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Ultra-Reliable Low-Latency 5G for Industrial Automation

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5G FOR LOW-LATENCY INDUSTRIAL NETWORKS

The first specifications for 5G New Radio (NR) have been agreed, and commercial 5G mobile broadband services are expected to launch in 2019. 5G NR, however, will enable many more commercial opportunities. This white paper discusses how, using the ultra-reliable low-latency communication (URLLC) capabilities of 5G, operators and enterprises can address diverse, high-performance use cases linked to industrial automation. This is part of a broader opportunity often described as Industry-X, Industry 4.0 or the Industrial Internet.

The paper focuses on the "factory of the future" concept and uses robotic motion control as an example of an application with extreme performance requirements. It shows how 5G can contribute to more efficient and flexible production processes and emphasizes how important it is that 5G integrates with existing, and emerging, industrial networking standards to make this transition faster and more effective.

Local-area networks based on wired Ethernet, WiFi and LTE are already used for industrial applications and provide a starting point for more demanding, transformative automation using 5G. Private, exclusive-use networks give the enterprise the ability to configure the network to exactly the performance it requires. Because it is not dependent on interworking with public networks, and because the factory owner has full control of the deployment environment, industrial networks can be designed and optimized for real-time performance, for extreme reliability and availability, and for stringent privacy and security restrictions.

5G & Industrial Automation

By design, and partly through fortune, 5G wireless technology is under development at a time when many industries are themselves transforming through greater automation using technologies such as the Internet of Things (IoT), machine vision, machine learning and robotics. The "factory of the future" is part of this broader trend and incorporates several use cases with differing performance requirements and desired outcomes.

Figure 1 shows three high-level categories of networking for factory automation that can be enabled by 5G: 1) real-time processes; 2) non-time-critical processes; and 3) broader enterprise communications. Each of these categories contribute to the better running of the factory, or similar industrial facilities, such as warehousing, logistics or extractive industries (mining, oil & gas, etc.).

Figure 1: 5G & Factory Automation Processes

Use-Case Category	Scenario	Impact
Time-critical processes	• Real-time, closed-loop robotic control • Video-driven machine-human interaction • AR/VR for maintenance & training	Increased efficiency & yields; safety
Non-real-time processes inside factory	• Tracking products & machine inventory • Non-real-time sensor data • Remote inspection & diagnostics	Optimized management of production facilities
Enterprise communication	• Logistics & warehousing • Employee & back-office communications • Tracking goods post-production	Improved business operations

Source: Heavy Reading, adapted from 5G-PPP "5G and the Factories of the Future"

The most demanding use cases are time-critical processes, of which robotic motion control, with a 2 ms "cycle time" and very low error rate, is an exemplar. In many production lines, human workers will also be involved, and the concept of co-working with machines – sometimes known as "cobotics" – also requires extremely low latency, perhaps also using machine-vision video, to detect humans and ensure safety. These types of low-latency, high-reliability applications are difficult to deliver without a local-area 5G network.

There are many other types of in-factory process that are also critical to operations, but not time-critical at the millisecond or microsecond level. For example, tracking parts, machine inventory and finished products through the production process into the logistics chain and, potentially, beyond the factory into the market. Sensor data, such as that used for energy and environmental monitoring, is similarly important, but doesn't require real-time processing and millisecond networking. Many of these use cases also have high-density operation in common, where 5G, by design, has major advantages over existing technologies.

Industrial Ethernet & 5G NR

Many industrial processes are already substantially automated, and companies continue to pursue greater efficiency, production speed and yields through new technology. 5G does not itself define industrial processes; it can, however, be an enabler of new operating models. In the first instance, the 5G network should replicate the functionality of wired systems to support existing controllers, switches, sensors and actuators. In the second, there is an opportunity to make 5G integral to the evolution of industrial automation as machines, processes and production lines are themselves redesigned and improved.

