5G – Not Just for Cell Phones Anymore

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Abstract

5G is an upgrade to the cellular system. It is not the same as prior generations, where the upgrade focused almost exclusively on improved rates for cell phones. Along with improved rate, enhancements include higher device density, lower latency, increased reliability, and a push for private deployment - that all combine to target a wider range of applications. Expected usage includes “Ultra Reliable Low Latency Communication” (URLLC) for real time control, “enhanced Mobile Broadband” (eMBB) for uses including augmented and virtual reality, and “enhanced/massive Machine Type Communications” (eMTC) for wide-area (usually battery powered) wireless. Not only did the cellular industry target industrial automation in their IMT-2020 vision, but there is a coordinated effort called 5G-ACIA to rally industrial automation behind 5G and to influence the 5G standards to meet industrial automation use cases and requirements. The 5G standards from 3GPP are delivered in a series of releases. Earlier releases had already included Ethernet bridging, IP routing, and DSCP-based QoS – valuable features to carry EtherNet/IP traffic. Release 15 is moving into the market, bringing many of the stated enhancements. Release 16 is in development and goes even further with the addition of TSN capability. Various visions include the replacement of wired switches and the enablement of collaborative mobile manufacturing platforms. This paper presents an overview of this topic area.

Keywords

5G, URLLC, eMBB, eMTC, IMT-2020, 5G-ACIA, 3GPP, ODVA, EtherNet/IP, TSN

Definition of terms

5G	-	The fifth-generation mobile telecommunication system
AR	-	Augmented Reality, superimposing a partial computer-generated image on a user's view of the real world
VR	-	Virtual Reality, substitutes a complete computer-generated image as a user's view
LPWAN	-	Low Power Wide Area Network, typically battery powered sensors
IoT	-	Internet of Things, connected devices (not people), wired and wireless
ITU	-	International Telecommunication Union, a part of the United Nations
ITU-R	-	Radiocommunication Sector of ITU
IMT	-	International Mobile Telecommunications, ITU-R initiative to create the vision for each generations of mobile telecommunication networks
IMT-2020	-	The vision document for 5G
5G triangle	-	Usage scenarios for 5G, defined in IMT-2020
5G spider diagram	-	Metrics for 5G, in comparison to usage cases and prior generations
URLLC	-	Ultra Reliable Low Latency Communication, 5G triangle usage categories
eMBB	-	enhanced Mobile Broadband, 5G triangle usage categories
eMTC	-	enhanced/massive Machine Type Communications, 5G triangle usage categories
3GPP	-	Third Generation Partnership Project, international organization specifying 5G, collaboration of telecommunication SDOs
SDO	-	Standards Development Organization
TSN	-	Time Sensitive Networking, a set of IEEE Std 802.1 standard protocols
5G NR	-	5G New Radio, Release 15, the first release of 5G in 2018
5G NR NSA	-	5G NR Non-Standalone, transition 5G using LTE for control plane
5G NR SA	-	5G NR Standalone, full native 5G, including the control plane
ZVEI	-	German Electrical and Electronic Manufacturers' Association
Industrie 4.0	-	Initiative to bring advantage of “digitization” to industrial automation
5G-ACIA	-	5G Alliance for Connected Industries and Automation, a Working Party of ZVEI
Six-Nines	-	The target reliability of 5G, 99.9999% error free packet delivery, equivalent to wired Ethernet

5GS	-	5G System architecture, including the three main components: 5G (R)AN, 5GC, and UE
5G RAN	-	5G Radio Access Network, includes a basestation (known in 5G as “gNodeB”) and antennas, providing the wireless interface point for User Equipment
5GC	-	5G Core
UE	-	User Equipment (e.g., Phone)
Interworking	-	3GPP methods to interconnect 3GPP User Equipment to non-3GPP Data Networks, and to interconnect differing Radio Access Technologies (RATs)
IP	-	Internet Protocol (IETF RFC 791)
Ethernet	-	IEEE Std 802.3
Spectrum	-	The worldwide frequency bands available to 5G
Multi-layer spectrum	-	Functional division of the frequency into three functional layers: “Coverage”, “Coverage and Capacity” and “Super Data”
FDD	-	Frequency Division Duplexing, splitting of transmit and receive signals to different frequencies, a 5G technique for better propagation at low frequencies
TDD	-	Time Division Duplexing, splitting of transmit and receive signals across time, a 5G technique for higher frequencies
mmWave	-	Spectrum between 30 GHz and 300 GHz, large available bandwidth, poor propagation, technically challenging to implement
NPN	-	Non-Public Networks, private usage of some or all portions of a cellular system
MNO	-	Mobile Network Operator
SIM	-	Subscriber Interface Modules, hardware enabling a device to access a cellular network
SLA	-	Service Level Agreement, contract obligating a service provider to maintain a specific level of service, in 5G it may be a specific amount of interference-free bandwidth
Slicing	-	Partitioning of the 5G network into multiple virtual networks, the core or RAN or both may be partitioned, Service Level Agreement (SLA) is accommodated by complete separation of the resources
Small cell	-	Technique being adopted in 5G to increase the spectrum density, basestations may be small enough to be placed on lamp posts, or even operated in small indoor areas
5G (sub)frame	-	A fixed 10 ms frame, consisting of 10 fixed subframes of 1 ms each
5G slot	-	A division of a subframe consisting of (typically) 14 symbols in time and a variable number of subcarriers

SCS	-	Subcarrier spacing, the frequency spacing of the carriers composing a symbol, 15/30/60/120 kHz are options for 5G
Symbol	-	A carrier modulated for a period of time to carry information
OFDM	-	Orthogonal Frequency Division Multiplexing, a symbol composed of a number of carriers that are modulated simultaneously
OFDMA	-	Orthogonal Frequency Division Multiple Access, a scheduling method for a resource consisting of multiple OFDM symbols, portions of the transmission may go to different receivers, or with a turn-around be received
LBT	-	Listen Before Talk procedure, unlicensed bands require listening before Transmitting, if the channel is in use a backoff procedure is performed – adding latency
MIMO	-	Multiple In Multiple Out, coordinated usage of antennas on transmitter and/or receiver, for increased capacity/reliability/distance
Massive MIMO	-	MIMO applying a very large number of antennas to a basestation, improving service to UEs
Beamforming	-	Coordinated use of multiple antenna to increase signal strength between transmitter and receiver
CoMP	-	Coordinated Multi-Point, a distributed MIMO technique
LTE-M	-	LTE upgrade to IoT, 1 Mb/s + roaming + voice, advantages disappear in high loss situations
NB-IoT	-	Narrow Band IoT
EC-GSM-IoT	-	GSM upgrade for IoT
MCL	-	Maximum Coupling Loss, channel independent measure to describe the expected wireless system coverage
WUS	-	Wake Up Signal for low power LPWAN
BEST	-	Battery Efficient Security Technique for LPWAN
Generalized Beamforming	-	Utilization of multiple simultaneous beams, utilizing reflections
IT	-	Information Technology
OT	-	Operational Technology
MES	-	Manufacturing Execution Systems
Industrial Ethernet	-	Fieldbus protocol operable over Ethernet
Switch	-	IEEE 802.3 bridge, forwarding based on MAC addresses

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5G Background

Mobile Phone Generations

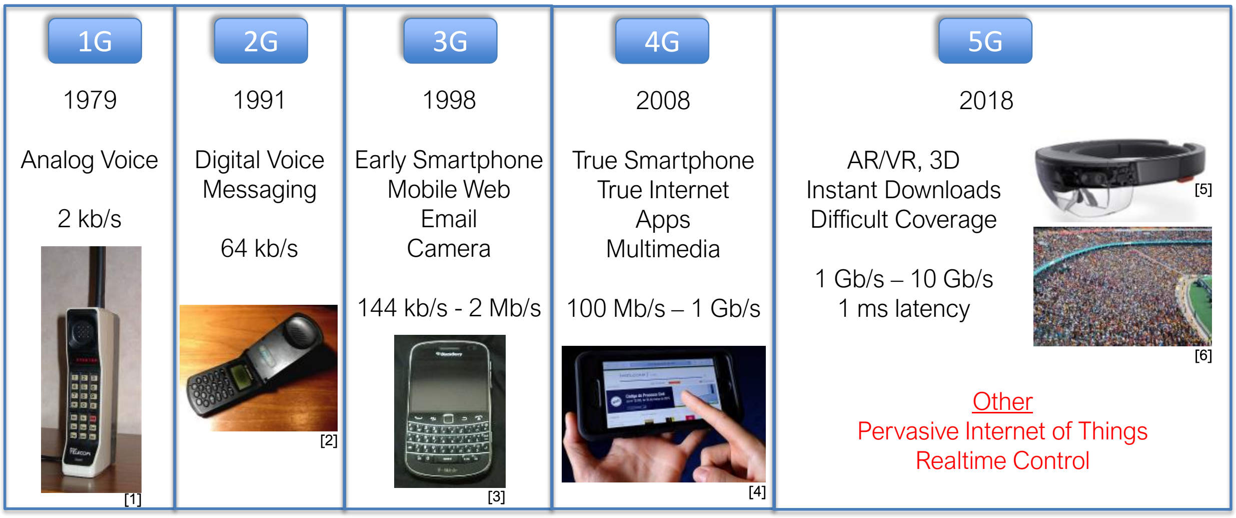

Figure 1: Mobile phone generations.

