Project: **SEAWave**

Report on RF components expected in Industry 4.0 Applications

Work Package:	WP2
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Abstract

Workplaces in Industry 4.0 where private networks applied may be surrounded by hundreds or even thousands of radio transceiver modules communicating with each other or with a central node via a wireless network, emitting **Radio Frequency Electromagnetic Fields** (RF EMF) to which employees are exposed. Although the time-averaged transmit power of each of such radio transceivers is likely to be low, the resulting overall magnitude and temporal pattern of RF EMF exposure (caused by all transceivers combined) to which workers are exposed in such situations is yet unknown.

Report D 2.1 clearly provides an overview on key elements and RF components that are applied in private networks in different sectors in a smart industry. In addition, it deals with technical specifications used in wireless networks applied for M2M and IIoT communications, which will then serve as a basis for the model development in Task 2.3 (Development of a generic model for estimation of occupational exposure, and identification of relevant input parameters). The report also provides a review of the sparse scientific literature on RF EMF exposure assessment in such environments.

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Contents

1 Summary

In Industry 4.0 deployments, mobile networks are becoming established as the superior platform for 'wire-free' networking in applications from factory floor automation through to automated warehousing, logistics, autonomous vehicle deployments in campus environments, mining, materials processing and more. A deployment option of increasing interest to many industrial enterprises is that of wireless ‘private networks’; that is, mobile networks that are for the exclusive use of that particular enterprise where all the devices operating on the network are part of a closed network community.

One of the main aspects of Industry 4.0 is the pervasive deployment of **machine-to-machine (M2M) communication** and **Industrial Internet of Things (IIoT)**. It is expected that most of these M2M and IIoT communication paths will be realized wirelessly, as the advantages of providing flexibility are obvious compared to hard-wired network installations.

Many sensors, actuators and other components in smart factories will be equipped with radio transceiver modules through which they can be wirelessly connected to private networks based on 4G or even 5G technology. Such private mobile networks are revolutionizing today’s businesses and setting them up for long-term operational success. To power this change, they are trusting the advanced communication capabilities that we believe only private networks can provide.

Consequently, workplaces in future Smart Factories where private networks applied may be surrounded by hundreds or even thousands of radio transceiver modules communicating with each other or with a central node via a wireless network, emitting Radio Frequency Electromagnetic Fields (RF EMF) to which employees are exposed. Although the time-averaged transmit power of each of such radio transceivers is likely to be low, the resulting overall magnitude and temporal pattern of exposure (caused by all transceivers combined) to which workers are exposed in such situations is yet unknown.

The goal is to obtain details about technical specifications used in wireless networks applied for M2M and IIoT communications, which will then serve as a basis for the model development in Task 2.3 (Development of a generic model for estimation of occupational exposure, and identification of relevant input parameters).

Since the development and deployment of wireless technology for/in industrial environments is still an ongoing process, this report focuses on a thorough examination of technical specifications of available and foreseeable transceivers including wireless network technologies (4G, 5G, Wi-Fi6, etc) and their potential applications in real Industry 4.0 environments.

In addition, special emphasis has to be placed on the scientific literature on exposure assessment in such environments.

It is clear that the wireless network has to be tailored for each particular deployment scenario. While doing so, a large variety of different aspects has to be considered, e.g., spectrum regulations, specific industrial site requirements, the overall business case, etc. Moreover, finding the most appropriate combination of the different radio network deployment options to meet the desired communication service requirements will typically be a complex effort which will eventually influence all the stakeholders: industrial partners, mobile network operators, service providers and the network vendors.

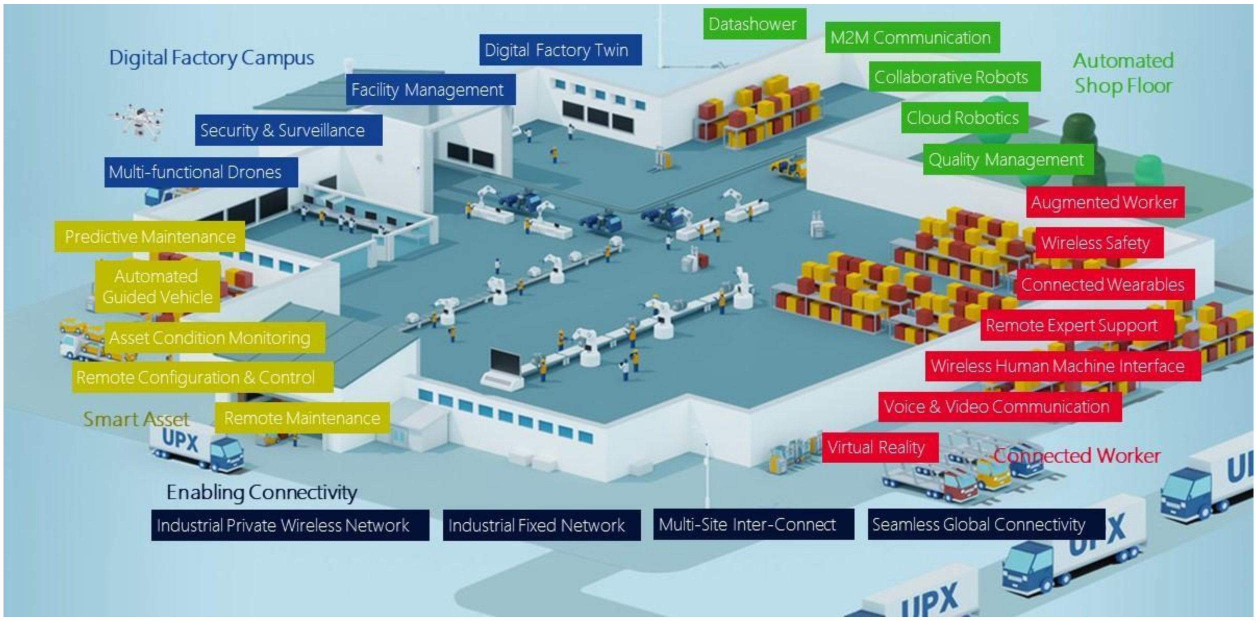

Figure 1: Industry 4.0 use cases apply to a variety of manufacturing contexts

2 Wireless networks for Industry 4.0

Wireless communications are bringing the greatest added value in mobility support offering an ability to mobile clients to maintain connection seamlessly. Data and voice connectivity is a part of modern life and most of the world is relying on wireless networks, regardless if they are for home or business use. Home and business use are two major groups dividing wireless communications depending on the intended use. Business group is the largest one, where industry accounts for a considerable share of all wireless communication deployments. Wireless Access brings availability, increased efficiency and flexibility, which lead to faster transfer of information within industry.

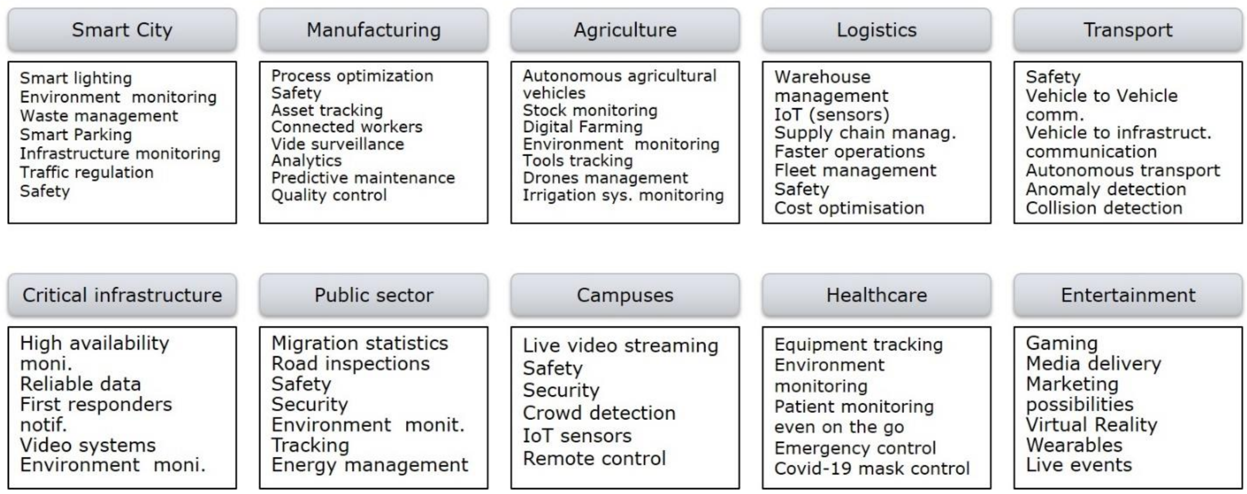

Figure 2: Stakeholders for wireless communications

Wireless communications are almost everywhere following us in our private or professional life (Figure 1). In general, two variants of wireless networks are present in everyday use. Public wireless network and private wireless network[1].

Public wireless network is often considered as a cellular network, using well known technologies such as 4G or even 5G. However, public wireless networks can be much more than that. Many companies, cities, or even countries have Wi-Fi as a possibility to get public access to the internet. Not to mention libraries, airports, metros offering Wi-Fi as an open wireless technology for internet access to the public, or to the service users like library visitors or passengers at airports.

On the contrary, speaking about private wireless networks, Wi-Fi is considered as the only possible wireless network solution, which can be managed as a private wireless Local Area Network (LAN). It is still not widely known that cellular technologies such as 4G and 5G can be used for private wireless cellular network solutions. What this actually means is that it is possible to buy 4G or 5G solutions and to set up a private wireless LAN. It means that industry or enterprises can set up their own 4G or 5G private wireless LAN, like mobile telecom operators do, but on a much smaller scale. In some countries national regulation is already offering special frequencies for industrial use. Therefore, it is country-specific whether you can buy or get frequencies to set up private 4G or 5G networks. The other possibility is to start a business relationship with a local mobile telecom operator.

[1] BAI communications. The power of private networks (2021). Retrieved from: https://www.baicommunications.com/g/whitepaper/the-power-of-private-networks/

Figure 3: Sectors where private networks are needed

New emerging private networks are focused towards industry or new smart manufacturing and digitalization in Industry 4.0 (Figure 3)[2]. It is clear that 5G is becoming the leading technology to support and enable transition of the industry to Industry 4.0, as it provides high-speed low-latency multiple-device wireless communication suitable for industrial applications. 5G networks for Industry 4.0 are based on a local 5G network in a licensed spectrum that can be provided by a network provider or deployed and operated standalone in locally leased or licensed spectrum.

Faster and faster digitalization of “everything” is pushing industry to adopt processes in order to be more and more flexible, competitive and agile. Industry 4.0 is here as fourth industrial revolution and it is a trend of automation, data exchange and data processing enabling advanced robotics, digital twins, big data analytics, machine learning, artificial intelligence, connected Industrial Internet of Things (IIoT), cloud computing and much more[3].

[2] Ceferin, P. Why do we need private networks. (2022). Kranj: SMART COM.

[3] i-SCOOP. Industry 4.0 and the fourth industrial revolution explained. (2021). Retrieved from: https://www.i-scoop.eu/industry-4-0/

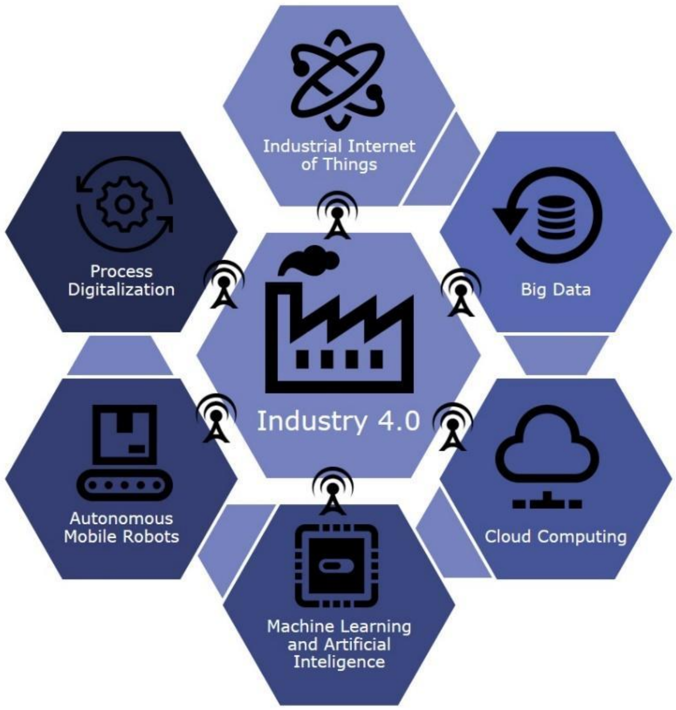

Figure 4: Industry 4.0

Mobile networks and their RF components, particularly those delivering 4G and 5G services, provide connectivity options applicable across the broad range of Industry 4.0 use cases, making these the superior choice for manufacturing and supply chain companies. Some of the features that are key to deployments, both for the Operational Technology (OT) network connecting production machinery and the Information Technology (IT) network enabling related business applications, are presented in this chapter.

2.1 User Equipment and IoT devices

User Equipment (UE) is considered any device used by an end user like a mobile phone as most represented. IoT devices are embedded computers, usually maximally stripped down to a maximum regarding hardware components because of simplicity, battery usage and price. UE and IoT devices connect wirelessly to a network and transmit or receive data. Regardless of the nature of operation only UE naming is used in standards.

3 4G for 2022 and beyond

4G stands for the fourth generation of broadband cellular network technology also known as Long Term Evolution Technology (LTE). It is the successor of 3G technology and now we can already confirm that 4G is the predecessor of 5G.

However, let's start with the history to see in the future. Dates can be country-specific but in general, in the 1980’s, the first mobile phones and network infrastructure were available to enable voice communication. Then, in the 1990’s, the first data transfer in cellular networks was introduced, letting us send SMS (Short Messaging Service) or use other low data capacity communication. With 3G technology, the internet was available to end devices in the 2000’s. It was the first time to integrate cellular technology into tablets and notebooks. Later 4G brought us fast internet experience in the 2010’s. 4G is the first wide area radio technology reaching performances that can compete with wireline internet access[4].

2G and 3G technologies were made primarily for voice transfer. On the other hand, 4G is designed especially for data transmission rather than voice. Compared to 3G, 4G brings much higher speed, lower latency and better spectral efficiency. 3G has a typical download speed of 28 Mbps while 4G reaches 100 Mbps and up to 3 Gbps in the latest releases. Improvement in speed is significant.

Because of this outstanding performance of 4G cellular technology, 4G reached almost every country. There is almost no LTE blind spot looking worldwide. 4G became the facto standard among all mobile operators worldwide.

It is important to know that inside cellular network technology there can be several releases that can significantly affect technology performance and functionality. 3rd Generation Partnership Project (3GPP) unites seven telecommunications standard development organizations with a mission of Mobile Broadband standard and specification creation. Each release is a set of standards and specifications.

Table 1: Release dates of 3GPP releases and included functionalities (3GPP, 2022)[5]

3G				4G							5G			
UMTS	**HSDPA**	**HSUPA**	**HSPA+**	**LTE**		**LTE - Advanced**			**LTE - Adv. Pro**		**NR**			**5G - Advanced**
Rel-99	Rel-05	Rel-06	Rel-07	Rel-08	Rel-09	Rel-10	Rel-11	Rel-12	Rel-13	Rel-14	Rel-15	Rel-16	Rel-17	Rel-18
1999-12-17	2002-09-12	2005-09-28	2008-03-13	2009-03-12	2010-03-25	2011-06-08	2013-03-06	2015-03-13	2016-03-11	2017-06-09	2019-06-07	2020-07-03	2022-06-10	2024-03-22

Table 1 shows that there are two major releases in 4G cellular network technology. Release 10 and Release 13 significantly improve 4G performance[5].

[4] Wikipedia. List of mobile phone generations. (2022). Retrieved from: https://en.wikipedia.org/wiki/List_of_mobile_phone_generations

[5] 3GPP. Releases. (2022). Retrieved from: https://www.3gpp.org/specifications-technologies/releases

Inside 4G technology, there are three different “sub technologies”. LTE, LTE–Advanced (LTE-A) and LTE-Advanced Pro (LTE-A Pro also known as 4.5G, 4.5G Pro, 4.9G). The main aim for each “sub technology” is to increase the data speeds and bandwidth of the predecessor[6].

Table 2: Difference between LTE, LTE Advanced and LTE Advanced Pro[6]

	LTE	LTE-Advanced	LTE-Advanced Pro
Carrier Bandwidth	20 MHz (1 carrier)	100 MHz (5 carriers of 20 MHz)	640 MHz (32 carriers of20 MHz)
Speed	Up to 100 Mbps	1 Gbps	3 Gbps
Latency	20 ms	15 ms	10 ms

Main goal of every next emerging technology or evolving of existing one is to increase speed and reduce latency. Unfortunately, both speed and latency depend on the physical laws. That is limitations of radio propagation and Radio Frequency (RF) receiver and transmitter equipment limitations. In general, data rate depends upon three factors[7]:

- bandwidth; is usually fixed and determined by regulations, laws and compliance on one hand and by use case and RF equipment limitations on the other;
- number of coding states inside modulation schemes;
- quality of the channel or Signal to Noise ratio (SNR). There is no noiseless channel and it can drastically influence data rate. The higher the noise is, fewer coding states are possible to transfer over the channel.

There are a number of different techniques or technologies that are incorporated into LTE-A Pro as a final and most advanced sub release of LTE. All of them are simply trying to find the space to improve existing technologies inside physical limitations mentioned above. Limitations cannot be bypassed, but technology can be improved in order to use more bandwidth, use more coding states or to lower Signal to Noise requirement which indicates channel quality. Improvements introduced in LTE to LTE-A Pro evolution[7,8]:

- **carrier aggregation** was introduced in LTE-A 3GPP Release 10. Data speed is increased by assigning multiple carriers (frequency blocks) to the same user. A larger amount of bandwidth is available for a single user, meaning a higher data rate. In LTE-A up to 5 carriers can be aggregated, allowing for transmission bandwidths of up to 100 MHz (5×20 MHz). In LTE-A Pro all the way up to 32 carriers can be aggregated, not just in-band (inside the same band), but also inter-band (between

[6] ETSI. Long Term Evolution (LTE). (2022). ETSI. Retrieved from: https://www.etsi.org/technologies/mobile/4G
[7] ETSI. LTE; Evolved Universal Terrestrial Radio Access (E-UTRA); Base Station (BS) radio transmission and reception (3GPP TS 36.104 version 14.3.0 Release 14). (2017). Retrieved from: https://www.etsi.org/deliver/etsi_ts/136100_136199/136104/14.03.00_60/ts_136104v140300p.pdf
[8] ETSI. LTE; Evolved Universal Terrestrial Radio Access (E-UTRA); User Equipment (UE) radio transmission and reception (3GPP TS 36.101 version 14.7.0 Release 14). (2018). Retrieved from: https://www.etsi.org/deliver/etsi_ts/136100_136199/136101/14.07.00_60/ts_136101v140700p.pdf

different bands). This means a huge benefit for the devices that request constant connectivity, especially when moving;

- **dual connectivity** was first introduced in LTE-A 3GPP Release 12. It allows user devices to be connected to more than one Evolved Node B (eNB). eNB is a hardware device, which is connected to the user device network. Small cells are being deployed within range of macro cell coverage to provide dual connectivity. Such a configuration significantly improves User Equipment (UE) data speed and mobility (handover).
- **MIMO** (multiple-input multiple-output) was first introduced in 3G. Based on 3GPP release 8 standardization (LTE) the goal is to enhance the technology only. The evolution is going on all up to Release 16. MIMO is evolving towards Massive MIMO, a key enabler for 5G. MIMO is an antenna technology that uses multiple transmitters and receivers to transfer more data at the same time. This means also that UEs must support MIMO antenna configuration.

3.1 4G as a first grade technology for Industry 4.0

To understand why LTE is an appropriate technology for industry 4.0 we should understand the purpose of LTE in terms of mobility, data speed and coverage. LTE continues to keep the main goal to serve mobility as a fundamental functionality in mobile networks. So users or devices can move between network cells without noticeable effect. Data streams must stay constant and with no interruptions. Mobile data transfer speed has finally reached the speed required by most of the applications we use on daily basis. From relatively lightweight applications alike e-mails or chats to very demanding like multimedia streaming. LTE connects people or machines. It is deployed and used globally not only for voice but primarily for data communication.