There are several industrial Ethernet systems – such as Sercos, PROFINET and EtherCAT – designed for communicating with industrial equipment and capable of real-time control of robotic equipment (e.g., within a 2 ms cycle time). One of the drawbacks of these systems is that they require physical cabling between machines, which means cables need to go through hazardous areas and may connect to moving parts, increasing the risk of failure and the need for maintenance. It also means the production line is a fixed configuration that cannot be easily reconfigured to make more efficient use of machinery, or to adapt to changing demand.

An immediate opportunity, therefore, is to use 5G to replace existing wired local-area networks already deployed in factories. LTE and WiFi can do some of this – with private LTE networks offering performance advantages over WiFi – but generally don't support the necessary Layer 1-2 performance (scheduling, latency, jitter, redundancy) needed for the most demanding applications. 5G can, as demonstrated by testbeds and proofs-of-concept, meet these time-critical requirements.

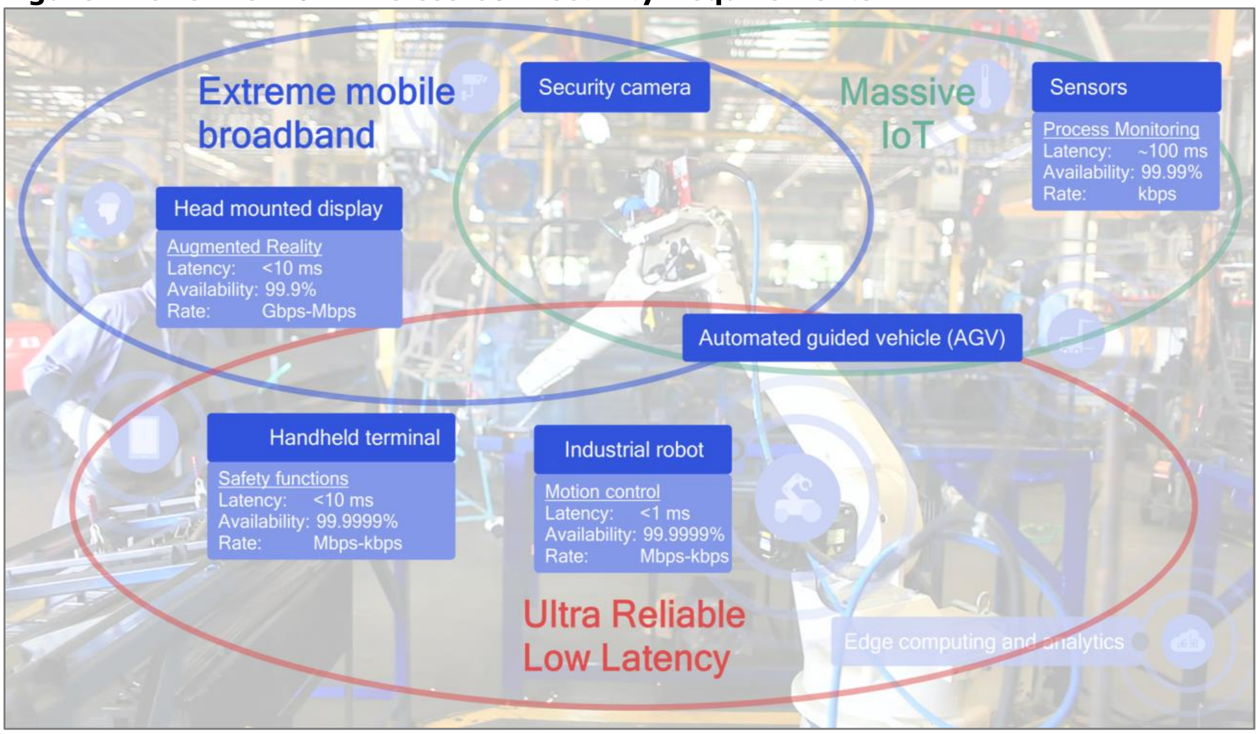
An important aspect of applying 5G to industrial automation is knowing which standards should be part of the design brief. It is the responsibility of the industry verticals (factory owners, in this case) to communicate their priorities. A promising development is the emergence of the 5G Alliance for Connected Industries and Automation (5G-ACIA), an industry group that is working to align requirements from different companies and sectors. One example of this is how the "Industry 4.0" cohort of companies has proposed to use the IEEE Ethernet standard known as Time-Sensitive Networking (TSN) for industrial networking. With many of the legacy industrial Ethernet protocols able to run over TSN, designers of 5G systems can therefore now focus on mapping TSN to the 5G radio interface. This greatly simplifies integration work and will accelerate development of industrial wireless networks.

