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Review

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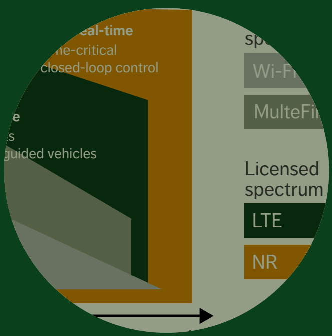

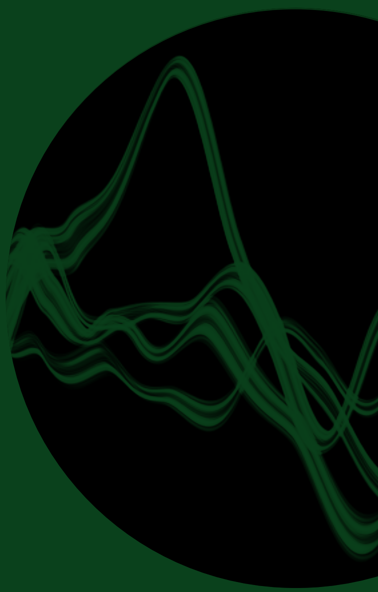

5G AND SMART MANUFACTURING

ERICSSON

BOOSTING smart manufacturing WITH 5G WIRELESS CONNECTIVITY

Industry 4.0 – the fourth industrial revolution – is already transforming the manufacturing industry, with the vision of highly efficient, connected and flexible factories of the future quickly becoming a reality in many sectors. Fully connected factories will rely on cloud technologies, as well as connectivity based on Ethernet Time-Sensitive Networking (TSN) and wireless 5G radio.

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The goal of Industry 4.0 is to maximize efficiency by creating full transparency across all processes and assets at all times. Achieving this requires communication between goods, production systems, logistics chains, people and processes throughout a product's complete life cycle, spanning everything from design, ordering, manufacturing, delivery and field maintenance to recycling and reuse. The integration of 5G ultra-reliable low-latency communication (URLLC) in the manufacturing process has great potential to accelerate the transformation of the manufacturing industry and make smart factories more efficient and productive.

■ Today's state-of-the-art factories are predominantly built on a hierarchical network design that follows the industrial automation pyramid, as shown in *Figure 1*. The fourth industrial revolution will require a transition from this segmented and hierarchical network design toward a fully connected one. This transition, in combination with the introduction of 5G wireless communication technology, will provide very high flexibility in building and configuring production systems on demand. The ability to extract more information from the manufacturing process and feed it into a digital representation known as the "digital twin" [1] enables more advanced planning processes, including plant simulation and virtual commissioning. Initiatives like the 5G Alliance for Connected Industries and