5G is an upgrade to the cellular system. It is not the same as prior generations, where the upgrade focused almost exclusively on improved rates for cell phones.

As shown in Figure 1, new cell phone generations emerge about every 10 years. The bandwidth of 1G was just adequate for analog voice. The increased 2G bandwidth enabled digital voice and messaging. The increased bandwidth of 3G, along with platform improvements, enabled transmission of pictures, optimized Web pages, and email. The increase in the platform capability eventually drove the first smart phone. With 4G, we entered the true smartphone era. High resolution screens allowed true internet access by apps. The higher bandwidth enabled the first multimedia streaming. Through all of this, the primary focus was on the improvement of cell phones.

With 5G, cell phone advancements are still important. The large density of cell phones at ballgames, airports, and other public venues presents a challenge to the cellular infrastructure. Users demand high-quality multimedia – regardless of the setting.

In combination with higher rates, 5G brings dramatic latency reduction to enable new capabilities. Mobile interfaces become wearable and immersive. Augmented Reality (AR) and Virtual Reality (VR) depend not only on high rates, they but must move large amounts of data with low latency, or risk making users nauseated.

Showing larger aspirations, 5G proposes to utilize its low latency for real-time control applications, including those in industrial automation.

On another front, 5G is pushing to be the dominant force in low-power wireless devices. While 4G brought features for Low Power Wide Area Network (LPWAN), 5G improves cellular' competitiveness.

Much of the extended focus is on devices other than traditional cellphones, the so-called Internet of Things (IoT). While each person may carry a single (relatively expensive) cell phone, they may wear multiple (relatively less expensive) devices. They may also utilize a dramatically larger number of devices in their homes, cars, and workplaces, as well as in public settings.

How/when did 5G features originate?

The vision documents for each future generation of mobile telecommunications have been emerging from a single source. Under the United Nations (UN) is the global-scope International Telecommunication Union (ITU). One part of the ITU is the Radiocommunication Sector (ITU-R). An initiative of ITU-R, named International Mobile Telecommunications (IMT), develops the vision documents.

5G is the third cellular generation based on these documents. The 3G vision document was completed in 1998, under the name of “IMT-2000”. The 4G vision document was completed in 2008, under the name of “IMT-Advanced”. The 5G vision document was developed between 2015 and 2018, under the name “IMT-2020”.

5G “Triangle” (IMT-2020)

IMT-2020 includes a usage scenario triangle as shown in Figure 2.

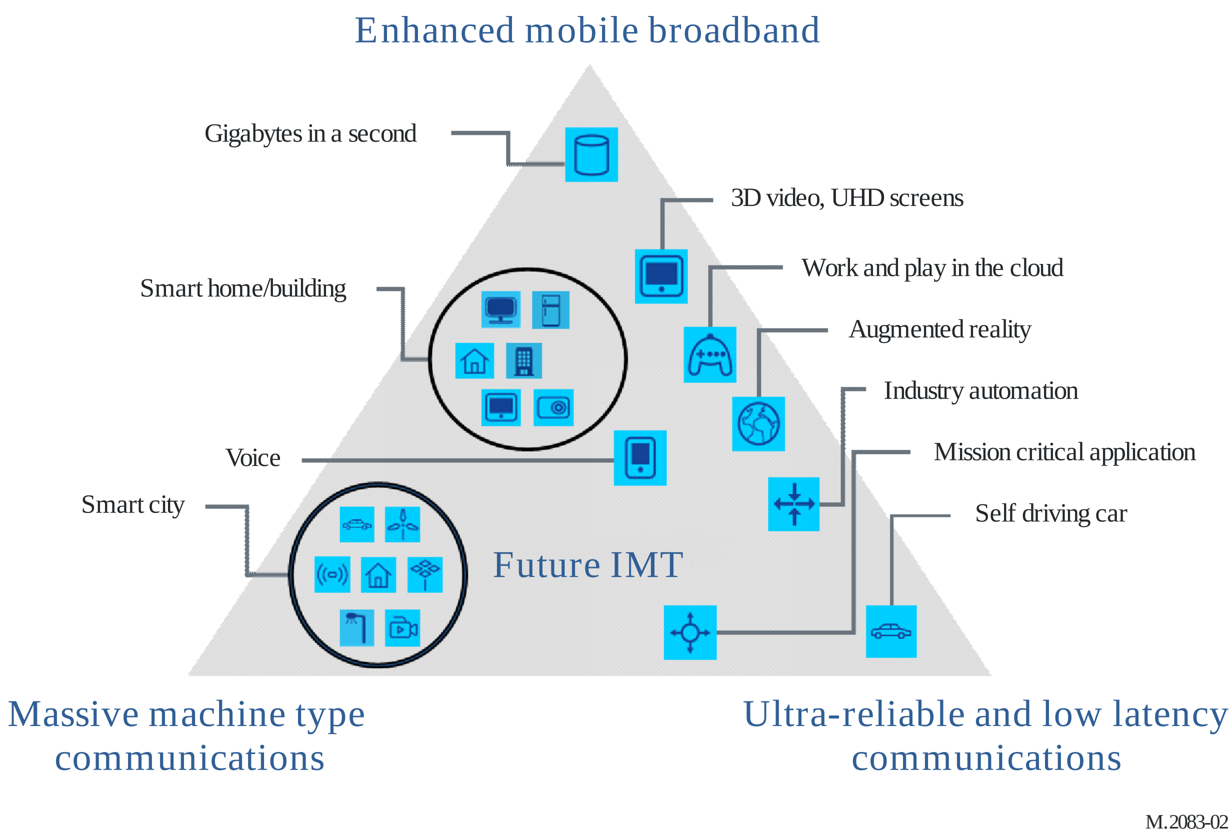

Figure 2: 5G triangle from IMT-2020 [7].

IMT proposed three broad usage categories on the vertices of the triangle: “Ultra Reliable Low Latency Communication” (URLLC) for real time control, “enhanced Mobile Broadband” (eMBB) for uses including augmented and virtual reality, and “enhanced/massive Machine Type Communications” (eMTC) for wide-area (usually battery powered) wireless.

The three corners of the triangle are roughly related to three aspects of improvement in 5G: increased rate, reduced latency, and LPWAN capability.

Within the triangle are more specific usage scenarios. These fall in place by their relationship to the broader categories. Industrial Automation is shown to rely more on high reliability and low latency, and less on high data rate or wide geographic spread.

5G “Spider Diagram” (IMT-2020)

IMT-2020 also includes spider diagrams for making comparisons. One is shown in

Figure *3*.