Overall, mobility and data speed are evolving and demands are kept at a high level. On the other hand, coverage is something that can be extremely costly in terms of density of base stations, spectrum and power consumption. Having in mind that most of the traffic comes from indoor, where attenuation plays a major role, two new technologies for Machine to Machine (M2M) communication were introduced inside LTE releases. **Narrow Band IoT (NB-IoT)** and **Long Term Evolution for Machines (LTE-M)** both created to be particularly suitable for industry 4.0, enabling local and global IoT connectivity. LTE-M and NB-IoT are both connectivity options for industries looking for new ways of communication. LTE-M and NB-IoT are designed for the Internet of Things. Furthermore, both technologies are future proof since both are part of 5G specifications![9],[10]

Both technologies tend to be globally available so in general, the telecommunication market is offering at least one technology on a local market. NB-IoT and LTE-M technologies are not completely comparable to each other. There are differences in global market coverage with NB-IoT or LTE-M. Europe and Asia focus on NB-IoT, while on the other hand North America started

[9] Masum, M. R. LTE-M and NB-IoT. (2018). Retrieved from: https://www.researchgate.net/publication/328277477_LTE-M_and_NB-IoT

[10] Telenor. LTE-M vs NB-IoT – A Guide Exploring the Differences between LTE-M and NB-IoT. (n.d.). Retrieved from: https://iot.telenor.com/iot-insights/lte-m-vs-nb-iot-guide-differences/

with LTE-M coverage. But today's global status shows that the global market slowly but surely tends to offer both technologies.[10,11]

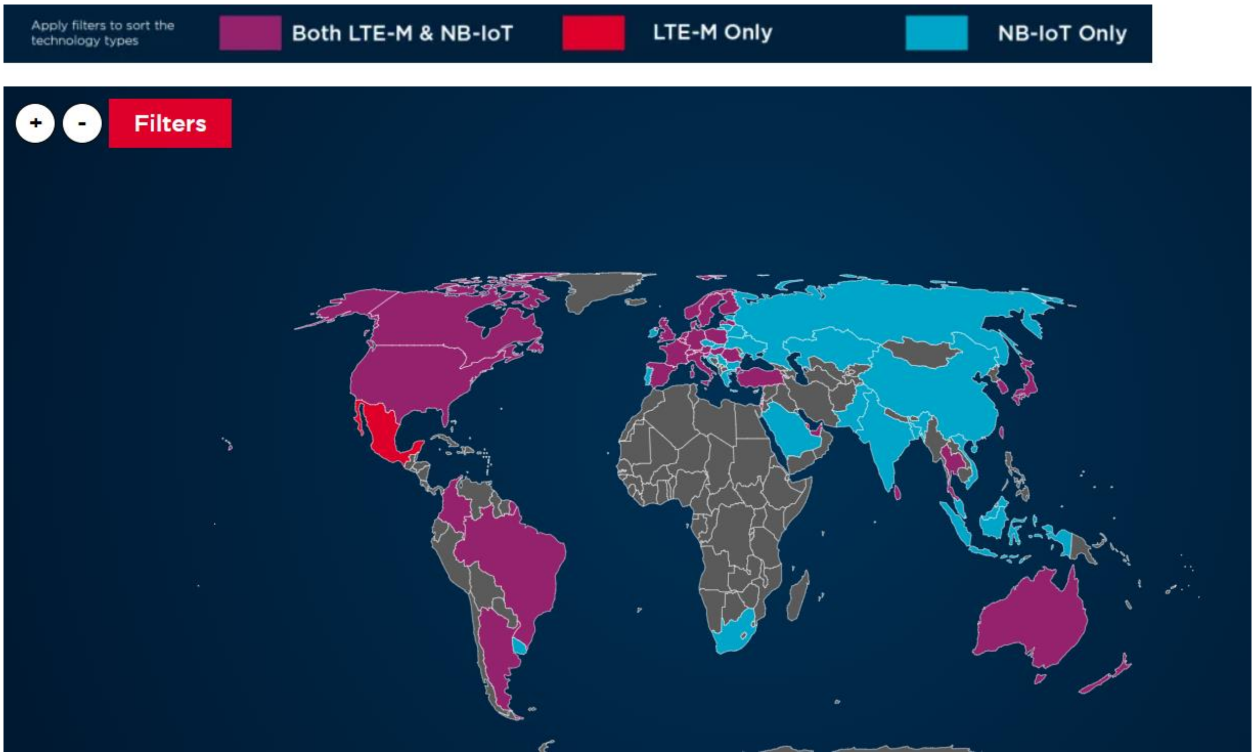

Figure 5: Mobile IoT Deployment Map on November 2022[12]

3.1.1 Narrow Band-Internet of Things (NB-IoT)

NB-IoT is a technology developed inside LTE release 13. Main purpose of NB-IoT is to offer wide area coverage using existing LTE infrastructure for new upcoming IoT devices, which are mainly battery powered. NB-IoT is a narrowband radio technology developed for excellent indoor coverage and long battery life at lower data rates. Because of its bandwidth efficiency, high density of the connected devices can be reached. Furthermore, because of maximum strip down of the device complexity, low cost devices (connection modules) are available on the market.[13]

NB-IoT is mainly intended to use for infrequent transmission of small amounts of data. It does not support handover between base stations, which means there is no mobility support. NB-IoT is designed for static devices. No voice, only data transmission is possible in NB-IoT. NB-IoT is Time Division Duplex (TDD) technology. It uses a single frequency band for both transmit and

[11] Quectel. Inside IoT's earliest 5G use cases. (n.d.). Retrieved from: https://www.quectel.com/thank-you-5g
[12] GSMA. Mobile IoT Deployment Map. (2022). Retrieved from: https://www.gsma.com/iot/deployment-map/
[13] Tabbanne, S. IoT standards Part II: 33GPP Standards Planning Internet of Things (IoTs) networks (2018). Retrieved from: https://www.itu.int/en/ITU-D/Regional-Presence/AsiaPacific/Documents/Events/2018/IoT-BDG/7.%20IoT%20Standards%20Part%20II%20-%20Sami%20Tabbane.pdf

receive which makes it Half Duplex technology. All these deficits on the one hand also bring advantages on the other hand. Long battery life, deep penetration into buildings and low price. [13,14]

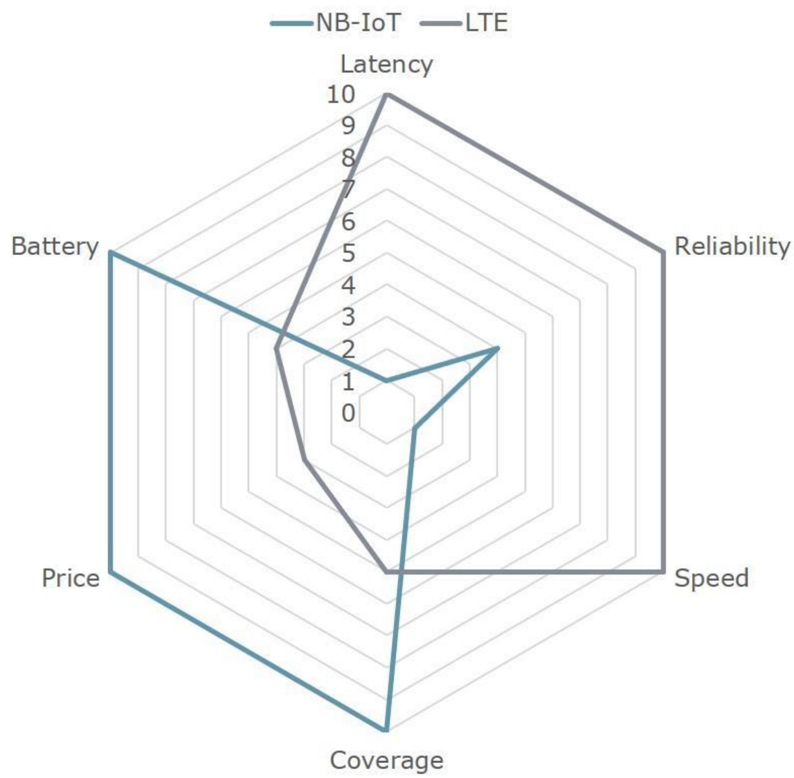

Figure 6: NB-IoT versus LTE diagram

Battery: energy saving is one of the primary functions of NB-IoT technology promising a decade of connectivity on a single battery.[13] Two features are available in order to reduce power consumption[15]:

- Power Saving Mode (PSM) is a feature of cellular networking maximizing the time that devices spend asleep. It can force devices to be placed in a low-power consumption mode. Devices can wake up on demand or timer-dependent and start communication with the network. However, the network cannot reach the device when in PSM state.
- Extended Discontinuous Reception (eDRX) is a mechanism that can also extend battery duration. With eDRX, the device can listen for pending data indications without having to establish a full

[14] 3GPP. Standardization of NB-IOT completed. (2016). Retrieved from: https://www.3gpp.org/news-events/3gpp-news/nb-iot-complete

[15] GSMA. NB-IoT Deployment Guide to Basic Feature set Requirements. (2019). Retrieved from: https://www.gsma.com/iot/wp-content/uploads/2019/07/201906-GSMA-NB-IoT-Deployment-Guide-v3.pdf

network connection. Just by listening in eDRX mode, the device uses less power than if it makes a full network connection.

Price: reducing complexity of a communication module has an impact on the final price of a communication module. Eliminating overhead complex LTE functions from a module has also an influence on battery consumption. There is no need to run complex functions like in a full- blown LTE module. Low memory storage, reduced radio frequency (RF) components and support for only one antenna leads to low complexity. NB-IoT complexity is reduced overall by 80-90 %.

Coverage enhancement method: NB-IoT technology is designed for use cases where deep indoor penetration is needed and to cover hard-to-reach areas. NB-IoT uses a mechanism of retransmissions in uplink and in downlink to get better penetration and coverage. The main goal of this mechanism is to repeat (re)transmission of data until sending data is successful. To achieve a better result by (re)transmitting data, low data rates make advantage because coding states at low data are easier to decode. [11,15]

3.1.2 Long Term Evolution for Machines (LTE-M)

Same as NB-IoT, LTE-M is also a technology developed inside LTE release 13 and is designed to offer wide area coverage using existing LTE infrastructure. It is important to know that LTE-M is completely new technology on LTE basis and is not a part of LTE infrastructure by default. Availability of LTE-M as an additional technology on top of LTE is telecom-specific and it must be enabled in the network. The same also applies to user devices. Chipsets for radio communication in user equipment must support LTE-M type of technology in order to be able to get all the features available in LTE-M. LTE-M technology also brings the same approaches to extend battery life (PSM and eDRX), reduced price of the module and achieving same coverage as NB-IoT.[16]

The aim of LTE-M is to fill the gaps where NB-IoT is no longer sufficient. Four major differences comparing to NB-IoT make LTE-M stand out:[16]

- Higher speed is available because of higher bandwidth of LTE-M technology. Bandwidth brings major improvement in speed.
- Full Duplex technology, which means that the device supports simultaneous transmission and reception. Full Duplex mode is TCP (Transmission Control Protocol) friendly and therefore easy to implement.
- Voice over LTE (VoLTE) support is added into LTE-M technology by default.
- Mobility is an important feature for all devices that are moving like tracking devices. Seamless changing between radio base stations is enabled using a mechanism called handover. There is no data stream interruption during a handover process.

However, all these additional features of LTE-M result in shorter battery life compared to NB-IoT and a bit higher price because of the LTE-M chipset complexity.

[16] GSMA. LTE-M Deployment Guide to Basic Feature Set Requirements. (2019). GSMA. Retrieved from: https://www.gsma.com/iot/wp-content/uploads/2019/08/201906-GSMA-LTE-M-Deployment-Guide-v3.pdf

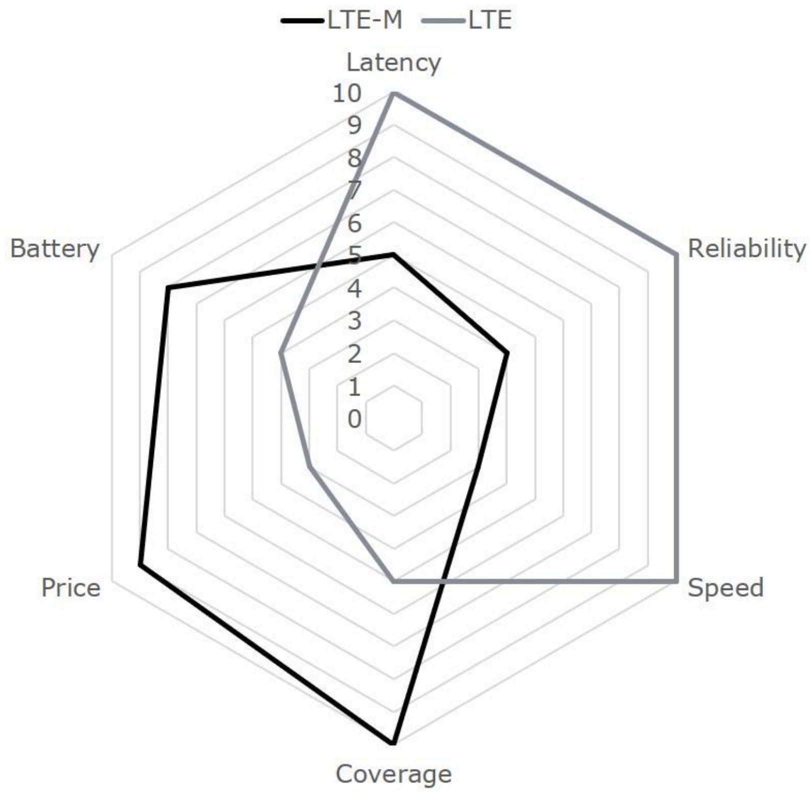

Figure 7: LTE-M versus LTE diagram[17]

3.1.3 Comparing NB-IoT and LTE-M

LTE-M will emerge faster and faster since it is easier for application development and maintenance, having always the door open for easy new use cases introduction.

NB-IoT is here now and that is the fact. Since it was available prior to LTE-M in the EU, it has a bit of advantage in terms of commercial progress. NB-IoT will stay mainly for simple applications on a larger scale. For example, sensors and meters, where functional requirements are firmly defined at the beginning of the project and are not subject to change and where deeper in-house penetration and wider range are necessary.[10] Features and special functionalities are presented in a comparison table below.[17,18,19]

[17] ETSI. LTE; Evolved Universal Terrestrial Radio Access (E-UTRA); Potential solutions for energy saving for E-UTRAN (3GPP TR 36.927 version 13.0.0 Release 13). (2016). Retrieved from: https://www.etsi.org/deliver/etsi_tr/136900_136999/136927/13.00.00_60/tr_136927v130000p.pdf

[18] u-blox. Solving the complexity of communicating between IoT devices and the enterprise. (2022). Retrieved from: https://content.u-blox.com/sites/default/files/documents/low-power-mqtt-sn-white-paper.pdf

[19] GSMA. Mobile IoT in the 5G Future. (2018). Retrieved from: https://www.ericsson.com/4a8d35/assets/local/reports-papers/5g/doc/gsma-5g-mobile-iot.pdf

Table 3: NB-IoT and LTE-M feature comparison table

Function	NB-IoT	LTE-M
3GPP Release 13	NB-IoT Cat-NB1 release	LTE-M Cat-M1 release
3GPP Release 14	NB-IoT Cat-NB2 release	LTE-M Cat-M2 release
Bandwidth Release 13	180 kHz	1,4 MHz
Bandwidth Release 14	180 kHz	5 MHz
Speed DL Release 13	27 kbit/s	1 Mbit/s
Speed DL Release 14	120 kbit/s	4 Mbit/s
Speed UL Release 13	60 kbit/s	1 Mbit/s
Speed UL Release 14	160 kbit/s	6 Mbit/s
Module price (approx.)	3,5 $	5 $
Final product price (approx.)	35 $	50 $
Voice (VoLTE)	no	yes
SMS	yes	yes
Mobility support	no	yes
Use Case - Firmware updates	no	yes
Use Case - Remote control	yes/no (use case dep.)	yes
Grow with Use Cases	no	yes
Standard IP protocols for fast dev.	no	yes
Tailor-made protocols (competence)	yes	no need
First focus - Asia	yes	
Secondary focus - Asia		yes
First focus - Europe	yes	
Secondary focus - Europe		yes
First focus – North America		yes
Secondary focus - North America	yes	
Static IP V4	yes	yes
IP V6 support	yes	yes
Connection mode	Half Duplex	Full Duplex
Latency	1,5 s – 60 s (harsh cond.)	50-100 ms
Battery life	+10 years (use case dep.)	up to 10 years (Use case dep.)
Advantages	coverage, price, battery life	higher speed, mobility
CoAP	yes	yes
MQTT	no	yes
MQTT over TCP data loss	90 %	
MQTT-SN over UDP data loss	3 %	

The intended use case defines the appropriate technology. After deploying thousands of IoT devices, there is no way back! Many mobile module providers offer both technologies in one chipset, so it is easy to switch between them if there is such a need. Graphical comparisons of main NB-IoT and LTE-M[20] features and comparison between all three technologies LTE, LTE-M and NB-IoT is available in the diagram below.

[20] LTE-M and NB-IoT are both a part of 4G technology (LTE as such). Thus, all power limitations used in 4G are also applied for NB-IoT and LTE-M - from user equipment and base station perspective.

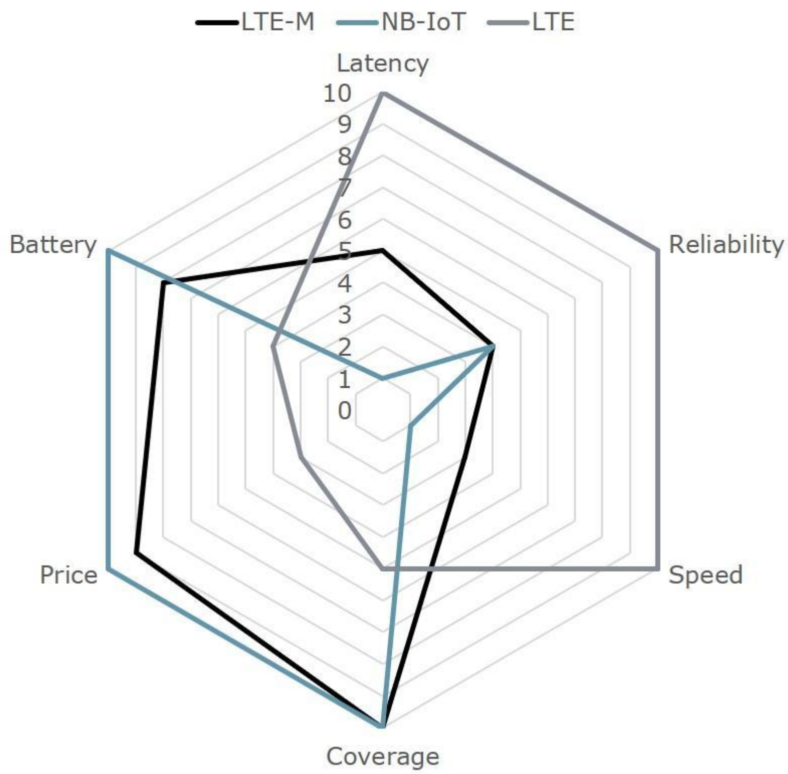

Figure 8: LTE, LTE-M and NB-IoT comparison[18]

3.2 First 4G private networks

Industry 4.0 describes the growing interest for massive data exchange, automation of processes, wider area radio coverage, high security local networks and mobility. LTE was the first technology reaching high demands of the industry 4.0 offering low latency, reliability and high speed needed for a wide range of applications. Consequently, **first private LTE (pLTE**) solutions became available on the market mainly supporting data transfer without voice communication, as it is common for public networks. Generally, pLTE networks are the same as used for mobile telecom services but simplified in order to make pLTE solutions less complex and more cost affordable.[21]

Basic pLTE topology includes three layers. User Equipment (UE), Radio Access Network (RAN) and Evolved Packet Core (EPC) as a part of the network topology.

User Equipment layer consists of devices, which are connected to radio, network and are able to communicate via LTE technology.

Radio Access Network consists of radio base stations for receiving and transmitting signal and an antenna part which actually converts transmitted signal into radio signal. The RAN layer has radio access on one side and data and signaling uplink on the other.

[21] Westrup, W. Should You Build a Private 5G or LTE Network?. (2022). Retrieved from: https://www.sierrawireless.com/iot-blog/what-are-private-lte-networks/

Evolved Packet Core cares for all functions that are available in the LTE environment like mobility support, user management, session management, quality of service, etc.[22]

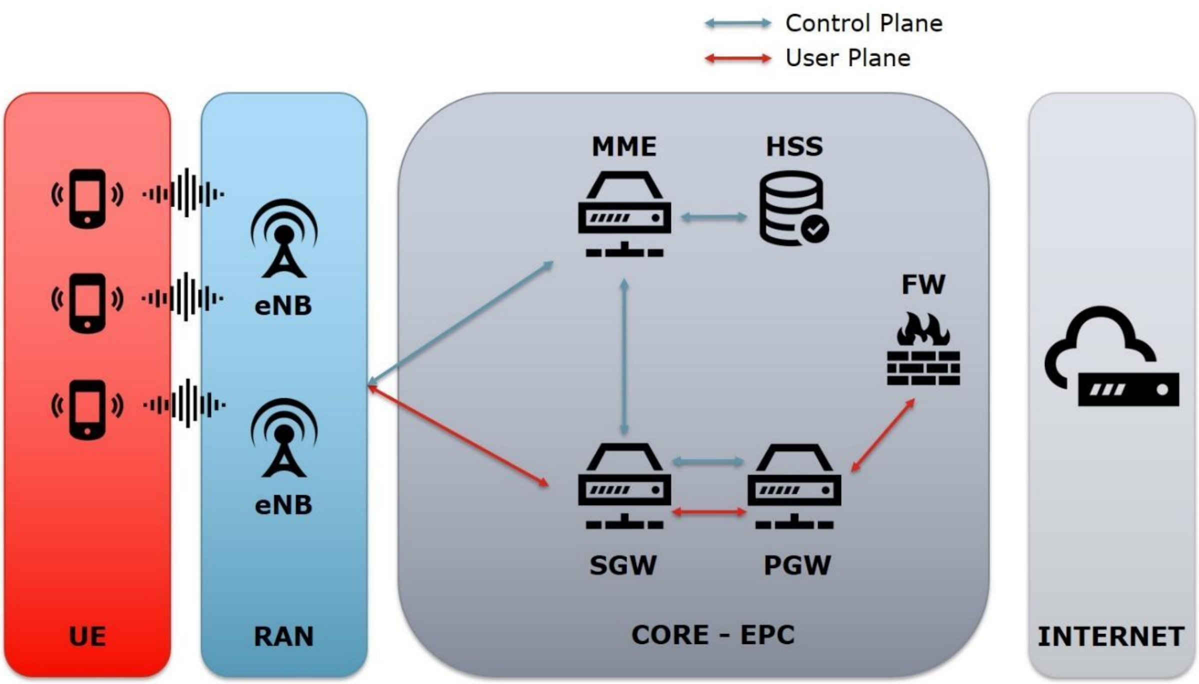

Figure 9: LTE network topology

Wi-Fi is the most frequently used radio data communication technology in industry, connecting mainly all mobile users. Private LTE networks come in place where Wi-Fi has weaknesses and Wi-Fi bottlenecks are still the main reason to migrate to private LTE or even private 5G today. Main cases where Wi-Fi becomes impractical are:

- maximum number of connected devices per access point is in theory 250, which can be easily reached in dense industrial environments;
- Wi-Fi suffers from its bandwidth available for communication because of limitation of license free spectrum. Data speed directly depends on bandwidth available;
- Wi-Fi is designed for short range and can work up to a few hundred meters. On the other hand, LTE can easily reach kilometers;
- mobility in terms of handing over UEs data stream between different access points handles Wi-Fi poorly. On the contrary mobility feature cellular mobile technologies were one of the main features starting with very first releases;

[22] Savić, Ž. LTE Design and Deployment Strategies. (2020). Retrieved from: https://www.cisco.com/c/dam/global/en_ae/assets/expo2011/saudiarabia/pdfs/lte-design-and-deployment-strategies-zeljko-savic.pdf

- free spectrum suffers also from interference, especially in dense environments. Because of unlicensed spectrum there is no guarantee, to have all the spectrum available for particular use case;
- Wi-Fi is historically less secure than cellular technologies. Security was the base for cellular communication standardization. All other cellular features must incorporate security as the main request. Thus, security is added into the very basic design of LTE, on the other hand Wi-Fi security is added on top.

3.3 Coexistence of technologies and migration towards 5G

There are many questions, and even more answers, why 2G and 3G are still present nowadays if there is 4G available as one of the most widely speeded technologies, available in every corner of the world. Furthermore, 5G is emerging and will cover the same territory as 4G in a few next years.