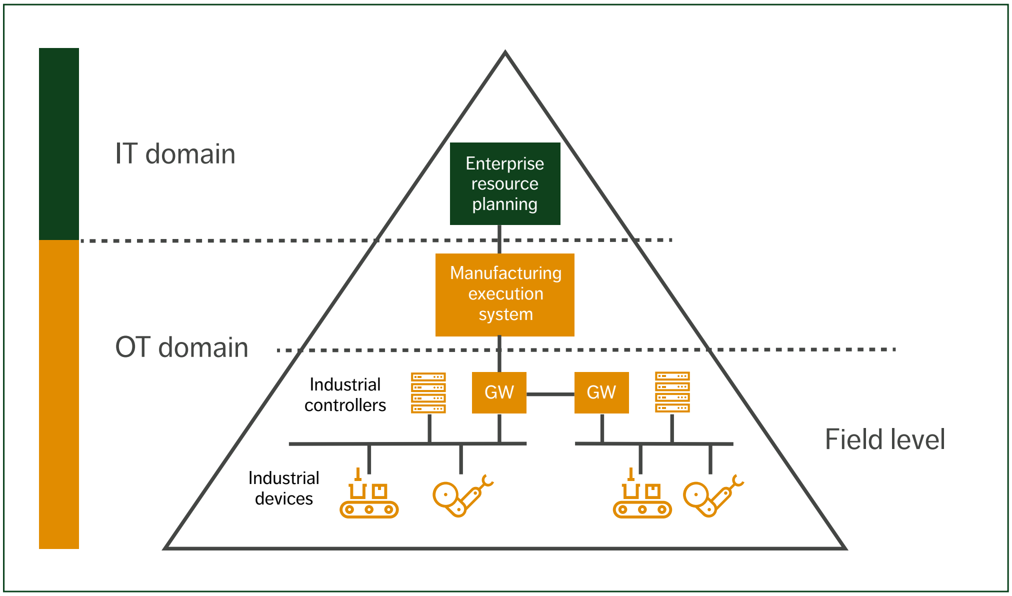

Figure 1 Hierarchical network design based on the industrial automation pyramid

Automation (5G-ACIA) [2] show that industries recognize this need for 5G technology.

The lower section of Figure 1 is often referred to as the operational technology (OT) part of the manufacturing plant, comprising both the field level (industrial devices and controllers) and the manufacturing execution system. The top section is the information technology (IT) part, made up of general enterprise resource planning. For connectivity at field level, a variety of fieldbus and industrial Ethernet technologies are typically used. Ethernet and IP are well established communication protocols at higher levels (IT and the top part of OT).

The OT network domain is currently dominated (>90 percent) by wired technologies [3] and is a heavily fragmented market with technologies such as PROFIBUS, PROFINET, EtherCAT, Sercos and Modbus. Currently deployed wireless solutions (which are typically wireless LAN based using unlicensed spectrum) constitute only a small fraction

Definition of key terms

- **Ultra-reliable low-latency communication** (URLLC) refers to a 5G service category that provides the ability to successfully deliver a message within a specified latency bound with a specified reliability, such as delivering a message within 1ms with a probability of 99.9999 percent.
- **The fourth industrial revolution** is considered to be the fourth big step in industry modernization, enabled by cyber-physical systems, digitalization and ubiquitous connectivity provided by 5G and Internet of Things (IoT) technologies. It is also referred to as Industry 4.0.

of the installed base; they mainly play a role for wirelessly connecting sensors where communication requirements are non-critical.

Today, the field level consists of connectivity islands that are separated by gateways (GWs), which helps to provide the required performance within each connectivity island. The GWs are also needed for protocol translation between the different industrial networking technologies. However, this segmented design puts limitations on the digitalization of factories, as information within one part of the factory cannot be easily extracted and used elsewhere.

One near-term benefit of leveraging wireless connectivity in factories is the significant reduction in the amount of cables used, which reduces cost, since cables are typically very expensive to install, rearrange or replace. In addition, wireless connectivity enables new use cases that cannot be implemented with wired connectivity, such as moving robots, automated guided vehicles and the tracking of products as they move through the production process. Wireless connectivity also makes it possible to achieve greater floor plan layout flexibility and deploy factory equipment more easily.

Key manufacturing industry requirements

The manufacturing industry has specific 5G requirements that differ significantly from public mobile broadband (MBB) services. These include URLLC with ultra-high availability and resilience, which can only be satisfied with a dedicated local network deployment using licensed spectrum.

The ability to integrate with the existing industrial Ethernet LAN and existing industrial nodes and functions is another fundamental requirement. Data integrity and privacy are also critical, as well as real-time performance monitoring. In addition, 5G capabilities in terms of positioning, time synchronization between devices, security and network slicing will also be essential for many manufacturing use cases.

Ultra-reliable low-latency communication

One of the two service categories of machine-type communication (MTC) in 5G – critical MTC (cMTC) – is designed to meet communication demands with stringent requirements on latency, reliability and availability. Intense standardization and R&D work is ongoing to ensure 5G New Radio (NR) technology is able to fully address the need for URLLC.

With NR we will see large-scale deployments of advanced antenna systems enabling state-of-the-art beamforming and MIMO (multiple-input, multiple-output) techniques, which are powerful tools for improving throughput, capacity and coverage [4]. Multi-antenna techniques will also be important for URLLC, as they can be used to improve reliability. The scalable numerology of NR provides good means to achieve low latency, as larger subcarrier spacing (SCS) reduces the transmission time interval.