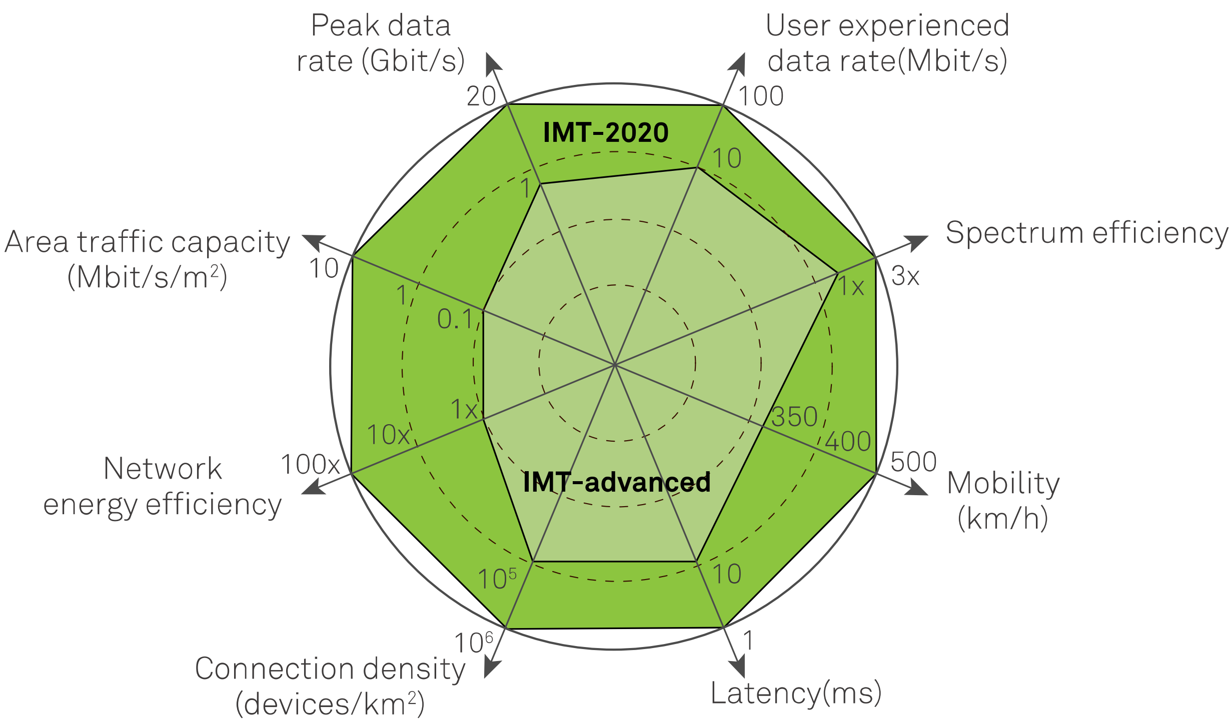

Figure 3: 5G spider diagram from IMT-2020 [7].

This diagram proposes eight technical metrics for improvement over IMT-Advanced (4G). These enhancements combine to target a wide range of usage scenarios.

While there is a 20x increase in the peak data rate, other metrics are worth noting.

Low latency of 1 ms (10x improvement) is an enabler for AR/VR applications. It is also an enabler for motion control, but only when combined with high reliability.

Data rates of 100 Mb/s at each automation device would match today’s typical expectation for wired Ethernet.

A capacity of 10 Mb/s/m^2 may begin to enable wireless in each sensor, especially if there can be 1 M devices/km^2.

5G Standards Development

The Third Generation Partnership Project (3GPP) is the organization where 5G specifications are created and maintained. The specifications are publicly available – free of charge.

3GPP was established in 1998 for the development of 3G cellular. It was established as an international collaboration of telecommunication standards development organizations (ARIB, ATIS, CCSA, ETSI, TSDSI, TTA, TTC). 3GPP was so successful that they have continued to develop standards for subsequent generations of cellular – beyond 3G. Still, the name was preserved.

3GPP is divided into Technical Specification Groups (TSG), each working on a specific aspect of the technology. The Radio Access Networks (RAN) group develops radio specifications from layer 1 through layer 3 for the basestation and the user equipment. Core Network and Terminals (CT) group develops the specifications for the layer 3 protocols (session control, mobility, etc.) between the core network nodes, and the interconnection with external networks. Services & System Aspects (SA) develops the specifications for the overall architecture and the services.

Importantly, TC WG3 develops specifications for "interworking" – the connection of the 5G realm to the rest of the world. In 4G/LTE, they created the "Evolved Packet Core" (EPC), which provided an Internet Protocol (IP) packet switching basis for subsequent cellular.

3GPP Releases

The 5G standards from 3GPP are delivered in "releases". A release is a formal specification development process – focused on agreed "work items" (features). A series of releases defines a cellular generation introduction and its enhancement and maintenance. The time to complete a typical release is variable. The releases overlap to reduce the time.

Release 15 is currently moving into the market, bringing many wireless enhancements. It is called 5G NR (New Radio). Two versions are defined. The Non-Standalone (NSA) version leverages the legacy LTE "control plane" to establish connectivity, to roam, and for other related management. The NSA data utilizes the 5G "data plane" for the application traffic. The full native version is Standalone (SA), which uses both control and data plane from 5G. This requires more extensive changes in the core.

Note that the NSA roaming is based on the slower LTE procedures. While it is desirable for control loops to utilize the 1 ms URLLC latency, packets will be delayed or dropped during the roaming interval. This is likely to limit the mobility of these time critical applications. SA roaming should not have this limitation.

As shown in Figure 4, Release 16 is (as of March 2020) in development. It brings the addition of TSN capability. This addition is made to cater to industrial automation use case requirements.

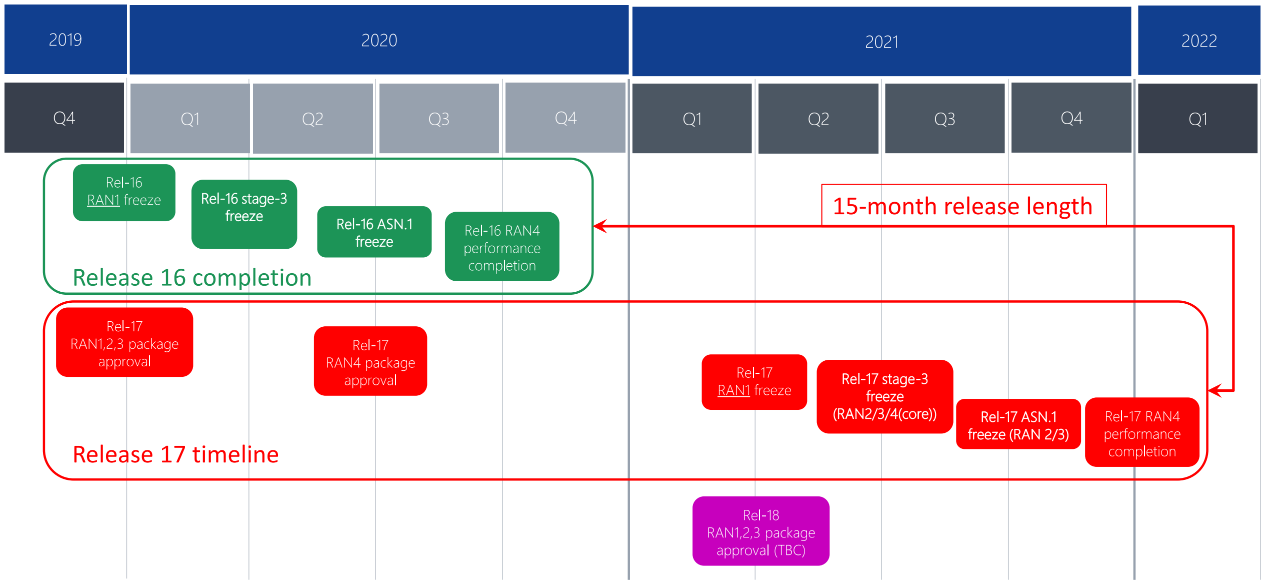

Figure 4: 3GPP schedule for Release 17 as of December 2019 [9].

5G-ACIA

Not only did the cellular industry target industrial automation in their IMT-2020 vision, but there is a coordinated effort called 5G-ACIA (5G Alliance for Connected Industries and Automation) with the purpose of rallying industrial automation behind 5G and to influence the 5G standards to meet industrial automation use cases and requirements.

5G-ACIA is a subgroup of ZVEI (a German Electrical and Electronic Manufacturers' Association). 5G-ACIA was established with the sole purpose of promoting 5G evolution to meet industrial automation needs. It is in part an outgrowth of the German government promotion of Industrie 4.0, which points to 5G as a key enabler in the digitization of industrial automation. Further German government influence led to lightly licensed industrial bandwidth, and German manufacturer commitment to 5G in factories (Volkswagen and Audi in particular).

The group meets regularly, on an international basis, to develop use cases, whitepapers (free to download), and requirements for 5G.

The membership of 5G-ACIA includes industrial automation leaders as well as telecommunication industry participants at all levels (operators, equipment providers, chip-level providers, etc.). The overlap of the two sets of participants results in the ability for industrial requirements to be brought back into 3GPP.

Figure 5 illustrates some use cases. These were brought into the 3GPP releases, along with the key performance indicators, to influence the specification enhancement process.

Note that some of the 5G use cases require 99.9999% (Six-Nines) reliability in packet delivery. This is equivalent to wired Ethernet reliability. This represents a Packet Error Ratio (PER) of 1 in 1 million or 10^{-6}. Assuming an average packet length of 1000 bits, this represents a Bit Error Ratio (BER) of 10^{-9}.

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	10000 devices per km^2	

Source: ZVEI

Figure 5: 5G-ACIA industrial automation use case metrics [10].

<u>5G Technology</u>

System Architecture and Interworking

At a high level, the 5G System architecture (5GS) of
Figure *6* includes three main components: the 5G Radio Access Network (5G (R)AN), the 5G Core (5GC), and the User Equipment (UE). The UE is typically a cell phone, but it can be any 5G enabled device. The 5G RAN includes a basestation (known in 5G as a "gNodeB") and the antennas, providing the wireless access point for the User Equipment. External components – the Application Function (AF), and the Data Network (DN) – link to the 5GC, but are not part of the 5GS specification.

