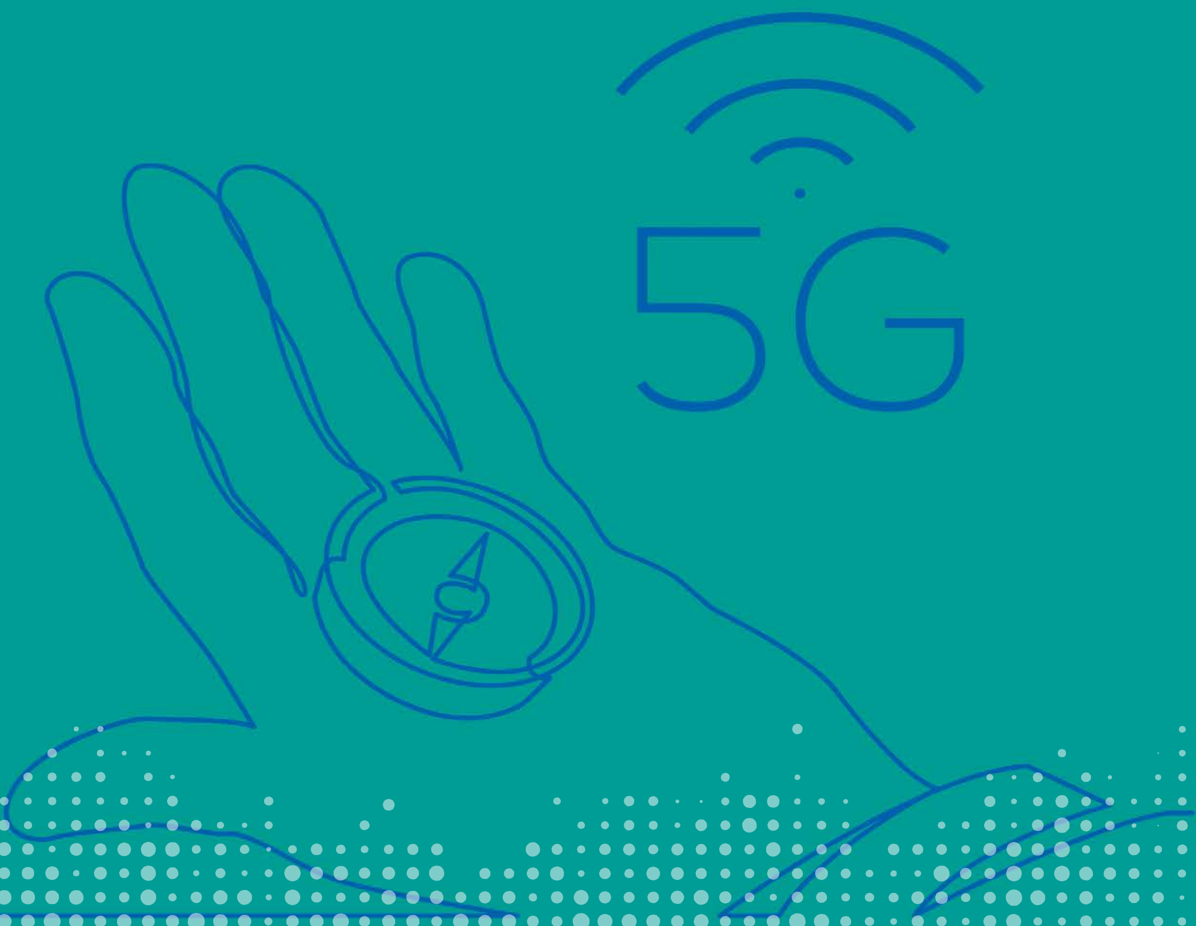
Federal Ministry
for Economic Affairs
and Energy

Guidelines for 5G Campus Networks – Orientation for Small and Medium-Sized Businesses

Concepts, terminology, operator models and selection criteria for manufacturing and logistics with implications for other sectors such as medical campuses and hospitals, ports, mining, construction sites and agriculture



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With the PAiCE technology programme (Platforms | Additive Manufacturing | Imaging | Communication | Engineering), the Federal Ministry for Economic Affairs and Energy (BMWi) supports the implementation of the overall 'Industrie 4.0' vision in business practice as part of the Federal Government's Digital Agenda. In 16 projects, companies and research institutions are testing the use of innovative digital technologies in production and logistics in large, application-oriented pilot projects. The Federal Ministry for Economic Affairs and Energy supports the more than one hundred partners in the various projects with a total of EUR 50 million. Together with the project partners' own shares, PAiCE has a volume of over EUR 100 million.

These Guidelines are based on the results of IC4F (Industrial Communication for Factories), a PAiCE flagship project that aims to develop a reference architecture for industrial communication using 5G, with a focus on IT security, reliability, real-time capability and resilience of industrial communication infrastructures. The Guidelines illustrate possible applications and describe the features and application areas for 5G campus networks. They offer orientation for deciders and communications infrastructures implementers in small and medium sized enterprises in the manufacturing sector and in logistics. The approach outlined here for setting up and operating 5G campus networks can be applied to other sectors such as medical campuses or hospitals, ports, mining, construction sites, mobile campus networks and agriculture.

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1 Summary

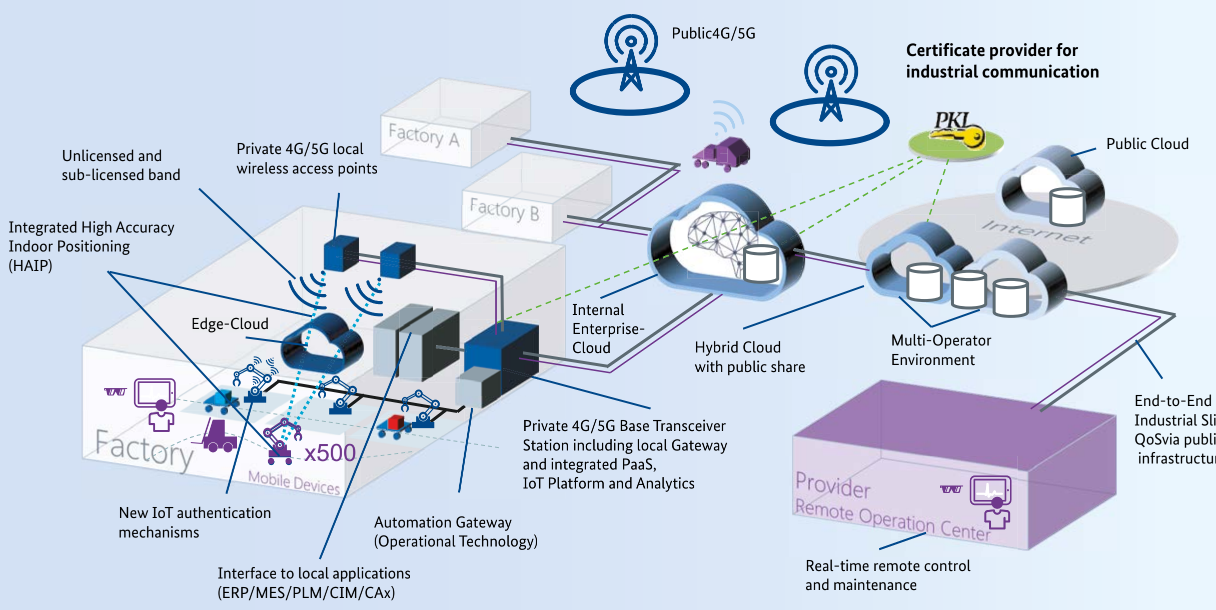
The term 5G Campus Network defines a geographically limited, local mobile radio network adapted to special requirements, for example industrial communication. 5G technology and the use of dedicated frequencies make it possible to fulfil the highest standards of service quality regarding latency, reliability and availability of communication networks. This makes 5G Campus Networks attractive for applications in various industrial sectors. For this reason, they are an important impetus for the factory of the future and currently are the topic of numerous reports in the media.

The factory of the future – 'smart factory' – will rely on a technologically much more sophisticated communications infrastructure. Figure 1 shows solution modules for creating reliable communication networks between machines, processes, robots, products, tools and humans. In contrast to wired networks, mobile network solutions allow for more flexible and dynamic manufacturing processes. Mobile communications provide new means for using the flexibility gained to achieve greater productivity.

Industry is currently conducting a lively debate on the technical framework for feasible operating models and the resulting value added provided by 5G Campus Networks in industrial value creation. On the one hand, the industrial sector is gaining more and more expertise regarding these technologies, yet the variety and breadth of such networks lead to many questions regarding suitable applications and the factors for success – and accordingly, the relevant criteria for choosing the right technology.

5G is not only an innovative radio technology that offers a broader frequency spectrum. It is the combination with new technologies such as the Internet of things (IoT), the demand-oriented and automated distribution of IT resources (Mobile Edge Cloud) and artificial intelligence (AI) that enables 5G Campus Networks to provide new technologies and services

Figure 1: Example for solution modules of a 5G campus network as envisioned in the IC4F project



Source: IC4F Consortium

that are not yet technically feasible on today's wi-fi and wired networks. 5G offers exceptional features for 5G Campus Networks in industrial environments and will become an important building block for Industrie 4.0 as digitisation progresses.

5G Campus Networks offer a high degree of reliability, predictable performance and integrated security for applications in the industrial environment. A decisive feature is seamless mobile coverage, without interruptions during handoffs from one cell to another, also at large sites, whether inside or outside. 5G Campus Networks provide functionalities for supporting applications in industrial production, that is, for applications with high standards regarding reliability and guaranteed, short response times (low latency). Thanks to wireless connections, the networks can be adapted at any time to changes in production conditions or in manufacturing or logistics processes.

