 m fully mechanized mining face)	20	0.8	10
Comprehensive sensing	Status	Health status, environment (gas, pressure, etc.), and equipment status monitoring	<1000	>100	Low requirements		
	Video	Videos of transportation sites for fault identification & locating	<100	Fixed and mobile cameras (in 200 m laneways)	10	0.3	5
	Positioning	Personnel, vehicle, and device positioning	<100	Meter-level positioning	Low requirements		
Real-time interconnection	Instant communication and remote diagnosis	Mobile communication with handheld wireless terminals for quick diagnosis anywhere	<100	Voice: 10 groups Video: 3–5 groups	10	0.2	5

The production environment and intelligent reconstruction of coal mines pose higher requirements on network capabilities such as latency, stability, security, multi-service concurrency, and positioning.

3.3.2 Application Scenarios and Value of 5G High Uplink in Mine Digitalization

Remote precise control and unmanned operation facilitate the realization of least-manned mining. Smart mining has the following requirements on 5G networks:

1

High uplink bandwidth

30 to 40 4K cameras for video upload on the fully mechanized mining face

2

Massive connectivity

At least 50,000 sensors are required for a smart mine, but it is unfeasible to connect them with cables.

3

Deterministic low latency

Real-time HD video upload is a typical lag-sensitive service requiring high uplink bandwidths. For example, the frame period of a 25 fps video is 40 ms. The transmission latency of videos requiring high real-time performance should be lower than the frame period.

4

High reliability

The coal industry has strict requirements on network reliability and requires operator-class devices.

5

One network for two purposes

This solution avoids repeated investment and waste caused by construction of two networks for underground B2B applications and B2C communications.

6

High security

The safe production of coal mines is a key energy strategy. 5G can provide a higher level of security.

5G Network Requirements

Underground coal mines are fully enclosed, making safety a prominent issue.

HD video upload is critical for 5G remote precise control, because clear videos of ambient environments are required. For example, on a 240-meter fully mechanized mining face, 40 fixed cameras are required at an interval of 6 meters. The camera resolution must reach 4K in order to capture clear views and accommodate machine vision in the future. For uplink transmission, each video channel must have a rate of 8 to 16 Mbps, and the bandwidth must be 320 to 640 Mbps over the length of 240 meters.

In June 2020, China Mobile, Yangquan Coal Industry (Group), and Huawei jointly built the first 5G smart mine in China — Xinyuan Coal Mine. The mine has built a 5G private network 534 meters underground, the lowest in China. This network provides ultra-gigabit uplink capabilities, facilitating intelligent management and providing a ready solution for the coal industry.

The 5G ultra-gigabit uplink solution greatly simplifies concurrent and low-latency video upload by multiple cameras.

China Mobile and Huawei jointly developed a complete set of communication devices for underground mining and acquired China's first explosion-proof certification of 5G devices. The 5G private network of Xinyuan Coal Mine enables unmanned operations in the electromechanical chamber, on the tunneling work plane, and on the fully mechanized mining face, realizing unmanned, automated, and visualized management.

Figure 9: Value of 5G smart mining for Yangquan Coal and market space

Least-manned or even unmanned onsite operations significantly reduce safety risks. Traditionally, underground inspection of devices entails heavy labor input. In contrast, 5G achieves remote inspection in the surveillance center with the help of HD cameras, reducing workers for a single laneway from 140 to 60. With 5G, a coal mine will require only 100 personnel, which translates into about CNY700 million labor cost saving according to rough calculation.

04 5G Innovative Solutions Help Enhance Uplink Capabilities

The industry is seeking ways to enhance uplink capabilities. The leading solutions include resource aggregation and timeslot configuration adjustment. In resource aggregation, more spectrums or higher bandwidths are combined on the serving uplink channel. Main technologies for this purpose include enhanced SUL and carrier aggregation (CA). In terms of timeslot configuration, the uplink-downlink timeslot configurations in TDD systems are adjusted to increase uplink timeslots. Alternative solutions such as multi-band networking, cell splitting, and mmWave can also be leveraged.