Many factors have a bearing on 2G and 3G availability after many years:

- every mobile operator checks regularly what kind of devices are connected to the network and which technologies are in use. It is simply not easy to decide to switch off certain technology if there are still devices in use;
- simply switching off certain technology would lead to enormous costs for industry. It means replacing all devices with new ones, supporting new technologies like 4G or 5G. In most cases there is no option to change only the communication module of the device, but can require to change the complete device with a new one, since communication modules are in many cases embedded into the device itself;
- there are still communication modules available in the market, supporting 2G or 3G communication or both at the same time. Prices for such modules are extremely low compared to 4G, not to mention 5G. This leads to product development using legacy communication technologies just to have a competitive price of the product on the market;
- because of robustness and simplicity of radio modulation used by 2G and 3G and antenna positioning into the area, both technologies have long range, wide coverage and deep penetration into objects. All this benefits for indoor metering forces communication module manufacturers to implement 2G and 3G technologies into 4G and 5G modules as fall back technologies. If the module is not able to connect to 4G or 5G technology because of poor signal, a module still has the option to try 2G and 3G technology as an alternative. Adding legacy technologies as a fall back has become reality, or better to say, has become standard. After all, all our mobile phones still have an option to set communication technology manually. Staring with 2G;
- speaking globally, people in less developed countries are still using 2G and 3G mobile phones.

Regardless of all the lines written about the benefits of 2G and 3G, their sunset is happening. It is here and is happening now.

- Mobile operators have a limited range of frequencies for network operation. Frequencies mean invested money. With growing adoption of 4G and 5G, mobile operators need to free frequencies for more and more demanding 4G, 5G and IoT technologies like LTE-M and NB-IoT.

- Cost saving, especially nowadays when electrical power costs are extremely high because of the worldwide energy crisis. Power consumption and operating all four networks simultaneously is extremely high.

There is no global date for 2G and 3G sunset. Every industry must check what kind of communication devices are in use and what technologies are supported by communication modules integrated into devices. After device evaluation each industry should create an adapted migration plan considering local mobile operators plans for switching off 2G or 3G. [23]

According to Global mobile Suppliers Association (GSA) summary for 2G, 3G Switch-Off in October 2022, they identified 142 operators that have completed or announced 2G, 3G sunset in 56 countries. Switching off will continue to 2026 onwards.[22]

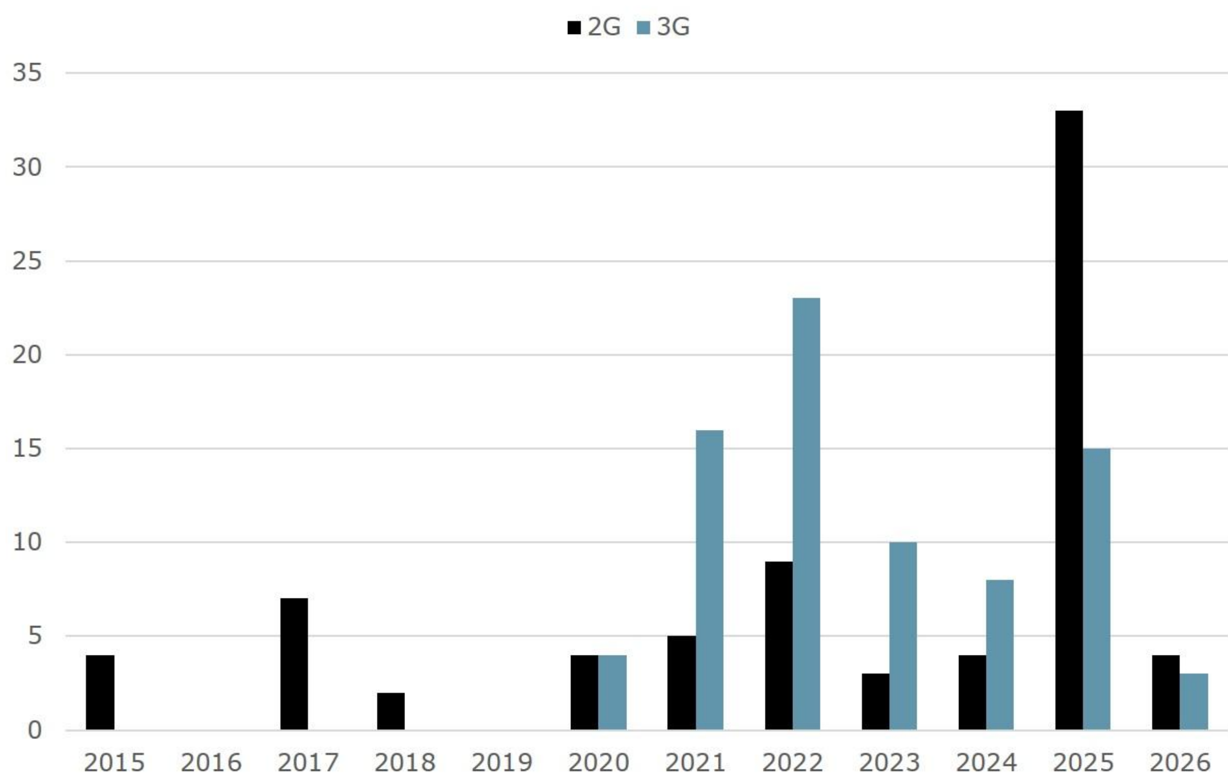

Figure 10: 2G, 3G sunset by year[22]

Mobile operators are upgrading to specific technology because of switching off 2G and/or 3G. Proportion of chosen technology to upgrade is presented in the graph below.

[23]GSA. 2G-3G Switch-Off October-2022 Summary. (2022). Retrieved from: https://gsacom.com/paper/2g-3g-switch-off-october-2022-summary/

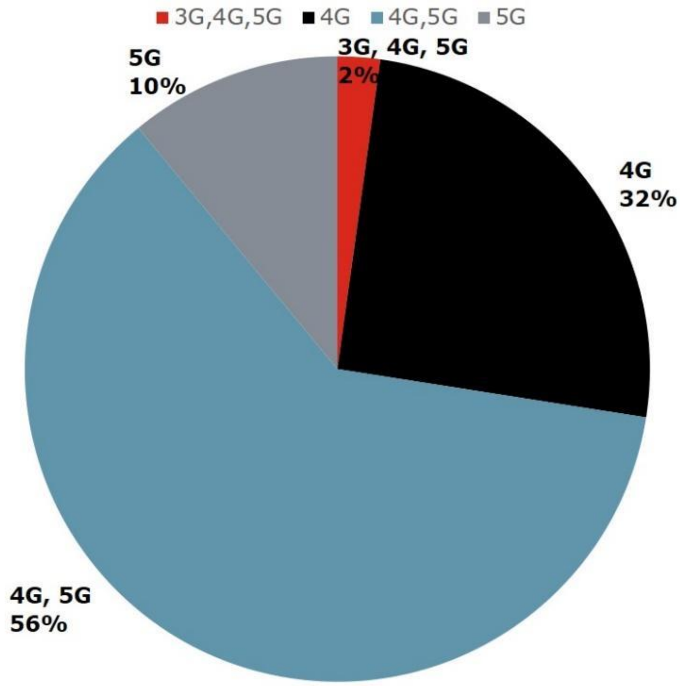

Figure 11: Portion of technologies to upgrade to[22]

4 5G technology as a prime driver for Industry 4.0

Mobile infrastructure with modern technology for more and more demanding applications is a driver for digitalization and automation. Manufacturing, automotive, healthcare, energy sector, gaming and media, security, and agriculture will all benefit from 5G technology.

The same as for 4G technology, 3GPP approved a set of standards to define 5G also known as New Radio (NR). 5G NR has two subsets, 5G NR Non-Standalone (NSA) and 5G NR Standalone (SA), which will be explained later. For better understanding, 5G NR NSA uses 4G for signaling and 5G for data transmission. 5G NR SA follows as a fully 5G network without any need for 4G infrastructure. 5G NR SA is technology to which all mobile operators are migrating to. Inside 5G NR new features or new concepts are defined:[24]

- **Enhanced Mobile Broadband (eMBB)**: eMBB provides greater data bandwidth to support modern application demands such as gaming, multimedia, even 360° video, real time data delivery, data for cloud computing, etc;
- **Ultra Reliable Low Latency Communications (URLLC)**: URLLC is here to support use cases that require high reliability and low latency communications starting with intelligent transport and autonomous driving vehicles. Industry cases such as robot control and Automated Guided Vehicles/ Autonomous Mobile Robots (AGVs/AMRs);

[24] Simeone, O., Popovski, P., Durisi, G., & Trillingsgaard, K. F. 5G Wireless Network Slicing for eMBB, URLLC, and mMTC: A Communication-Theoretic View. (2018). Retrieved from: https://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=8476595

- **Massive Machine Type Communications (mMTC)**: Massive Machine Type Communications started in release 13 (NB-IoT and LTE-M) and is continuing in 5G. mMTC must support also new the technology which is coming in the future in 5G, called Red-Cap;
- **Multiple Transmission and Reception Point (mTRP) for URLLC and eMBB**: Multiple Transmission and Reception Point is achieved by beam forming and improving mobility features. For this purpose, user equipment can use multiple antennas.

3GPP releases and focus of each upcoming release are presented in Table 4 and Figure 12.[25]

Table 4: 3GPP releases and focus of each upcoming release[26,27,28,29]

5G			
5G NR NSA eMBB mMTC	**5G NR SA URLLC positioning**	**5G NR SA mTRP**	**5G - Advanced**
Rel-15	Rel-16	Rel-17	Rel-18
2019-06-07	2020-07-03	2022-06-10	2024-03-22

Additional frequency ranges were allocated to 5G technology in order to meet the needs for faster data rates. In order to meet the request two different frequency ranges are available for the 5G technology:[30]

- **Frequency Range 1 (FR1)** - coincides with the traditional cellular spectrum. Formerly FR1 range was defined for the frequencies below 6 GHz. But after the World Radio Conference in 2019 new frequency allocations were agreed and FR1 was extended to 7.125 GHz.
- **Frequency Range 2 (FR2)** - higher frequencies intended to support 5G with short range and high data rate capacity are introduced. FR2 is also known as millimeter wave (mmWave). Ranges at such high frequencies are much shorter, but it can be more easily re-used.

[25] moniem-tech. 5G 3GPP Releases from Release 15 to Release 18. (2022). Retrieved from: https://moniem-tech.com/2022/09/16/5g-3gpp-releases-from-release-15-to-release-18/#:~:text=September%2016%2C%202022

[26] 3GPP. Release 15. (2022). Retrieved from: https://www.3gpp.org/specifications-technologies/releases/release-15

[27] 3GPP. Release 16. (2022). Retrieved from: https://www.3gpp.org/specifications-technologies/releases/release-16

[28] 3GPP. Release 17. (2022). Retrieved from: https://www.3gpp.org/specifications-technologies/releases/release-17

[29] 3GPP. Release 18. (2022). Retrieved from: https://www.3gpp.org/specifications-technologies/releases/release-18

[30] ETSI. 5G; NR; Base Station (BS) radio transmission and reception (3GPP TS 38.104 version 15.2.0 Release 15). (2018). Retrieved from : https://www.etsi.org/deliver/etsi_ts/138100_138199/138104/15.02.00_60/ts_138104v150200p.pdf

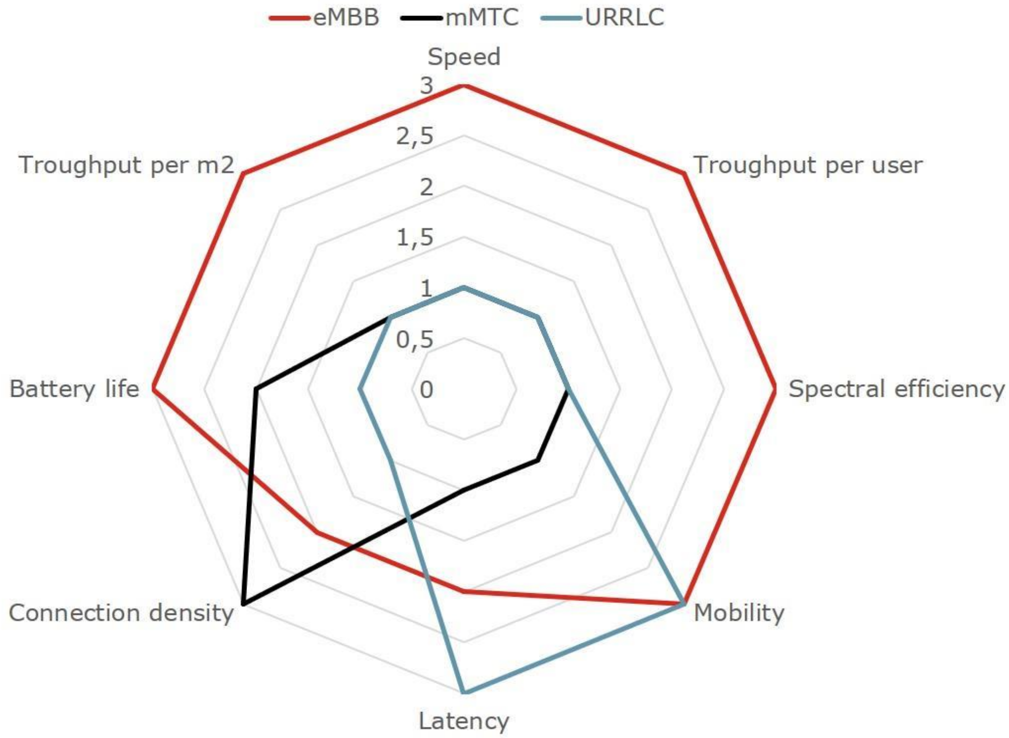

Figure 12: eMBB, URLLC, mMTC features requirements[25,26,27,28]

Table 5: Frequency range definitions[29]

Frequency Range 1 (FR 1)	Frequency Range 2 (FR 2)
410 MHz – 7,125 GHz	24,25 GHz – 71,0 GHz

Carrier aggregation principle is the same as it is in 4G. For 4G LTE networks, channel width can be up to 20 MHz as already explained in 4G chapter. On the contrary, 5G has a maximum channel width up to 100 MHz. That is the major fact why 5G radio can be faster than 4G and in theory it can be up to five times faster than 4G technology. As mentioned in the 4G section, transfer speed is limited by three factors. Bandwidth (or channel width), number of coding states and quality of the signal. Bandwidth, or channel width has the biggest influence, that is why one of the basic ideas in 5G was to increase channel width. On the Figure 13 below there are types of carrier aggregation presented.[29]

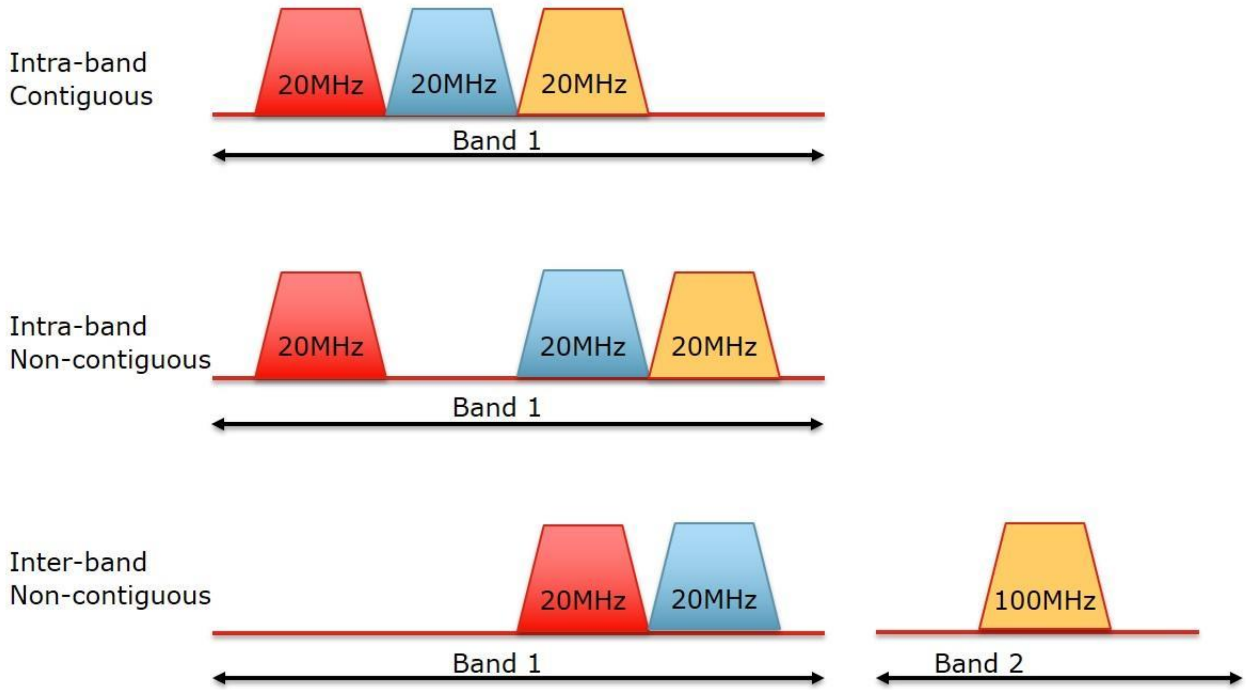

Figure 13: Carrier aggregation types[29]

The channel width determines the data transfer rate. If the channel width is 10 MHz, then the data transfer rate is the same, regardless of the frequency we use. However, it is necessary to know that the width of the channel might be historically conditioned by low and is narrower at lower frequencies. At higher frequencies, however, the width of the channel is wider, as the width is easier to achieve.[29]

Dual Connectivity acts the same as in 4G, so it can combine signals from two different radio stations that are in range. User equipment can receive 4G and 5G signals and then aggregates data flow from both technologies. Dual Connectivity simply combines bandwidth of two technologies into one channel.[29]

Dynamic Spectrum Sharing (DSS) uses the same frequencies for hosting 4G and 5G technologies. DSS dynamically allocates frequency resources between 4G or 5G technology. In fact, both technologies coexist on the same frequency spectrum. This allows mobile operators to incorporate more frequency spectrum to 5G technology and to be backward compatible at the same time. Mobile operators do not need to invest into new antennas, but just reuse existing ones. DSS can be achieved only by upgrading software, which is much more cost effective.[29]

Massive MIMO (Massive multiple-input multiple-output) allows devices to transmit signals over multiple antennas simultaneously. 4G MIMO technology allows 4 simultaneous connections, 5G on the other hand using Massive MIMO can establish up to 100 simultaneous connections. That way 5G technology can “massively” influence the speed.[29]

Quadrature Amplitude Modulation (QAM): If we increase the number of coding states inside modulation, then the quality of the signal must be higher in order that we are able to decode the states from the signal on a receiving device. Beamforming is such a technology, which provides better signal to noise ratio and consequently allows higher coding starts. mmWave is covering smaller areas because coverage using high frequencies is much smaller. Smaller areas mean less interference, which mean better signal to noise ratio. In latest releases 4G technologies support QAM 256, but 5G will be able to support QAM 1024 and beyond in future releases.[29]

Network Slicing: One of the key aspects of 5G is that the technology is built on a virtualized infrastructure. Network Functions (NF) are implemented as a piece of software in data centers (Clouds) and not on dedicated devices as was the practice in the past. Virtualization empowers developers to change the functionality of the network and adapt it to use cases more easily. Each virtual network can be developed and managed through a central point.

Full slicing functionality is available in 5G SA architecture only. Network slicing is a tool for creating multiple mutually isolated networks, configured for different use cases, where they all share the same basic hardware resources. Network slices are understood as logically (i.e. virtually) isolated.[31]

Full isolation of network slices: Unlike VLANs, network slices are truly separate networks. Each slice has its own entities (virtual functions) for control and management (only the slice orchestrator and manager are shared). So network slices are truly separate networks in terms of fault tolerance and performance management. One slice cannot affect the operation of another slice in any case, and information cannot leak out due to incorrect configuration.

Using the latest technologies such as SDN (Software Defined Network), the slices behave completely dynamically. In contrast to the VLAN approach, where we set the architecture at the beginning and did not change it later, the slices can change completely dynamically. We can imagine a service defined by the business logic of the end user, and a slice as a set of physical and virtual resources that realize this logic.

Slicing is a technology that industry has not yet included to the list. But slicing will be the standard in the network. Even telecommunications companies do not know how to foresee the real use of slicing in practice. In practice, slicing has all the answers to the industry's doubt about the security of networks that are not completely isolated (Air Gap). The point of slicing is to adapt public networks to the needs of enterprises in such a way that slices meet all the required criteria of modern industry. High security as well as reliability, speed and isolation.

Network slicing can be configured differently. Different approaches are presented below.