It is necessary to conduct a comprehensive and detailed analysis of what the planned applications will require, to ensure that the systems implemented are successful. These requirements include secure connections and monitoring of machines in a production line, locating tools at any time, controlling mobile transportation vehicles or creating sensors for the logistics of goods. A formal requirement analysis is a significant help in identifying the best solution for the company [1].

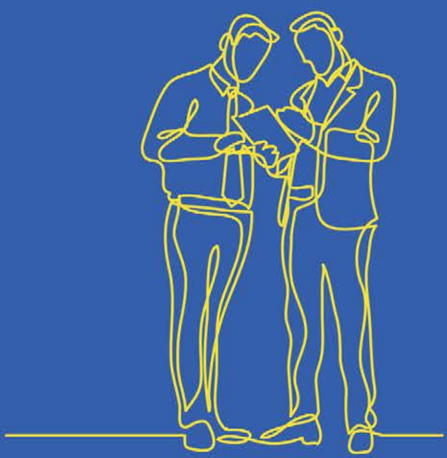
These Guidelines provide orientation to small and medium-sized businesses that are looking for communication solutions using 5G for their digital transformation processes. These Guidelines contain basic concepts, terminology and applications as well as a comparison of alternative operating models, to allow company decision makers with an interest in this technology a well-founded assessment of its potential. In the future, in addition to the standard radio applications, more and more products will be 5G-compatible and the market will provide modules for retrofitting machines. The following chapters provide facts and insights for analysing requirements and network planning or designing a private network or campus network. Furthermore, acquiring a radio licence and the various possibilities of network operation will be evaluated. Various manufacturers of 5G networks and service providers offer product portfolios for the various phases of planning, implementing and operating 5G Campus Networks.

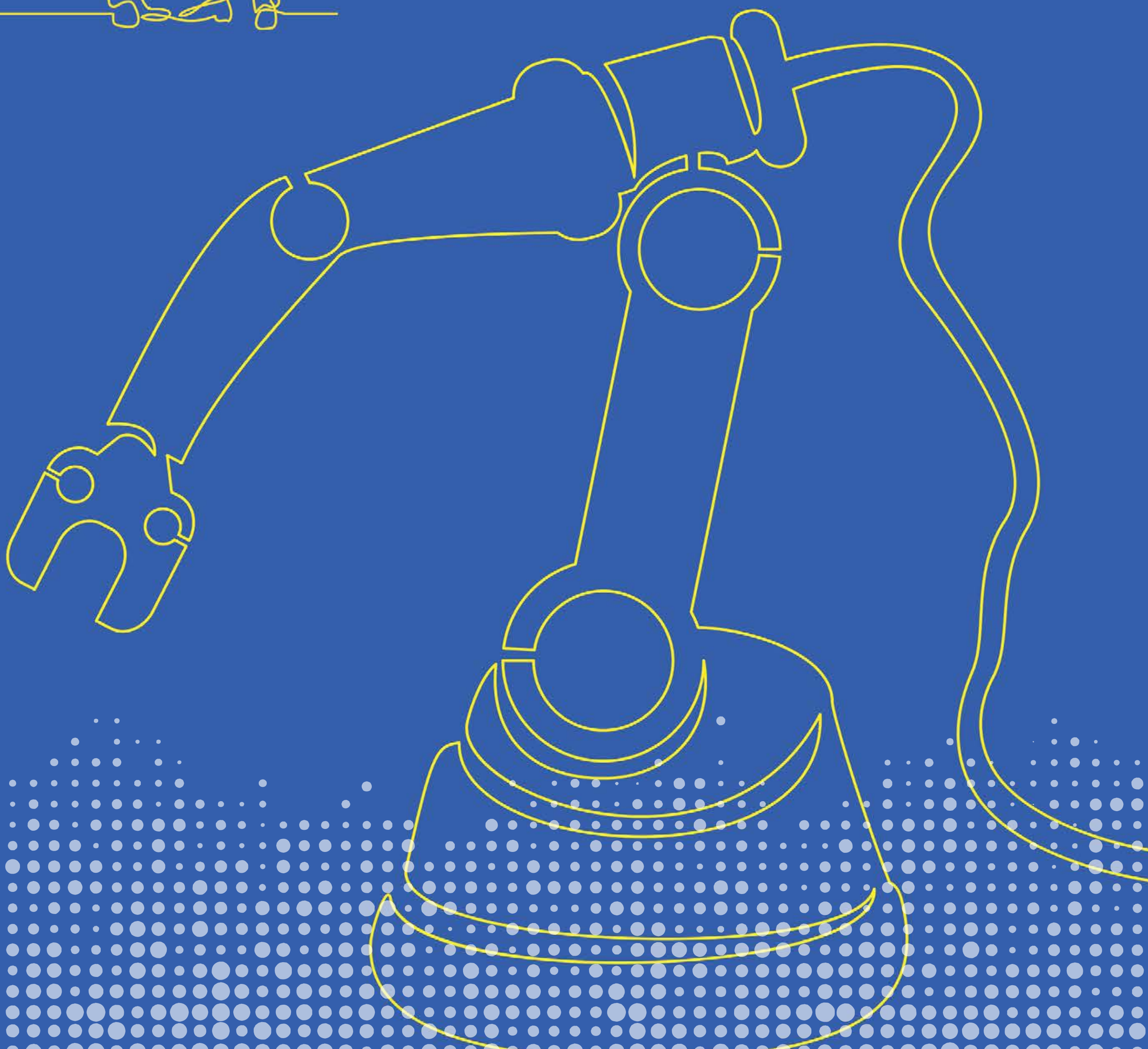
Chapter 2 provides a quick overview of basic technologies and the frequency spectrum of 5G campus networks. It also describes what is currently happening on the market. Chapter 3 reviews use cases for various industrial sectors that potentially represent the major market for 5G-Campus Networks. Chapter 4 describes various solutions and provides a short description of the basic network architecture. This is followed by a comparison of the various operating technologies of 5G Campus Networks, possible operator models and the criteria for creating and operating 5G Campus Networks. Finally, chapter 5 describes 5G standardisation efforts and provides an outlook on further developments.

These Guidelines reflect the work of the 'IC4F Industrial Communication for Factories' flagship project that receives most of its funding from the Federal Ministry for Economic Affairs and Energy as part of the Industrie 4.0 initiatives.

In the IC4F project, industrial applications using 5G Campus Network solutions are created, tested and validated by a consortium of partners from industry and the scientific community. The consortium partners have compiled their results and insights in this paper as means of orientation for small and medium-sized businesses and for any interested parties.

2 Introduction and Overview





The digital transformation has ushered in a number of new challenges that give communication networks an important role. Machines, tools, products and humans involved in the creation of value are interconnected. This fundamental transition makes current information and knowledge regarding processes, manufacturing and products available to the whole operation and reliably directs data processing power to the areas where it is needed.

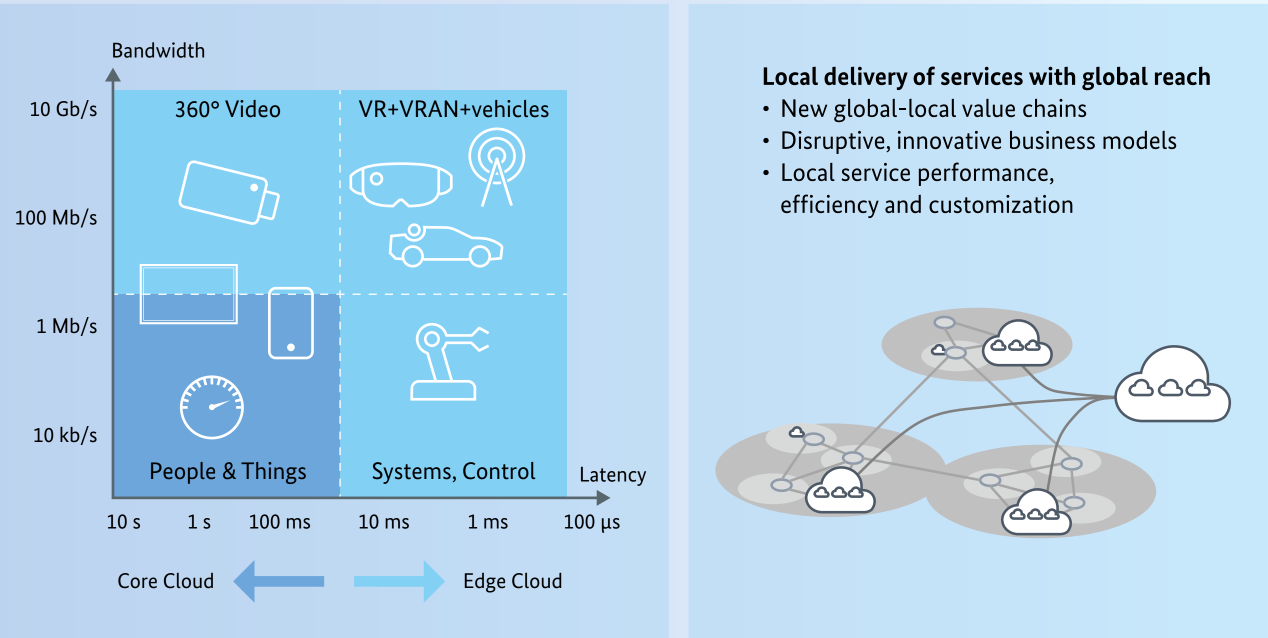
The rapidly expanding number of smart devices and systems as well as the ongoing development of business applications require substantially greater bandwidth, in order to provide larger amounts of information on system status and the operating environment. The following provides a short description of the important technological requirements. Figure 2 shows the categorisation of the main improvements in communications technology.