4.1 Dedicated Frame Structure Solution

The simplest and most direct way to enhance uplink capabilities is to increase uplink timeslots by adjusting the uplink-downlink timeslot configurations in TDD systems. The mainstream downlink-uplink slot configurations include 7:3, 8:2, and 1:3. Downlink timeslots are far more than uplink timeslots, and accordingly the downlink capabilities are far higher. Therefore, a special downlink-uplink timeslot configuration, for example, DSUUU (1D3U), is introduced to enhance uplink capabilities by increasing uplink timeslots.

In field tests, adjusting the timeslot configurations in the TDD system increased uplink rates proportionally, but downlink rates dropped due to shortage of available timeslots.

Subframe Configuration	5 ms single period 8D2U	2.5 ms dual period 7D3U	2.5 ms dual period 1D3U
Uplink Peak Rate	250Mbps	375Mbps	747Mbps
Average Cell Capacity	250Mbps	242Mbps	482Mbps
Uplink Cell Edge Rate	14.4 Mbps	2.8 Mbps	5.6 Mbps

Table 2: Comparison of test data between the special and the original timeslot configurations

Currently, multiple vendors of 5G networks and chipsets have folded the 1D3U timeslot configuration into their offerings. Additionally, this timeslot configuration has been field-tested at Ningbo Zhoushan Port, achieving an uplink peak rate of 747 Mbps. It is estimated that this timeslot configuration can be commercially adopted for end-to-end applications at the beginning of 2021 to accommodate high uplink requirements of industries.

In conclusion, 5G special timeslot configurations can substitute for solutions to enhance uplink capabilities on a single frequency band. They can improve uplink capabilities and coverage of single UE and increase the average cell capacity. The 1D3U special timeslot configuration may differ from common timeslot configurations used on public networks, which may cause cross-timeslot interference. Therefore, the special timeslot configuration is applicable to enclosed environments (such as mines) that require high uplink rates and larger uplink capacities and indoor scenarios (such as factories) that require service isolation.

4.2 Enhanced SUL Solution

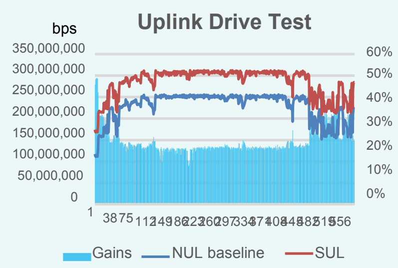
In essence, the enhanced SUL solution coordinates spectrums of two different bands, mutually complements for what's weak between high and low bands, and aggregates time- and frequency-domain resources. It leverages the large-bandwidth advantages of high bands and strong penetration capabilities of low bands. This solution improves the uplink bandwidth at the cell center, enhances the uplink coverage at the cell edge, and lowers the network latency.

Assume there is a TDD high band and an FDD low band. At the cell center within the TDD coverage area, when uplink data is transmitted in the TDD band, no uplink data is transmitted in the FDD band. In this way, the uplink throughput is increased because the TDD bandwidth is naturally high and two transmit channels are open for a device. Alternatively, when downlink data is transmitted in the TDD band, uplink data is transmitted in the FDD band, switching timeslots in the FDD and the TDD bands so that uplink data is transmitted in all timeslots. At the cell edge, the TDD system cannot provide wide uplink coverage. With this solution, the FDD band can be leveraged for uplink transmission when a device moves out of the TDD uplink coverage scope, extending the coverage of the TDD system.

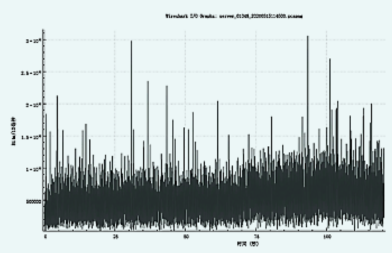
In field tests, the coordination between TDD 100 MHz and FDD 20 MHz enables the uplink peak rate to reach 321 Mbps at the cell center, extends the TDD downlink coverage by 6 dB at the cell edge, and increases the downlink TCP rate by 100 to 200% at the cell edge.

In the remote control testing of RTG cranes at Ningbo Zhoushan Port, the enhanced SUL solution met the concurrent video upload requirements of multiple cameras and guaranteed the end-to-end latency. On the 5G network of the port, the TDD + FDD SUL uplink solution helps achieve an uplink rate of 310 Mbps, allowing 10 RTG cranes to work at the same time. In addition, the average latency in the durability test reached 9 ms, which can fully meet the latency requirements of remote control for RTG cranes.