INDUSTRIAL IoT PERFORMANCE REQUIREMENTS

Factory-of-the-Future End Point Connectivity

Future factories incorporate many digital processes (use cases), which can benefit from mobile connectivity on locally deployed, private networks. **Figure 2** shows a selection of these use cases and devices, with their associated performance requirements.

Figure 2: Overview of Wireless Connectivity Requirements



Source: Qualcomm

This diversity of device types – from sensors to automated guided vehicles (AGVs), to untethered AR/VR, to security cameras, and robotic control – generates different requirements for mobility, throughput, density, latency, power and availability. LTE and WiFi can meet some of these needs. Others, in the category of URLLC, will need 5G performance.

In the meantime, there are important innovations in private LTE, such as support for low latency and IoT (using NB-IoT, LTE-M), that factories and other industrial users can benefit from. An advantage of LTE technology is that it is relatively mature, and therefore appeals to risk-averse customers with production-critical use cases, but still has a compelling development roadmap and an operating lifespan of well over a decade.

LTE provides a starting point for the introduction of private 5G networks into industrial environments. For example, industrial users may choose discrete 5G implementations for critical real-time applications (e.g., robotic control) in the first instance to reduce risk, while keeping non-real-time services on LTE. Over time, because 5G is designed to support all these use cases simultaneously on the same network, including advanced time-critical applications, it will take over services from LTE and WiFi networks.

5G URLLC Performance for Industrial Automation

Developed in consultation with industrial end users, the 3GPP Study on Communication for Automation in Vertical Domains (TR 22.804) has identified a set of performance targets for industrial automation using 5G. These are summarized, according to the use case and across various other criteria, in **Figure 3**.

Figure 3: Industrial Automation Performance Requirements for 5G

Use Case (High Level)		Availability	Cycle Time	Typical Payload Size	# of Devices	Typical Service Area
Motion control	Printing machine	>99.9999%	< 2 ms	20 bytes	> 100	100 m x 100 m x 30 m
	Machine tool	>99.9999%	< 0.5 ms	50 bytes	~20	15 m x 15 m x 3 m
	Packaging machine	>99.9999%	< 1 ms	40 bytes	~50	10 m x 5 m x 3 m
Mobile robots	Cooperative motion control	>99.9999%	1 ms	40-250 bytes	100	< 1 km^2
	Video-operated remote control	>99.9999%	10-100 ms	15-150 kbytes	100	< 1 km^2
Mobile control panels with safety functions	Assembly robots or milling machines	>99.9999%	4-8 ms	40-250 bytes	4	10 m x 10 m
	Mobile cranes	>99.9999%	12 ms	40-250 bytes	2	40 m x 60 m
Process automation (process monitoring)		>99.99%	> 50 ms	Varies	10,000 devices per km^2	

Source: 3GPP, ZVEI

These performance criteria can be summarized as follows:

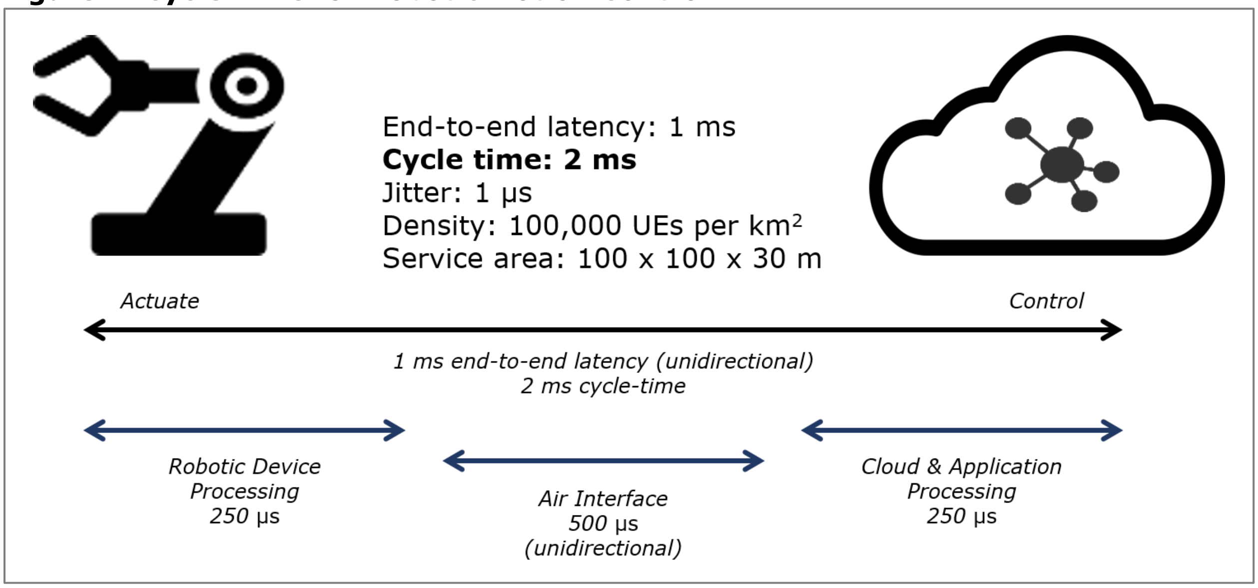
- **Service Availability:** This refers to the percentage of time the end-to-end communication service is delivered, according to an agreed service level. For industrial automation, this is important to "dependability," which is the combination of reliability, availability, maintainability, safety and system integrity. Dependability is a critical metric in industrial production systems, because the cost of downtime is very high.
- **Cycle Time & Latency:** Cycle time refers to the time allowable for a control system to generate a command, transport it across the network to a sensor or actuator, and then receive confirmation that the command was successfully delivered. The latency allowable over the network is thus a fraction of the overall time budget. A 2 ms cycle time, for example, may only allow 500 µs for transmission.
- **Service Area & Density:** This refers to the service area within which the performance target should be achieved. Factory automation generally means local-area networks of just a few hundreds of meters, or even tens of meters, in dimension. Density is the number of endpoint devices within the service area. Especially where sensors are used, densities may be very high relative to today's wide-area cellular networks.

Robotic Motion Control Example

One of the most demanding use-case categories for any networking system is robotic motion control. This refers to the control of devices such as machine tools, assembly robots, packaging machines and precision AGVs. The 3GPP developed a 1 ms one-way latency target to guide specification of the 5G system to be able to address this market. The target is based partly on the simple math that to control a device moving 1 mm at a speed of 1 meter per second requires updates every millisecond, and partly on work with industries to determine what real-world cycle times are needed in practice.

Where a "cycle time" of 2 ms is the design target, **Figure 4** shows how this latency budget may be distributed across actuation, network transmission and processing. In this example, this equates to 500 µs of one-way air interface delay. Using "mini slots," 5G NR can potentially deliver even lower latency if required.

Figure 4: Cycle Time for Robotic Motion Control



Source: Heavy Reading

Robotic motion control also needs highly reliable network services with six-nines availability. This is challenging to deliver to moving objects in factory environments that are characterized by blocking due to metallic structures, and where the latency requirement makes retransmission impossible or impractical. One of the ways 5G lowers latency is the self-contained sub-frame, which omits the need for network ACKs, delivered over short time slots. Should a blockage occur, it may not disappear within 1 ms, making retransmission ineffective. A proposed solution is to use multi-path connectivity between device and network.