Mission-critical applications that operate remotely, controlling manufacturing systems, e.g. in industry automation and in the smart grid, as well as controlling autonomous vehicles requires substantially greater reliability of communication services and far less latency.

In order to fulfil these requirements and achieve industrial productivity gains, communication networks must have enhanced capabilities:

- **Network access:** various access technologies (wireless, wired and optical) must work together.
- **Elasticity:** networks will become dynamic and programmable. When new sites are added, manufacturing facilities are modified, production processes are dynamically (re-)organised or requirements for network quality fluctuate, the

Figure 2: The digital transformation defines requirements for further development of 5G networks



Source: Nokia

communication network must automatically adapt and computing capacity will be provided dynamically in local edge and hybrid clouds.

- **Powerful:** the network should provide controllable connections with a predetermined Quality of Service for all applications being used, regardless of the varying requirements of the applications.

- **Failure-safe:** the network should ensure availability for mission-critical applications. Reliable operation of between 99.99% and 99.9999% availability is a condition for productivity and operational safety.

- **Security:** networks are a part of the enterprise security solution. Data security is a primary requirement for security. A smart network structure helps minimise specific threats to security.

- **Scalability:** networks should be designed to anticipate expanding bandwidth, processing and other capabilities, and should adapt accordingly. Extensive data surveys provide a deeper context and higher value, and each investment cycle will undoubtedly see many convincing new applications.

2.1 5G Campus Networks: a technological overview

From a technology point of view, 5G is a step-by-step enhancement of 4G mobile radio technology, which already incorporates the applicability to vertical markets in its architecture. In the 5G network architecture there are various phases of implementation. The 5G Non-Stand-Alone architecture (NSA) continues to use the LTE core network as a basis, but terminal devices communicate using 5G wireless technologies. Network control however still takes place using LTE technology, and this also requires dual radio hardware in the network elements and terminal equipment. The implementation phase termed 5G Stand-Alone (SA) architecture defines a completely independent 5G mobile network infrastructure.

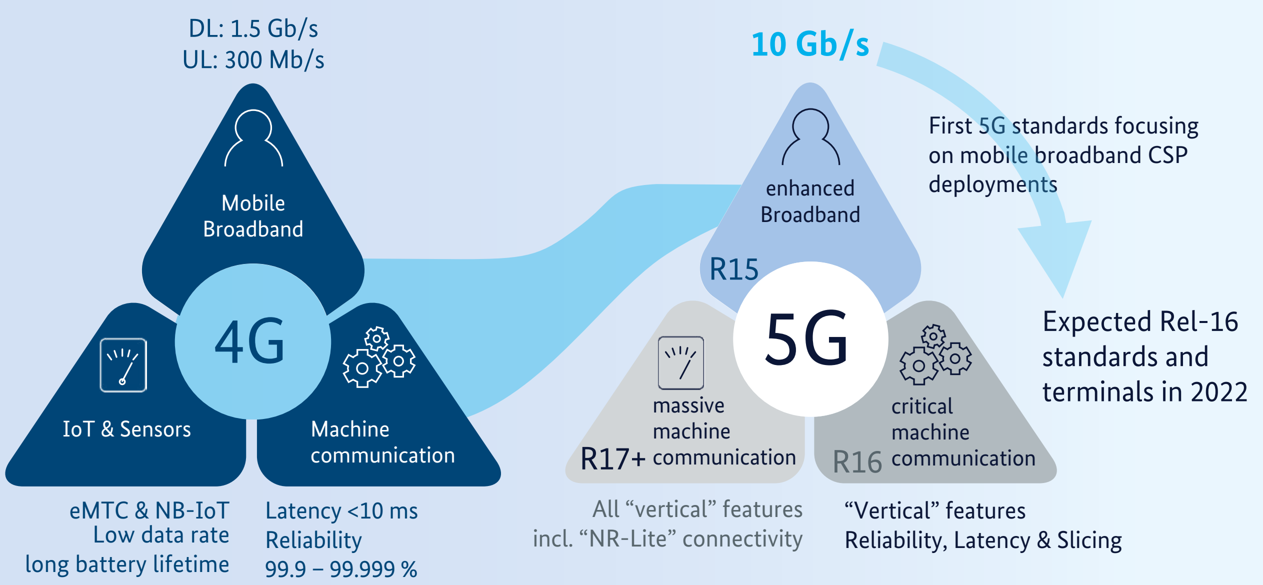
5G introduces new technology to the following areas:

- **New radio interfaces (5G New Radio):**
5G provides improved performance especially with a new method for radio interfaces (5G New Radio). The efficient use of varying, sometimes completely new and non-contiguous frequencies is a major challenge for 5G New Radio. Expanded coding and multiplexing processes help improve performance with respect to throughput, latency and energy efficiency. Another feature of 5G New Radio is 'Massive MIMO'. MIMO (Multiple Input Multiple Output) is an antenna technology that can achieve data transmission rates of up to 10 Gbps by using hundreds of antennas in a single base transceiver station. The greater the number of antennas used on the base transceiver station, the more data streams can be processed and the more terminal equipment can be served simultaneously. At the same time, the transmitting power can be reduced and the data rate increased. These additional antennas that parallelise processing of digital signals make it possible to concentrate the energy used for sending and receiving signals on continually smaller areas – this is called beamforming. Several antennas are used to create a directed signal to reach a specific receiver. This receiver profits from the signal gain and improved interference cancellation. With the help of these techniques, 5G New Radio provides higher bandwidth than previous radio techniques, lower latency and a significantly higher number of terminal devices per area.

- **Expansion of the core network (5GC):**
A new service-based architecture is being introduced that allows for agile network configuration for adapting to application requirements. In the 5G releases 16 and 17 a number of topics are being implemented that are important for 5G Campus Networks. Examples include LAN services, support of TSN (Time Sensitive Networking), time synchronisation, monitoring the service quality from the user's side, partial configuration of the 5G network by users (slicing) and support for non-3GPP authentication for campus networks.

- **Virtualizing networks (SDN/NFV):**
  One new approach is to convert functions previously carried out by hardware to purely software functions. As is already the case in other areas of IT, this allows for virtualization of the networks, which can accordingly become much more flexible and dynamic. Software-defined Networking (SDN) and Network Function Virtualization (NFV) are key features of 5G. These features make it possible for specific services to be developed, tested, operated and combined into integral solutions, independently of each other. SDN separates the control and data layers in networks, which is essential for achieving virtualization. Networks thereby become multi-tenant capable and support a centralised view and configurations of network components. SDN is the basis for prioritisation, quality of service and slicing. NFV decouples network functions from the hardware, making them exchangeable, geographically flexible and placeable. In addition to implementing network functions, NFV also makes it possible to execute new functions from the application layer on network hardware, for example data aggregation. 5G networks are not only a communication platform but can also develop into dynamic application platforms. The entire 5G network accordingly is equipped with a programmable, flexible and universal infrastructure, starting with the terminal equipment, including transmission networks, edge clouds, the core network and on to 'traditional' cloud computer centres.

Figure 3: 5G wireless technology builds on existing 4G/LTE technology and opens up new possibilities in industrial manufacturing



Source: Nokia

The key performance indicators of 5G networks exceed those of 4G/LTE in three dimensions (Figure 3):

- eMBB – enhanced Mobile Broadband: data volumes attain 10 Tbps/km2 and peak data rates of 10 Gbps
- mMTC – massive Machine-Type Communications: high IoT terminal equipment density of one million/km^2 and optimal energy consumption of 10% for LTE systems
- URLLC – Ultra-Reliable Low-Latency Communications: one-directional latency below 1 ms, availability of 99.999%

2.2 Local spectrum

Industrial customers are increasingly interested in more flexibility in controlling and managing their company processes. Wireless communication and connectivity play a key role in this, and access to frequencies is decisive.

In the summer of 2019, a two-phase process for awarding frequencies was initiated by the Bundesnetzagentur. First, a 5G frequency spectrum for use in Germany was awarded in an auction to the mobile network operators Deutsche Telekom, Telefonica and Vodafone as well as 1&1 Drillisch.

Then an allocation scheme for local 5G frequencies was started. The Bundesnetzagentur reserved an additional 100 MHz frequency band of 3.7 to 3.8 GHz exclusively for local and campus networks. The allocation procedure allows for awarding frequency blocks exclusively to one or several plots of real property if requested and under certain conditions [2]. According to the desired network solution and network design, industry and service providers have various options for collaboration.

This makes it possible for the first time for many industrial companies to create their own, customised network that is adapted to their applications and needs.

The licence fee is calculated using the formula: €1000 + B · t · 5 · (6 · a1 + a2). “B” is the bandwidth in MHz between 10 MHz and 100 MHz in intervals of ten; “t” is term of the contract in years; and “a” is the surface in km^2, whereby there is a difference between residential and traffic areas (a1) and other areas (a2) [2]. A10-year frequency assignment of 30 MHz for an area comprising 25 ha (500m x 500m) would accordingly cost €3,250 (residential area), which corresponds to an annual fee of €325.

More information is available on the Bundesnetzagentur website [3], including detailed administrative provisions [2], application forms and fee models.