The 5GC includes a Service-Based Architecture (SBA) with functional modules. These include the Access and Mobility Management Function (AMF), controlling access to the system, and facilitating mobility/roaming. Specialized AFs may also be developed and share the SBA. These remaining Network Functions (NF) are described in [11]:

NSSF	Network Slice Selection Function
NEF	Network Exposure Function
NRF	NF Repository Function
PCF	Policy Control Function
UDM	Unified Data Management
AUSF	Authentication Server Function

A primary function of 5G is to convey information between the wireless UE and non-5G DNs – e.g., the Internet. This is known in the 5G specifications as "interworking". The DN is most typically a routed network using Internet Protocol (IP), or an Ethernet network.

The User Plane Function (UPF) acts as a gateway to the data plane, forwarding, filtering, and converting packets. The Session Management Function (SMF) acts as the control plane to configure the UPF, creating sessions between UE and DN.

The numbers in the 5GS diagram are called "reference points". They designate the interactions between functions. N3 and N9 use the General Packet Radio Service Tunneling Protocol User plane part (GTP-U) to convey Protocol Data Unit (PDUs) of end-user protocol packet [48]. 5GS requires a routed IP network, between gNodeBs and UPFs, then overlays GTP-U tunneling. This managed tunnel structure is the mechanism that performs the packet switching for the core. Tunnels may be unicast or multicast. They may also aggregate traffic from sessions with equal priority. N9 indicates the a UPF may have a tunnel to another UPF. This allows protocol conversions. It also allows forwarding, useful with mobility anchors and roaming.

Two important interworking methods are in place: 1) an Internet Protocol (IP) routing method (
Figure 7), and 2) an Ethernet bridging method (
Figure 8). The two methods include related services, including linkage to outside security. The UPF plays a key role in data movement.

The IP routing includes use of IPv4 or IPv6 and DSCP-based QoS, with the SMF acting as DHCP client/server, as well as linkage to RADIUS/AAA and other security services.

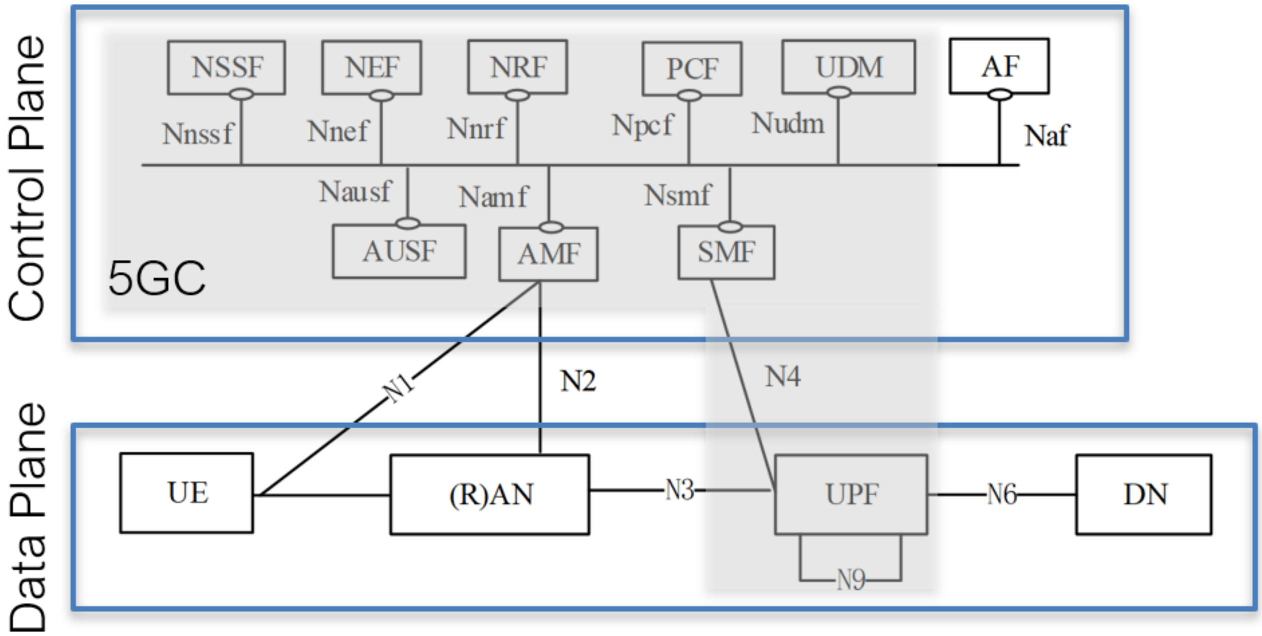

Figure 6: 5G system architecture diagram from 3GPP Release 15 [11, annotated].

The Ethernet bridging utilizes the User Plane Function (UPF) to strip and adds Ethernet headers on ingress and egress, stores Media Access Control (MAC) addresses for bridging decisions, and acts as an Address Resolution Protocol (ARP) proxy.

Note that the UE may also include routing or bridging function internally. This allows compliant design of an adapter to a wired subnet or the creation of a fully embedded wireless solution.

These 5G interworking specifications are valuable features to carry EtherNet/IP traffic. Early testing by Rockwell Automation indicates that unmodified EtherNet/IP protocols can run over 5G.

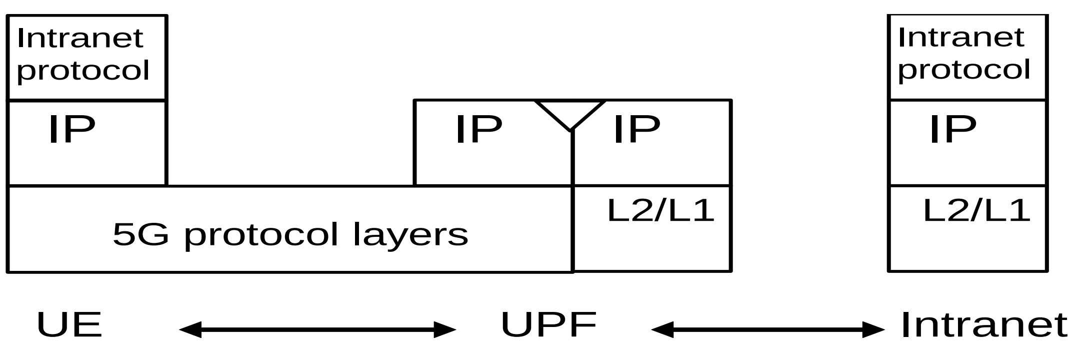

Figure 7: Interworking of 5G by Internet Protocol [12].

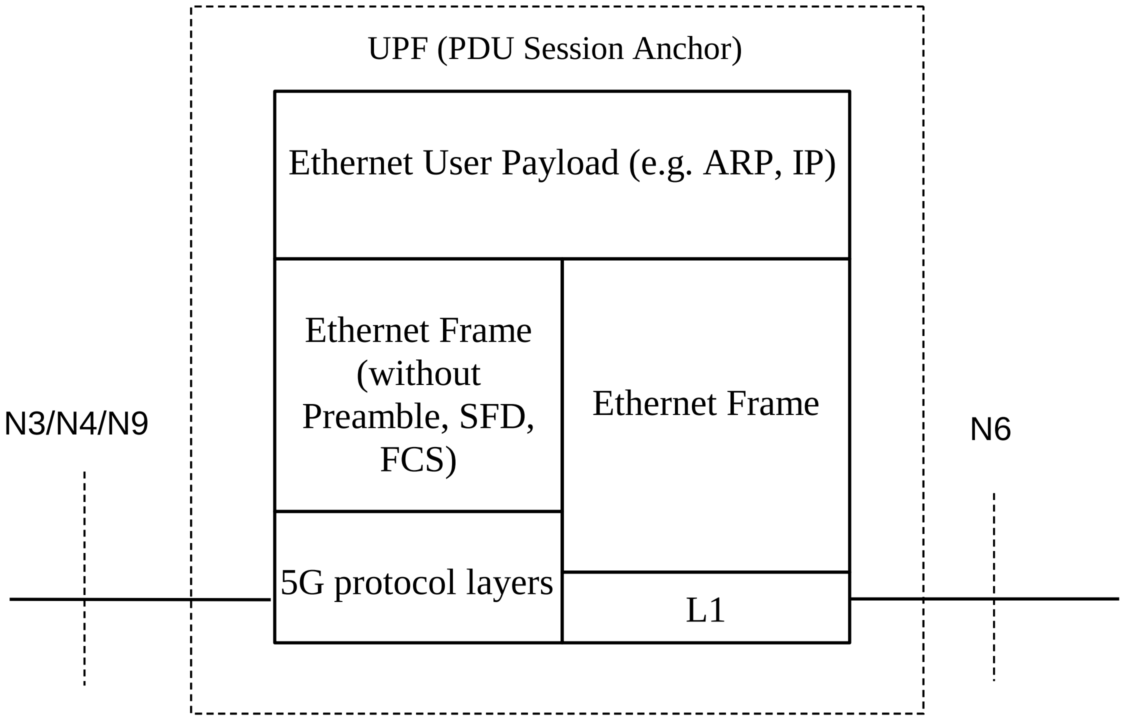

Figure 8: Interworking of 5G by Ethernet [12].