Addressing the dual demand for high availability and low latency will require deployment architectures optimized for local-area operation using path diversity between the network and the endpoint device – in this case, a robotic arm; in other cases, perhaps an AGV.

Diversity can be time diversity, frequency diversity or spatial diversity. Since URLLC requires low latency, there is a limit to the extent to which time diversity can help. Since 5G NR is already wideband (e.g., a 100 MHz channel), there are also limited gains in additional frequency diversity. Spatial diversity is therefore a promising approach to achieve ultra-reliability. One spatial technique that is already standardized for 5G NR and shows a lot of promise in this regard is Coordinated Multi-Point (CoMP). CoMP increases system capacity, and is traditionally thought of in these terms; this capacity can however be traded off against higher reliability by sending duplicate data streams over diverse paths.

MAPPING INDUSTRIAL STANDARDS TO 5G NR

There are many established protocols and technologies in use in industrial networks. 5G should integrate with these environments and contribute to their ongoing development. Collaboration of this type can help create new technology platforms and processes that are applicable industry-wide, driving economies of scale.

Time-Sensitive Networking

Industrial networking is characterized by multiple standards, often selected according to regional or sector preferences. "Standard" WiFi and Ethernet are supplemented by quasi-proprietary enhancements to achieve the performance required for real-time use cases. For example, industrial Ethernet systems, such as Sercos, PROFINET and EtherCAT, are widely used in factory production lines. For the industrial sector, this diversity, which has arisen over time, means duplication and inefficiency. In the same way that consolidation of cellular standards has been beneficial, a common, high-performance networking standard would be useful for industrial automation. The proposed answer is the IEEE Time-Sensitive Networking (TSN) standard.

TSN is part of the 802.1Q family of standards and is designed to provide deterministic messaging on standard Ethernet networks. It is a Layer 2 technology that is centrally managed and uses coordinated scheduling to ensure performance for real-time applications. Real-time, deterministic communication is important to many industries – for example, aerospace, automotive, transportation and utilities, and of course, manufacturing.

TSN is likely to become the baseline networking technology for real-time industrial networking. One advantage is that existing systems, for example those based on PROFINET, can run as an application, over TSN, without major modification. Over time, new systems and equipment can be designed using TSN natively. This consolidation on TSN greatly simplifies the work of 5G NR integration, because standards groups and system designers now only need to map TSN requirements to the 5G radio interface, and do not need to duplicate work across a range of similar but different protocols.

Mapping TSN to 5G NR

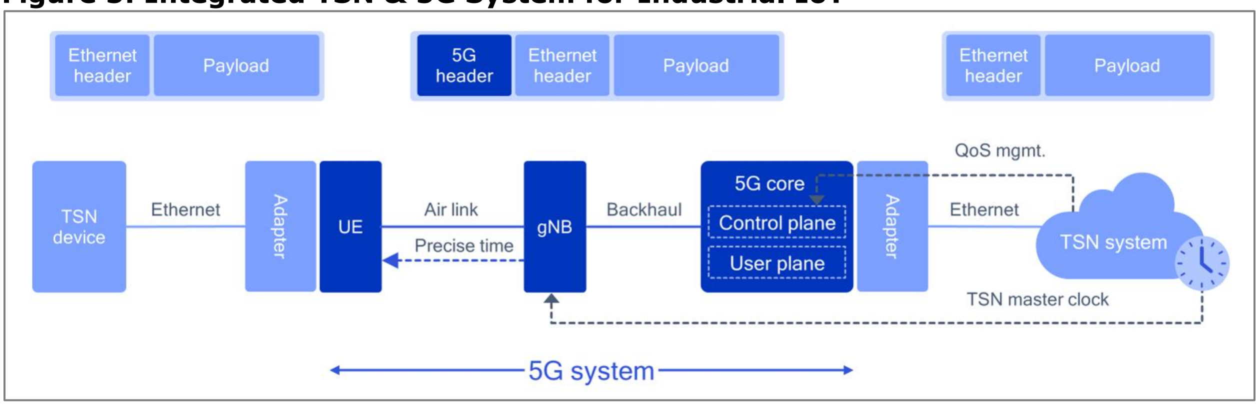
TSN is similar to 5G NR in that it uses timeslot reservations and can classify flows at Layer 2 to provide connections with the latency and availability needed for industrial IoT. Ethernet transport over 5G radio is already supported in R15 using PDCP encapsulation. And so, at a high level, the match is well made.