2.3 Current market developments

Market participants and their associations are currently very interested in 5G campus networks. Market forecasts indicate a demand of between 5,000 to 10,000 5G campus networks in Germany by 2025, whereby the majority of these networks will be used by small and medium-sized enterprises [4]. According to a survey conducted by the German Mechanical Engineering Industry Association (VDMA), about 35% of the companies surveyed have already decided to create 5G campus networks. Of these, around 50% want to install a network on their own, and around 20% want to operate it themselves.

The market for 5G campus networks is currently in the initial phase, now that spectrum can be acquired and commercial components become available. The following includes a few examples of articles and studies that illustrate market activity from various perspectives:

- In a White Paper, 5G-ACIA describes various introduction scenarios for 5G Campus Networks for IIoT (Industrial IoT) applications that were agreed on by 3GPP. This White Paper was published in July 2019 [6].

- The VDMA, Europe's largest industry association, is preparing a publication for Q2 2020 on the topic '5G in Engineering' [7]. Several IC4F project partners are involved.

- Arthur D. Little expects industrial demand and regulatory changes to open up new possibilities for established network suppliers and operators, as well as offering new providers the opportunity to enter the market with specific components and solutions for 5G Campus Networks [8].

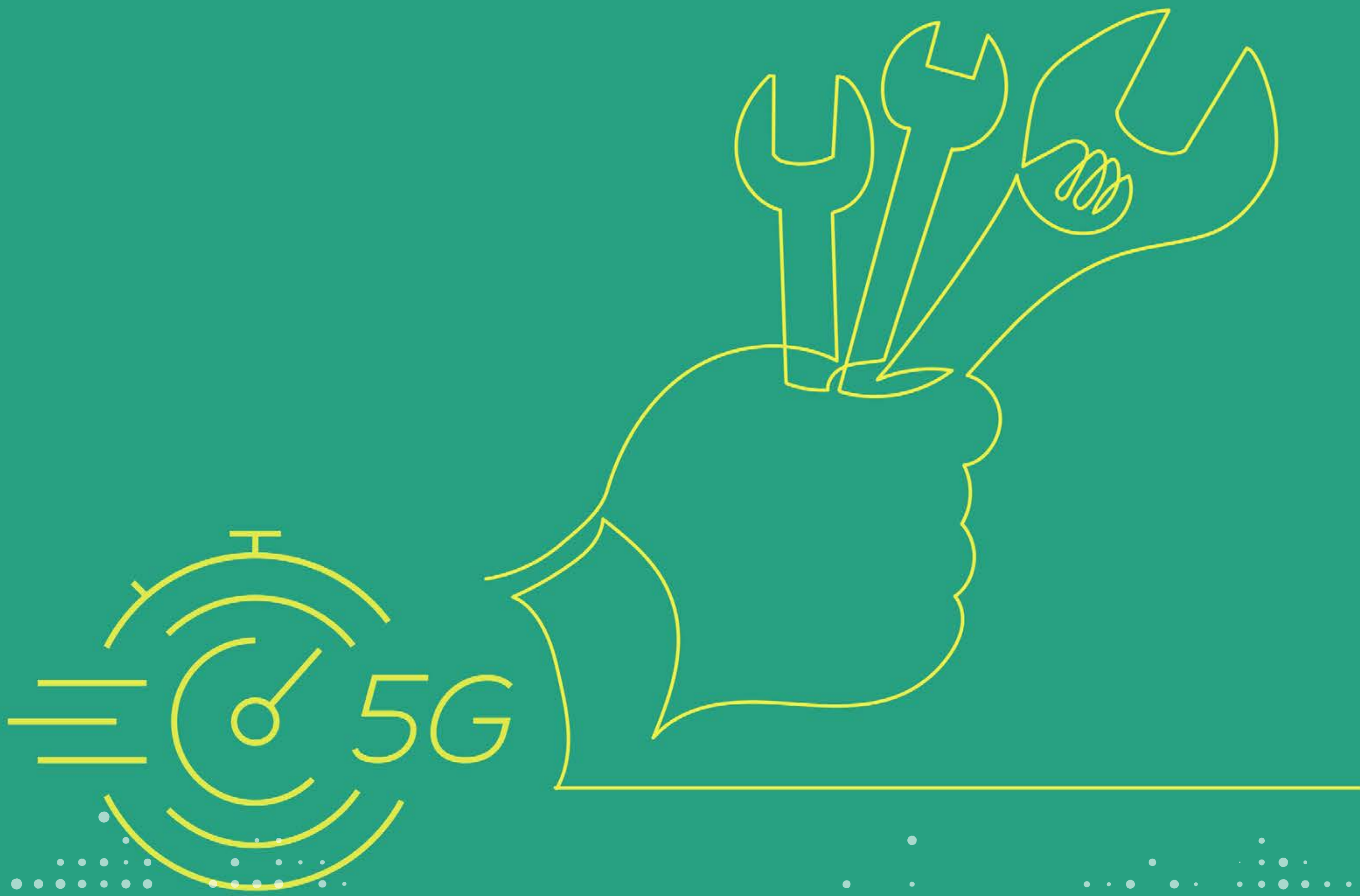
- Network operators such as Telekom are working on 5G campus networks that guarantee high availability, provide high bandwidths for industrial IoT processes, fast response times and that satisfy the requirements for mobile applications [9].

- The Bundesnetzagentur has published calculations for 5G campus network charges, which were noted by the Federal Association for Broadband Communication, among others, as being "moderate" [10].

- T-Systems describes IIoT scenarios for 5G Campus Networks to enable use of Industrie 4.0 applications [11]. Slicing in the context of campus networks is described in the document 5G Campus Networks – LTE and 5G-Technology for local company networks [12].

When using cellular technology, especially in the higher frequency bands reserved for 5G, there are some concerns about potential effects on humans and the environment. According to the Federal Office for Radiation Protection, many findings from studies on the possible effects of electromagnetic fields generated by mobile communications are applicable to some extent to 5G. This relates in particular to all frequency bands up to 3.6 GHz. It is also expected that future frequency bands of 26 GHz, 40 GHz or up to 86 GHz will not create a health hazard if they remain below the current maximum permissible levels [13]. Bitkom also sees no health hazards from electromagnetic fields with the frequencies used by 5G cellular systems if the current maximum permissible levels are adhered to.

3 New application scenarios with 5G



3.1 Use in manufacturing

Industrie 4.0 and changing markets and customer expectations are raising new challenges to the manufacturing environment as it exists today. Manufacturers and their suppliers are looking for more agility and ability to forecast in order to improve just-in-time production and to better serve rapid changes in consumer demand. In view of the slowdown in productivity growth, manufacturers are looking for more efficient ways to manage supply chains and logistics, to create more agile manufacturing and to support their employees with modern technology. Many manufacturers are already largely automated, yet their assembly line robots and automated transportation vehicles are tied to static workflows. The next generation of industrial automation promises to optimise production, making it easier to modify workflows and quickly adapt production equipment to new requirements, even for small lots, down to production of individual items, which requires fast conversion.

In addition to connecting machines, it will be important to include goods, products, tools, transportation vehicles and employees in the digital transformation in order to be able to access information at all times regarding the status and progress of the manufacturing process. Interconnected sensors and actors, tools and machines (Industrial IoT), analytics, methods for artificial intelligence and machine learning are promising in view of the improvement to real-time information and control of automated processes. When this data and information is combined, a digital image of production processes, that is, a digital shadow or digital twin is created. Analysis, understanding and interpreting the data and information collected makes it possible to initiate action and changes that can help improve production or operating efficiency and help make decisions.

5G promises to fulfil these expectations. 5G can for example interconnect a multitude of sensors so that flexible sensor systems can be linked directly to control units of autonomous robots and problems related to control or production can be predicted in advance. The systems themselves can also be controlled with low-latency connections. High availability and reliability of 5G communication can even facilitate the mobile and flexible use of security-relevant processes. The high data rates make it possible to use high-resolution camera systems in manufacturing and controlling, to deliver real-time and reliable information on the quality of the product and status of production. An extensive list of use cases in production can be found in publications [15] and [16]. Numerous use cases are being implemented in the IC4F project [17].

3.2 Use in intralogistics

5G provides new use cases for intralogistics, in particular for mobile industrial applications that have not been possible up to now. These are not the traditional fleet management systems for forklifts and conveyors with their customary time and volume requirements that can also be run on 4G or WLAN – the new systems are usually autonomous. For one thing, it is highly likely that the number of these systems will sky-rocket in the future, and for another, they will need to manage increasingly complex tasks, as they take over humanoid tasks to improve productivity. Autonomous systems of the current generation are usually extremely self-sufficient and therefore require only a limited mobile connection. The tasks of calculating routes, localisation, strategies for solving problems and safety functions are directly integrated in the vehicles. As a rule, only destination coordinates and task data are transmitted from outside the vehicle, and a limited amount of operating data is retrieved. The next generation of autonomous vehicles will benefit from 5G, because edge cloud computing provides a powerful and highly stable communications connection that will make it possible to outsource partial functions. In the first place, functions related to calculating routes and providing information for maintenance will be reallocated. New AI strategies can therefore receive the necessary data and real-time intervention on the basis of digital twins will be feasible. Latency of less than 10 milliseconds and handover times of 1 millisecond allow for seamless communication and are essential conditions for this development. The advantages of managing large fleets of automatic guided vehicles (AGVs: driverless vehicles) are reducing processor capacities in the vehicles, the nearly limitless capacity for data storage, and outsourcing of data-intensive image processing, for example. Solution strategies that are necessary for operating such large fleets can therefore be moved to the edge cloud, where all vehicle data is available. Plans for the next but one AGV generation envisage to move the security systems into the global context, which will make it even easier to manage individual AGVs.