Spectrum

5G spectrum is only roughly harmonized on a worldwide basis.
Figure 9 shows that most of the spectrum is currently licensed (under control of the operators). Unlicensed and flexibly licensed bands exist and are growing in availability. The US promotes 3.5-3.7 GHz (CBRS band) with a license database to reserve exclusive use of channels within a limited geography. Germany introduced 3.7-3.8 GHz with company licensing. Unlicensed spectrum generally requires Listen Before Talk (LBT), impacting determinism.

In Release 15, 3GPP specified two broad frequency bands: FR1 (410 MHz to 7.125 GHz) and FR2 (24.5 GHz to 52.6 GHz). Technical differences are specified for radios that are designed for each band.

The cellular industry created a further logical division [42] into three functionally different layers: 1) The “low-band”, below 1 GHz, applying only Frequency Division Duplexing (FDD), and known as the “coverage layer” due to better propagation characteristics, 2) The “high-band”, above 24 GHz, applying only Time Division Duplexing (TDD), and known as the “Super Data Layer” due to high data rates, and 3) the “mid-band”, between 1 and 6 GHz, applying mostly TDD, and known as the “Coverage/Capacity Layer” as it is a compromise between the other two bands.

The low-band services provide for remote rural coverage as well as LPWAN. Standard cell phone usage falls into the mid-band. Applications demanding the highest rates and lowest latency will utilize the high band. Coverage is then more difficult due to the poor propagation characteristics of the mmWave signals (blocked by most everything, including windows). On the other hand, the poor propagation facilitates channel reuse by blocking the signal at a facility boundary.

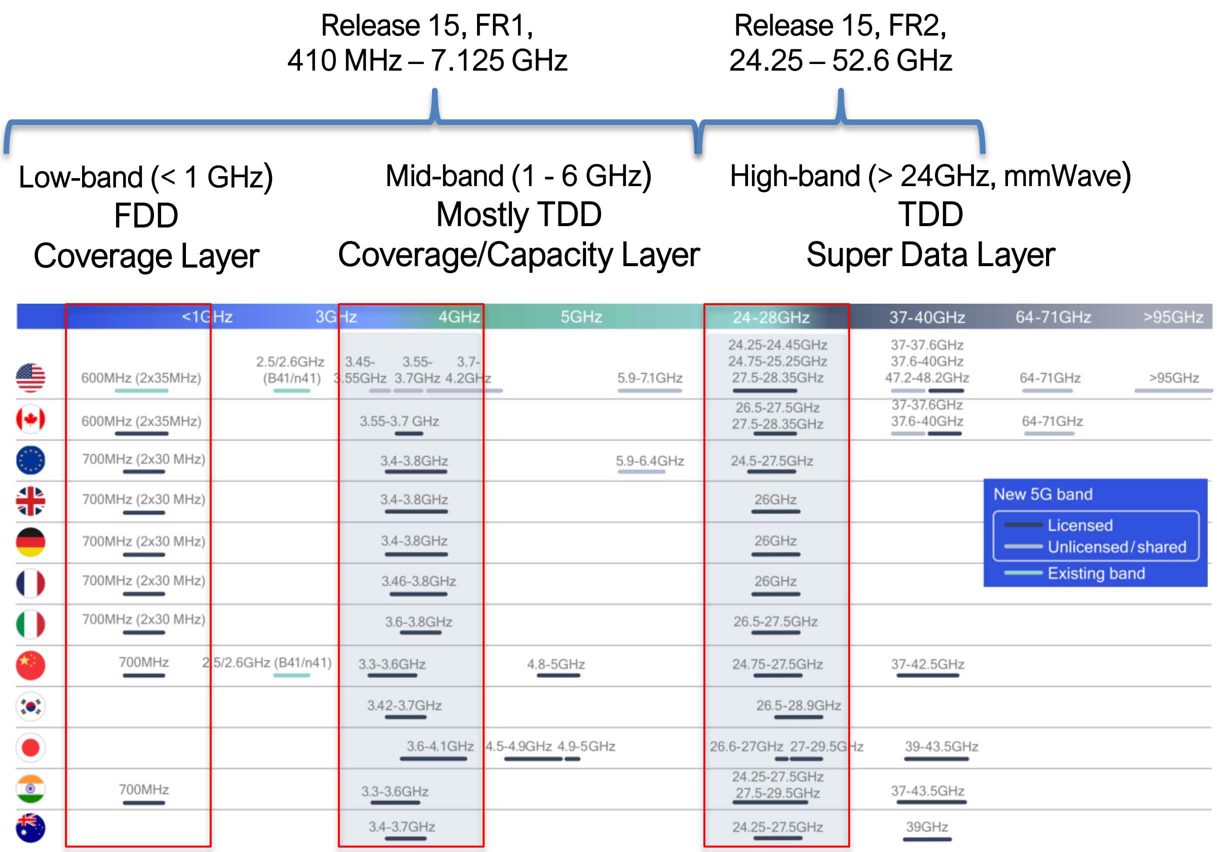

Figure 9: Spectrum overview for 5G as of November 2019 [13, annotated].

Non-Public Networks (NPN)

New deployment models are emerging with 5G. Previously, cellular systems were totally controlled by the Mobile Network Operators (MNOs). End users could develop the UE, adding Subscriber Interface Modules (SIMs) to bring them into a Public system. 5G brings options for Non-Public Networks (NPN) to the end users.

Several NPN models exist, starting with a full stand-alone NPN (Figure *10*), where the end user owns all the equipment, the control plane or 5G core (5GC), the data plane (UPF), the Radio Access Network (RAN), and the private spectrum. In hybrid models (Figure *11*), only some portions are private.

Based on market studies, cellular participants estimate that NPN deployment will lead to 3x increase in the number of basestations that are deployed [43]. This is high motivation for equipment vendors. The bulk of the estimate is for industrial automation deployment.

Local equipment can improve URLLC performance, closing the loop closer to the equipment. The easy containment and high rates of mmWave may also be of benefit.

Challenges exist in achieving the NPN vision. The traditional cellular system is comprised of a large set of specialized equipment. The size and cost must be reduced and ease-of-use improved dramatically to enable practical use by the average industrial automation site. One positive trend is the emergence of "small cells". This brings more bandwidth to smaller areas. The equipment must then be small and economical.

Another challenge is that private spectrum is difficult to procure. Since operators may benefit by NPN participation through sub-licensing spectrum, selling equipment, or providing installation/management services, this cooperation may be key to providing adequate bandwidth and avoiding interference between sites. 5G's "slicing" technology allows operators to partition their 5G network into virtual networks (both the RAN and the 5GC), coordinating between industrial automation sites, and providing Service Level Agreements (SLAs) to each site.

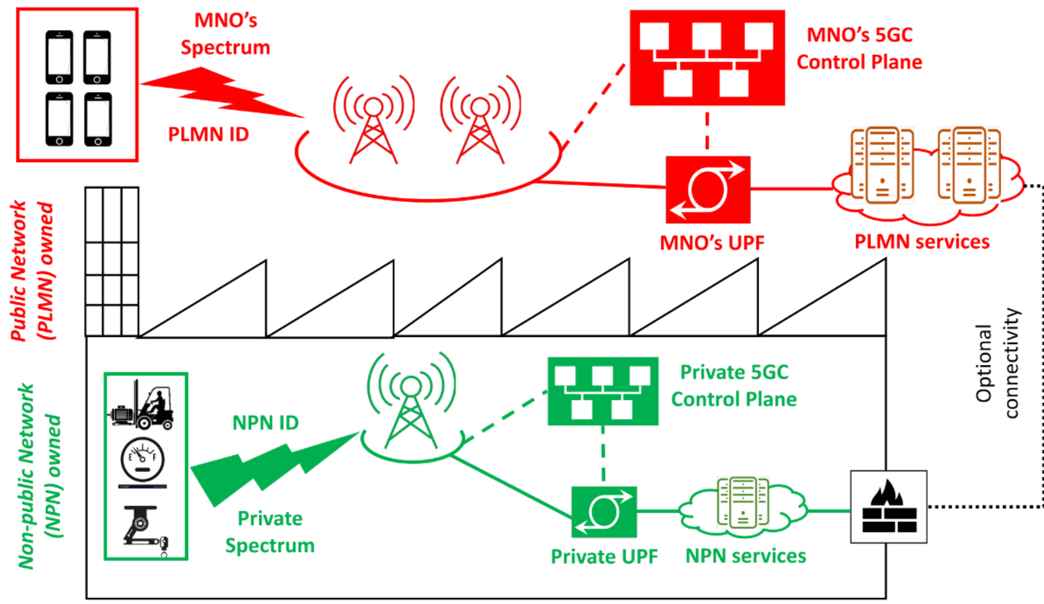

Figure 10: Standalone NPN [14].