SUL gains improve by 24% to 50%, with the peak rate to 310 Mbps.



The average concurrent uplink rate of five RTG cranes is 300 Mbps, with the average E2E delay of 10 ms.



Durability test: The PLC delay and jitter are small, with the average delay of 9 ms and no packet loss, after continuous work for 48 hours.

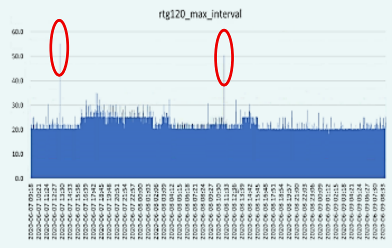


Figure 10: Testing for the uplink bandwidth and network latency at Ningbo Zhoushan Port

In addition, to meet the ultra-large bandwidth requirements in the industry, the dedicated uplink large-bandwidth spectrum (50–100 MHz) coordinated with the TDD band is introduced to improve the uplink throughput. In lab tests, the carrier aggregation between TDD 100 MHz and dedicated uplink 100 MHz achieves an uplink peak rate of over 1 Gbps, further meeting the requirements of most industry customers.

Notably, the CA bands are decoupled between the uplink and downlink, allowing different bands to be aggregated in the separate direction. Therefore, the FDD or SUL-dedicated frequency bands can be coordinated with the TDD band, improving the uplink capability; other FDD or TDD bands with a larger bandwidth can also be aggregated with the downlink band, improving the downlink capability.

The 5G SUL solution was initiated in 3GPP Release 15, and more bands were supported for aggregation in 3GPP Release 16. Currently, some vendors preliminarily support this solution, but more industry investment is required to promote the maturity of the industry.

In conclusion, the enhanced SUL solution improves the single-UE uplink capability and coverage. The TDD + FDD SUL solution is applicable to the industry WANs and LANs with requirements on the uplink bandwidth and coverage. The TDD + dedicated uplink large-bandwidth band SUL solution is applicable to the scenarios with requirement on the uplink rate over 1 Gbps or higher.

4.3 Uplink CA Solution

Rate is closely related to the spectrum resources obtained by users. Spectrum addition is the most direct method to increase capacity and rate. However, the bandwidth of a carrier is determined by spectrum allocation and also restricted by standard protocols. To obtain more bandwidth, carrier aggregation technology aggregates a plurality of component carriers, enabling UEs to use all spectrums of multiple carriers. Therefore, the rate is also correspondingly increased. Based on this principle, uplink CA aggregates the uplink frequency bands of different carriers to improve the uplink capability.

In uplink aggregation of TDD and FDD carriers, data can be transmitted over two carriers at the same time in the cell center or at a medium distance from the cell center. The peak uplink data rate reaches the sum of the peak data rates of the two carriers. At the cell edge, the TDD uplink carrier is unavailable for CA due to limited coverage of TDD bands. In this case, FDD low bands are used for uplink data transmission, maximizing uplink coverage.

Theoretically, the peak uplink rate reaches 400 Mbps in the case of 2.6 GHz 160 MHz uplink CA, and 500 Mbps in the case of 2.6 GHz + 4.9 GHz CA. More bands can be aggregated in the future, further improving the uplink capability.

However, uplink CA also requires downlink carriers to be bound, meaning that if the uplink resources of a carrier involve in uplink CA, the downlink CA involved with the downlink resources of the carrier also has to be performed. Therefore, this solution needs to be considered based on the usage of the downlink resources of a carrier in actual network deployment.

Uplink CA has been supported in 3GPP Release 15 and has been enhanced and improved in 3GPP Release 16. It is expected that networks, chips, mobile phones, industrial modules, and industrial terminals will be ready for the end-to-end commercial use next year. Currently, the 2.6 GHz 160 MHz CA with slot configuration of 1D3U has been verified at Shanxi coal mine. The measured peak rate with uplink CA reaches 1,100 Mbps.