When providing the relevant infrastructure for autonomous systems, there are certain conditions that must be met to facilitate operation. Large fleets with data-hungry communication must have access to a large number of 5G cells. The cellular network must be redundant to be able to relocate security-related functions and avoid production downtimes for central control.

In addition to these technical possibilities, however, extensive standardisation will be necessary to implement such extensive systems. Whereas a 5G Campus Network involves a uniform communication infrastructure, companies usually use vehicle fleets with a mix of brands from various manufacturers. All of these systems must therefore behave uniformly on the various communication levels and have a uniform security concept. This will require adapting many interfaces in the future. Furthermore, various service channels will be required for manufacturers, so that their complex systems can be properly maintained.

3.3 Use in logistics

3.3.1 Transport in ports

Today, approximately 90% of global goods according to weight are transported by sea [18]. Container ports play a decisive role in managing fluctuations in traffic and ensuring quick processing for customers. The scope and advantages of digitalisation are enormous, because a large part of current operations is based on manual processes. Many of these ports have begun to rely increasingly on automation, in order to improve processes, efficiency and the security of the goods they move. When a ship with more than 20,000 containers docks in a port, the goods must be unloaded quickly and securely for further transport. Automation and digitalisation make it possible for ports to manage the enormous volumes of data that come with ship containers and that must be generated for the onward journey. Several companies are frequently involved in the activities, each company with its own demand for dedicated connectivity in the port. Furthermore, these efforts must be closely coordinated. The first application that is most often requested is to create a real-time overview of port operations, using cameras in order to give despatchers the possibility of operating cranes and straddle carriers. These cameras are also used to assess the condition of the containers upon arrival and to prevent theft in the port. In future, ports will need to use remote-controlled, automated heavy goods vehicles, straddle carriers and cranes, in order to further improve efficiency and security.

3.3.2 Rail and trucks

Automation of logistics begins at ports or airports, but people live in the cities. To get from the ports to the cities, modes of transportation such as the railroad and trucks are used. Here, too, automation and connectivity are increasing in order to improve both efficiency and security. Train stations have quick and flexible communication between the infrastructure, the trains and also personnel and are able to react more quickly to service interruptions, prioritised transports and unforeseeable incidents. A fully interconnected smart camera system that can read out images in real-time and is connected with the control system can prevent accidents involving passengers, but also avoid congestion by switching trains or adding train cars without interrupting service. In addition, a wide selection of updated information and multimedia products can be made available to passengers, because the central controlling system is continually updated on all incidents and delays and can flexibly manage rail routes. In train stations in particular, 5G provides a wide range of possibilities to the large number of users who at the same time benefit form high data rates and low latency.

3.4 Applications in the Smart City

Now available in the city, 5G provides limitless possibilities and business models for companies and private individuals as well. The gain in convenience is immense when a reliable internet communication link connects everyone to everything. This could be individuals amongst each other, individuals with the infrastructure but also the infrastructure with itself. A few examples for interconnected infrastructure include vehicles, traffic lights, door, supermarkets and much more. The various improvements offered by 5G compared with previous generations of mobile communications can be implemented to the maximum and, especially in private campus networks, provide a huge potential for operators of shopping centres, schools, office complexes, and also for entire inner city infrastructures, where reducing dependence on a public infrastructure opens up many opportunities.

3.5 Applications for power utilities

Creating a secure and reliable energy supply from energy sources that often fluctuate requires monitoring and control of devices installed in private households, companies and distribution networks, at a speed and volume that greatly exceeds current parameters. This switch will lead to radical changes in network functions and business models. Major amounts of power are generated in consumer buildings and independent decentralised locations, with the consequence that power from the neighbourhood and the municipality is exchanged. Retail markets for energy are being created to facilitate real-time energy transactions with the help of blockchains and to make it easier to conduct these transactions.

Widespread automation, use of data analysis to support new supply applications and use of expanded information systems by sales personnel will change utilities operations. Enormous sums were invested in the centralised energy network of the past. Now this infrastructure – originally conceived for one-way power flows – must manage bidirectional energy flows. It is essential to protect existing assets to keep energy costs low for consumers. Accordingly, utilities must provide a number of sensors and controllers to ensure that their networks are not congested and power quality is maintained. There are myriad possibilities for digital efficiency in the power grid.

3.6 Applications in mining

In a strong economy, mining benefits from an unquenchable thirst for minerals. Under favourable economic conditions, productivity in mining is limited mainly by bottlenecks in mineral extraction or in the supply chain. The industry is also burdened with exorbitant operating costs and cost of capital. These factors are forcing mining to achieve every greater efficiency. The risks inherent in the mining environment (dust, use of highly explosive material, extremely high temperatures and moving heavy equipment) leads to a strong emphasis on work safety in this industry.

The need to continually improve safety, productivity and efficiency leads to an unprecedented demand for digitalisation, automation and optimisation of all aspects of mining operations, from the pit to the port. Introducing automation to open-pit mining has led to an improvement in operating efficiency.

3.7 Applications in medicine

To meet future challenges of demand-driven and personalised medicine, the advantages of digitalisation must also be efficiently applied to the health sector. It will be decisive to use appropriate communication infrastructures. In addition to the technical requirements of various medical applications, data security is also a key requirement of the communications network.

5G offers enormous connectivity and high speeds, which will help transform health care.

Medical campus networks for hospitals and care facilities provide a suitable communication framework for ensuring the security of highly sensitive health data and on the other hand, to fulfil future application-specific requirements. New areas of use are in particular the fast transmission of large volumes of data from medical imaging systems, expanding telemedicine and reliable real-time patient monitoring, digital assistance systems such as AR/VR or holographic visualisation for new operation techniques.

3.8 Mobile campus networks

Some areas such as agriculture or construction sites cannot be served with permanently installed private infrastructure or a slice of the public network. The latter is usually due to the fact that there are still large areas with only sporadic cell coverage or none at all. However, to be able to use modern technology and efficiency-boosting processes, it is important to ensure reliable connectivity in the field or at the construction site, with high data rates and low latency. It is important that applications can be run locally and independently, because often only a satellite connection with low data rates is possible, or a partially active directional radio connection. In addition, applications for event technology can be implemented with mobile private 5G networks for mobile events (e.g. concert festivals) [19].

3.8.1 Applications in agriculture

In modern agriculture, terms such as ‘smart farming’ and ‘precision farming’ are prevalent. However, traditional mobile radio applications using wide area networks are not capable of sufficiently supporting such applications. Mobile campus networks on private frequencies make it possible to implement reliable and high-transmission-rate mobile communications in agricultural areas. This allows for interconnecting autonomous driving vehicle fleets, drones that cooperate with each other and high-precision fertilising and spraying. Because cellular coverage is only needed at certain times, e.g. when planting, harvesting or fertilising, it is important that the network is installed on a portable, independently run platform and is available quickly and flexibly to the farmer. 5G provides these possibilities by means of private campus networks and also facilitates many applications due to its flexibility and configurability, such that the networks between them do not have to stand idle at times, rather can be used for other application scenarios.

3.8.2 Construction sites

Another use case is the construction site of the future. Whereas many builders today are working at full capacity because they cannot find the sufficiently qualified personnel to operate machines, in the future, a smart, autonomous excavator will be able to work on its own. The needed information for operation will either be provided locally with an edge cloud on-site, or using a connection to the company's own cloud or a cloud operated by the machine manufacturer. Here, too, mobile campus networks are the cornerstone for such applications, because they enable networks to be set up flexibly in areas where there are insufficient networks or the existing network does not satisfy the requirements for latency or data rate. This is particularly necessary when several construction machines shall interact with other machines or even with workers in collaboration. Only local, custom-configured networks can satisfy the requirements of such constellations. Mobile campus networks can ensure safety at construction sites, improve efficiency and shorten construction time. A construction machine that is waiting for an operator or to be transferred to a different construction site will be a thing of the past. High connectivity and high-precision GPS and 5G-controlled localisation will improve the utilisation of these machines exponentially. These approaches are currently being addressed in the DigitalTWIN project [20].

3.8.3 Mobile factory

A mobile factory is a self-contained production unit. It consists of serviceable modules in the form of freight containers that can be set up and installed at a selected site in very short time [21]. Successful use cases for this 'factory-in-a-box' are production lines in the electronics industry, the consumer goods sector and the food and drinks industry. The factory-in-a-box utilises various concepts that are key to Industrie 4.0, such as hyperflexible manufacturing processes with cloud-based applications, sensors on partial levels, manufacturing execution systems (MES) and robotics. Mobile factories make it possible to standardise investment in operations technologies. The factory-in-a-box uses sensor networks, AR/VR applications or collaborative robotics, depending on the production phase. The connection of the factory-in-a-box to cloud services for each machine being used or to higher levels of the company infrastructure is possible at almost any location, thanks to 4G and 5G radio technology.

3.9 Summary of requirements

The 5G use cases described here are quite varied. To facilitate comparison of use cases, their specific requirements are listed in Table 1, broken down by number of terminal devices, required data rate and latency. The uses can be divided into three big categories. The first use case is motion control. This means the direct and highly precise control and regulation of actuators. This requires very low latency between transmission and reception of a control command, in order to avoid dysfunction. However, it is not necessary to have a large number of user devices or a high data rate. The second area of use is autonomous vehicles that are not on public roads and that can drive autonomously. This includes intralogistic AGVs, autonomous drones and tractors in agriculture and autonomous construction machines such as excavators. These application cases are characterised by high data rates and relatively good latency, yet with less end devices involved. The third group are large Internet of Things networks with a large number of participants, but low data rates and high, acceptable latency.