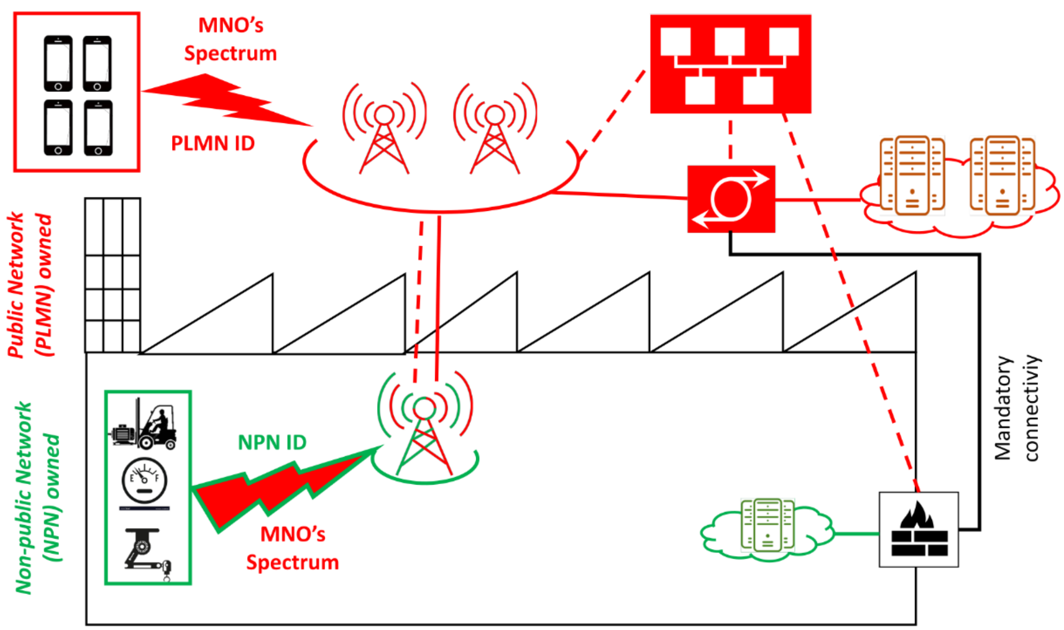

Figure 11: Fully shared NPN [14].

Frame Structure

5G communication is based on a standard frame structure as depicted in Figure 12.

5G repeats a fixed 10 ms radio "frame". The frame contains 10 fixed "subframes" of 1 ms each. This fixed frame structure provides the basic timing, matching the legacy LTE fixed frame structure.

Within a subframe, there are a variable number of "slots". The slot length, and number of slots in a subframe depend on the "subcarrier spacing" (SCS). Small SCS (i.e., 15 kHz) has less bandwidth and is extended in time to compensate (increasing the energy per bit to improve the signal to noise and interference ratio). Large SCS (i.e., 120 kHz) has more bandwidth and the slot can be shorter in time (125 us).

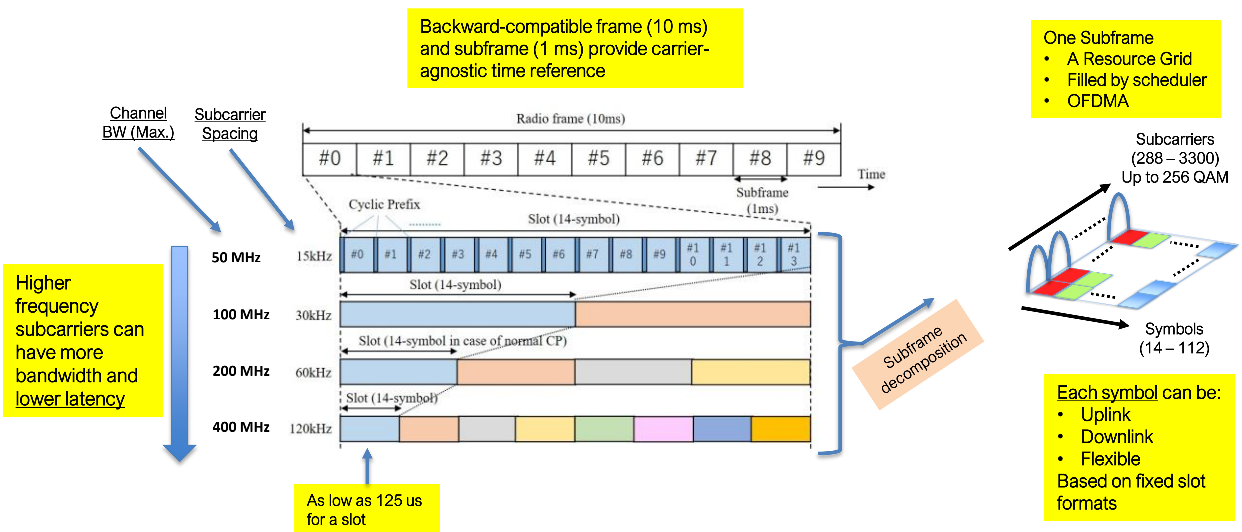

Figure 12: Overview of 5G frame structure.

Slots are composed of symbols, where symbols are the smallest periods of transmission or reception. A slot normally consists of 14 symbols.

The symbol is formed by using Orthogonal Frequency Division Multiplexing (OFDM) - the simultaneous modulation of a set of subcarriers for a fixed time period. A variable number of subcarriers (up to a maximum bandwidth) may be modulated. Each carrier may be modulated to carry up to 8 bits during a given symbol period (i.e., up to 256-QAM).

Considering the frame in frequency and time, it composes a resource grid. Blocks of user data can be packed into the grid by a scheduler using Orthogonal Frequency Division Multiple Access (OFDMA).

The 5G frame can mix upstream and downstream traffic within slots. Each symbol may be assigned as uplink, downlink, or flexible, following a set of predefined slot formats. Some formats have more downstream symbols, some more upstream, and some alternate for sub-slot turnaround and reduced latencies.

Note that the same basic frame structure can be used for all purposes. While this section described TDD, where transmission and reception occur on a single channel, the same basic frame structure applies to FDD, where there is continuous transmission and reception on separate channels. The same frame structure also supports unlicensed band usage, where the start of a slot is sacrificed for the Listen Before

Talk (LBT) procedure. There may also be “mini-slots”, with a small number of symbols and a flexible start time. This allows low latency for URLLC transmission. [46]

Fading

Wireless channels are not constant, but experience impairments. The fluctuation of the signal strength at the receiver is known as “fading”.

Fading can be broken down into types (Figure 13). Some classifications consider “path loss” as a type of “large scale fading” based on transmit distance, which can be compensated by increased signal. Another type is “small scale fading”, where the signal fluctuates rapidly over short time and distance – making it hard to compensate. Changes may be induced not just by motion of the transmitter and receiver, but by changes in the surrounding environment (e.g., moving metallic objects).

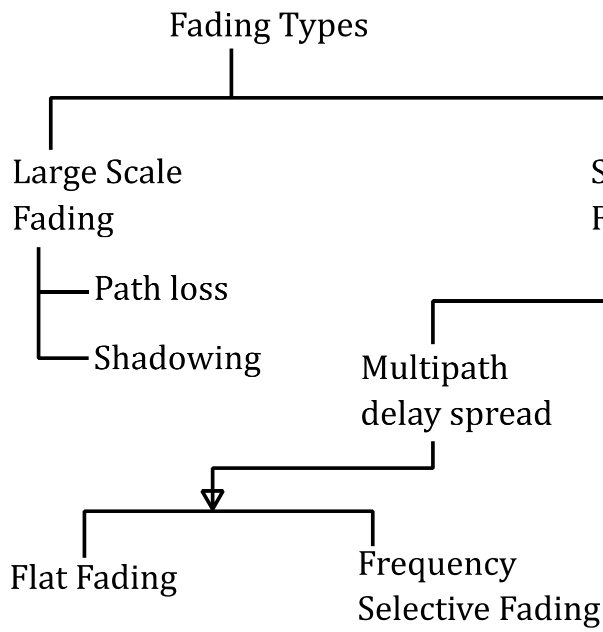

Figure 13: Classification diagram for RF fading [24].