To further reduce latency and increase reliability, several new MAC (medium access control) and

Terms and abbreviations

cMTC – Critical Machine-type Communication | **CN** – Core Network | **DL** – Downlink | **GHz** – Gigahertz | **GW** – Gateway | **IoT** – Internet of Things | **kHz** – Kilohertz | **LTE-M** – LTE Machine-type Communication | **MBB** – Mobile Broadband | **mMTC** – Massive Machine-type Communication | **mmWave** – Millimeter Wave | **ms** – Millisecond | **MTC** – Machine-type Communication | **NB-IoT** – Narrowband IoT | **NR** – New Radio | **OT** – Operational Technology | **RTT** – Round-trip Time | **SCS** – Subcarrier Spacing | **TSN** – Time-sensitive Networking | **UE** - User Equipment | **UL** – Uplink | **URLLC** – Ultra-reliable Low-latency Communication

PHY (physical layer) features as well as new multi-connectivity architecture options have been added to the 5G NR specifications in 3GPP release 15, and additional enhancements are being studied in release 16. The goal in release 16 is to enable 0.5-1ms one-way latency with reliability of up to 99.9999 percent. New capabilities include faster scheduling, smaller and more robust transmissions, repetitions, faster retransmissions, preemption and packet duplication [5]. All in all, they ensure NR is equipped with a powerful toolbox that can be used to tailor the performance to the demands of each specific device and traffic flow on a factory shop floor.

The achievable round-trip time (RTT) depends both on which features and spectrum are used. For example, the RAN RTT for a mid-band deployment optimized for MBB can be in the order of 5ms (FDD 15kHz SCS or TDD 30kHz with DL-DL-DL-UL TDD configuration). The corresponding RTT for a URLLC-optimized millimeter wave (mmWave) deployment (TDD 120kHz SCS, DL-UL TDD configuration) can be below 2ms, thus matching the 3GPP one-way latency goal.

There is a trade-off between latency, reliability and capacity, and different scheduling strategies can be used to achieve a certain level of reliability and latency. A packet can be encoded with a very low and robust code rate, and just be transmitted once, but if the RTT is shorter than the application latency constraint, it can be more efficient to use a higher, less robust initial code rate and perform retransmissions based on feedback in case the initial transmission fails. Thus, the shorter the RAN RTT is compared with the application latency constraint, the higher spectral efficiency (capacity) may be achieved.

> “MMWAVE IS A GOOD COMPLEMENT TO MID-BAND FOR IN-FACTORY DEPLOYMENTS”

Licensed spectrum for interference control

The availability of spectrum resources is key to meeting requirements on capacity, bitrates and latency. To provide predictable and reliable service levels on the factory shop floor, the spectrum resources need to be managed carefully. The achievable performance depends on several factors:

- the amount of spectrum available
- which spectrum is used – low band (below 2GHz), mid-band (2-5GHz) or high band/mmWave (26GHz and above)
- which licensing regime applies
- whether the spectrum is FDD or TDD
- which radio access technology is used
- the coexistence scenarios that apply for the spectrum.

Estimates of spectrum needs are in the range of tens to hundreds of megahertz. Most new mid-band spectrum that is currently being allocated uses TDD, while large parts of the spectrum already allocated to mobile operators are FDD. Latency for an FDD system is inherently lower than that of a corresponding TDD system.

Mid-band spectrum is well suited for indoor deployments since its propagation characteristics make it easy to provide good coverage with a limited set of transmission points. Coverage at mmWave is generally spottier, requiring denser radio deployment, but mmWave is still a good complement to mid-band for in-factory deployments since it enables:

- higher system capacity, as larger bandwidths are available and as advanced antenna systems and beamforming can be implemented in a small form factor suitable for indoor deployment
- significantly shorter latencies (even though the spectrum is TDD), as a higher numerology with shorter transmission time intervals is used
- easier management of the coexistence between indoor shop floor networks and outdoor mobile networks, as mmWave radio signals are easier to confine within buildings.