[31] 3GPP TS 28.530. Technical Specification Group Services and System Aspects; Management and orchestration; Concepts, use cases and requirements (Release 15). (2019). Retrieved from: https://www.3gpp.org/ftp/tsg_sa/WG5_TM/TSGS5_128/SA_86/28530-f30.doc

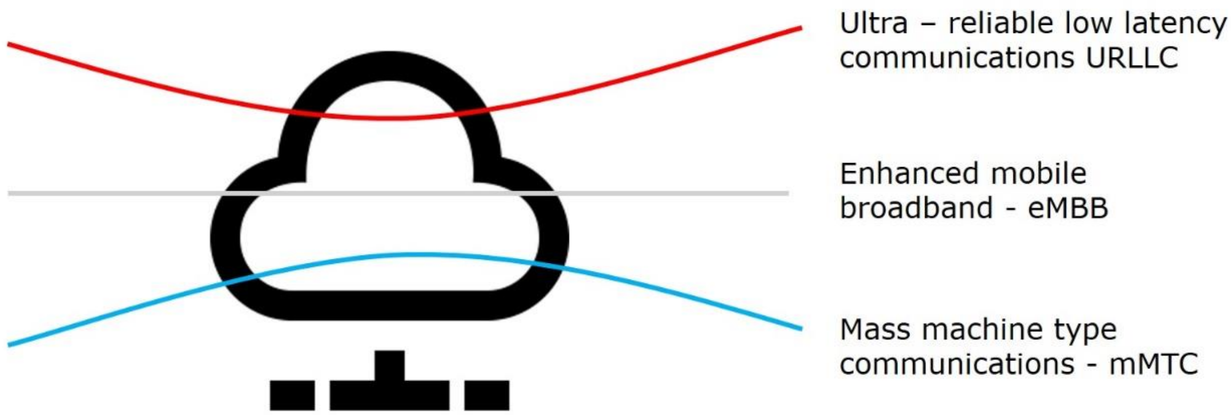

Figure 14: Using just three generic slices for all users[34]

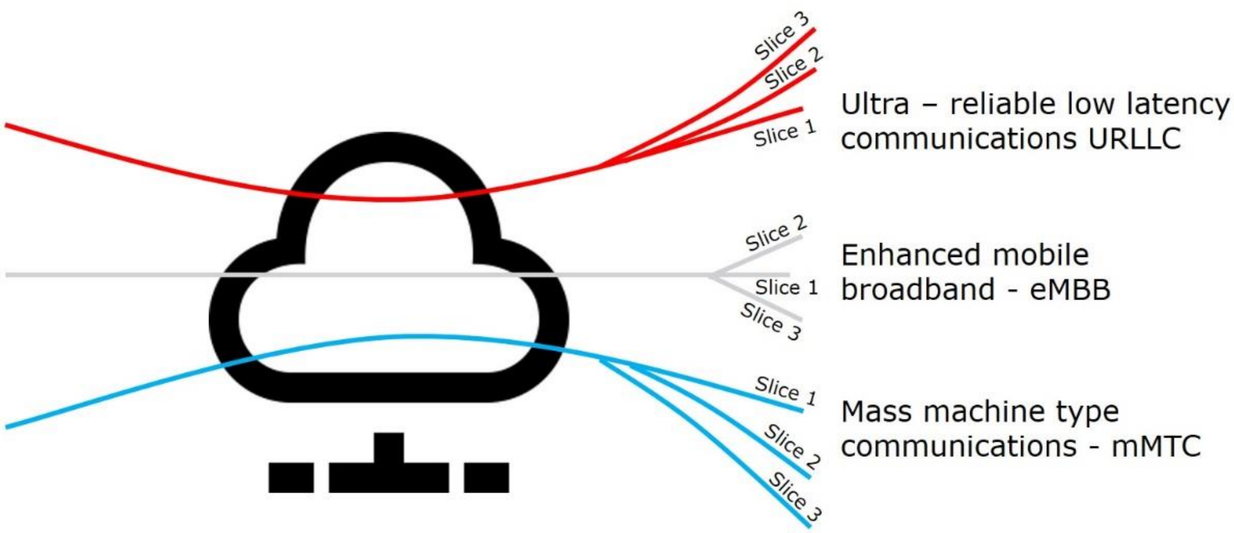

Figure 15: more slices for the same functionality - grouping users[34]

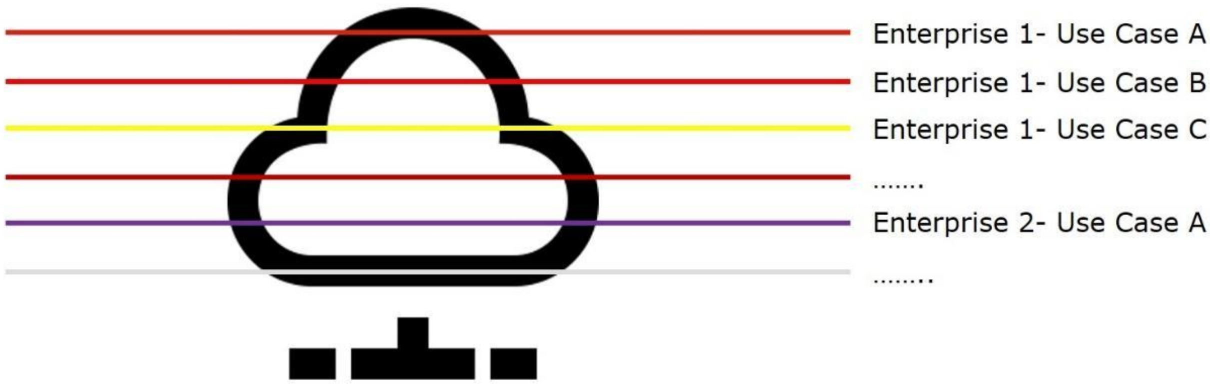

Figure 16: Customer specific slicing[34]

4.1 5G standalone (SA) versus non-standalone (NSA)

It is not very well known that according to 3GPP there are many 5G implementation architectures available that offer different possibilities to successfully implement 5G technology. Better to say, offer migration from 4G to pure 5G. In this context, 3GPP has foreseen two different architectures:[25,26,27,28]

- 5G Standalone Architecture (5G SA),
- 5G Non-Standalone Architecture (5G NSA).

Regardless of the technology in use, mobile cellular architecture consists of radio and core parts. Furthermore, 4G technology is a fact in almost all mobile networks. That is the present situation in almost all countries over the world offering complete infrastructure including radio and core parts. If 4G Core is involved in 5G architecture or if 4G Radio is involved in 5G architecture it defines 5G NSA architecture. 5G NSA uses 4G radio and core in NSA architecture. On the other hand, 5G SA uses only 5G radio and 5G core in SA architecture.[32]

5G NSA is defined in 3GPP release 15 where 4G technology is still used mainly for signaling or controlling plane transmission. Anyway, the final goal is to have fully blown 5G SA configuration. For better explanation, both architectures are presented in the picture below. As it can be seen, 4G is part of the 5G ecosystem. IAs both NB-IoT and LTE-M will be supported inside 5G, they are future proof. Many industries calculate total costs of ownership (TCO) for 10 or even 15 years. Thus, devices in use today, running NB-IoT or LTE-M technology are future proof.[25,26,27,28]

[32] 5G-ACIA White Paper. 5G Non-Public Networks for Industrial Scenarios. (2021). Retrieved from: https://5g-acia.org/wp-content/uploads/5G-ACIA_5G_Non-Public_Networks_for_Industrial_Scenarios_09-2021.pdf

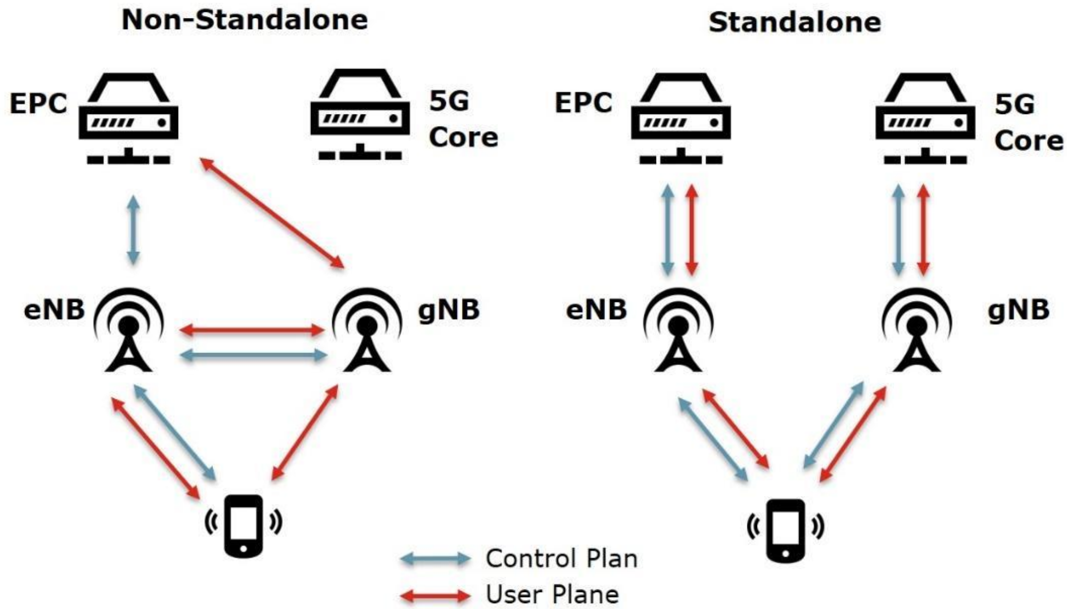

Figure 17: 5G Non-Standalone and 5G Standalone architecture [25,26,27,28]

According to 3GPP there are many other options for setting up 5G NSA topology.

- If there are 4G radio and core involved in 5G NSA topology, three different options are available, known as Option 3, Option 3a and Option 3x (presented in the picture above). Difference between these options is just how the control plane and user plane (data) are connected between user equipment, radio and core.
- If there is only 4G radio involved inside 5G NSA content transmission, according to 3GPP Option 4 and Option 4a are available. They differ only in control plane and user plane paths between entities.

5G NSA topology overview:

- It enables and facilitates faster roll out of 5G technology. It acts as a step between 4G and full 5G SA infrastructure.
- Making full use of the existing 4G network.
- Starting 5G with lower investment.
- Lack of 5G full range of 5G functionalities.
- For the time being, service providers who want to offer 5G speeds will start with NSA and, once 5G coverage is established, implement standalone 5G.

But industry digitalization is what is going to pave the way for new revenue streams for service providers. And 5G use cases requiring ultra-low latency and much higher capacity will only be feasible with the SA 5G and the 3GPP core network architecture for 5G Core.

5G SA topology overview:

- All capabilities available in URLLC, eMBB and mMTC
- Full stack of functionalities is available like Network Slicing

- Architecture of network functions makes complete topology more flexible in terms of load and performance.
- Investment in pure 5G SA is high.
- New technology – new challenges.

4.2 Variants of 5G for Industry 4.0

Private networks, industrial applications such as manufacturing facilities, transportation systems and other vertical industries are ready to take advantage of the faster speeds, lower latency, and higher data throughput of 5G. What can 5G do for Industry 4.0 and other commercial use cases?

4.2.1 5G Private network

A private 5G network is a radio network covering a certain industrial or campus area with a 5G (or 4G) independent radio network. Private setups of 5G networks are the future of 5G technology and are an independent private network deployed at the enterprise. 5G technologies are one of the key enablers for the digital transformation of manufacturing in the industry 4.0.[33]

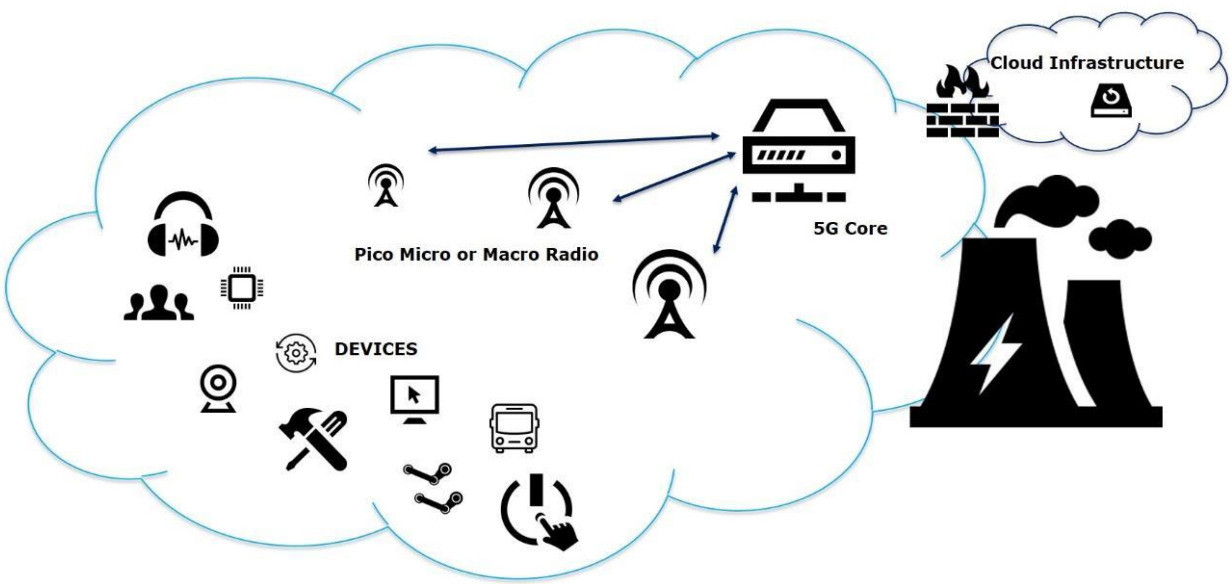

Figure 18: Private 5G network[32]

The general idea is that smart industries can deploy private 5G physical infrastructure quickly and efficiently. When all needed configuration data defining a private 5G network are available, a vendor can prepare a setup, which can be deployed within a few hours. In theory, only servers and radios must be installed. After installation only powering on the solution is needed and it can be used immediately out of the box.

[33] GSMA. 5G IoT Private & Dedicated Networks for Industry 4.0. (2020). Retrieved from: https://www.gsma.com/iot/wp-content/uploads/2020/10/2020-10-GSMA-5G-IoT-Private-and-Dedicated-Networks-for-Industry-4.0.pdf

5G SA architecture is an appropriate choice to set up private 5G since enterprises do not have prior setups of 4G available on premises. That means no transition from 4G via 5G NSA to 5G SA is required. So, the only logical choice for industry is to jump directly into 5G SA architecture.

4G is reaching the technical limits of the amount of data, which must be transferred over the radio network because of modern application demands. New technologies such as cloud computing, artificial intelligence, real time processing, big data and analytics, digital twins, automation etc. require more and more from modern connectivity. Demands for more devices working reliably and uninterrupted inside the same area are higher and higher.

Application demands are presented on a triangle, taking into account 5G improved features.

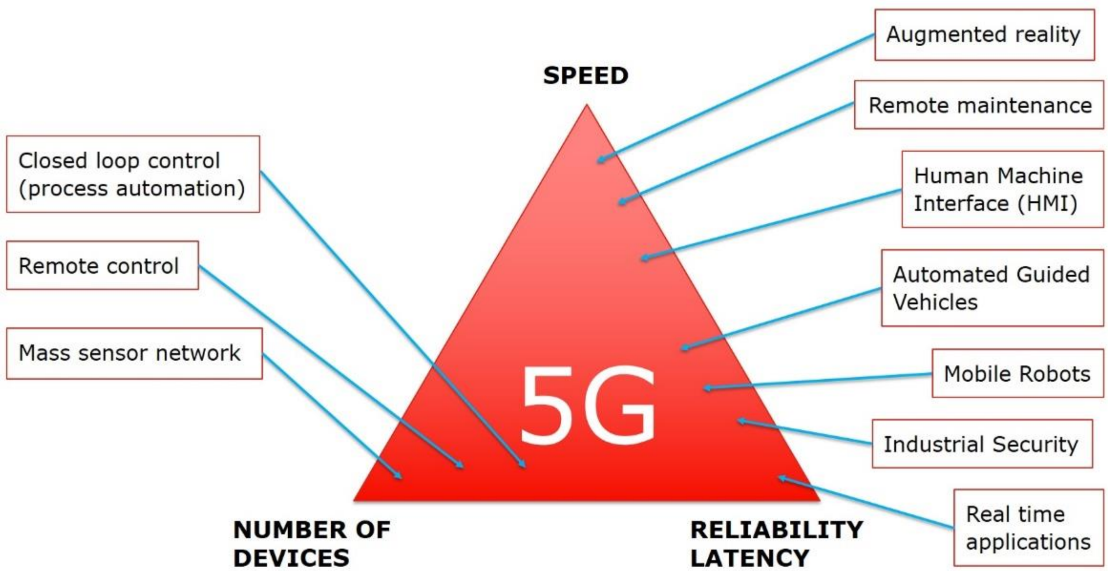

Figure 19: The triangle of application demands for 5G network[34]

4.2.2 RedCap

RedCap (stands for **Red**uced **Cap**abilit) is a part of 5G NR and belongs to the IoT segment of technologies. It was also known as NR-Light initially, but the name was changed later. RedCap is a part of 3GPP release 17 and above and will be commercially available in the future 5G NR. Release 17 will enhance system performance and expand to new devices and applications.[35]

RedCap will address the market segment of "smart" IoT devices, which requires higher speed than already known IoT technologies like NB-IoT and LTE-M. On the other hand, RedCap will

[34] HUAWEI. Up in the air with 5G. (2016). Retrieved from: https://www.huawei.com/en/technology-insights/publications/huawei-tech/80/up-in-the-air-with-5g

[35] Qualcomm. What is 5G NR-Light, a.k.a. RedCap, and how will it accelerate the growth of the connected intelligent edge? (2022). Retrieved from: https://www.qualcomm.com/news/onq/2022/07/what-is-5g-nr-light--a-k-a--redcap--and-how-will-it-accelerate-t

require better coverage and indoor penetration compared to eMBB where speed, reliability and latency is all about. Therefore, RedCap is trying to position a new IoT technology somewhere in the middle between eMBB on one hand and NB-IoT and LTE-M on the other. RedCap contrast is shown on the picture below.

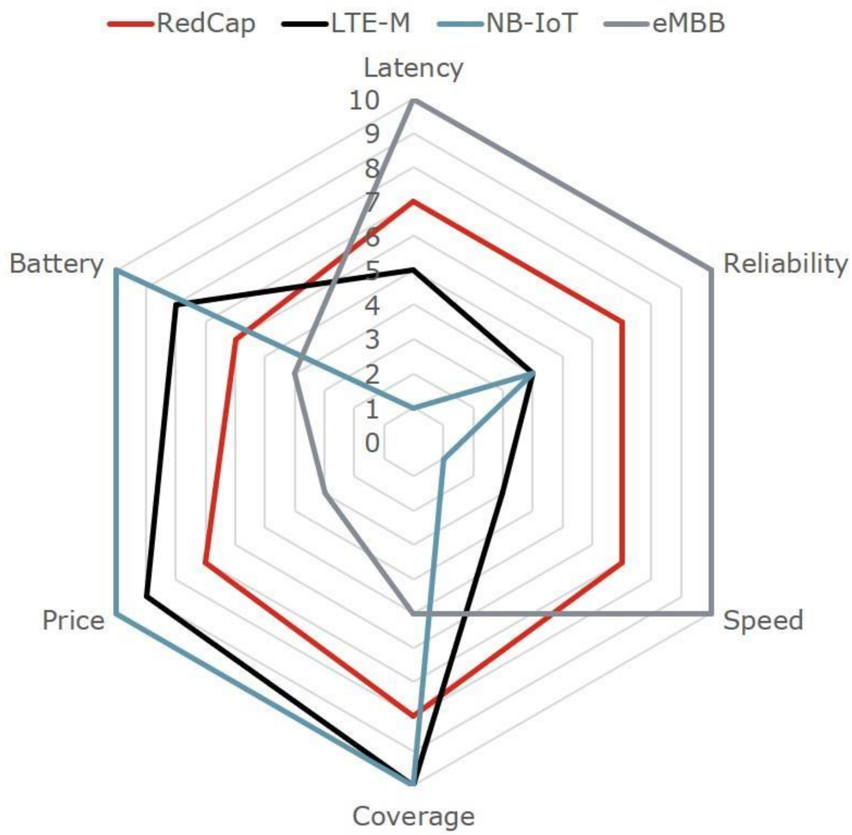

Figure 20: LTE, LTE-M, NB-IoT and RedCap comparison[36]

RedCap is trying to cover use cases in industry where lower latency is required than it is available for traditional IoT technologies. Also better speed will be available compared to NB-IoT and LTE-M. Typical use cases are video streaming with lower quality, sensors in industry that require lower latency, wearables for health monitoring etc. It looks like wearables will be the most appropriate devices, which will benefit the most from RedCap. Mid-speed requirements about data and battery life may be expected up to a few weeks in terms of wearables. RedCap simply expands device ecosystem. As it can be seen from the figure above, 5G NR is trying to cover as many use cases as possible offering appropriate technology.

[36] blog.3g4g. Introduction to 5G Reduced Capability (RedCap) Devices. (2021). Retrieved from: https://blog.3g4g.co.uk/2021/07/introduction-to-5g-reduced-capability.html

5 IoT and unlicensed spectrum

5.1 Wi-Fi 6

Besides cellular technology, Wi-Fi is one of the most used radio communication technologies nowadays.

Behind the Wi-Fi trademark is a global non-profit organization called Wi-Fi Alliance which drives global Wi-Fi adoption and evolution. Wi-Fi Alliance is an association of several companies which promote Wi-Fi and lead standard development.

Table 6: Wi-Fi History[37,38]

Standard	802.11	802.11a	802.11b	802.11g	802.11n	802.11ac	802.11ax	802.11ax	802.11be
Wi-Fi Alliance name	Legacy	Wi-Fi 1	Wi-Fi 2	Wi-Fi 3	Wi-Fi 4	Wi-Fi 5	Wi-Fi 6	Wi-Fi 6E	Wi-Fi 7
Frequencies	2.4 GHz	5 GHz	2.4 GHz	2.4 GHz	2.4/5 GHz	2.4/5 GHz	2.4/5 GHz	2.4/5/6 GHz	2.4/5/6 GHz
Speed	2 Mbps	54 Mbps	11 Mbps	54 Mbps	54 Mbps	1.7 Gbps	2.4 Gbps	5.4 Gbps	40 Gbps
Year of release	1997	1999	1999	2003	2009	2014	2019	2019	2025

Two different names for Wi-Fi 6 exist. Wi-Fi 6 and Wi-Fi 6E which can be seen also from the table above. Main difference between them is that Wi-Fi 6 operates on 2.4 GHz and 5 GHz, Wi-Fi 6E operates also on 6 GHz as well as on 2.4 GHz and 5 GHz.

Figure 21: OFDM versus OFDMA spectrum utilization

[37] Wi-Fi Alliance: https://www.wi-fi.org/
[38] IEEE. Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications IEEE Std 802.11ax™-2021. (2020). Retrieved from: https://ieeexplore.ieee.org/document/9442429

Key features for better and faster Wi-Fi 6/6E:

- **Orthogonal Frequency Division Multiple Access** (OFDMA) significantly improves spectrum utilization and is one of the key technologies that makes Wi-Fi 6 stand out from its predecessors. Wi-Fi 5 uses Orthogonal Frequency Division Multiplexing (OFDM), which is not able to utilize spectrum as efficiently as OFDMA. OFDMA is subdividing Wi-Fi channels into subcarriers or smaller frequency allocations, transmitting smaller frames to multiple users at the same time. In addition, multiple stations can transmit frames for the same user. OFDMA can provide additional advantage by permitting greater transmit power level per device.
- **Basic Service Set** (BSS): Coloring is another technology that helps improve spectrum utilization by preventing network congestions. Old versions of Wi-Fi while they were trying to attach to the network, devices have to listen first before they start to transmit. If there is noise even from the neighbor network, the device has to wait for a clear channel. That means there are two access points offering the same channel to nearby devices and this situation is known as co-channel interference or Overlapping Basic Service Sets (OBSS). Wi-Fi 6 access points use so called color in order to identify access points. Two access points in neighboring rooms use different colors so that devices can distinguish by which access point they are served. If there is a traffic on the same channel but it is not the same color (same access point) the device can ignore that traffic and continue transmitting.[38]
- **Multi-User Multiple Input Multiple Output** (MU-MIMO) and MU-MIMO subset Beamforming. Beamforming is another technology known also from the cellular world and can significantly improve quality of the signal or SNR and consequentially achieve higher speed. In MU-MIMO, a base station sends multiple data streams towards the user extending user's throughput 8x8 Mu-MIMO is currently available.[38]

5.2 Wi-Fi 6 vs 5G for Industry 4.0

Wi-Fi 6/6E has made significant steps forward adding major improvements towards modern industry 4.0 needs. Capacity, efficiency, and flexibility are moving towards 5G technology. New Wi-Fi 6E offers a new 6 GHz frequency, 8x8 MIMO, wider channels up to 160 MHz. OFDMA improves Wi-Fi performance. Since Wi-Fi is widely accepted and there is no industry that does not have Wi-Fi as local connectivity, it will continue to serve in the future.

On the other hand, 5G can offer specific technologies such as eMBB, mMTC and URLLC which are directly addressing industrial needs. It can cover a wider area much more efficiently if needed. Furthermore, mobility support which works out of the box in 5G, represents powerful functionality for automatic guided vehicles.