Statistical models are developed for the fading channels. Radios can be designed against the statistical models, but the real channel may vary in dynamic ways. Rapid channel measurement can enable compensation. Depending on relative motion, the channel can only be assumed to meet the measurement for a fixed time period (the “coherence time”), then it must be re-measured.

Some impairments, such as “fast fading” can be compensated by retransmission, as the fading only lasts for a short period. This and related techniques can add unpredictable latency, contrary to URLLC goals.

Fading can change faster than adaptations are made. The result is additional retransmissions to compensate for the unreliable channel, leading to unpredictable latency.

Channel Hardening

Considering a channel between a transmitter and a receiver, the gain may vary (in time and frequency) due to fading. Decreasing the variation is known as “channel hardening”. If the variation is adequately reduced, the channel behaves deterministically – as if there is no fading.

Channel hardening can be achieved by applying "spatial diversity". If the number of antennas is increased between the transmitter and the receiver, each with a slightly different path with regard to the fading, by combining the antenna signals we approach an average channel gain (over a large enough period, we can average out the fading) for the instantaneous value. This is illustrated in Figure *14*.

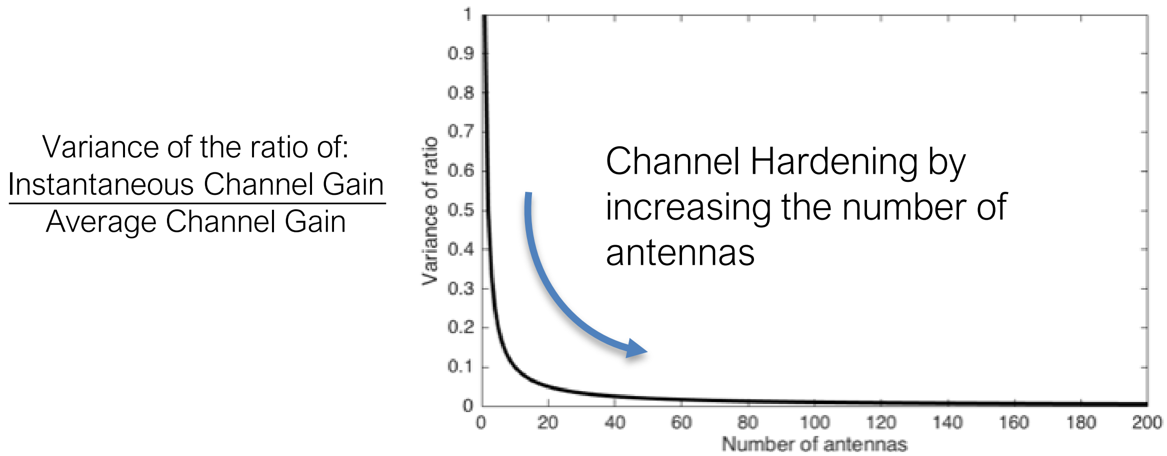

Figure 14: Channel hardening versus number of antennas [25].

There are now several practical implications. The signal is improved across both time and frequency. Latency is lower and transmissions can be scheduled.

An additional benefit is the ability to utilize (only) uplink pilots for channel estimation. By utilizing TDD, reciprocity can be applied [26]. The upstream and downstream channel can be estimated to be the same. A single upstream pilot from a UE arrives to multiple antennas at a basestation (Figure *15*). The large number of antennas is used for channel hardening. The basestation can compensate for the channel in both directions [27], by combining the multiple receive signals and by manipulating the multiple transmit signals.

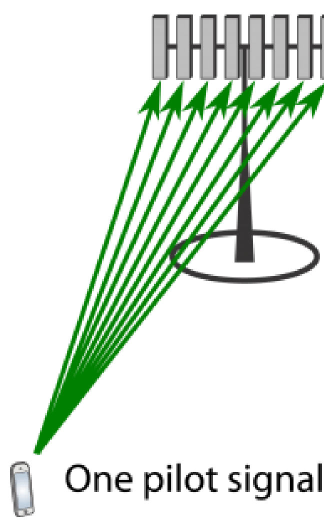

Figure 15: Uplink pilot reception [26].

Massive MIMO

“MIMO” (Multiple In Multiple Out) is a technique that combines multiple antennas (in the same channel) for various improvements [30]. Much like some directional antennas, “beamforming” uses multiple antennas with the same data stream to increase the gain and to steer the signal, improving distance and decreasing some interference. Spatial multiplexing sends different data streams from the multiple antennas to increase throughput.

5G brings “massive” to MIMO, deploying a very large number of antennas attached to the basestation (ideally 100’s). This can bring benefits to even unmodified UE. Some argue that this is the single improvement that makes 5G worthwhile.

> *“Massive MIMO, which depends on using a large array of antennas, is the keystone technology for realizing the improvement necessary to justify the evolution from 4G to 5G wireless networks.” [29]*

Figure 16 shows an example massive MIMO system. The large antenna array targets multiple users. The large number of transmit and receive chains are coordinated at a system level.

An 8 x 8 array (64 dual-polarized antennas) is typical. The array transmission and reception can be configured to form multi-antenna beams to multiple users.

The benefits include full cell capacity for each user, high reliability, and low latency – based on channel hardening and rapid channel estimation.

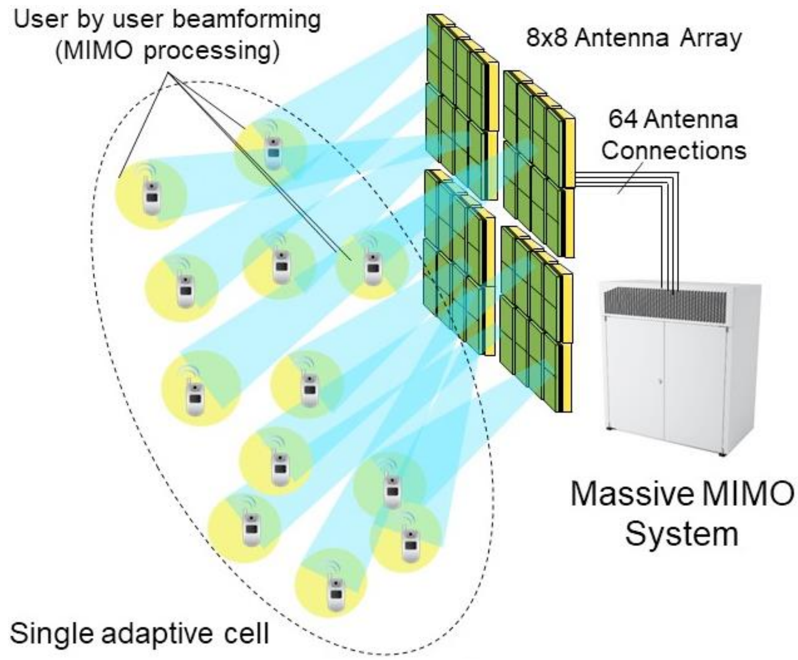

Figure 16: Massive MIMO system illustration [29].

Interested readers are encouraged to review [28] for a discussion of multiple antenna paths, upstream pilot, reciprocity (TDD), detection and pre-code matrices, constructive upstream and downstream multipath signals, and separate user data stream detection.

Coordinated Multi-Point

The massive MIMO technique can be extended by spreading the antennas across a site. This technique is known as Coordinated Multi-Point (CoMP), or as “distributed MIMO”. CoMP bring the same general improvements – an increase in the capacity within the site and/or low latency with increased reliability. It can also further harden the channel by increasing the antenna diversity.

As explained by Qualcomm (Figure 17), sudden drops in signal strength can be created by fast moving metal objects. These obstructions block the signal and create new reflection patterns. It is implied that (CoMP) can maintain reliable operation and low latency under such conditions.

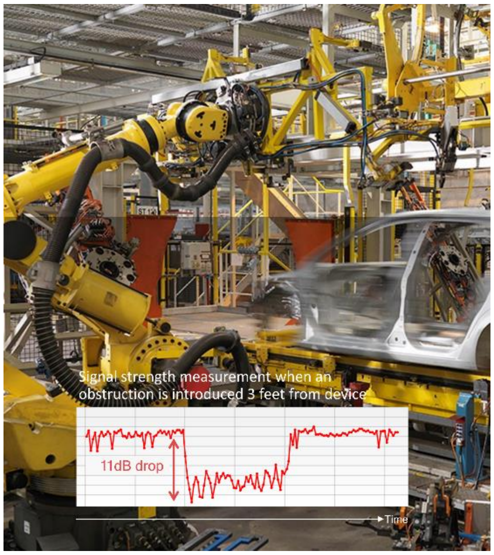

Figure 17: Rapid signal strength variation due to moving obstructions [31].