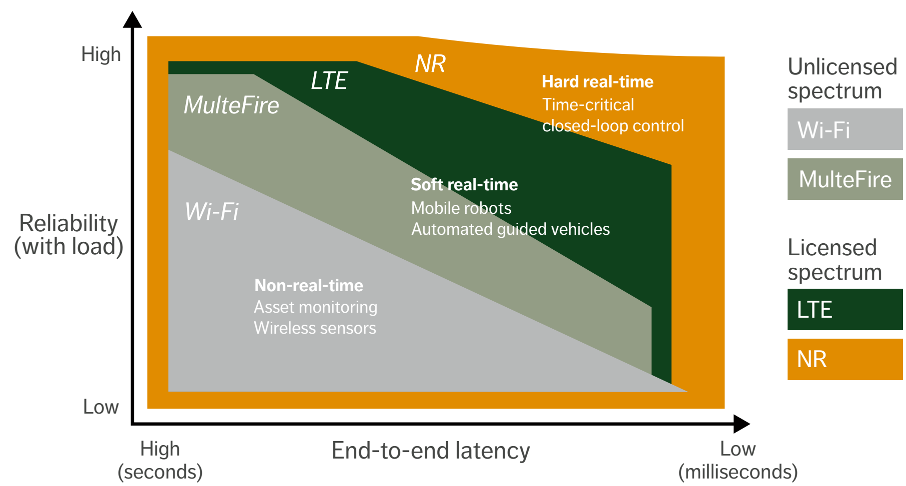

Figure 2 Latency and reliability aspects of spectrum and technology choice

For critical applications, there must be guarantees against uncontrolled interference, which implies that licensed spectrum is necessary. As illustrated in *Figure 2*, unlicensed technologies such as Wi-Fi and MulteFire cannot guarantee bounded low latency with high reliability as the load increases. This is due to the use of listen-before-talk back-off, which does not perform well during uncontrolled interference. Unlicensed spectrum may nonetheless be relevant for less critical applications.

Licensed spectrum can be provided by operators as part of a local connectivity solution, including network equipment. Operators may also choose to lease parts of their spectrum assets locally to industries without providing the connectivity solution. Another emerging option is for regulators to set aside dedicated spectrum for local licensing to industries, as is under consideration in some European countries such as Germany and Sweden on 3.7-3.8GHz.

Integration with industrial Ethernet and TSN

The introduction of 5G on the factory shop floor will happen in steps. When 5G is added to existing production systems, the various parts of the system will be moved to 5G connectivity at different stages, depending on the evolution plan of the production system and where the highest benefits of wireless 5G communication can be obtained. Over time, more parts of the shop floor can be migrated to 5G, in part due to the introduction of new capabilities in future 5G releases. Even in greenfield industrial deployments, not all communication will be based on 5G. The need for wireless connectivity may not be prominent for some subsystems, while others may require performance levels (isochronous sub-millisecond latency, for example) that are not currently addressed by 5G. Consequently, a local industrial 5G deployment will coexist and require integration with wired industrial LANs. To this end, the transport of Ethernet traffic is required, and

Ethernet transport has been specified within the release 15 standard of the 5G system.

As part of the ongoing industrial transformation, the wired communication segments of industrial networks are expected to evolve toward a common open standard: Ethernet with TSN support [6]. Therefore, a 5G system needs to be able to integrate with a TSN-based industrial Ethernet, for which 3GPP has defined different study and work items in release 16 of the 5G standards.

TSN is an extension of the IEEE 802.3 Ethernet and is standardized within the TSN task group in IEEE 802.1. A profile for TSN in industrial automation is being developed by the IEC/IEEE 60802 joint project [7]. TSN includes the means to provide deterministic bounded latency without congestion losses for prioritized traffic on an Ethernet network that also transports traffic of lower priority. TSN features include priority queuing with resource allocation mechanisms, time synchronization between network nodes and reliability mechanisms via redundant traffic flows.

5G enhancements include support of redundant transmission paths, which can be combined with the TSN feature 'Frame replication and elimination for reliability' (FRER) that is standardized in IEEE 802.1CB. One of the resource allocation features of TSN for bounding the latency for periodic control traffic is 'Time-aware scheduling' (standardized in IEEE 802.1Qbv), for which transmission queues are time-gated in every switch on the data path to create a protected connection. This requires all Ethernet switches to be time-synchronized according to IEEE P802.1AS-Rev. Features that are being developed in 5G standardization to support time-aware transmission across a mixed TSN-5G network are to time-align the 5G system with the TSN network and provide 5G transmission with deterministic latency.