However, it is not only a matter of transporting an Ethernet payload. Making 5G integral to industrial Ethernet also requires the system to support all functions in 802.1Q that make it suitable for time-sensitive processes (Ethernet bridging, QoS, etc.). These features are not part of the 3GPP standards, and there is, therefore, a need to map TSN to the 5G MAC layer. For example, a new 5G QoS identifier for TSN needs to be defined to ensure over-the-air performance. After a study phase, it looks likely that TSN to 5G mapping will be addressed in 3GPP Release 16, although the extent of the work – and the extent to which this mapping will be mandatory or optional and left to implementation – is to be determined. The prize is worth fighting for, however: If 5G and TSN can be combined into an integrated system, using robust specifications, many companies from across industry sectors will benefit from the economies of scale, innovation and competition associated with open standards.

A high-level of view of an integrated TSN-5G system is shown in **Figure 5**. The TSN system elements are shown in light blue and the 5G system in dark blue. There are three key points of integration:

1. **Between the TSN system and the 5G core.** The TSN system generates control and data traffic to pass to the 5G network. This includes critical TSN QoS information, which must transfer to the 5G system for implementation in the network.
2. **Within the 5G system.** Ethernet frames, including headers, must be mapped to 5G frames and be transported over the air according to the QoS required by TSN. Admission control and over-the-air scheduling are performed by the gNB (5G base station). The 5G radio must also deliver a very precise time signal generated by the master clock in the TSN system.
3. **Between the 5G device (UE) and the industrial equipment.** A 5G radio, with integrated Ethernet adapter, can be connected to the equipment (shown as the "TSN device" in the diagram). This radio device could be integrated with new industrial equipment or retrofitted to existing equipment.

Figure 5: Integrated TSN & 5G System for Industrial IoT



Source: Qualcomm

Spectrum for Industrial Users

Which spectrum bands will be used for industrial 5G is a key question. Very reliable networks can be designed to operate in unlicensed frequencies such as 5 GHz, although generally not using today's listen-before-talk techniques. Traditionally, larger facilities, especially those with more demanding use cases, tend to prefer licensed spectrum due to the risk of interference and the cost of production downtime. This will remain the case in the 5G era for some organizations; however, there is emerging research that shows it is possible to build highly reliable (six-nines) wireless networks in unlicensed and shared spectrum, particularly using spatial diversity techniques.

In the U.S. the 3.5 GHz CBRS shared spectrum band (known as the "innovation band") may prove attractive, with Priority Access Licenses more exclusive than General Access Licenses. In Europe, meanwhile, and in Germany and France in particular, the upper part of the 3.7 GHz band is being discussed as a potential band that could be made available to private local-area network users, such as enterprises. Dedicated and protected shared-spectrum of this kind would be very interesting. It is currently a work in progress and will take time to harmonize and allocate, but it appears to have reasonably broad support across Europe.

Another alternative is to use licensed spectrum under agreement with the mobile operator. There is precedent for this, with some private LTE networks using this model today, typically for larger, sophisticated, high-value clients. Scaling efficiently to the wider industrial IoT sector will require greater operator participation in this segment to create the correct business frameworks. Operator participation in the 5G-ACIA is promising in this regard.