The distributed antennas must be tightly coordinated. A CoMP server (Figure 18) tunes the signals from each antenna set.

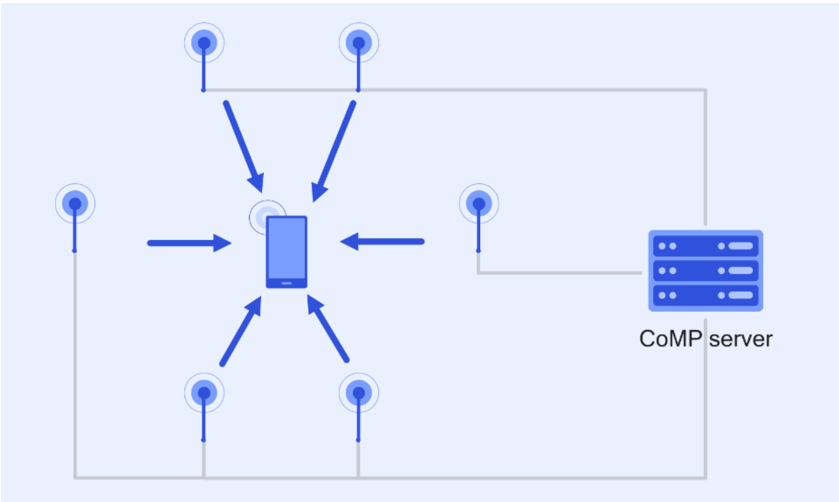

Figure 18: Coordinated multi-point (CoMP) system illustration [31].

Note that CoMP is not a new technique. It was applied to LTE in 2009.

Low Power Wireless

5G promises improvements in low power wireless. LTE-M, NB-IoT and EC-GSM-IoT are specified. While these low power radios are not new, there have been enhancements.

The Maximum Coupling Loss (MCL) is a channel-independent measure to describe the expected wireless system coverage. While nodes could transmit > 10 km under ideal conditions, citywide coverage is a primary target, with interstation distance in the range of 250 m to 2 km. Deeply embedded nodes are the challenge, where in parking garages for example, we may lose 50 dB through concrete walls. In order to work under these lossy conditions, redundant transmissions are applied – reducing throughput, limiting battery life, and adding latency.

It has been shown [40] that all three technologies can achieve battery life longer than 10 years under extreme conditions of 164 dB CL (channel loss). An analysis using two AA batteries totaling 5 Wh demonstrates the compromises. Reporting a 200-byte message, once per day, the data rates drop below 1 kb/s, and latency approaches 10 seconds. LTE-M1 only achieves 8.8 years. Shorter messages, longer reporting interval, or larger batteries allow the 10 years. A reduction of CL by even 10 dB (a wall or two) nearly triples battery life.

Release 15 continued adding improvements [38] to help meet increased performance requirements relative to LTE (4G). The number of messages needed to participate in the network were reduced. Small cells, located closer to UE, allowed the reduction of transmit power. A small Wake Up Signal (WUS) was introduced. A battery-efficient security technique (BEST) was added – in-part as a confidence builder for IoT proliferation.

Active transmission uses the most power. LTE-M and NB-IoT radios have 164 dB MCL and transmit at 14, 20, or 23 dBm. Each halving of the distance can gain back 6 dB. Mesh techniques are also considered for better coverage and to reduce distances. "Generalized" beamforming (Figure *19*) is another technique that can be applied. Each doubling of the antennas can add 3 dB of gain [33]. In one study, 200 antennas demonstrated 28 dBi [32]. Reductions of transmit signal power do not translate in a linear fashion, but chipsets are improving each generation to be more efficient by utilizing more efficient power amplifiers.

5G IoT radios are under continuous improvement, driven by a huge technical community.

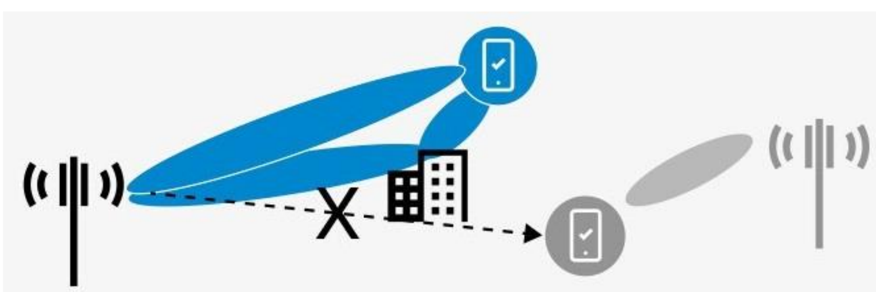

Figure 19: Generalized beamforming example [33].

Wrap-up

5G Industry Vision

5G is arriving with one of the largest marketing pushes ever. In virtually every manufacturing company of any size, someone is assigned to develop their 5G vision. While wireless has been available for a long time, and applied in numerous industrial automation applications, it has not become ubiquitous. 5G may bring some new vision, or at least may deliver better capabilities to meet unsatisfied visions.

As stated by the 3GPP Chair (from Nokia) [35], Release 16 pursues Ethernet replacement in the factory. This includes the addition of TSN. One source of this vision is undoubtedly 5G-ACIA.

One vision (
Figure *20*) is the replacement of wired switches with 5G wireless. Supervisory control may be a good candidate due to the lower rates to interlock and coordinate across equipment, and the larger distances of cable runs. This includes the IT/OT boundary and MES connections.

Another vision is the enablement of lean collaborative mobile manufacturing systems. Besides replacing Ethernet between fixed machines/cells/lines (which has benefit), wireless untethers the equipment. While the mobile equipment may just move materials (AGVs), mobile platforms can also carry parts-in-process to fixed application platforms. Each part can be different. Process reconfiguration can be rapid.

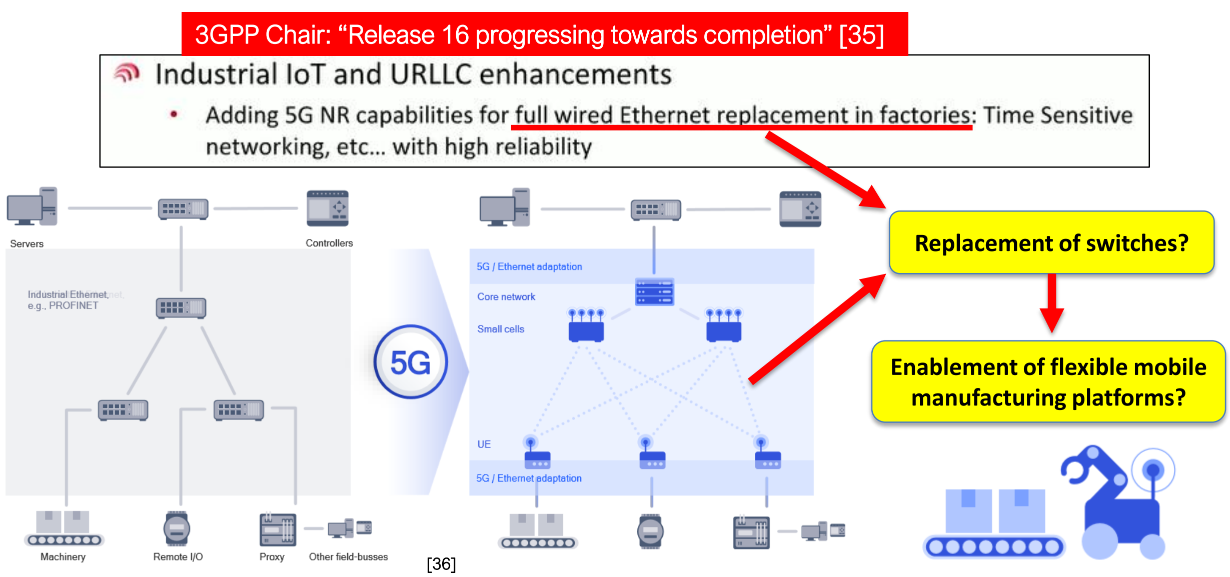

Figure 20: 5G industry vision of wired Ethernet replacement and potential implications [36].

Conclusions

5G will implement a wide range of technical enhancements over 4G.

These enhancements improve on prior wireless solutions and may open new market areas – including industrial automation.

5G has already emerged – capabilities are limited, but enhancement will continue.

For the first time, we have a substantial set of industrial automation players pushing for a common wireless standard – 5G.

Since 3G, the 3GPP standards have included: packet switched Internet Protocol, Ethernet connectivity, and quality of service - matching EtherNet/IP needs.

Paradigm shifts may be either an opportunity or a threat.

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