In conclusion, uplink CA improves the uplink capability and coverage of a single UE. However, this solution has some restrictions on the downlink spectrum and needs to be considered based on the usage of the downlink resources. It is applicable to industry WANs and LANs with requirements on uplink bandwidth and coverage.

4.4 Networking Solution

Increasing number of FDD bands (such as 700 MHz, 800 MHz, 900 MHz, 1800 MHz, and 2.1 GHz) and TDD bands (such as 2.6 GHz, 3.5 GHz, and 4.9 GHz) have become the mainstream for 5G commercial use. The networking mode with low frequency bands for coverage and multiple high frequency bands for capacity has also become a trend, enabling complementary advantages to improve the uplink capability, including the uplink capacity and coverage. In massive MIMO scenarios, uplink soft splitting and inter-cell joint reception are used, significantly improving uplink capacity and coverage. With the gradual deployment and commercial use of mmWave, its large bandwidth feature can be fully utilized to improve the uplink rate and capacity.

In conclusion, the flexible combinations between the networking solution and the dedicated frame structure, SUL, as well as uplink CA, provide customized solutions and network services for different customers in outdoor WAN, outdoor LAN, indoor, and fully-enclosed scenarios, meeting differentiated high uplink requirements.

05 Summary and Prospect

With the rapid development of the digital economy and its increasingly prominent position in the national economy, the digital transformation of industries is accelerating. Based on the analysis of typical service scenarios of smart port, steel, and mining, the 5G high uplink bandwidth can meet the requirements of most enterprises in typical application scenarios, such as HD surveillance, remote control, and machine vision. It quickens the automation, informatization, and digital platform building for enterprises, reducing costs and improving efficiency. Therefore, the 5G high bandwidth capability, as the core capability of 5G networks and the urgent requirement of enterprises, will be quickly put into commercial use in the digital transformation of the 5G industry.

To meet increasing current and future industry requirements, operators need to prepare for network planning in advance to reserve uplink capabilities. Based on the requirements on WAN, LAN, closed, and open scenarios and uplink capacity and coverage, 5G dedicated frame structure, SUL, and uplink CA, supplemented with multi-frequency networking, cell splitting, and mmWave networking can be used to improve uplink capability. In addition, the continuous promotion of the high uplink capability requires the joint efforts of standardization organizations, equipment vendors, and terminal vendors. The standardization organizations need to accelerate the definition and improvement of the high uplink technology. Equipment vendors need to launch related network devices quickly based on the preceding technical direction. Terminal vendors need to accelerate the launch of corresponding chips and modules. In this case, this enables quick adaptation to different industry scenarios, reduces the end-to-end cost of implementing automation in various industries, and scales up the industry of mobile connections.

The next decade is the decade of 5G. The potential of 5G industry digitalization is infinite, and the exploration of 5G industry applications is still in the preliminary stage. However, it is an inevitable trend for industry connections to evolve from wired to wireless access. 5G, with its advantages in high bandwidth, low latency, and wide connections, is also an inevitable trend to normalize, industrialize, and scale up fragmented wireless connection technologies in the industry over the past 20 years.

Therefore, all participants need to work together in the future to inject new momentum into industry digitalization based on the wide network connections with 5G and technologies, such as cloud and AI. Operators will exert their expertise in the connectivity field to build unified network infrastructure laying a foundation for connectivity, and perform professional network maintenance to achieve scale effects and reduce industry costs. Equipment manufacturers will continue to innovate, combine the definition, development, and evolution of 5G technical standards with industry requirements, and build more comprehensive network capabilities to meet the requirements of various industries. Industry customers need to proactively embrace changes and accelerate the involvement of 5G and other technologies through the transformation of production service processes and management regulations to enable them to play their roles. For regulators, the formulation of a series of policies, such as globally coordinated spectrum policies, industry laws and regulations, and support policies for network construction and industry development, is conducive to forming scale effects and accelerating the commercial use of technologies.

Appendix: Acronyms and Abbreviations

TEU:	Twenty-feet equivalent unit
SUL:	Supplementary uplink
eMBB:	Enhanced Mobile Broadband
URLLC:	Ultra-reliable low latency communication
mMTC:	Massive Machine-Type Communications
GDP:	Gross Domestic Product
TDD:	Time division duplex
FDD:	Frequency division duplex