One interesting approach under consideration is a hybrid model where the factory owner (or its contractor or equipment supplier) runs the critical, real-time local-area network, which is in effect part of the production line, and takes responsibility for downtime, while an operator provides managed network services for less time-critical applications (sensors, employee communications, etc.) and can provide a bridge to the wide-area network.

For 5G NR and Industrial IoT, mmWave frequencies are very interesting, because spectrum is relatively plentiful and available on an unlicensed and licensed basis. The major challenge is how to manage the path loss and obstructions that impact radio link performance in these bands. This will need system design and deployment architectures that enable the network to overcome these challenges. Advanced antenna arrays, beam-forming, beam-tracking, path diversity and CoMP will be important to this.

PRIVATE NETWORKS & 5G SYSTEM ARCHITECTURE

Industrial automation will require local-area networks, deployed on the factory premises to consistently meet URLLC performance targets. The 5G system architecture is designed with this deployment option in mind, with specifications that enable operation on a standalone basis, without dependency on external networks.

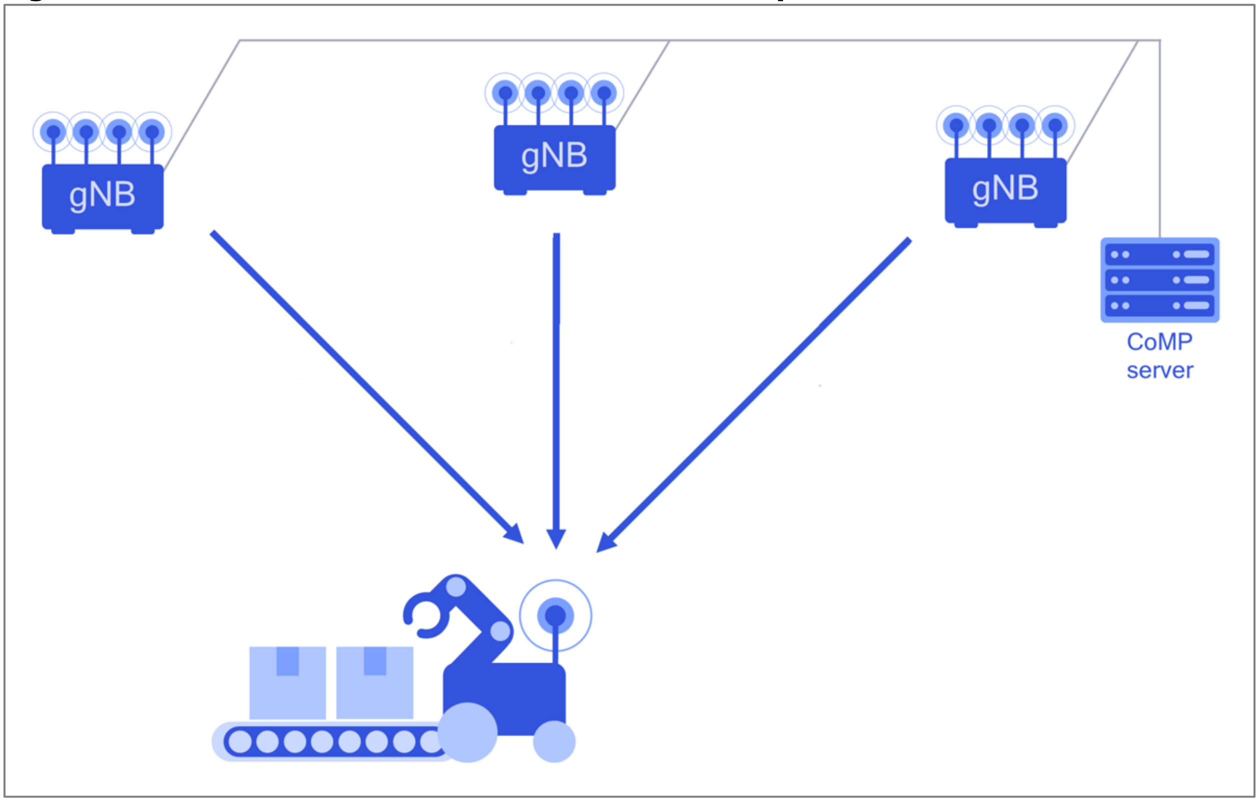
Local-Area 5G Networks

Private 5G wireless networks comprise RAN and core elements. The radio base stations (gNBs) can scale from low to high capacity and power output, according to needs. They connect to a core network that provides authentication, session, management, QoS-control and mobility. In this scenario, the industrial control application is colocated with the 5G core network, which itself is deployed on edge compute nodes installed on-premises – i.e., within the factory environment.

In addition to enabling high reliability and low latency, deployment of edge compute nodes for 5G industrial applications has a number of other potential benefits for industrial use cases. For example, edge computing can be used to offload processing from sensors, enabling simpler designs, longer battery life and lower cost. It also means the enterprise is not dependent on WAN links, and that operational data does not have to leave the premises.

In this time-critical example, shown in **Figure 6**, an automated guided vehicle (AGV) connects to industrial control services that provide routing and job instructions over the 5G network. To ensure availability, the AGV is served by two (or more) radio base stations and combines the signal from each. A system using a single base station and an AGV with an advanced antenna system, would typically offer high reliability relative to today's WiFi networks, given recent advances in signal processing and so on. In this case, however, the base stations are synchronized such that redundant data streams are sent and received to/from the AGV. By combing the signal from multiple base stations, highly dependable communications, which are resilient to moving objects and physical obstructions, can be achieved, consistent with the availability targets listed in **Figure 3**.