Wi-Fi and 5G will coexist. It is a matter of use case and business models which technology to take. In some cases, both technologies can be complementary, on the other hand, they can be very different.

Table 7: 5G versus Wi-Fi 6/6E comparison

	5G	Wi-Fi 6/6E
Speed and data transfer	high	high
Specific technologies UC oriented	yes, eMBB, mMTC, URRLC, NB-IoT, LTE-M, Red-Cap	partially, for IoT devices
Security	very strong, SIM as hardware for user authentication	strong
Indoor and wide are coverage	yes	Indoor yes, no wide area possibility
Non wanted interference	no, licensed spectrum	yes, unlicensed spectrum
Mobile handover	yes	partially, not so smooth
mmWave support for extreme speed	yes	yes
Easy of deployment	more complex	easy
UE availability	less at this time	wide range of UE

5.3 LoRa

It should be mentioned that at the beginning of 2000, a new unlicensed public spectrum technology named **LoRa** was invented in order to connect low power devices to the internet. In 2015, the LoRa Alliance was founded and the technology was renamed into "LoRaWAN." The basic idea of LoRa technology was to use unlicensed public spectrum for all IoT devices. Devices are considered as devices sending a really small amount of data and are battery powered. The LoRa Alliance has defined two frequency bands for the usage in Europe. EU433 from 433.05 to 434.79 MHz and EU863 from 863 to 870 MHz.[39,40] The LoRa network consists of LoRa gateways capable of communicating over wireless interfaces with devices and forwarding information towards the internet. Technical data of LoRa technology used in Europe are presented in Table 8.

Table 8: Technical data of LoRa in Europe[39,40]

Uplink max. transmission power	≤+ 14 dBm
Downlink max. transmission power	≤+ 27 dBm
Max duty cycle (channel dependent)	0,1% - 1.0 %
Maximum allowed antenna gain	≤+ 2,15 dBi
Uplink airtime	30 s
Downlink messages	10 messages per day

6 Market statistics for private networks

The exact number of existing private mobile networks is hard to determine, as details are not often made public. Even trying to track the number of existing customers (where one or many private networks could be deployed) can also be challenging.

In this section some statistical data are given as they appear in the Market Status Update of GSA edition on Private Mobile Networks (Aug. 2022)[41]. According to GSA's definition "… a private

[39] lora.readthedocs. LoRa. (2018). Retrieved from: https://lora.readthedocs.io/en/latest/
[40] ETSI. EN 300 220-2. (2018). Retrieved from: https://www.etsi.org/deliver/etsi_en/300200_300299/30022002/03.02.01_60/en_30022002v030201p.pdf
[41] Private Mobile Networks, © Global mobile Suppliers Association (GSA), Aug. 2022 (https://gsacom.com/paper/private-mobile-networks-august-2022-member-report/)

mobile network is a 3GPP-based 4G LTE or 5G network intended for the sole use of private entities, such as enterprises, industries and governments." The network must

- use spectrum defined in 3GPP,
- be generally intended for business-critical or mission-critical operational needs, and
- where it is possible, identify commercial value. The database only includes contracts worth more than €100,000, to filter out small demonstration network deployments

Non-3GPP networks such as those using Wi-Fi, TETRA, P25, WiMAX, Sigfox, LoRa and proprietary technologies are not taken into account. Network implementations using solely network slices from public networks or placement of virtual networking functions on a router are also excluded. Where identifiable, extensions of the public network (such as one or two extra sites deployed at a location, as opposed to dedicated private networks) are excluded.

GSA has collected information about 889 organizations, from 70 countries and territories, known to be deploying LTE or 5G private mobile networks (Figure 22). 5G is being deployed by 39.8 % of these customers (Figure 23). Although the proportion of 5G deployments makes up a significant number of references, real operation in industrial situations represents a limited number of them due to long-term expensive trials and deployments within educational and testbed or validation facilities. However, it is notable that of the 140 private network customers announced in 2022, 5G was used in 50 % of references. As it can be clearly seen in Figure 24 the manufacturing sector is a strong adopter of private mobile networks in terms of the number of customer deployments while mining and power utility companies share a significant portion. The remarkable growth of manufacturing among user types in the last years is also shown in Figure 25.

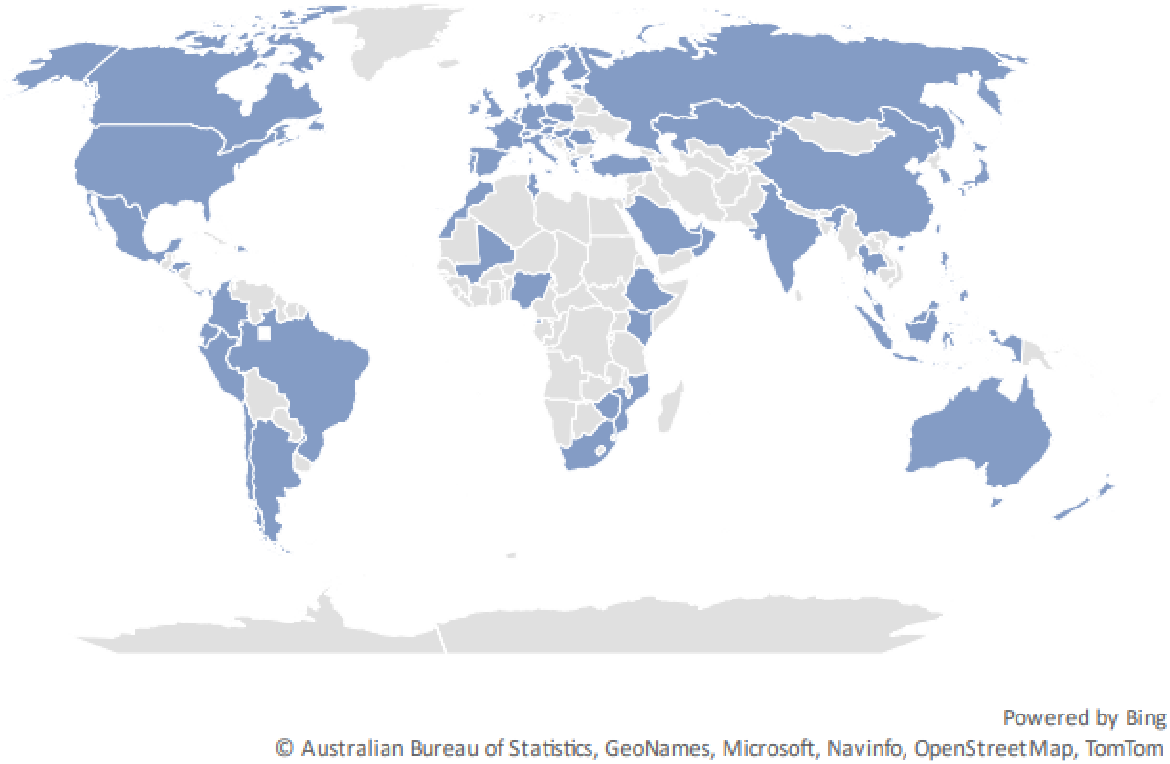

Figure 22: Countries and territories with organizations cataloged as deploying private mobile networks

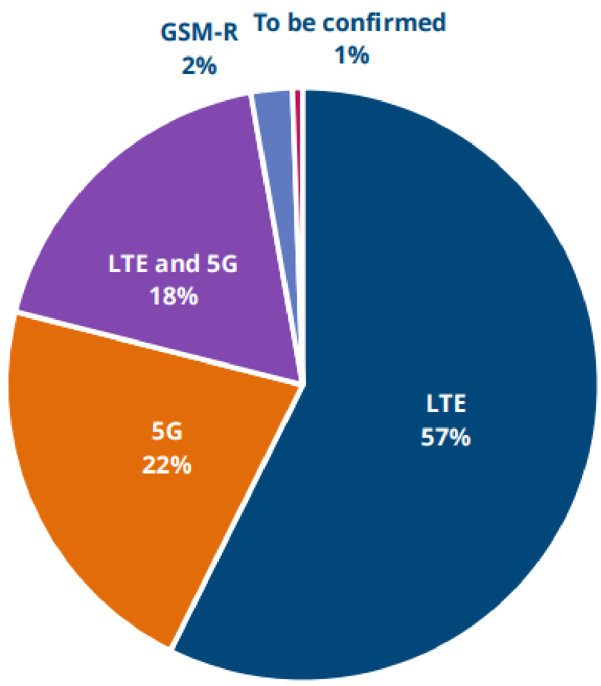

Figure 23: Private mobile network customers by technology used (base: 889 cataloged customers deploying private wireless networks)

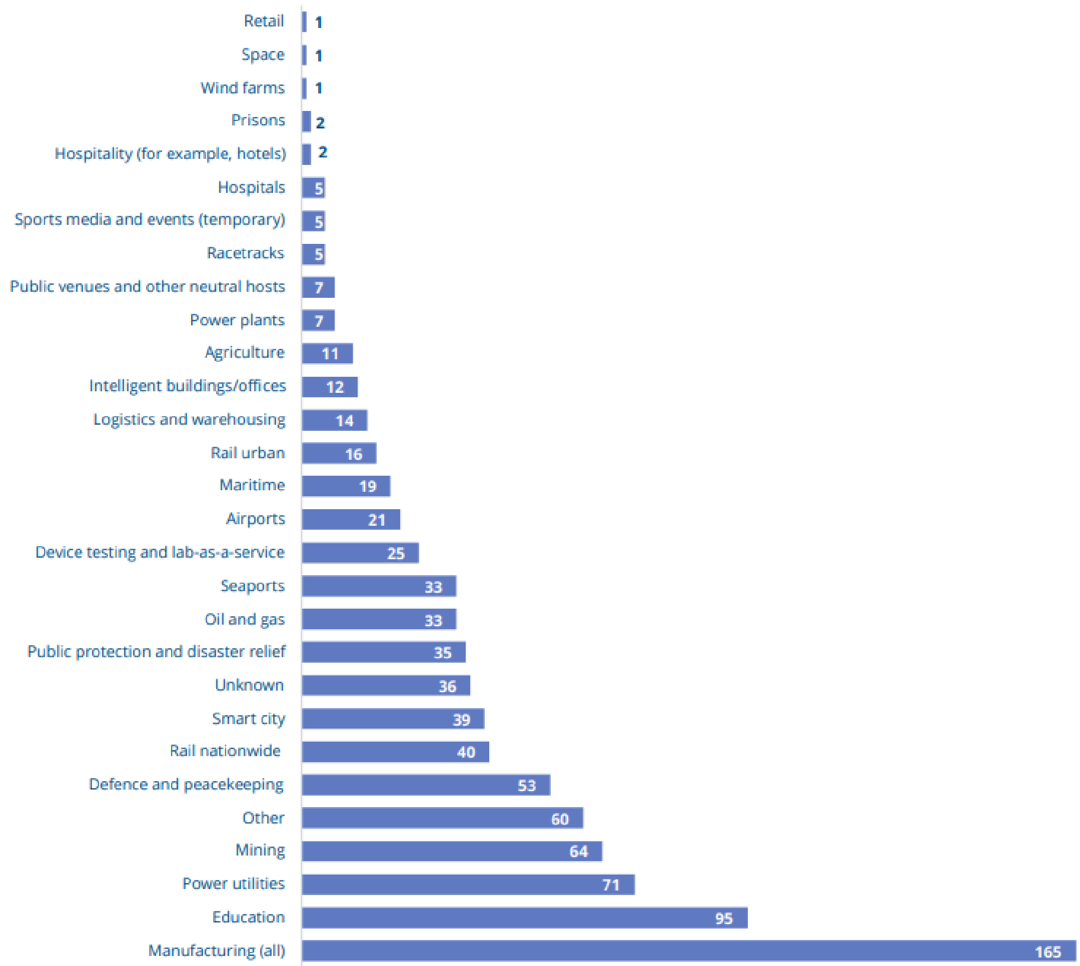

Figure 24: Number of identified customers deploying private mobile networks in trials and commercially, by sector (base: 889 organizations)

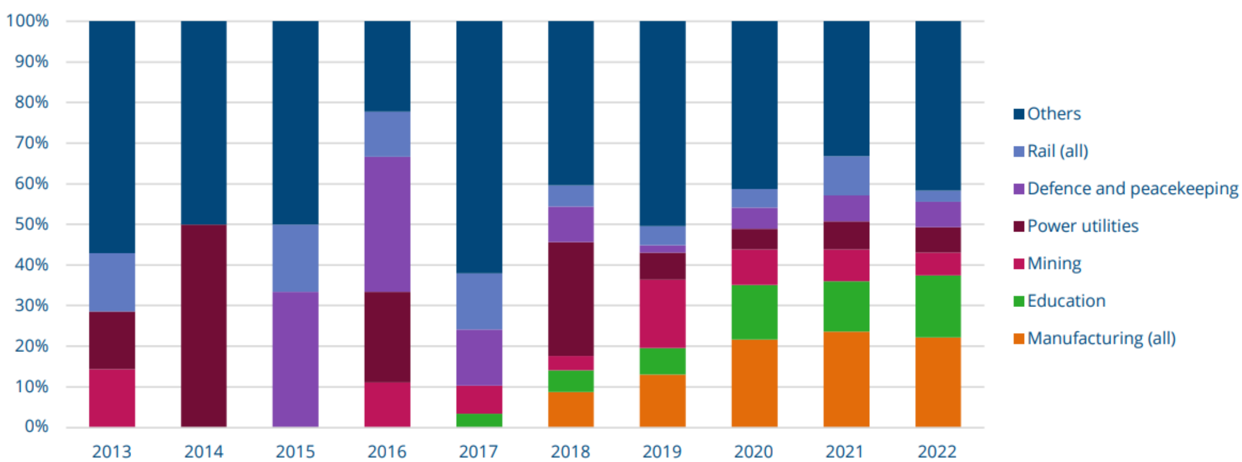

Figure 25: Total private mobile network customers by user type per year

Looking at the subcategories of the manufacturing sector, automotive has the most customer deployments, (Figure 26), followed by machinery and equipment, electrical equipment, appliances and components, and then multiple product types.

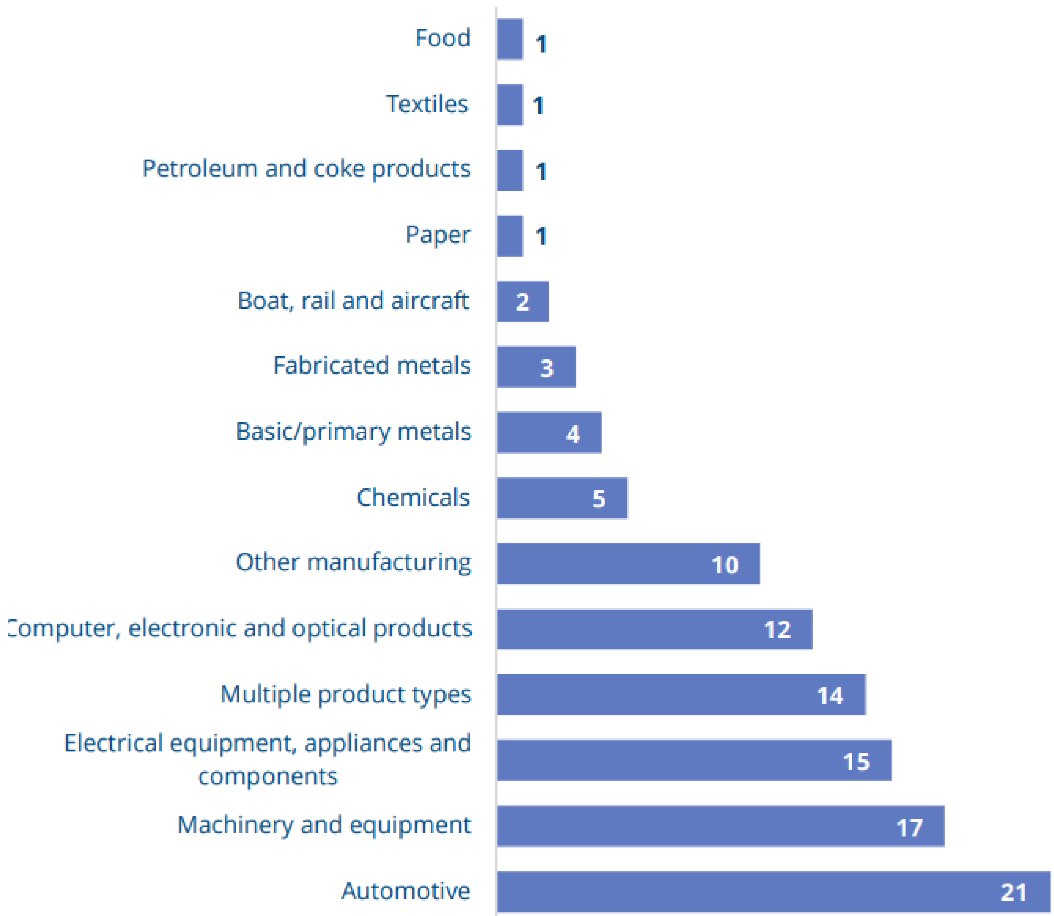

Figure 26: Number of manufacturing customers deploying private mobile networks in trials and commercially by subcategory where identified (base: 103 organizations)

GSA also tracked the spectrum bands being used for customer deployments assigned specifically for local or private network purposes (Figure 27 left). Telecom regulators tend to make allocations of dedicated spectrum available for private mobile networks — typically small tranches in specified locations. This could be acquired directly by organizations instead of by mobile operators, giving industries an alternative deployment model. Dedicated spectrum has already been allocated in some European countries, (Figure 27 right), and GSA expects this trend to be followed in more countries in the near future.

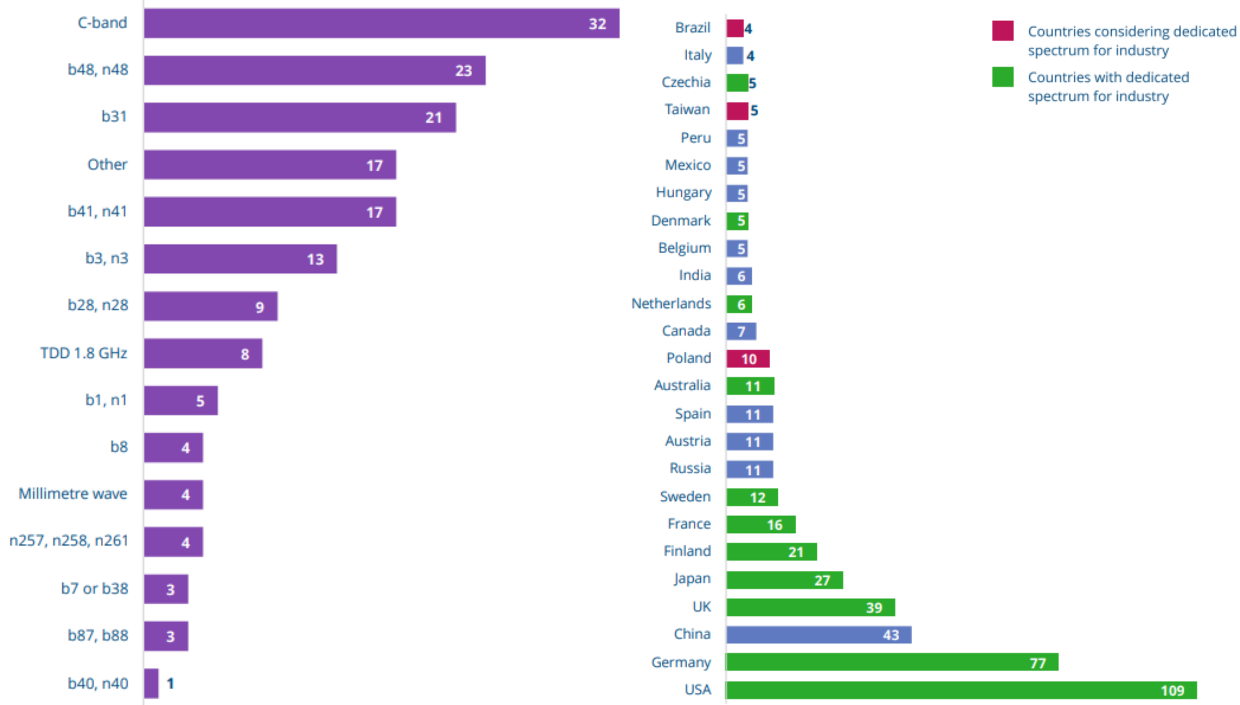

Figure 27: Left: spectrum bands used for private mobile networks; number of customer deployments identified using each band (base: 203 organizations). Right: number of private network customers by country indicating the adoption scale of dedicated spectrum allocation (base: 498 organizations, where country has been identified).

7 RF components in Industry 4.0

Industry 4.0 brings along the pervasive deployment of machine-to-machine (M2M) communication and IIoT. It is expected that most of these M2M and IIoT communication paths will be realized wirelessly, as the advantages of providing flexibility are obvious compared to hard-wired network installations.

Moreover, the technical specifications of 5G fully cover the requirements for such Smart Factories. Much research has already been done to characterize the radio channel in industrial environments, which has special characteristics due to the reflective nature of such environments. It is foreseeable that sensors, actuators and other components in future manufacturing processes will be equipped with radio transceiver modules through which they can be wirelessly connected to private networks based on 4G/5G technology. Consequently, workplaces in Smart Factories are surrounded by a large number of radio transceiver modules communicating with each other or with a central node via a wireless network, emitting radio frequency EMF to which employees are potentially exposed. Although the time averaged transmit power of each of such radio transceivers is likely to be low, the resulting overall magnitude and temporal pattern of EMF exposure to which workers are exposed in such situations is yet unknown. To better understand the potential EMF exposure scenarios of employees, in depth insight into RF components that are key elements of the private networks in Industry 4.0 is essential.

7.1 Radio-interface architecture

7.1.1 eNodeB in 4G

Evolved NodeB is an important component in 4G architecture and represents an access module for radio communication using 4G technology. eNodeB consists of a Base Band Unit (BBU) which manages a complete base station and Remote Radio Unit (RRU) which acts as transmitter and receiver for radio signals. Common Public Radio Interface (CPRI) is a standard for connecting RRU and BBU.