The application cases for ports are not listed in Table 1, but they can be evaluated by combining all three application types described. To monitor containers on the port property, a large number of sensors is necessary to transmit the position of the containers and the temperature of cooling containers. To transport containers on the port property and reload them onto trucks, autonomous vehicles are used that have communication requirements similar to those of intralogistics.

Table 1: Requirements for 5G in individual use cases

Use case	Number of terminal devices	Data rate	Latency
Machine control (Motion control)[1]	100	100 kbps	2 ms
Intralogistic AGVs[1]	100	10 Mbps	20 ms
Agriculture (autonomous drones and tractors)[2]	20	20 Mbps	20 ms
Construction sites (autonomous construction equipment)[2]	20	20 Mbps	20 ms
Smart City (metres, environmental sensors, IoT)	10^2	100 bit/sec	10 seconds
Energy supply (frequency control)[1]	10^2	100 bit/sec	< 50 ms

1 Source: [16]
2 Numbers derived from [16]

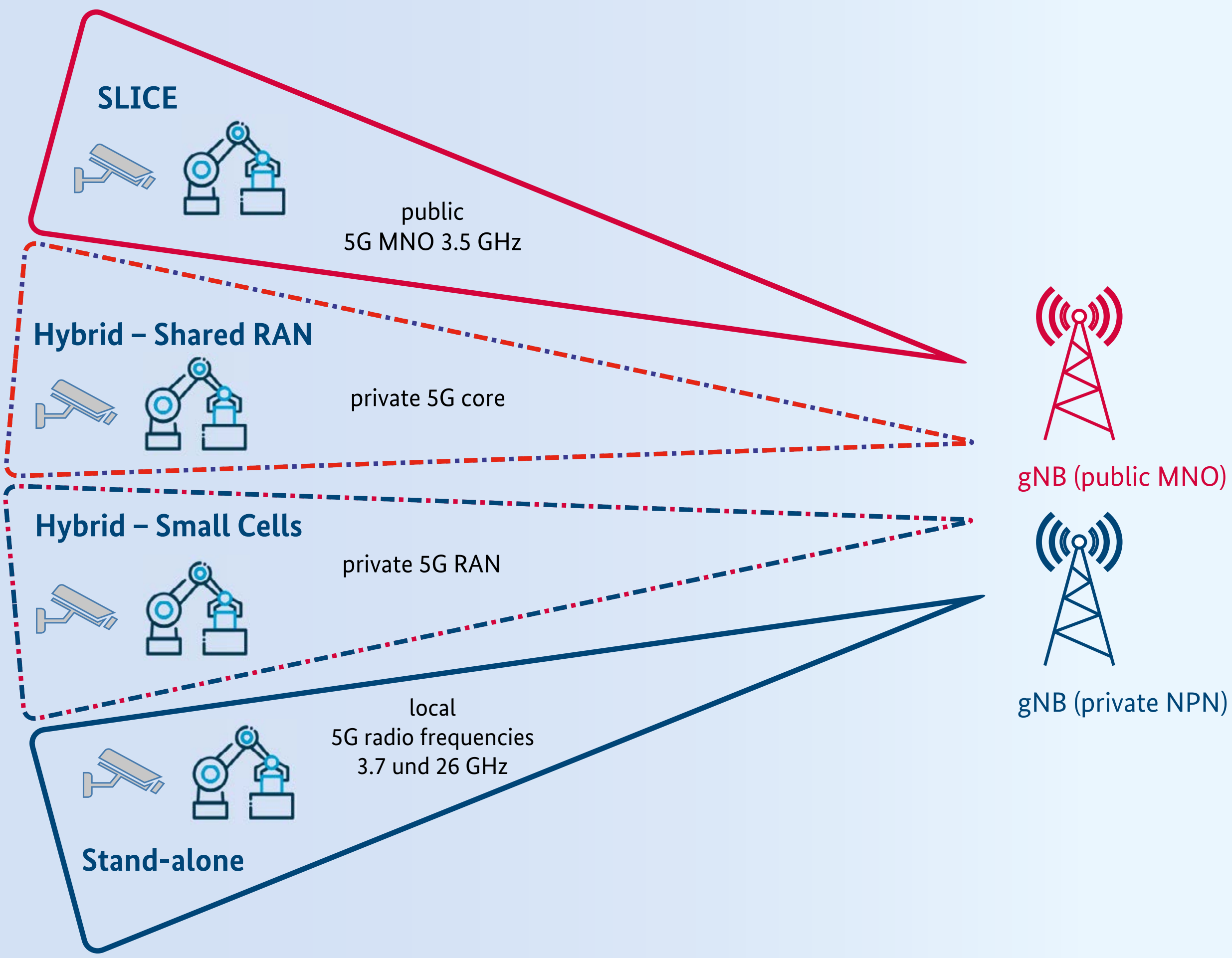
4 5G campus networks – topologies and operating models

5G campus networks can be set up in various levels of depth regarding integration with 5G mobile radio networks of the national ('public') mobile network operators (MNO) (see Figure 4). In addition to stand-alone non-public (private) networks (in-house operation) and virtual networks that are based fully on public networks, various intermediate forms can also be used. Three levels of integration describe the most important types of 5G campus networks: stand-alone private networks (in-house operation), the hybrid networks (partially linked to an MNO network, partially in-house operation), and virtual, internal networks as part of an MNO network (slices), with or without dedicated local hardware.

4.1 Architecture of 5G campus networks

The most important network elements of a 5G network are illustrated in Figure 5. The mobile network (RAN: radio access network) connects the terminal devices across the base stations (gNB: next generation Node B) with the user plane function (UPF) and with

Figure 4: Frequency spectra and operator models for 5G campus networks



Source: IC4F Consortium

the 5G core control plane (5GC-CP). The gNBs consist of transmitting devices, the accompanying antennas and sometimes a remote unit for signal processing. The UPF is the gateway to controlling and forwarding user plane data. The 5GC-CP is the core network that consists of a number of individual elements that are required for separating, prioritizing and access control. User identities are managed in the unified data management (UDM) that contains user information and specific profiles and rules.

An important new aspect of 5G networks is the possibility of providing local or network-based computing capacity using the Mobile Edge Cloud (MEC), a local cloud infrastructure that allows applications to process programmes on-site and therefore without long delays.

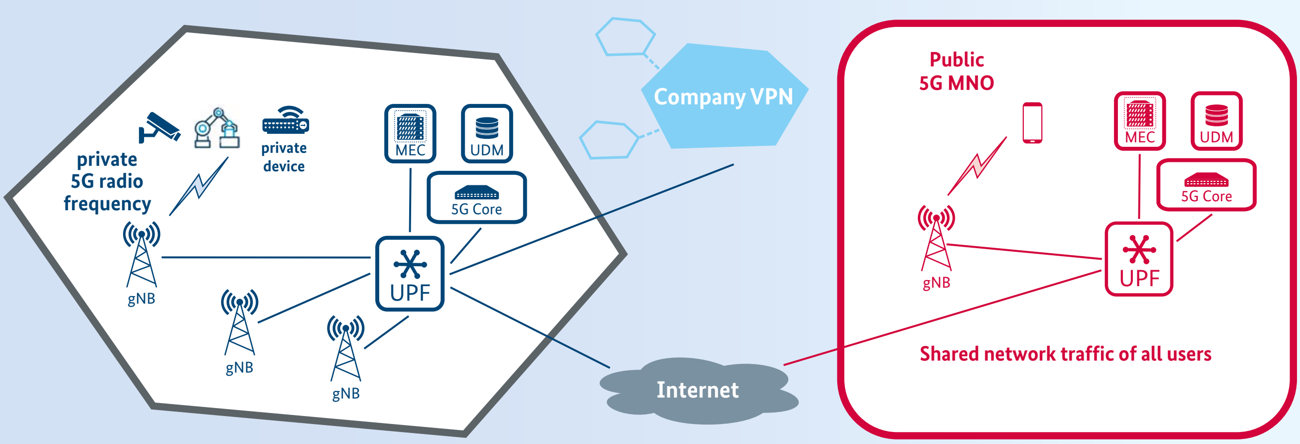
4.2 Operator models

There are various operator models for implementing application scenarios and use cases. They differ in the various schemes for distributing 5G network functions and their operation among 5G campus network operators and public mobile network operators. In this chapter, important models and aspects are explained to help in the selection process of operator models.