Keeping things local

On top of URLLC performance and integration with industrial Ethernet networks, many manufacturers also require full control (that is, independent of external parties) of their critical OT domain connectivity in order to fulfill system availability targets. Full control can be expressed as requirements on keeping things local:

- local data – the ability to keep production-related data locally within the factory premises for security and trust reasons
- local management – the ability to monitor and manage the connectivity solution locally
- local survivability – the ability to guarantee the availability of the connectivity solution independently of external factors (for example, shop-floor connectivity must continue uninterrupted even when connectivity to the manufacturing plant is down).

Additional requirements and features of interest

One 5G feature that could have significant importance for manufacturing use cases is positioning. For 3GPP release 16, the objective is to achieve indoor positioning accuracies below 3m, but NR deployed in a factory environment has the technology potential to support much more precise positioning. There are several aspects which all contribute to better positioning accuracy:

- the wide bandwidths of mid- and high-band spectrum enable better measurement accuracy
- beam-based systems enable better ranging and angle-of-arrival/departure estimation
- the higher numerology of NR implies shorter sampling intervals and hence improved positioning resolution
- dense and tailored deployments with small cells and large overlaps improve accuracy and, together with beam-based transmissions, provide more spatial variations that can be exploited for radio frequency fingerprinting.

In 5G release 16, a new requirement is being introduced, whereby the 5G system will be able to synchronize devices to a master clock of one or more time domains [8]. One reason for this is that several

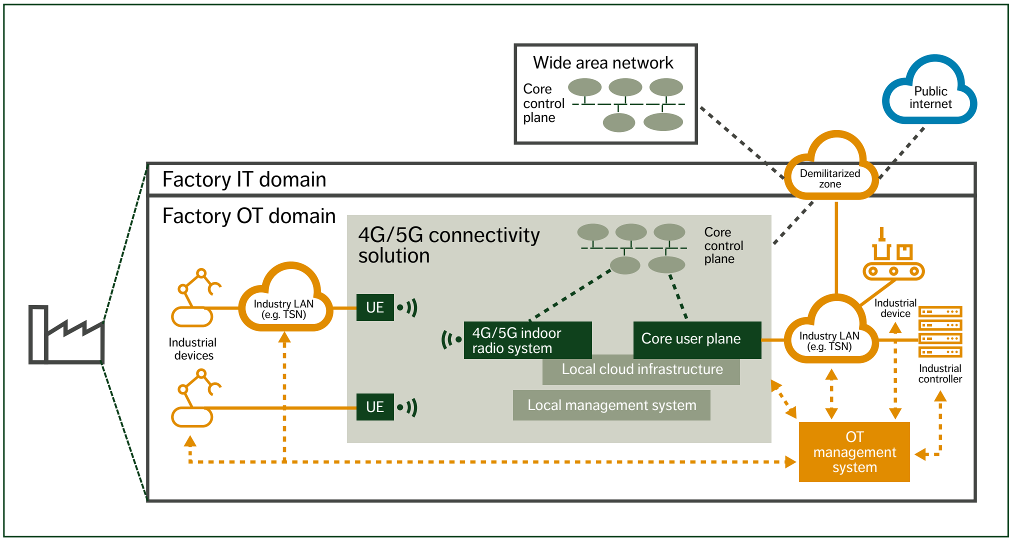

Figure 3 5G manufacturing solution architecture

industrial applications require time-synchronized actions of multiple machines. This can be a collaborative common task performed by multiple industry robots, where the control of the different robots needs to be coordinated in time. NR in release 16 will supply the capability for a base station to provide precise timing references to devices down to microsecond precision. It will also make it possible to relate this time reference to the reference clocks of one or more time domains used in an industrial system. The time alignment of the 5G system with the external industrial LAN is also a basis to enable TSN time-scheduled communication over a combined 5G-TSN network.

Security in cellular networks has matured with every generation to enable confidential communication services, user privacy, authentication of users for network access and accountability, and authentication of the network so users know they are connected to a legitimate network. To address new use cases and the evolving threat landscape, 5G includes new security features that benefit industrial deployments [9]. Examples include improved confidentiality of user-plane data achieved by both the encryption and integrity protection of data to prevent eavesdropping and modification as it passes through the 5G system. With 5G, industrial networks gain additional options for device authentication supporting both SIM-based and certificate-based authentication. Lastly, 5G standards prevent IMSI (International Mobile Subscriber Identity) catching attacks, as the user's or device's long-term identifier is never transmitted over the radio interface in clear text [10].