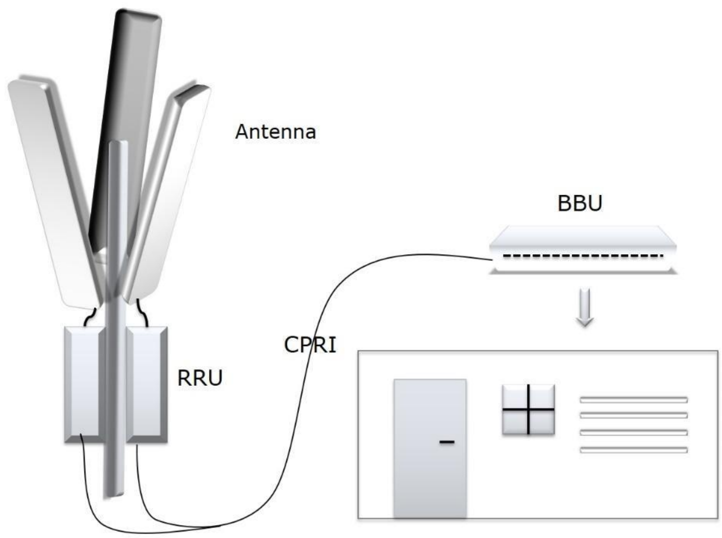

Figure 28: eNodeB architecture

7.1.2 gNodeB in 5G

The basic difference between eNodeB and gNodeB is that BBU functionality is split into two functions. Distributed unit (DU), responsible for real time processing, and a centralized unit (CU) responsible for non-real time processing. 5G is moving towards virtualization of all functions that can be virtualized. CU and DU can be moved to a central or edge cloud; it depends on configuration and RRU serving needs.

7.2 Spectrum for cellular 4G and 5G

The frequency range in which the wireless communications network is operating greatly affects many technological parameters of the deployed wireless network like coverage, latency, etc. Usually licensed spectrum bands are used, as these frequency bands are dedicated to such use and therefore protected from other possible users that might deliberately or inadvertently generate interference leading to lower reliability or achievable bandwidth.[42] With the introduction of 5G services new spectrum parts are added to already used ones:

- lower frequency bands (under 1 GHz) which offers good coverage of larger areas,
- mid frequency bands, (3 GHz to 6 GHz) for general indoor and outdoor coverage with higher bandwidths and
- high frequency 'millimeter wave' bands (26 GHz and above) providing very high bandwidths on limited areas indoor or outdoor to support new most demanding uses as automated driving, machine vision, autonomous robots, etc.

For example, in Slovenia all frequency bands are intended to provide mobile services to end users and are technologically neutral. Slovenia is following directives, regulations, recommendations and guidelines of the European Commission for electronic communications.

Table 9: 5G radio spectrum allocation in Slovenia[43]

5G			
FREQUENCY	**SPECTRUM**		
700 MHz FDD 2x30 MHz	703 MHz	733 MHz	uplink
	758 MHZ	788 MHz	downlink
700 MHz SDL	738 MHz	753 MHz	
1500 MHz SDL	1427 MHz	1517 MHz	
2100 MHz FDD 2x60 MHz	1920 MHz	1980 MHz	uplink
	2110 MHz	2170 MHz	downlink
2300 MHz TDD	2320 MHz	2390 MHz	
3600 MHz TDD	3420 MHz	3800 MHz	
26 GHz TDD	26.5 GHz	27.5 GHz	

Table 10: 4G radio spectrum allocation in Slovenia[44]

4G			
FREQUENCY	**SPECTRUM**		
800 MHz FDD 2x30 MHz	791 MHz	821 MHz	uplink
	832 MHZ	862 MHz	downlink
900 MHz FDD 2x35 MHz	880 MHz	915 MHz	uplink
	925 MHZ	960 MHz	downlink
1800 MHz FDD 2x75 MHz	1710 MHz	1785 MHz	uplink
	1805 MHZ	1880 MHz	downlink
2100 MHz FDD 2x60 MHz	1920 MHz	1980 MHz	uplink
	2110 MHz	2170 MHz	downlink
2100 MHz TDD 35 MHz	1900 MHz	1920 MHz	
	2010 MHz	2025 MHz	
2600 MHz FDD 2x70 MHz	2500 MHz	2570 MHz	uplink
	2620 MHz	2690 MHz	downlink
2600 MHz TDD 50 MHz	2570 MHz	2620 MHz	

[42] 5G smart. Radio network deployment options for smart manufacturing D1.4. (2020). Retrieved from: https://5gsmart.eu/wp-content/uploads/5G-SMART-D1.4-v1.0.pdf

[43] AKOS. Javni razpis za mobilna omrežja. (2020). Retrieved from: https://www.akos-rs.si/radijski-spekter/raziscite/javni-razpisi-za-mobilna-omrezja

[44] AKOS. 4G. (n.d.). Retrieved from: https://arhiv.akos-rs.si/4g

There is just preparation going on for a new tender with public auction for radio frequency bands 2300 MHz and 3600 MHz for local use. Buyer's obligation is to ensure coverage of 40 % of the population with each of the assigned frequencies in each municipality or 20 % of the territory in each municipality or 90 % of the area of its campus. Purpose of the tender is to ensure conditions for digitalization by cellular radios for business users and to follow the world's most developed countries in introducing Industry 4.0.

Table 11: Upcoming auction for 2300 MHz and 3600 MHz for local use[45]

UPCOMING AUCTION FOR 2300MHz and 3600MHz		
FREQUENCY	**SPECTRUM**	
2300 MHz TDD 20 MHz	2300 MHz	2320 MHz
2300 MHz TDD 10 MHz	2390 MHz	2400 MHz
3600 MHz TDD 10 MHz	3400 MHz	3420 MHz

Since all local mobile service providers have frequencies already dedicated for public network coverage, we can assume that these frequencies will be mostly used for industry.

7.3 Power regulation

7.3.1 4G transmitted output power

According to 3GPP TS 36.104 version 14.3.0 Release 14[46] there are four different types of antennas: Wide Area Base Stations, Medium Range Base Stations, Local Area Base Stations and Home Base Stations.

Table 12: 4G Maximum Base Station output power[46]

4G LTE RATED BASE STATION OUTPUT POWER		
TYPE OF ANTENNA	**MAXIMUM OUTPUT POWER**	**NOTE**
Wide Area Base Station	No upper limit	
Medium Range Base Station	≤ +38 dBm	
Local Area Base Station	≤ +24 dBm	
Home Base Station	≤ +20 dBm	one transmit antenna port
Home Base Station	≤ +17 dBm	two transmit antenna ports
Home Base Station	≤ +14 dBm	four transmit antenna ports
Home Base Station	≤ +11 dBm	eight transmit antenna ports

Use case for covering an area determines which antenna to use. According to name of the antennas, we can assume that:

[45] AKOS. Javni razpis z javno dražbo za dodelitev radijskih frekvenc v radiofrekvenčnih pasovih 2300 MHz in 3600 MHz za lokalno uporabo. (2022). Retrieved from: https://www.akos-rs.si/fileadmin/user_upload/dokumenti/Javna_posvetovanja_in_razpisi/2022/JAVNI_RAZPIS_Z_JAVNO_DRAZBO_ZA_DODELITEV.pdf

[46] ETSI. LTE; Evolved Universal Terrestrial Radio Access (E-UTRA); Base Station (BS) radio transmission and reception (3GPP TS 36.104 version 14.3.0 Release 14. (2017). Retrieved from: https://www.etsi.org/deliver/etsi_ts/136100_136199/136104/14.03.00_60/ts_136104v140300p.pdf

- Wide Area Base Stations are designed to cover large areas. Typically used for lower bands because of better coverage of lower frequencies.
- Medium Range Base Stations are designed for base stations in dense areas, typically operating on higher frequencies to cover larger areas in cities for example.
- Local Area Base Stations are appropriate for covering smaller areas, typically campuses, industrial environment, public areas, larger halls, etc.
- Home Base Stations as the name suggests, for home indoor use.

According to the use case or type of antenna, base stations need to have limited maximum output power. According to 3GPP TS 36.104 version 14.3.0 Release 14, maximum output powers for listed types of antennas are presented in Table 12.

If a base station is operating under normal conditions, the output power can deviate ±2 dB, if a base station is operating under extreme conditions, the output power can deviate ±2.5 dB from the value declared by the manufacturer.

7.3.2 5G transmitted output power

According to 3GPP TS 38.104 version 15.5.0 Release 15[47] describing the 5G Base Station power limitation, the output power is listed in the table below. Antenna types are the same as for 4G.

Table 13: 5G Maximum Base Station output power[47]

5G NR RATED BASE STATION OUTPUT POWER	
TYPE OF ANTENNA	**MAXIMUM OUTPUT POWER**
Wide Area Base Station	No upper limit
Medium Range Base Station	≤ +38 dBm
Local Area Base Station	≤ +24 dBm

The required level of isolation between the macro network and the factory network will be reduced if the factory network is able to sufficiently dominate the macro network, such as by raising the downlink and uplink transmission powers. Downlink transmission power is defined in 3GPP and consequently limited. By forcing the power control mechanism for UEs to be more intrusive, it can improve SNR. On the other hand, if a private network is planned with the mobile operator using telecom frequencies, there is no need to force UEs into aggressive mode of operation. The mobile operator will ensure that the private network will not interfere with public networks and vice versa. Correct radio planning and correct management of base stations is all that is needed.

[47] ETSI. 5G; NR; Base Station (BS) radio transmission and reception (3GPP TS 38.104 version 15.5.0 Release 15). (2019). Retrieved from: https://www.etsi.org/deliver/etsi_ts/138100_138199/138104/15.05.00_60/ts_138104v150500p.pdf

7.4 Antenna design and limitations

Choosing correct antenna design and appropriate placement of antenna into the environment is one of the most important steps when designing wireless radio communications. Appropriate receiving power must be available to the mobile device in order to provide reliable operation.

Landscape form and objects that represent obstacles to the radio waves propagation must be taken into account and carefully considered during radio planning. If antennas are covered by objects that do not allow radio waves to penetrate through, this causes signal shadowing, reducing reception quality.

By choosing the right antenna design, we can significantly influence the direction of radio waves propagation. In general, antennas are divided into the following major groups: non-directional antennas, directional antennas and beamforming antennas.

7.4.1 Non-directional antennas

Isotropic antenna is the mathematical definition of an antenna with no preferred propagation direction. In theory it radiates radio waves uniformly in all orientations. Regardless of the fact that it cannot be made in nature, it is used as a reference antenna for comparing all other real physical antennas. Real transmitting or receiving antennas have at least some direction of radio waves propagation. Direction of maximum propagation defines gain. Antenna gain describes how effective an antenna is in comparison to a reference source (isotropic antenna), in the direction of maximal radiation. It is expressed in Decibels relatively to isotropic antenna (dBi).

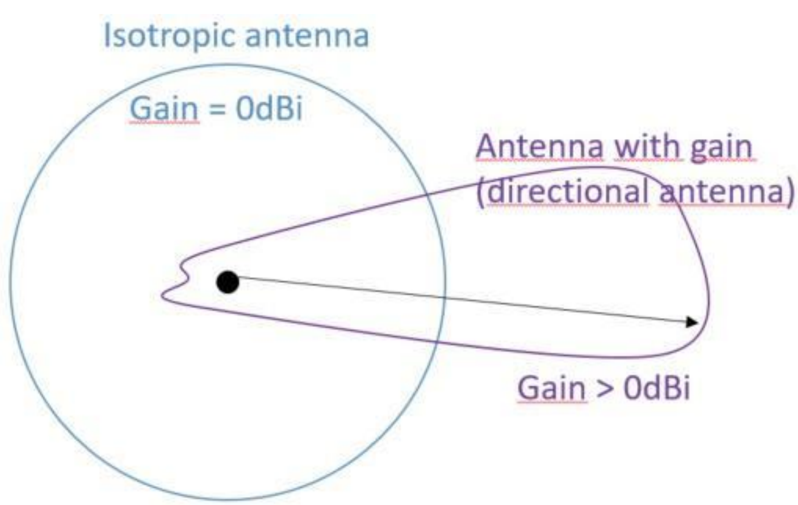

Figure 29: Isotropic antenna and antenna with gain

Omnidirectional antenna is an antenna that radiates radio waves equally in all directions of a plane. It radiates perpendicular to the placement of the two quarter wave rods.

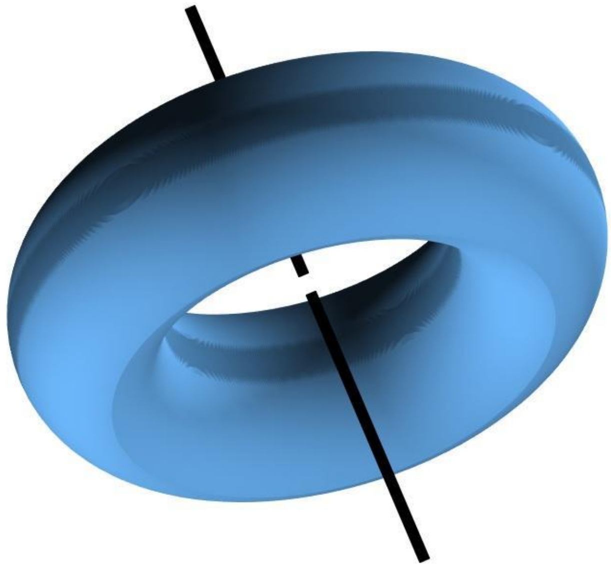

Figure 30: Omnidirectional antenna with low directivity with so called antenna lobe.

7.4.2 Directional antennas

Directional antennas are used for specific area covering. The most typical setup of the antennas for wide area coverage is using 3 antennas in 3 sectors. With mechanical changes to the antenna there is the possibility to influence the directive pattern or antenna lobe. It can be made more narrow or wide. Also the tilt of the lobe (direction in the elevation plane) can be adjusted. In the picture below, there are three antennas covering three sectors presented with corresponding lobe.

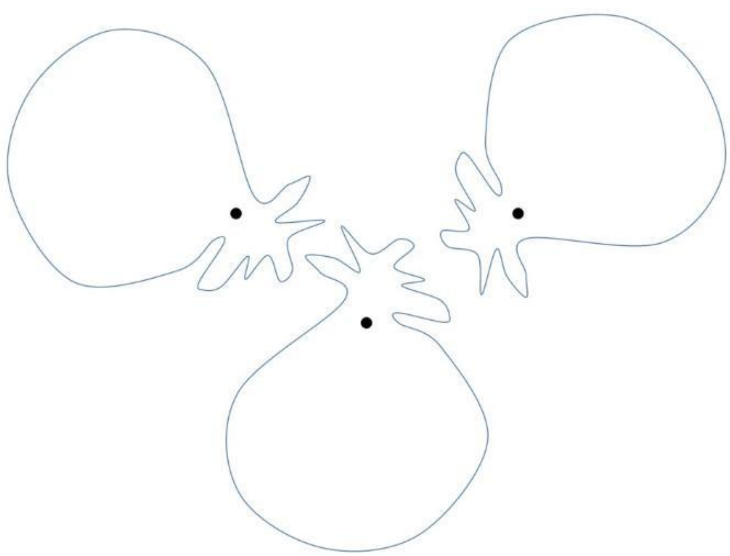

Figure 31: three sector antenna coverage

7.4.3 Beam forming antenna

There are three different types of beamforming antennas: digital, analog and hybrid beamforming[48]. Beamforming will have a positive influence reducing interference between cells and also interference between different networks. If the signal is more efficiently pointed to a UE it does not influence other mobile users since they are out of the main lobe of the antenna. Beamforming is resulting in much better quality of the receiving signal, improving the signal to noise ratio. Digital beamforming is presented in the picture below.

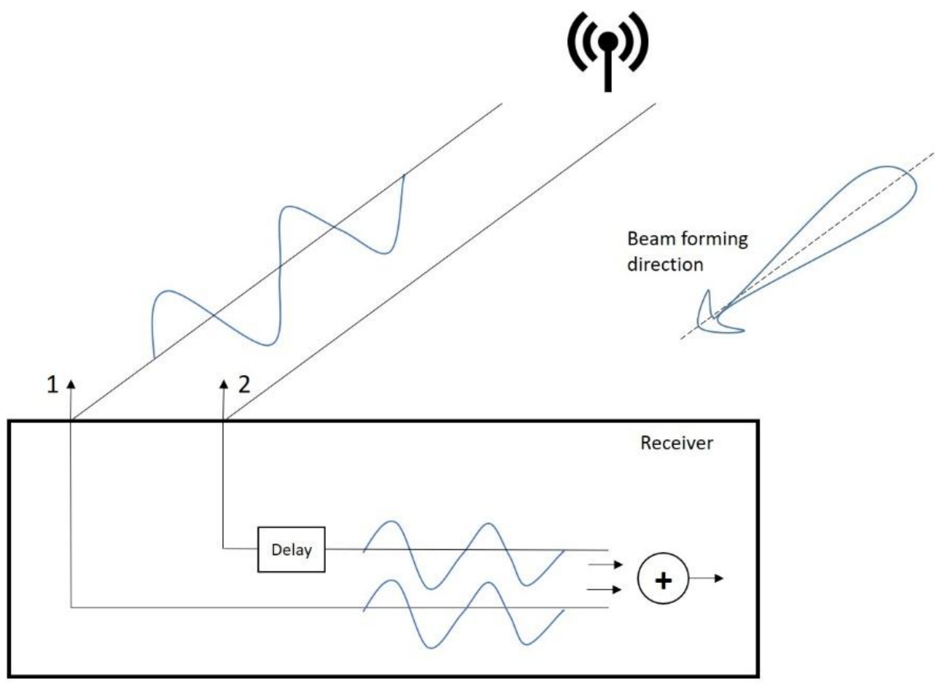

Figure 32: Digital beamforming

It is assumed that the transmitting station is far away, so incoming waves reaching the antenna are in phase looking perpendicular to lines to antenna 1 and antenna 2. Signal that is coming to the first antenna is a bit delayed compared to the signal from the second antenna. Inserting a tunable delay into antenna 2 circuit can make that outcoming signals from both antennas are in phase. That is how a digital beam towards a transmitting antenna can be formed. Changing the delay parameter makes the beam move according to the transmitting antenna direction. Analog beamforming is presented in the picture below.

[48] mmMAGIC. Millimetre-Wave Based Mobile Radio Access Network for Fifth Generation Integrated Communications (mmMAGIC). (2017). Retrieved from: https://ec.europa.eu/research/participants/documents/downloadPublic?documentIds=080166e5b35788bd&appId=PPGMS

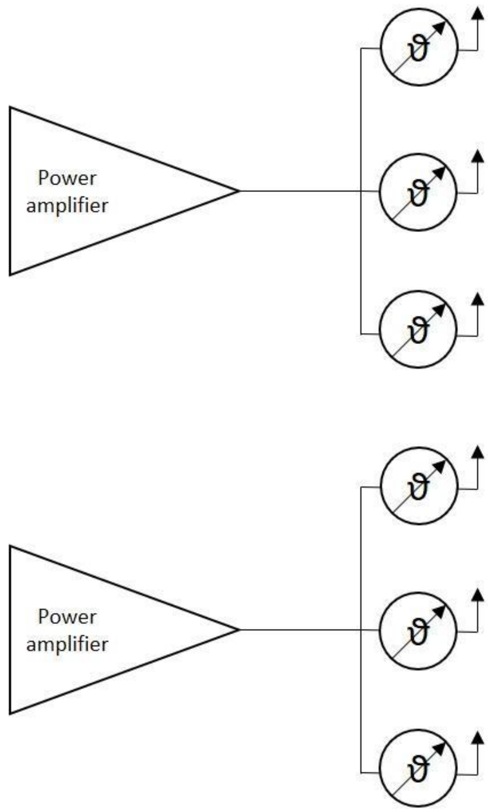

Figure 33: Analog beamforming

Beamforming can also be done by phase shifting of the signal just before entering a particular antenna inside an antenna array. By changing the phase of the signal, a beam is formed in a particular direction and it can be moved according to the device or base station. Especially at higher frequencies, when antenna elements become very small and it is hard to get desired gain from small elements it is absolutely necessary to use beamforming techniques to get maximum gain in the desired direction.

Hybrid antennas are just a mixture of both technologies and can form even higher and more direct beams.

According to practice the gain of antennas depends on antenna's purpose; whether it is for wide area, medium range or local indoor coverage. Most widely used antenna parameters are presented in table below.

Table 14: Expected antenna gain

5G AND 4G BASE STATION ANTENNA GAIN	
TYPE OF ANTENNA	**EXPECTED ANTENNA GAIN**
Wide Area Base Station	17 dBi
Medium Range Base Station	9 dBi
Local Area Base Station	0 dBi

7.4.4 5G UE power and gain limitations

3GPP specifies 4 different classes of UE, namely Power Class 1, Power Class 2, Power Class 3 and Power Class 4. UE classes are needed to ensure that the base station can communicate correctly with the UE. Power Class 1 devices are intended to be used for Fixed Wireless Access (FWA), which enables network operators to deliver ultra-high-speed broadband to homes and offices, and have the highest transmit power capability. Power class 2 is intended for vehicle communication (URLLC). Power Class 3 is the most standard class including handhelds. Power class 4 is foreseen to run high power non-handheld equipment (IoT). Frequency ranges are presented in table below.

Table 15: FR1 and FR 2 frequency ranges

Frequency Range 1 (FR1)	Frequency Range 2 (FR2)
410 MHz – 7.125 GHz	24.25 GHz – 71.0 GHz

According to standard specification 3GPP TS 38.101-1[49] maximum power and corresponding gain can vary as shown in Table 16. 3GPP TS 38.101-1 specifies just power classes to be used, Class 2 and Class 3 for FR1.

7.4.4.1 FR1 limitations

Limitations for 5G NR in FR1 are presented in table 16 below.

Table 16: Power limitations for 5G NR FR1[49]

5G NR Frequency range 1			
Power Class	**Maximum output power**	**Operating bands**	**Typical gain**
Power class 2	≤ +26 dBm	N41, N77, N78, N79	2 dBi
Power class 3	≤ +23 dBm	all FR1 bands	0 dBi - 2 dBi

7.4.4.2 FR2 limitations

3GPP TS 38.101-2[50] specifies the all four Power Classes for FR2 use.

Limitations for 5G NR in FR2 are presented in table 17 below.

[49] ETSI. 5G; NR; User Equipment (UE) radio transmission and reception; Part 1: Range 1 Standalone (3GPP TS 38.101-1 version 15.3.0 Release 15). (2018). Retrieved from: https://www.etsi.org/deliver/etsi_ts/138100_138199/13810101/15.03.00_60/ts_13810101v150300p.pdf
[50] ETSI. 5G; NR; User Equipment (UE) radio transmission and reception; Part 2: Range 2 Standalone (3GPP TS 38.101-2 version 16.4.0 Release 16). (2020). Retrieved from: https://www.etsi.org/deliver/etsi_ts/138100_138199/13810102/16.04.00_60/ts_13810102v160400p.pdf

Table 17: Power limitations for 5G NR FR2[50]

5G NR Frequency range 2		
Power Class	Maximum Radiated Power (TRP)	Maximum EIRP
Power class 1	≤ +35 dBm	≤ +55 dBm
Power class 2	≤ +23 dBm	≤ +43 dBm
Power class 3	≤ +23 dBm	≤ +43 dBm
Power class 3	≤ +23 dBm	≤ +43 dBm

7.4.5 4G UE power and gain limitations

According to standard ETSI TS 136 101[51] UE in 4G can operate as noted in the table below.