4.2.1 Separate 5G campus network (in-house operation)

In a stand-alone 5G campus network, the campus operator becomes the local, private 5G network operator. Setting up and operating the stand-alone 5G campus network is the sole responsibility of the

Figure 5: Network elements of a 5G network, operated completely separately, in-house



Source: IC4F Consortium

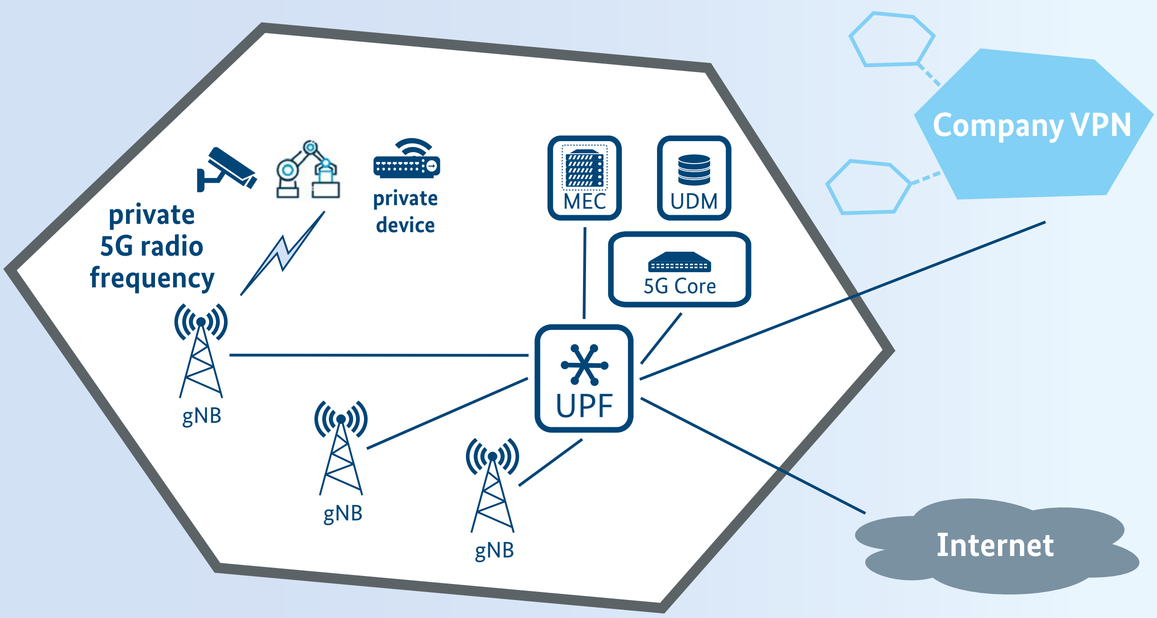
campus operator. There is no integration into the public mobile radio network.

- An individual, privately used mobile radio network is created, with an individual network ID and strict delimitation from the public mobile radio network by means of separate software and hardware, as well as using disparate radio frequencies (stand-alone).
- The campus operator must apply for a local radio licence issued by the national regulatory office, e.g. Bundesnetzagentur in Germany (see section 2.2).
- It is permissible to use a conventional security certificate (non-3GPP).
- The network may be set up and/or operated either independently or by a service provider.

All network elements in Figure 6 are provided entirely by the operator of the 5G campus network and are its responsibility. The network operator must also fulfil the obligations associated with acquiring a licence. It is possible, however, to transfer these obligations to service providers. There is no integration with public mobile radio networks.

Operating a 5G campus network in-house is recommended in situations in which a high level of communication with many systems is anticipated, also very high standards for reliability and availability of communication services as well as long-term operation. Cost estimations of such systems should include costs of setting up, operation and maintenance. The cost of creating the network are the highest in this operator model, because to start out with, all of the equipment must be acquired. Operating costs are usually con-

Figure 6: Deployment scenario as a separate 5G Campus Network (in-house operation, no MNO integration)



Source: IC4F Consortium

stant and should therefore be linked to the volume of communication. Accordingly, operation can be more cost-effective for the operator with large facilities. Furthermore, stand-alone operation requires technical know-how, supplied either by a separate technical department or continuous external support. Technical responsibility is clearly defined. This 5G campus network is usually also technically the most powerful of all operator models, because all of the systems are on-site and local radio licences prevent interference with external users. It is accordingly predestined for real-time applications, because there is no added latency. Moreover, it can be set up redundantly to ensure high availability. Because it is set up as a separate entity, this network provides less points of attack and accordingly meets higher data security standards.

- Private campus radio connections with Quality of Service (QoS) in a private 5G network without links to network components used externally.
- Secure transmission quality for sophisticated IoT data services in a private network.
- Dedicated transmission technology and capacities for factory and campus communication.
- Full access to management functions of the 5G campus network, including all current and historic diagnosis data (QoS also for monitoring and diagnostics).
- Suitable for sophisticated real-time applications and for applications with very high communication reliability.
- Applications permitted on the network are limited to purely campus-internal applications; business-to-business applications along the value-added chain are only possible using a local access to the internet.
- Neighbouring 5G campus networks with local radio licences require consensus of the operators [2].

4.2.2 Virtual 'Slice' in the public network of mobile network providers

In the deployment scenario in which the 5G campus network is fully integrated into that of a public mobile network provider, a 'network slice' is used to set up a logically independent network within the public 5G network of the mobile network operator (see Figure 7). Sufficient radio coverage with the public 5G network of the mobile network operator is a precondition. The campus operator does not need to make any investment in its own network hardware (with the exception of user equipment). Any necessary network capacity expansion is undertaken by the MNO, if necessary, with the consent of the campus operator regarding the commercial aspects. All transmitters and elements of the 5G core network are also accessible in the public slice to all mobile network operator customers for their use. In this manner, all customary MNO services (e.g. voice communication or IoT services of the MNOs) can be used. The private slice is used exclusively for in-house applications of the campus operator. The MNO can provide additional 'public' capacity. The campus owner operates internal services on the public MNO network, making a local termination impossible as a rule. The users and terminal equipment of the 5G campus network must be registered with the public MNO and have a SIM (SIM card or eSIM) from the mobile network operator.

- Private campus radio connections with agreed QoS in a virtual private network ('slice') using a public MNO network.
- Secure and guaranteed transmission quality for sophisticated IoT data services in a private network ('slice').
- Use of the infrastructure of the public 5G mobile radio network.

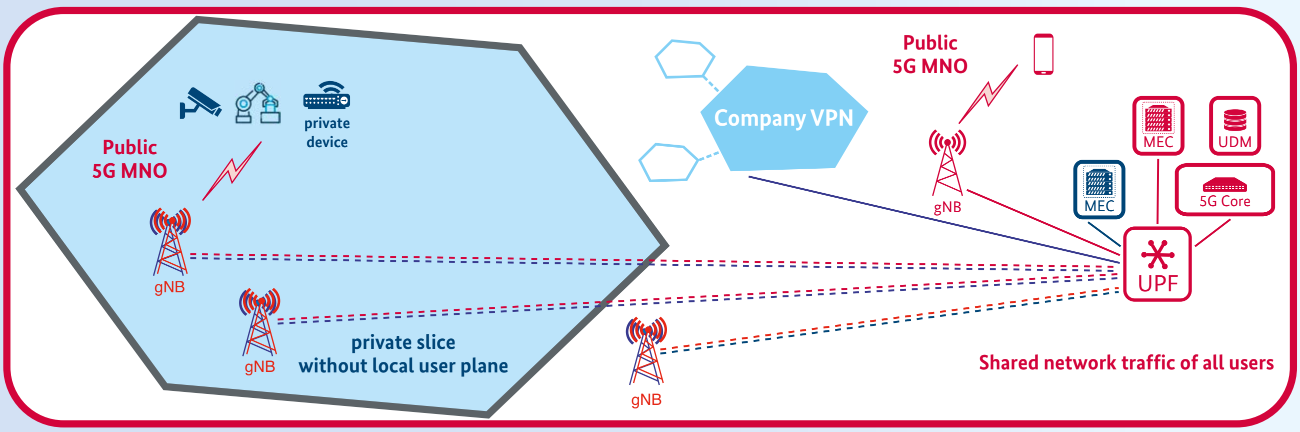
For virtual campus networks, the MNO provides its external, public communication infrastructure and decouples company data using special gateways. This ensures that data traffic is separate from public data.

This type of operator model is suitable both for temporary applications and for situations in which extensive hardware installation is to be avoided. Because the public communication infrastructure is also be used by other subscribers, there may be temporary limitations in bandwidth and QoS. The cost structure is largely dependent on the MNO, the agreed QoS and the service level, and can only be assessed to a limited degree. However, there is good scalability, such that even the smallest applications can be implemented. The special nature of the infrastructure renders this type of system less suitable for time-sensitive and real-time applications.

4.2.3 'Network slice' in the public network of the mobile network providers with a separate user plane

This variation is also based on the transmission infrastructure of an MNO network, but is complemented with on-site components, in particular a local user plane function (UPF) is provided (see Figure 8). This enables local connection to a mobile edge cloud (MEC) that is provided as a dedicated computing service for the campus operator. The user data remain in the area of the campus, only control and management of the 5G campus network take place externally, from the MNO network. The local radio network is enhanced with additional radio units (RU). This makes it possible to keep data completely isolated in the on-site 5G campus network, and at the same time applications can be run that require very low latency.

Figure 7: Virtual 5G campus network as a 'slice' in the MNO network



Source: IC4F Consortium

- Setting up a customised, privately usable virtual 5G campus network with its own network ID within the public 5G mobile radio network, supplemented with local network components.
- Private campus radio links with QoS in a 5G mobile radio network with local network components and local users, on the basis of a transmission infrastructure shared with the MNO network.
- Secure and guaranteed transmission quality for sophisticated IoT data services in the private slice.
- Local user plane (UPF) for connecting to a Campus Edge Cloud and for local data ownership.