5G's network slicing capabilities enable the provision of a dedicated slice both locally and in wide area networks, enhance service differentiation including isolation of the critical traffic from other service types and enable segmentation into security zones as required for the OT domain.

5G connectivity solution for the factory shop floor

A local, on-premises 4G/5G connectivity solution that uses licensed spectrum such as the one shown in *Figure 3* is the best way to meet the requirements of the manufacturing industry. This solution can support cMTC, MBB and massive MTC (mMTC) use cases, and it can easily be integrated with mobile operator-provided wide area networks.

While cMTC addresses the critical communication needs of the manufacturing industry, mMTC, also included in 5G, is ideal for sensor communication. Narrowband Internet of Things (NB-IoT) and LTE machine-type communication (LTE-M) are examples of mMTC solutions that were developed for 4G and remain well equipped to support the needs of the manufacturing industry for a long time.

MBB and mMTC based on 4G and 5G provide the shop-floor connectivity required by industrial sensors, cameras, smartphones, tablets and wearables to support use cases like data acquisition, predictive maintenance, human-machine interaction and augmented reality. Beyond factories, there are also wide-area use cases like smart logistics that will rely on the MBB and mMTC services supplied by mobile operator-provided networks.

Network operators are in an excellent position to leverage their spectrum assets, wide area network infrastructure and know-how to address the needs of the manufacturing industry. Alternatively, the solution can be deployed by the industries themselves or by third parties using leased or dedicated spectrum.

The optimal local connectivity solution requires a well-planned 4G/5G indoor radio system using licensed spectrum to enable ultra-reliable low-latency performance. The virtualization of core network (CN) functions and support of control and user-plane separation enables flexible CN deployments. The CN user plane needs to be deployed in the factory, not only to provide URLLC but also high availability, local survivability, security and privacy. The requirements on full local control would indicate that CN control functions need to be deployed on-premises, but depending on the specifics of the requirements, such as how long survivability duration is required, it may be possible to use more cost-efficient solutions where some of the control functions are provided from a central location, such as a mobile network operator's CN.

An easy-to-use local management system is required to monitor and manage the end-to-end connectivity, including local network infrastructure and connected devices. The local management use cases include both software management and fault, performance and configuration management. The management system also needs to integrate with other elements of the OT systems and the industry IT systems. A low-latency cloud infrastructure is required both for 5G network functions and industrial applications, and all pieces need to be connected using an integrated local transport infrastructure.

The resulting solution can provide both IP and Ethernet connectivity to industrial devices and GWs on the shop floor, with performance tailored to each device's individual needs. The integration between the 5G infrastructure and the industrial Ethernet domain extends beyond simple user-plane forwarding of Ethernet frames to include integration with the time synchronization, scheduling and resilience schemes used in the industrial Ethernet domain, using TSN features, for example.

“5G INCLUDES NEW SECURITY FEATURES THAT BENEFIT INDUSTRIAL DEPLOYMENTS”

Conclusion

5G is a prime enabling technology to facilitate the industrial transformation to Industry 4.0, providing wireless connectivity in and around the factory based on a global standard with global economy of scale. It can connect a variety of industrial devices with different service needs, including industrial sensors, video cameras or advanced control panels with integrated augmented reality. 5G can also provide deterministic ultra-reliable low-latency communication to bring wireless connectivity to demanding industrial equipment, like industrial controllers and actuators.

A 5G-connected factory is based on a local 5G radio network using licensed spectrum. It can either be provided as a service by a mobile network operator, or it can be operated standalone by a factory owner or system integrator in locally leased or dedicated spectrum. A local core network enables low-latency connectivity, fulfilling strict requirements on availability, local survivability, data security and privacy. The integration of a 5G system with wired industrial LAN equipment – which in future will mainly be based on TSN – is mandatory. Further 5G enhancements provide additional value to industrial services like precise indoor positioning, and time synchronization for industrial end devices.

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Further reading

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