Table 18: Power limitations for 4G[51]

4G Frequencies			
Power Class	Maximum output power	Operating bands	Typical gain
Power class 2	≤ +26 dBm	B41, B47	2 dBi
Power class 3	≤ +23 dBm	all bands	0 dBi - 2 dBi

7.5 Wi-Fi 6 wireless part

7.5.1 Spectrum for Wi-Fi 6E and maximum power in EU

Different radio bands require different regulatory power limits. All values listed in Table 19 below are valid for Europe and are taken from standards published by the European Telecommunications Standards Institute (ETSI). All values for maximum transmitted power are given in Equivalent Isotopically Radiated Power (EIRP). EIRP is calculated using equation below:

$$EIRP = transmit\ power\ (dBm) + antenna\ gain\ (dBi) - cable\ loss\ (dB)$$

If a Wi-Fi transmitting antenna is using beamforming, then EIRP is calculated using equation below:

$$EIRP = transmit\ power\ (dBm) + antenna\ gain\ (dBi) + log\ (number\ of\ antennas)\ (dB) - cable\ loss\ (dB)$$

EIRP is the maximum radiated power that an antenna or antenna array can radiate given transmitter power from a power amplifier, antenna's gain. Cable loss must be subtracted.

We can assume that Wi-Fi manufacturers follow European standards for frequency range and maximum radiated RF power. Frequency ranges and corresponding EIRP for Wi-Fi 6E are represented in tables below. In general, Wi-Fi 6E can use four frequency bands, 2.4 GHz, 5 GHz, 5.8 GHz and 6 GHz.

[51] ETSI. LTE; Evolved Universal Terrestrial Radio Access (E-UTRA); User Equipment (UE) radio transmission and reception (3GPP TS 36.101 version 14.17.0 Release 14). (2021). Retrieved from: https://www.etsi.org/deliver/etsi_ts/136100_136199/136101/14.17.00_60/ts_136101v141700p.pdf

2.4 GHz Wi-Fi frequency range power limitations are presented in table below.

Table 19: Mean EIRP limits for RF output power at 2.4 GHz[52]

2.4 GHz		
	Frequency range (MHz)	Maximum transmit power (EIRP)
Transmit	2400–2483.5	≤ +20 dBm
Receive	2400–2483.5	

5 GHz Wi-Fi frequency range power limitations are presented in table below.

Table 20: Mean EIRP limits for RF output power at 5 GHz[53]

5 GHz				
	Frequency range (MHz)	Maximum transmit power (EIRP) with TCP	Maximum transmit power (EIRP) without TCP	Function
Transmit	5150-5350	≤ +23 dBm	≤ +20/ ≤ +23 dBm*	indoor
Receive	5150-5350			indoor
Transmit	5470-5725	≤ +30 dBm**	≤ +27 dBm**	indoor/outdoor
Receive	5470-5725			indoor/outdoor

* The applicable limit is 20 dBm, except for transmissions whose nominal bandwidth falls completely within the band 5150 MHz to 5250 MHz, in which case the applicable limit is 23 dBm.
** Slave devices without a Radar Interference Detection function shall comply with the limits for the frequency range 5250 MHz to 5350 MHz

5,8 GHz Wi-Fi frequency range power limitations are presented in table below.

Table 21: Mean EIRP limits for RF output power at 5.8 GHz[54]

5.8 GHz					
	Frequency range (MHz)	**Channel Width**	**Max power into antenna (dBm)**	**EIRP (dBm)**	**Function**
Transmit	5725-5875	10	≤ +27 dBm	≤ +33 dBm	indoor
Receive	5725-5875	10			indoor
Transmit	5725-5875	20	≤ +30 dBm	≤ +36 dBm	outdoor
Receive	5725-5875	20			outdoor

[52] ETSI. ETSI EN 300 328 V2.2.2 Wideband transmission systems; Data transmission equipment operating in the 2.4 GHz band; Harmonised Standard for access to radio spectrum. (2019). Retrieved from: https://www.etsi.org/deliver/etsi_en/300300_300399/300328/02.02.02_60/en_300328v020202p.pdf
[53] ETSI. ETSI EN 301 893 V2.1.1 5 GHz RLAN; Harmonised Standard covering the essential requirements of article 3.2 of Directive 2014/53/EU. (2017). Retrieved from: https://www.etsi.org/deliver/etsi_en/301800_301899/301893/02.01.01_60/en_301893v020101p.pdf
[54] ETSI. ETSI EN 302 502 V2.1.1 Wireless Access Systems (WAS); 5,8 GHz fixed broadband data transmitting systems; Harmonised Standard covering the essential requirements of article 3.2 of Directive 2014/53/EU. (2017). Retrieved from: https://www.etsi.org/deliver/etsi_en/302500_302599/302502/02.01.01_60/en_302502v020101p.pdf

6 GHz Wi-Fi frequency range power limitations are presented in table below.

Table 22: Draft mean EIRP limits for RF output power at 6 GHz[55]

6 GHz			
	Frequency range (MHz)	**Maximum transmit power (EIRP) LPI use**	**Maximum transmit power (EIRP) VLP use**
Transmit	5945-6425	≤ +23 dBm	≤ +14 dBm
Receive	5945-6425		

8 Identification of the exposure scenarios of private networks

8.1 Initiatives from industry

In this section, some real demonstrations of private LTE and 5G networks are presented, organized by industry segments. Examples are provided from across the globe, with a focus on Europe.

According to Statista Internet of Things, annual revenue worldwide will reach from 2019 – 388 billion U.S. dollars to 2030 – 1058.1 billion U.S. dollars. 197.8 billion U.S. dollars in 2030 just for Connected Vehicles.[56]

Many industries are already experiencing the benefits of wireless connectivity starting with 2G connecting low data rates devices. With 5G technology a complete ecosystem is available to industry 4.0.

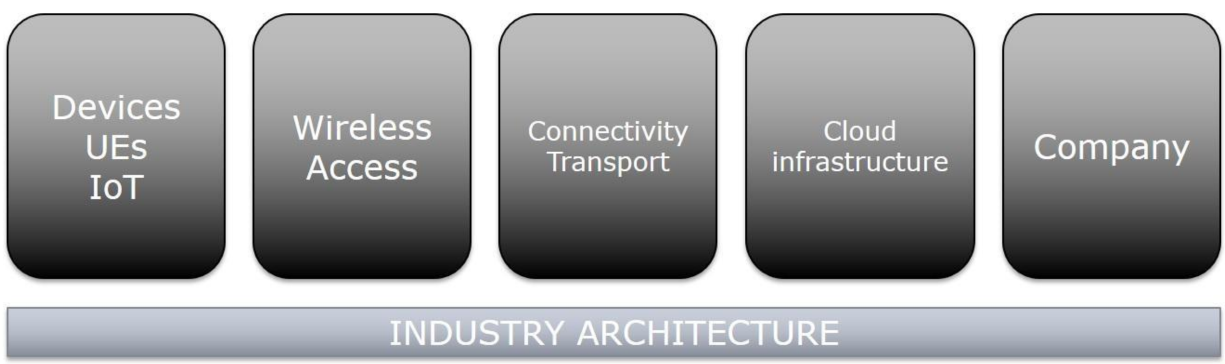

Figure 34: General Industrial case architecture

[55] ETSI. Draft ETSI EN 303 687 V1.0.0 6 GHz WAS/RLAN; Harmonised Standard for access to radio spectrum (2022). Retrieved from: https://www.etsi.org/deliver/etsi_en/303600_303699/303687/01.00.00_20/en_303687v010000a.pdf

[56] Statista. Internet of Things (IoT) total annual revenue worldwide from 2019 to 2030 (2020). Retrieved from: https://www.statista.com/statistics/1194709/iot-revenue-worldwide/.

The 5G Automotive Association (5GAA) was established in 2016 to unite automotive and telecommunication industries to set standards and develop end-to-end solutions for mobility in the future.[57]

Cooperative Intelligent Transportation Systems (C-ITS) is a service which offers better quality traffic information to transport systems for safety and energy saving. Main technologies for transport communications are vehicle-to-vehicle (V2V) communication, vehicle-to-infrastructure (V2I) communication, vehicle-to-network (V2N), and vehicle-to-pedestrian (V2P) communication. Generally known also as V2X communication (vehicle-to-everything). The 5GAA supports the idea that 5G will be the ultimate platform to enable C-ITS and the provision of V2X.[58]

The 5G Alliance for Connected Industries and Automation (5G-ACIA), established in 2018 with the purpose to make a bridge between Operational Technology (OT) and Information and Communications Technology (ICT). The ambition of 5G-ACIA is to introduce 5G technology to industries, especially in manufacturing and process branches. Key driver is to implement digital possibilities in order to push manufacturing and process towards industry 4.0.[59]

8.1.1 Manufacturing

Kista, Sweden – Ericsson Smart Factory[60,61,62]

As part of the 5G Smart project Ericsson and ABB built a 5G testbed to evaluate 5G private networks against the requirements of three industrial robotics' use cases:

1. 5G-connected robots and their collaboration

   For this use case a setup has been implemented where a mobile robot transfers an object, navigating the factory floor between stationary robots, and having one of the stationary robots grasp and move the object.

2. Vision-supported real-time human-robot interaction

   This use case is instantiated by a human worker programming a stationary robot to autonomously execute an object pick-and-place operation by demonstration. Instead of writing a robot program, the worker mimics grasping and moving the object using an application on a mobile device, which the stationary robot then executes.

3. Advanced visualization for the factory floor

   In this use case a technician on the factory floor uses an AR headset to display information on stationary and mobile robots by utilizing different gestures.

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[57] 5GAA https://5gaa.org/
[58] C-ITS https://www.car-2-car.org/
[59] 5GACIA https://5g-acia.org/
[60] https://5gsmart.eu/
[61] 5G-SMART – Deliverable 2.1 (https://5gsmart.eu/wp-content/uploads/5G-SMART-D2.1.pdf)
[62] 5G-SMART – Deliverable 2.3 (https://5gsmart.eu/wp-content/uploads/5G-SMART-D2.3-v1.0.pdf)

The deployed network uses the 5G non-standalone architecture on a FR2 frequency band. More specifically, the Ericsson Radio Dot System is used for the 4G LTE anchor (uplink on 1780.1 – 1785.0 MHz and downlink on 1875.1 – 1880.0 MHz). The 5G NR is implemented in the mmWave spectrum, in the range of 27.5 – 27.9405 GHz, using 200MHz of bandwidth and TDD. The robots are connected to WNC 5G packet routers which support both 4G and 5G wireless connectivity. Network equipment, such as Baseband Unit, core network, switches, a firewall, local Edge cloud computing resources, etc., is installed in a 19” cabinet.

Figure 35: Overview of the 5G network

The 4G Radio Dot is installed on the ceiling to cover the complete testing area, where the robots are deployed. The 5G mmWave radio is wall-mounted and similarly covers the testing area. The base stations are connected to a local 5G core network. The core network is co-located with the Edge cloud platform and installed nearby the testing area and the radios.

Sindelfingen, Germany – Mercedes-Benz Factory 56[63,64]

Ericsson and Telefónica Germany built a 5G Private network for Mercedes-Benz at the company’s Factory 56 plant in Sindelfingen. The network has been deployed to facilitate data linking or product tracking on the assembly line. The 5G private network in conjunction with a high-performance WLAN provides the basis to support modern Industry 4.0 applications and digital production technologies. With digital tracking of each vehicle on the production line via a positioning system the vehicle data that are relevant to the employees are displayed on the line in real time, using digital devices and display screens making the factory completely paperless. Machines and production equipment are interconnected throughout the entire factory.

[63] https://www.ericsson.com/en/news/2019/6/mercedes-benz-ericsson-and-telefonica-5g-car-manufacturing
[64] https://group.mercedes-benz.com/innovation/digitalisation/industry-4-0/opening-factory-56.html

Wolfsburg, Germany – Volkswagen HQ plant[65,66]

Nokia deployed a 5G Standalone Private Network at Volkswagen HQ plant, providing coverage to the production development center and pilot hall. Volkswagen intends to test the new network on use cases such as wireless upload of data to manufactured vehicles and intelligent networking of robots and wireless assembly tools. The network is operating in the dedicated 3.7-3.8 GHz band for local private wireless networks that Volkswagen applied for and was allocated by the Federal Network Agency.

Loutraki, Greece – Calpak[67]

Cosmote (Greek MNO) in partnership with Ericsson deployed an LTE Private network at Calpak's fully automated solar water heater production facility. The network utilizes licensed spectrum providing excellent security and highly reliable services that perform well even under heavy data loads. COSMOTE integrated the plant's connected robotic arms, as well as an Industrial IoT (IIoT) and Augmented Reality (AR) platform into this network. Using machine learning algorithms and data analytics procedures, critical data from the robotic arms are collected in near real-time and utilized for providing a series of innovative applications. These include production monitoring from anywhere, the introduction of predictive maintenance processes, and remote expert guidance in the event of production line malfunctions.

Lewisville, Texas, USA - Ericsson[68,69]

Ericsson deployed a 5G smart factory in Lewisville, Texas, USA. The factory was identified by the World Economic Forum as a pioneer of Industry 4.0. By using the fast and secure 5G connectivity, 25 different use cases were developed. Some of the factory's key use cases along with their potential applications are highlighted in Table 23.

Table 23: Ericsson USA 5G Smart Factory use cases and their potential applications

Use case	Potential applications
energy monitoring and management	manufacturing, agriculture, retail & smart buildings
AR for remote support	manufacturing, energy & utilities, healthcare
digital adherence for safety and quality	manufacturing, energy & utilities, healthcare
end-to-end digital thread for radio production	manufacturing, healthcare
automated unpacking process	manufacturing, agriculture
ML based visual inspection	manufacturing, energy & utilities

65 https://www.rcrwireless.com/20211206/5g/nokia-deploys-5g-private-network-at-volkswagen-plant-in-germany
66 https://www.nokia.com/about-us/news/releases/2021/12/06/nokia-deploys-5g-private-wireless-network-for-volkswagens-pilot-project-in-germany/
67 https://www.cosmote.gr/cs/otegroup/en/smart_manufacturing.html
68 Wen M., Li Q., et al., "Private 5G Networks: Concepts, Architectures, and Research Landscape". *IEEE J. of Selected Topics in Signal Processing*. vol. 16, no. 1, pp.7-25, Jan 2022, DOI:10.1109/JSTSP.2021.3137669.
69 https://www.ericsson.com/en/about-us/company-facts/ericsson-worldwide/united-states/5g-smart-factory

Compared with a traditional factory, the 5G smart factory with more than 200 robots in operations is featured by 120 % improved output per employee and 65% reduction in manual material handling.

Tokyo, Japan - Mitsubishi Electric Corporation[70]

Mitsubishi Electric Corporation has verified wireless transmission between local 5G base stations and Mitsubishi Electric's FA products. The demonstration test was based on a local 5G system which Japanese government licensed for use in a limited area and operated at the band, 28.2-28.3 GHz. In the coming future, the company expects to deploy local 5G systems to deliver new services and businesses incorporating a wide range of Factory Automation (FA) and other products. It will also help to confirm various possible uses of envisioned local 5G systems, such as remote operation and maintenance support and usage of augmented and virtual reality for enhanced work efficiency, and more.

In addition, on June 28, 2021, Mitsubishi Electric Corporation announced that it would begin operating the 5G OPEN INNOVATION Lab™ to collaborate with customers and partner companies on research and test demonstrations of "local 5G" private mobile communication systems[71]. The lab's 4.8 GHz-4.9 GHz test environment is used to research and demonstrate solutions for specific business, etc. needs from initial stages. In particular, they will perform comparative verifications of local 5G and other wireless methods, such as Wi-Fi 6 and private LTE, to determine the best communication method for each application and purpose.

Worcestershire, UK – Mettis Aerospace[72,73]

Mettis Aerospace, a U.K. company that designs, manufactures, and assembles precision forged and machined components primarily for the aerospace and defense industry, partnered with Wireless Broadband Alliance (WBA) to conduct a Wi-Fi 6 Industrial Enterprise and IoT trial. The trial took place at the company's 27-acre facility with the objective to evaluate whether Wi-Fi 6 technology can provide total connectivity across the factory floor and enable improved synchronization of factory floor machinery and equipment with centralized monitoring and control systems. The following tests were carried out to assess the Wi-Fi 6 network's performance:

- 4k streaming from a webcam mounted on machinery within the factory
- 4k YouTube streaming
- Uploads of very large video files
- Roaming, Latency and persistent connectivity during video calling

[70] https://emea.mitsubishielectric.com/en/news/releases/global/2020/0518-a/pdf/200518-a_3353_en_g.pdf
[71] https://www.mitsubishielectric.com/news/2021/0628.html
[72] https://wballiance.com/wireless-broadband-alliance-members-successfully-complete-first-phase-wi-fi-6-industry-4-0-trials-with-mettis-aerospace/
[73] https://www.landmobile.co.uk/news/wba-completes-wi-fi-6-industry-4-0-trials-first-phase/

- Augmented reality testing of machinery

The tests were considered successful in terms of performance, reliable connectivity, and consistent coverage. Speeds reached 700 Mbps using 80 MHz channels and the average latency was less than 6ms while the maximum observed latency was 11ms.

8.1.2 Mining

Chalkidiki, Greece – Hellas Gold Kassandra Mines[74]

Cosmote (Greek MNO) has deployed a private LTE network in an underground mine in Olympiada, Chalkidiki. The network is installed at a depth of 300 m below ground level, providing cellular coverage to 10 km of tunnels. Using tablets, workers, machinery operators, and drivers working underground can reliably communicate with the Control Center at the surface where all operations are supervised and coordinated. This results in increased uptime as shifts, production and fleet management are organized more efficiently. In addition, critical operational data such as the type and weight of ore during loading, possible machinery failures, etc., are transferred in real time. The company has plans to further utilize the campus network by developing new applications and technologies that will enable features like remote mining, remote loading control and vehicle telemetry. Additionally, through a gas monitoring sensor network that will be deployed in the mine, the Control Center will be able to adjust the air supply or even to withdraw underground workers.

Zinkgruvan, Sweden - Zinkgruvan Mining[75,76]

Swedish mobile network operator, Telia and mobile core network provider Athonet have deployed a private LTE network, upgradeable to 5G, for the Zinkgruvan Mining Company in Sweden. The network was designed to offer high performance, reliability, and accessibility to the mine's entire area comprising 48 km of tunnels and transport routes down to a depth of 1300 meters. The benefits of the deployment include:

- Remote control mining
- Through reliable broadband video and telemetry mining equipment (haulers, excavators etc) can be remotely controlled from a secure, above ground control-room, increasing operators' safety.
- Automation
- Massive deployment of sensors with backhaul or direct communications over LTE can enable the automation and digitalization of crushing, processing and extraction plants, movable machinery and haulage equipment.
- Real-time inspection
- Inspection in the field can be enhanced by AR applications using LTE for backhaul.
- Environmental optimization

[74] https://www.kathimerini.gr/life/environment/561960667/to-proto-exypno-metalleio-stin-ellada-apo-tin-ellinikos-chrysos-kai-tin-cosmote/ (in Greek)
[75] https://athonet.com/use-cases/driving-reliable-communications-deep-underground-with-private-lte/
[76] https://business.teliacompany.com/blog/zinkgruvan-mine-gets-its-own-cellular-network---1km-underground

- Monitoring employees' and machines' location the company can optimize air conditioning, heating, and other environmentally sensitive operations accordingly.
- Health and safety
- Reliable video communications support remote incident analysis in case of accidents.
- Improved surveillance
- Video surveillance via drones and stationary cameras can improve perimeter and spatial security.

Quebec, Canada - Agnico Eagle[77]

Agnico Eagle, a senior Canadian gold mining company, needed to improve voice and data communications between workers and equipment deep underground, and operations staff on the surface. Working with its partner, Ambra Solutions, and leveraging radio technology from Ericsson, Agnico Eagle deployed a first-of-its-kind private LTE network 3.2 kilometers beneath the earth's surface—the deepest in the world. As a result, the company improved safety and work experience for miners, enabling them to stay connected with colleagues and family above ground. Agnico Eagle is also able to continuously track the precise location of people, vehicles, and machinery to prevent dangerous situations. Additionally, the company gained remote operating capabilities and intelligent environmental monitoring, improving mine efficiency and productivity, advancing its sustainability objectives, and helping to lower costs.

Ericsson software supports LTE Radio Access Network, Massive IoT (LTE-M/NB IoT) and is upgradable to 5G NR.

High bandwidth and low latency are among the solution advantages, which supports voice, mission-critical push-to-talk (MC-PTT), autonomous machines, remote control, predictive maintenance and environmental sensing. The system is also cost-efficient, requiring a factor of 10 fewer communication nodes to cover the same area compared to Wi-Fi.

Shanxi province, China - Yangquan Coal Group[78]

China Mobile, Yangquan Coal Group, and Huawei built China's lowest underground 5G network at Xinyuan Coal Mine in Shanxi province. The private 5G network is located as deep as 534 meters underground and achieves an upload speed of more than 1000 Mbps. Based on the 5G network, a 5G smart coal mine was launched and three 5G-enabled unmanned applications were developed to inspect electromechanical chambers, operations on the coalface, and comprehensive mechanized coal mining operations. These applications reduce workers' workloads and improve their security.

China Mobile also built an internet data center (IDC) room in the underground lanes to offer low-cost, safe and reliable data center service.

[77] Agnico Eagle case: Making underground mining safer and more efficient, © Ericsson May 2022, Rev. 1 (https://www.ericsson.com/49bb18/assets/local/cases/customer-cases/2022/agnico-eagle-case-study.pdf)
[78] http://en.sasac.gov.cn/2020/06/24/c_5145.htm

8.1.3 Electric Utilities

Sao Paulo, Brazil – Elektro[79,80]

Nokia deployed a private LTE network for the Brazilian electric power distributor, Elektro. The network operates in the 400MHz and 3.5GHz frequency bands and provides wireless connectivity for grid equipment, smart meters, substations, and distributed energy generation sources throughout Sao Paulo, enabling grid automation through real-time exchange of information between these devices and Elektro's operations center. In its first phase the network provides connectivity for 78,000 smart meters, 1,300 load balancers and 850 concentrators, serving 75,000 homes and businesses. All connected equipment can be managed through a single dashboard making operations more efficient.

Georgia, USA – Southern Linc[81]

Southern Linc provides the mission-critical wireless network used to help keep Southern Company's electric utilities up and running. Southern Linc partnered with Ericsson to build the first dedicated mission-critical LTE network in the U.S. Today, this 4G LTE Advanced network enables Southern Linc to deploy new applications and solutions 80 % faster than in the past. Moreover, the LTE network scales to handle 100 times more data at speeds up to 1,000 times faster than was possible on the iDEN (Integrated Digital Enhanced Network) network that was previously used.