Figure 6: Local-Area 5G Network With Path Diversity



Source: Qualcomm

In this way, the design of the local-area 5G network helps to ensure the dependability of the system and makes it robust to environmental changes and to frequent reconfiguration of production lines and processes. Ultimately, this "robust flexibility" enables industrial users to be more adaptable to demand and to market opportunities.

ADVANCING INDUSTRIAL IoT WITH 5G NR

Industry-X, Industry 4.0, Industrial IoT or the Industrial Internet – take your pick of the terms – offer tremendous opportunities to transform productivity across many sectors. Software-driven operating processes, linked to automation of machinery and production lines, are critical to achieving these benefits.

Industrial automation requires commensurate sophistication in the network to connect application control software to machines within very tight performance tolerances. Using the factory of the future and robotic motion control as an example, this white paper has discussed extreme performance in terms of latency, availability and dependability. This in turn drives the need for private, exclusive-use networks that give the factory owner the ability to configure the network to exactly the performance, and security profile, it requires.

Some advanced networking requirements can be met with LTE and WiFi, and these remain important technologies. LTE particularly has a strong development roadmap for private networks, with capabilities spanning from high reliability to low-power IoT and high-bandwidth services, and relative to today's wireless networks, low latency. Private LTE will prove an important foundation for the 5G NR in industrial networks needed for more demanding URLLC use cases. These private 5G networks will, over time, absorb a wide variety of services and end points.

One critical aspect of this development is the integration of 5G with industrial processes and technologies. Time-Sensitive Networking has emerged as a unifying baseline for industrial networks, and mapping TSN to 5G is now a priority for industrial IoT. A second critical aspect is the design and specification of the 5G radio itself. The baseline capabilities already specified for NR in Release 15 are a good start; the challenge is to take this work forward in Release 16 and beyond, and for the industry to continue to develop technologies that enable robust deployments using spatial diversity and CoMP.

In this context, the creation of the 5G Alliance for Connected Industries and Automation (5G-ACIA) is important. This forum will be instrumental in helping to align requirements from different companies and sectors and communicating that to the wireless industry and the companies that will design, deploy and operate high-performance, highly dependable 5G networks for industrial IoT.