8.1.4 AirPorts

Hamburg, Germany – Lufthansa Technik[82]

Lufthansa Technik, a subsidiary of the Lufthansa Group, which provides worldwide maintenance, repair, and overhaul (MRO) services for aircraft, engines, and components, purchased a ten-year license for the 3.7 – 3.8 GHz band from the German Federal Network Agency and deployed a private 5G network at its headquarters in Hamburg airport. The company uses the 5G private network to provide virtual engine parts inspection and digital borescopes for its civil aviation customers over fast, reliable, high-definition video streams. The company's customers can therefore interact remotely with the mechanics on site and make important repair decisions without having to travel to Hamburg.

[79] https://enterpriseiotinsights.com/20181016/channels/news/nokia-gets-brazilian-private-lte-gig
[80] https://pages.nokia.com/T003AH.Iberdrola.elektro.case.study.html
[81] "Southern Linc case: Assuring communications when the power goes out", © Ericsson Jan. 2022, Rev. 1 (https://www.ericsson.com/496e32/assets/local/cases/customer-cases/2022/southern-linc---ericsson-case-study.pdf)
[82] https://www.lufthansa-technik.com/press-releases/-/asset_publisher/Xix57wMv0mow/content/pressrelease_5g-extension-ham?_101_INSTANCE_5cSbhaGarZET_redirect=%2Fmedia

Paris, France – Group ADP[83]

Hub One Digital Technologies, subsidiary of ADP Group, deployed a private network to support the 120,000 employees who work at Charles de Gaulle (CDG), Orly, and Paris–Le Bourget, three of the four airports in the Paris area. The LTE private network operates in licensed spectrum purchased by the French government and in particular Band 38 (2570-2620 MHz). One hundred macro and small cell radios have been installed outdoors and over 1,000 for indoor coverage. The network supports mission critical push-to-talk (PTT) service as well as instant messages, video calls, data sharing between departments and automatic notifications improving airport safety and security and enhancing technical intervention (plane refueling, baggage handling, data retrieval, etc.). Hub One eventually plans to upgrade the network to 5G which will enable the implementation of new services such as the rapid download of flight data upon landing of the aircraft, the use of augmented reality in remote maintenance and the deployment of autonomous vehicles.

8.1.5 Ports

Koper, Slovenia

The port of Koper is an important port for central Europe with access to the Adriatic and Mediterranean. The port area consists of 274 hectares of land, with 50.7 hectares of warehouses and 109 hectares of open-air storage areas.

Figure 36: Koper Port in numbers (2019)[84]

[83] https://www.fiercewireless.com/private-wireless/private-network-connects-french-airports

[84] 5G-LOGINNOV. Deliverable 1.1 5G-enabled logistics use cases. (2021). Retrieved from: https://5g-loginnov.eu/library/

As part of a Horizon project 5G-LOGINNOV[85] Port of Koper is establishing a Living Lab targeting implementation of novel 5G technologies (Management and Network Orchestration-based services and network orchestration, Industrial IoT, artificial intelligence/machine learning based video analytics, drone-based security monitoring etc.) and cutting-edge prototypes tailored to be operated in port environments. Also, 5G capabilities and services under test (e.g. eMBB, mMTC, MEC, the use of drones) represent an add-on to the existing port infrastructure and complement the overall service portfolio, not substituting any of its vital parts. Technical teams responsible for operation of existing port infrastructure will be involved in planning, deployment and integration activities in order to ensure minimum or no negative effects of the newly introduced technology into the established port environment and to get operational insight into novel 5G technologies. Private 5G-based mobile services provided by the national MNO (Mobile Network Operator), tailored to the needs of port operation, will be provisioned and operated over the public MNO infrastructure.

Dedicated private mobile system that will be built as standalone and self-operated 5G network and services platform infrastructure.

To support use case operation, two concurrent scenarios will be supported. In the case of logistics and port operation support scenario, operating port ship to shore cranes will be equipped with industrial cameras for capturing and transfer of UHD streams to the cloud-based video analytics system. Each targeted crane will have up to 5 cameras installed and connected to the 5G network, so 5 different angled images will be received from each container in real-time. Captured video streams from cameras will be transferred in real time over the deployed 5G network in the Living Lab Koper to the video analytics platform, where a streaming management module will identify and prepare video streams to be processed by the markers' detection and damages' detection modules.

Markers' detection module will first identify the area containing text in the image; second, an Optical Character Recognition will identify which characters are part of the text, and third, to differentiate the marker from the other texts in the container, a semantic layer will be included. Damages' detection module will detect if the container is damaged, and where the damage is present (5 streams per container will be available). To automate the detection process, Deep Learning models will be applied to detect damages in the containers. These models will be trained with real images extracted from the scenario, where damages will be annotated in order to be considered for the detection.

As part of the use case, telemetry data will be collected from some of the vehicles (e.g. terminal tractors) that operate within Living Lab Koper. This information will be collected from the vehicle CAN-Bus, using the 5G-enabled IoT Device, and transmitted via the 5G network, to the backend installed within the internal IT infrastructure. The telemetry data gathered by the IoT device is dependent on the type of vehicle/equipment being monitored. Typical data to be collected

[85] https://5g-loginnov.eu/

include vehicle position, battery level, fuel level and consumption, oil level, tire pressure. Results of the telemetry data gathered by the device will be analyzed and computed, stored in a local database, and will be available to be used by other port operating support systems in the Living Lab Koper.

Hamburg, Germany - Hamburg Port Authority[86]

Nokia collaborated with the Hamburg Port Authority (HPA) and Deutsche Telekom on a successful 5G field trial at the Port of Hamburg in Hamburg, Germany's largest port and the third largest container port in Europe.

The Port of Hamburg is a complex and dense collection of transport networks, which includes waterways, roads, 118 bridges, and 300 km of railways. The HPA needs to manage and monitor all these assets in an efficient way. It is noted that by 2025, the port is expected to grow to approximately 18 million containers/year, tens of thousands of trucks/day including self-driving and remote-controlled vehicles, and approximately 100,000 mobile sensors.

The installed telecommunications network was comprised of 350 km of fiber and a mix of radio technologies used for nautical operations, public LTE, and Wi-Fi for indoor usage in its office buildings (LoRa LPWAN IoT). However, since these technologies use license-free sub-gigahertz frequencies, they do not offer guarantees regarding interference and QoS and were hence considered as insufficient solutions for supporting use cases which require service level agreements (SLAs). Network slicing, as a core feature of 5G mobile networks, is thus needed for those specific applications and guarantee the required network quality. The three features of the 5G spectrum

- Ultra-Reliable and Low Latency Communications (URLLC),
- Enhanced Mobile BroadBand (eMBB) and
- Massive Machine Type Communication (mMTC),

that are needed for each of the use cases tested in the trial, are indicated in Table 24, along with their characteristics concerning slicing, latency and jitter.

The 3 partners deployed a 5G network as a proof of concept (testbed) part of the European funded research project 5G-MoNArch. All network slices used the same 5G radio infrastructure: Two base stations were deployed with one antenna each using a 10 MHz FDD carrier at 700 MHz. The antennas were mounted at an elevation of 180 m above ground, in order to guarantee a good coverage of the port area. These base stations were then connected to a local data center of DT in Hamburg located about 3 km from the port, as well as to a regional data center 500 km away in Nuremberg. The slices requiring low latency rely on the local data center, while slices with higher performance but less strict latency requirements were deployed at the regional data center. Low latencies of less than 20ms could be achieved. Latency results varied according to

[86] https://pf.content.nokia.com/t004f5-private-wireless-ports/use-case-5G-smart-sea-port

how close to the edge the used data center is. In any case, the local data center is also important not only to maintain low latencies, but also to keep the sensitive data on premise.

Table 24: Testbed use cases and respective requirements

Use cases/requirements	Slicing	Latency	Jitter
Sensors installed on mobile barges (mMTC)	important	not important	important
HoloLenses – AR and video streaming (eMBB)	important	very important	occasionally acceptable
Traffic Light (URLLC)	very important (slice isolation)	very important	important

8.1.6 Warehouse

Georgia, USA – US Department of Defense[87]

The US Department of Defense developed a smart warehouse at the Marine Corps Logistics Base in Albany, Georgia, using a private 5G wireless network with the technical assistance of Cisco and other technology companies. The private 5G wireless network uses CBRS and millimeter wave spectrum. The framework triggers plenty of smart use cases, including

- robotics,
- barcode scanning,
- holographic and
- AR/VR.

These applications improve operations and increase efficiencies in storage, inventory control, maintenance, and auditing.

[87] Wen M., Li Q., et al., "Private 5G Networks: Concepts, Architectures, and Research Landscape". *IEEE J. of Selected Topics in Signal Processing*. vol. 16, no. 1, pp.7-25, Jan 2022, DOI:10.1109/JSTSP.2021.3137669.

9 Literature review on EMF exposure assessment of the workers in Industry 4.0

Wireless communication is essential for the Smart Factory and Industry 4.0 because it enables seamless, pervasive, and scalable connectivity among machines, people, and sensors as well as with mobile entities such as mobile robots, automated guided vehicles (AGVs), drones, and humans.[88]

Although the journey towards private (5G) networks in Industry 4.0 has already begun, there have been very few reported papers on EMF exposure assessment of the workers. This shortage of reporting has led to incomplete data with effects that are often anecdotal and notably, not thoroughly tested. There are only a few papers published in peer-reviewed academic journals, conference reports or written as academic working papers exploring the health risk assessment when implementing private networks/5G technologies in Industry 4.0.

We reviewed the existing literature regarding EMF exposure studies related to Industry 4.0. These studies can be categorized according to device type, type of antenna and operation mode (beamforming, MIMO), operating frequency (sub 6 GHz or mm-wave frequencies), distance to the transmitting antenna, and environment. Furthermore, deterministic as well as stochastic exposure studies are found in literature.

9.1 Exposure guidelines, standards and methodologies

To protect against established adverse health effects from exposure to radiofrequency electromagnetic fields, international bodies, such as the International Commission on Non-Ionizing Radiation Protection (ICNIRP) and the Institute of Electrical and Electronic Engineers (IEEE) developed exposure guidelines[89,90]. In Europe, the European Commission has set recommendations for the general public[91] and a binding regulation (EU Directive) for occupational exposure to RF fields[92]. Both of them are based on the ICNIRP 1998 EMF

[88] 5G-ACIA, 5G for Industrial Internet of Things (IIoT): Capabilities, Features, and Potential 5G Alliance for Connected Industries and Automation 5G-ACIA White Paper. (n.d.).

[89] International Commission on Non-Ionizing Radiation Protection (ICNIRP). (2020). Guidelines for Limiting Exposure to Electromagnetic Fields (100 kHz to 300 GHz). Health Physics, 118(5), 483–524. https://doi.org/10.1097/HP.0000000000001210

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[91] The Council of The European Union. (1999). COUNCIL RECOMMENDATION of 12 July 1999 on the limitation of exposure of the general public to electromagnetic fields (0 Hz to 300 GHz) (1999/519/EC). Official Journal of the European Communities, L199, 59–70.

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guidelines[93]. Within the European Union, countries can set more strict exposure limits than recommended by the European Commission.

An enabling technology in Smart Factory and Industry 4.0 is the Internet-of-Things (IoT). IoT interconnects physical objects (IoT devices) to exchange data with each other and with systems over the internet or communication networks. Depending on the application, the wireless communication range of an IoT device might be short (less than 1 km) or long (greater than 1 km) and operating frequencies span radio frequencies as well as millimeter wave frequencies. To assist in the exposure assessment of IoT devices, the IEEE has published a guide for EMF exposure assessment of IoT technologies and devices[94]. The IEEE guide provides flow charts of the exposure assessment paths for devices and population of devices; and identifies gaps in compliance standards with respect to exposure assessment of IoT devices.

In the ICNIRP 2020 guidelines, the absorbed power density (APD) averaged over 4 cm^2 for frequencies above 6 GHz was introduced as the quantity for the basic restriction. Current dosimetric measurement setups are designed to evaluate peak spatial averaged SAR over 1 g or 10 g for frequencies up to 6 GHz. Lee et al[95] investigated if the APD averaged over 4 cm^2 could be derived from the measured peak spatial averaged SAR over 8 g or 10 g. With deviations of less than 0.44 dB, they stated that APD can be calculated from the 8 g or 10 g SAR for frequencies between 6 GHz and 10 GHz.

Ziane et al[96] explored a novel technique to assess the absorbed power density (APD) in the near field accounting for antenna/body coupling above 6 GHz. This method uses a semi-transparent skin-equivalent structure optimized to reproduce the reflection coefficient from human skin at one interface and providing the possibility to sense the field at the opposite interface. The APD is retrieved from the tangential component of the E-field vector at the phantom interface opposite to the wireless device under test. They obtained a very good agreement between the reconstructed and simulated APD induced by a 16-element patch antenna array and a conical

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horn antenna (maximum relative differences for the APD peak, averaged over 1 cm^2, and 4 cm^2 are 3.62 %, -6.28 %, and -5.65 %, respectively).

9.2 Mobile devices

The variety of communication devices found that employ 5G for communication networks for Industry 4.0 ranges from mobiles, VR headset, IoT devices for monitoring, etc.

Sacco et al[97,98] studied the influence of aging and textile on the power deposition and body heating in a skin-equivalent model due to near-field exposure by a representative multi-beam radiating structure at 26 GHz and 60 GHz. They found that the absorbed power density (APD) increased with age. The highest value is observed for seniors (+8.8 % at 26 GHz and +6.9 % at 60 GHz with respect to the reference value at 35 year) and the lowest for youth (−4.5 % at 26 GHz and −3.7 % at 60 GHz) with a plateau between roughly 20 and 50 years. When considering the presence of a textile, the APD can increase or decrease depending on the textile thickness and permittivity as well as on the thickness of the air gap between the textile and skin. For cotton and wool, the maximum increase of the APD compared to the bare skin was about 40 %. For plane wave exposure, they found that a textile in contact with skin increases the absorbed power density up to 41.5 % and 34.4 % at 26 GHz and 60 GHz, respectively. The textile can act as a matching layer and maximize the absorption. Considering also the presence of an air gap between the textile and skin, the EM power deposition in the human tissues can decrease or increase, depending on textile complex permittivity and on the thicknesses of the air gap and textile. textile in contact with skin increases the steady-state temperature rise up to 52 % at 26 GHz and 46 % at 60 GHz. In the presence of an air gap between textile and skin the temperature variations range from −3.5 % to 20.6 % at 26 GHz and from −11.1 % to 20.9 % at 60 GHz.

Zradziński et al[99] evaluated the absorption in a user 's head of an electromagnetic field (EMF) emitted by the Wi-Fi and/or Bluetooth module of a wearable small Internet of Things (IoT) electronic device (emitting powers of up to 100 mW) using a meandered inverted F antenna (MIFA) and ellipsoidal head model. They concluded that only wearable IoT devices (similar in construction and way of use to the investigated device) emitting at below 3 mW EIRP from Wi-

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Fi/Bluetooth communication modules may be considered environmentally insignificant EMF sources.

Gallucci et al[100] determined the exposure of a male human model to the EMF emitted by a patch wearable antenna tuned at a frequency of 26 GHz in terms of the absorbed power density averaged over 4 cm^2. For an input power of 1 W, they observed a peak absorbed power density equal to 27.7 W/m^2, but only 0.2 % of the data is higher than the 90 % of the peak value.

9.3 Small cell base stations

Bonato et al[101] investigated the local peak SAR over 10 g (SAR10g) in the head of a user exposed to a uniform planar array operating at 3.7 GHz and 14 GHz. They found that the highest peak SAR10g was observed when the uniform planar array was placed laterally to the head (0.195W/kg and 0.223 W/kg for adult and child head models and an input power of 100 mW, respectively).

Baily et al[102] provided a brief overview of small-cell exposures at millimeter wave frequencies. They calculated typical far-field exposure from a 60 Watt ERP 5G source at 39 GHz mounted on a pole 25 feet above ground and found that the calculated exposure at 50 feet is 0.7 % of the FCC's standard (i.e., FCC's maximum permissible exposure limit on power density of exposures of the general public (1 mW/cm^2) between 1.5 GHz and 100 GHz) directly in the main beam of the antenna, assuming all transmitted power is focused in a single direction.

Shikhantsov et al[103] investigated statistically massive MIMO exposure at 3.5 GHz using a Maximum Ratio Transmission precoding scheme in the downlink from a 36-element antenna array in an industrial indoor environment. They found that most of the massive MIMO DL exposure was produced in the vicinity of the UE as they observed an enhancement of the time-averaged Poynting vector by 10 dB at the location of the receiver. In addition, they found that the peak spatial-averaged SAR in 10 g in the phantom's head was directly proportional to the hot-spot power flux density and that the normalized peak spatial-averaged SAR in 10 g complied with the ICNIRP basic restrictions.

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Tognola et al[104] used machine learning to estimate the electric field exposure in complex indoor scenarios. They designed a neural network to assess the exposure from multiple WiFi sources at 2400 MHz in a complex indoor scenario. The exposure included both DL (from access points) and UL exposure (from several clients, such as laptops, printers, tablets, and smartphones).They stated that neural networks might be successfully applied to estimate the field exposure in a multi-source WiFi indoor scenario as the median prediction accuracy of the 'target' field exposure by the proposed neural network was 0.0 dB with a root mean square error of 2.1 dB.

Vermeeren et al[105] evaluated the exposure to electromagnetic fields from fixed wireless access (FWA) points at 60 GHz by a generic 8x8x phased array. Fixed wireless access is considered as an excellent alternative for expensive fiber-to-the-home networks. The exposure was numerically evaluated in a layered and realistic human body model at a short distance (< 1 m) of the FWA access point. They found that the exposure was more than two times below the ICNIRP limits for occupational exposure. For general public exposure, a compliance distance of 10 cm and 9.4 cm was observed for the incident power density and absorbed power density averaged over 1 cm^2, respectively.

Joshi et al[106] monitored the time-averaged power transmitted by several massive MIMO base stations operating at 28 GHz over a period of several days to analyze the effect of beamforming and beam-steering on the RF exposure. They observed that the directional time-averaged power is well below the maximum possible power of the base stations as the maximum 6-minute time averaged power varied between 32.5 % and 35 % of the maximum possible power and 95 % of the power samples transmitted with less than 12.5 % of the maximum power.

Aerts et al[107] estimated the exposure of users and non-users of small cell base stations widely deployed in 5G new radio (NR) networks from measurements in the vicinity of an advanced antenna system (AAS) with an array antenna at low height and the lower-power microcell base station on an accessible flat roof. They observed measured exposure levels below the MPE limits for occupational (at distances between 0.5 m and 1 m from the base station) and general public

[104] Tognola, G., Plets, D., Chiaramello, E., Gallucci, S., Bonato, M., Fiocchi, S., Parazzini, M., Martens, L., Joseph, W., & Ravazzani, P. (2021). Machine Learning for the Estimation of WiFi Field Exposure in Complex Indoor Multi-Source Scenario. 2021 34th General Assembly and Scientific Symposium of the International Union of Radio Science, URSI GASS 2021. https://doi.org/10.23919/URSIGASS51995.2021.9560437
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exposure (> 1 m) issued by ICNIRP. The maximum exposure ratios were 0.15 (occupational) and 0.68 (general public). The authors state that the exposure of a non-user within an active network depends on the distribution of users, their usage, and the AAS capabilities of the base station radio.

Shikhantsov et al[108] simulated the human RF EMF exposure to a distributed massive MIMO array system at 3.5 GHz deployed in an industrial indoor setting. They generated stochastically a set of environments and employed a hybrid approach (raytracing and finite-difference time-domain technique) to assess peak spatial averaged SAR in 10 g in the head of users and non-users. Multi-user scenarios with the Zero-Forcing downlink precoding were investigated. The authors found that the peak spatial averaged SAR in 10 g of users that is nearly 8 times higher than the one experienced by non-users.

9.4 Connected vehicles

Tognola et al[109] did a survey about EMF exposure generated by the whole ensemble of connectivity technologies in cars. First, the survey provides an overview of the RF technologies employed in connected cars. These technologies span a broad frequency range from 13.56 MHz (smart car access/key) up to 140 GHz (vehicle occupant detection radars). Next, an overview is provided of past exposure studies for RF technologies applied in connected cars. Results from past exposure studies suggested that in no case EMF exposure was above the safety limits for the general population. Finally, they addressed some challenges for future EMF exposure assessment for connected cars: more realistic scenarios and simultaneous and combined exposure to fields from multiple sources at different frequencies.

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10 Appendix

10.1 List of abbreviations

ABBREVIATION	MEANING
3G	Third generation of broadband cellular network technology
3GPP	3rd Generation Partnership Project
4G	Fourth generation of broadband cellular network technology
5G	Fifth generation of broadband cellular network technology
5G NR	5G New Radio
5GAA	5G Automotive Association
5G-ACIA	5G Alliance for Connected Industries and Automation
AGV	Automated Guided Vehicles
AMR	Autonomous Mobile Robot
AMR	Autonomous Mobile Robots
APN	Access Point Name
BSS	Basic Service Set
dBi	Antenna gain in decibels relatively to isotropic antenna
DSS	Dynamic Spectrum Sharing
eDRX	Extended Discontinuous Reception
EIRP	Equivalent Isotropically Radiated Power
eMBB	Enhanced Mobile Broadband
eNB	Evolved Node B
eNodeB	Evolved Node B in 4G radio
EPC	Evolved Packet Core
ETSI	European Telecommunications Standards Institute
FR1	Frequency Range 1
FR2	Frequency Range 2
gNB	Next Generation Node B
gNodeB	Next Generation Node B
GSA	Global mobile Suppliers Association
ICT	Information and Communications Technology
LAN	Local Area Network
LTE	Long Term Evolution Technology
LTE-A	LTE–Advanced
LTE-A Pro	LTE-Advanced Pro
LTE-M	Long Term Evolution for Machines
M2M	Machine to Machine
MIMO	Multiple-Input Multiple-Output
MMS	Multi Media Service
mMTC	Massive Machine Type Communications
mmWave	millimeter wave
mTRP	Multiple Transmission and Reception Point
MU-MIMO	MU-MIMO
NB-IoT	Narrow Band IoT
NSA	Non-Standalone
OBSS	Overlapping Basic Service Sets
OFDM	Orthogonal Frequency Division Multiplexing
OFDMA	Orthogonal Frequency Division Multiple Access
OT	Operational Technology
pLTE	Private LTE Network
PSM	Power Saving Mode
QAM	Quadrature Amplitude Modulation
RAN	Radio Access Network
RF	Radio Frequency
SA	Standalone
SMS	Short Messaging Service
SNR	Signal to Noise ratio
TCO	total cost of ownership
TDD	Time Division Duplex
UE	User Equipment
URLLC	Ultra Reliable Low Latency Communications
VoLTE	Voice over LTE
VPN	Virtual Private Network

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