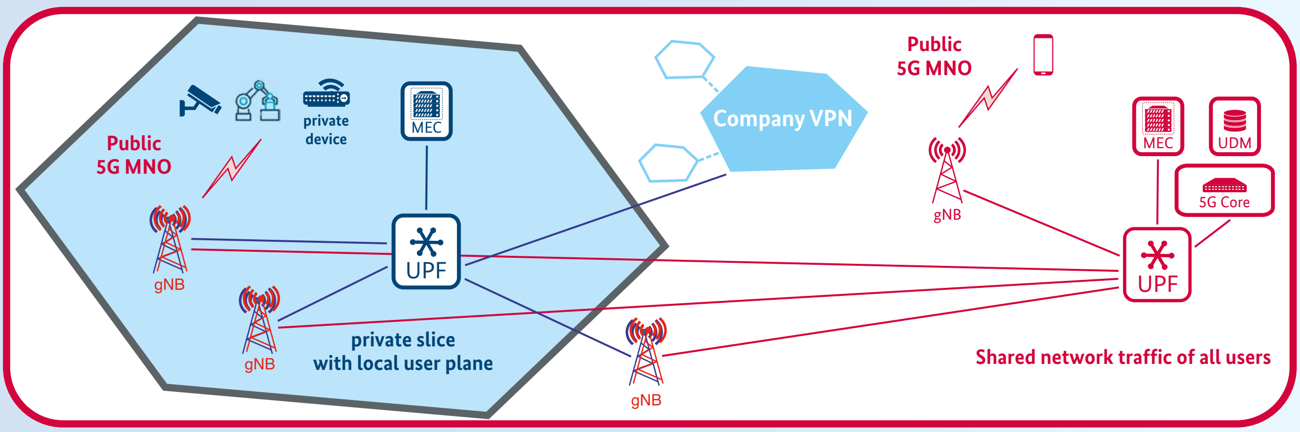
The devices of the 5G campus network are also subscribers of the public mobile radio network and require a SIM (SIM card or eSIM) from the mobile network provider.

4.2.4 Additional 'hybrid' forms and variations

Numerous hybrids are possible between the two operator models already mentioned: 'completely independent' and 'completely virtual'. One example was already introduced in the previous section. Because the 5G core contains numerous individual functions, it is conceivable that these, too, can be partially local and partially MNO-operated. One example is access management (UDM).

Hybrid 5G campus networks are usually provided by large MNOs. They consist of on-site equipment, but may also include external 5G core networks in computing centres, which manage the data traffic

Figure 8: Deployment scenario with local UPF and MEC (local user plane)



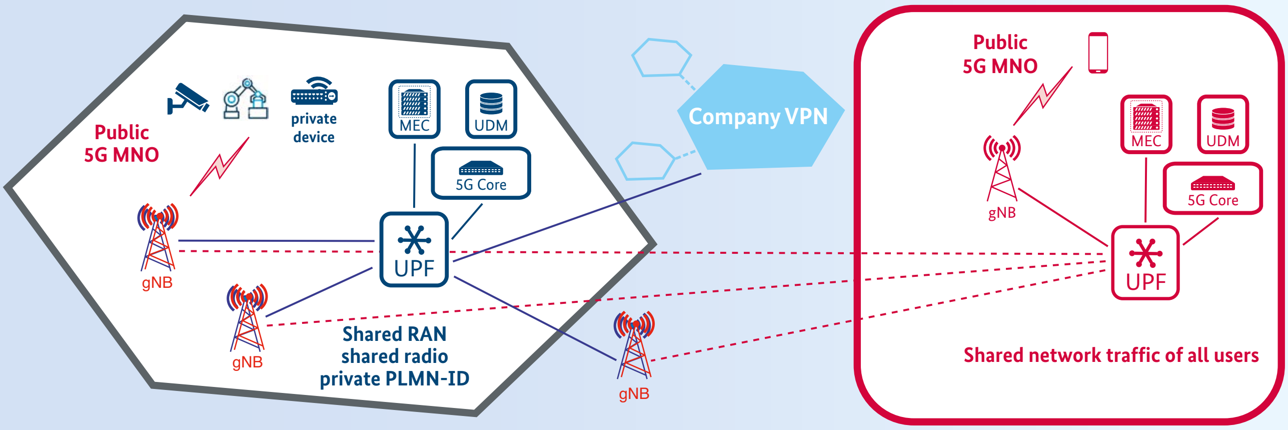
Source: IC4F Consortium

and/or network control traffic, depending on the how they are distributed. These installations combine the advantages of the local 5G campus network (a completely independent communication infrastructure) with the convenience of an externally managed system. Both, local 5G frequency bands – as with in-house operation – and the frequencies of MNOs can be used, depending on the degree and type of hybrid. Solutions are scalable without restriction and can therefore be used for any area of application. The security requirements related to communication and data security must be coordinated with the MNO, so that if the need arises, manufacturing operations are also possible. As examples, the following will demonstrate two fundamentally different variations, the RAN sharing model and the small-cell gateway model.

The **RAN sharing model** is a hybrid deployment scenario which allows only for joint use of the transmission infrastructure (RAN) in accordance with the 3GPP specifications by both the 5G campus network and public mobile radio network of the MNO. All other elements and functions are separate. The 5G campus network user data remain completely within the campus. Public applications can be run on the public mobile network or be uncoupled to run locally (see Figure 9).

It is possible to set up additional base transceiver stations in the 5G campus network which are available exclusively to users of the 5G campus network. This use scenario with RAN sharing has strong similarities with that of a separate 5G campus network (see section 4.2.1). Data flows, control and management of the 5G campus network and user equipment remain in

Figure 9: Hybrid deployment scenario as a separate 5G Campus Network with a shared RAN



Source: IC4F Consortium

the hands of the campus operator, on-site. RAN sharing enables more efficient use of the base stations, yet separation is not as strict. An agreement on RAN sharing with the MNO involved is essential.

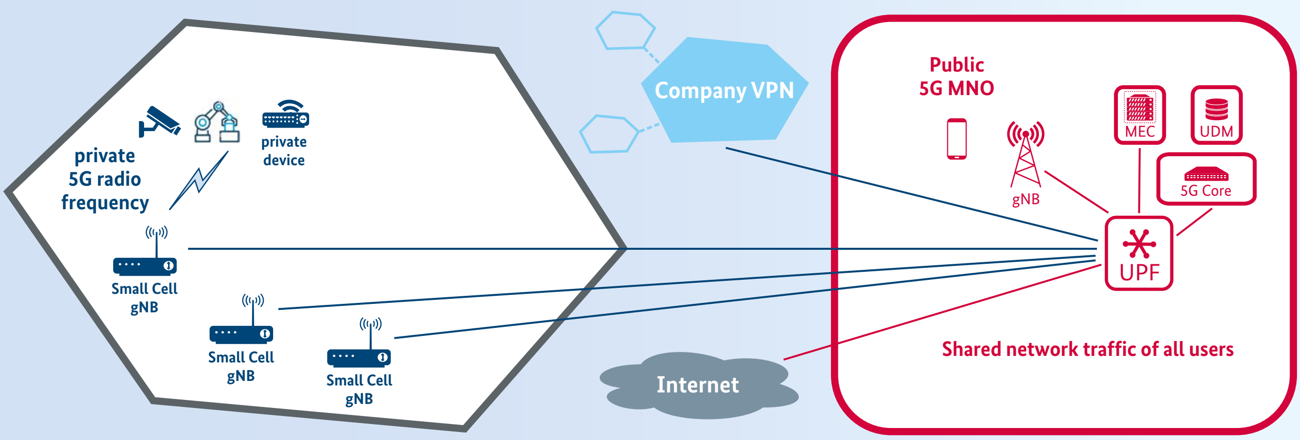
The **small cell gateway model** (see Figure 10) is another hybrid variation that allows for easy implementation of 5G campus networks, on the basis of small radio cells. Small cells are equipped with small 5G base stations (gNBs) that are more similar to WLAN access points with regard to performance and form. In this case, the campus operator can modify the radio network on its own, whereas an MNO provides the 5G core network, connections to user equipment and computing capacity. Only a suitable (LAN) network infrastructure is required for installing this type of 5G network.

4.2.5 Assessment and comparison

Obviously, implementing a completely independent 5G campus network involves more effort than simply purchasing such a network as a 'managed service', using an existing infrastructure (the 5G network of the MNO). However, the variants involving on-site core components exhibit strong advantages also with regard to other criteria, such as run times and latency. It is not surprising that there needs to be a balance between complexity (for the campus operator) and the time to implement and the operating expenses. Table 2 shows the individual variants categorised by criteria that indicate their advantages and disadvantages.

Since the individual criteria cannot be weighed up against each other easily, it is essential to make an extensive requirement analysis (on the basis of an

Figure 10: Small cell gateway model with local 5G frequency, outsourced 5G core network and data processing



Source: IC4F Consortium

Table 2: Simplified assessment of the various use scenarios

	Separate network/ in-house operation	Virtual slice	Slice with local user plane	Hybrid
Criteria	dedicated, independent 5G campus network (4.2.1)	5G campus network within the public network of an MNO (4.2.2)	5G campus network with local user plane and network elements within the public network of an MNO (4.2.3)	Combination of components and services on-site (own responsibility) and provided by MNO (4.2.4) Variation: shared RAN/small cells
Time to implement	-	+	o	o / o
Set up costs	high	low	low to medium	medium / medium
Competency of campus operator personnel	high	low	medium	medium / low
Data ownership	++	o	+	+ / o
Network security	high	high	high	high / high
Security certificates	Flexible; customary (non-3GPP) or SIM	SIM (SIM card or eSIM)	SIM (SIM card or eSIM)	SIM (SIM card or eSIM)
Long-term operability (>10 years)	++	+	+	+ / +
Flexible and adaptable (spatial, capacity, technology)	++	-	o	o / +
Robustness (external and internal disruptions)	+	+	o	o / +
configurable for high availability	++	o	+	o / o
configurable for highly time-sensitive applications (TSN)	++	o	++	+ / o
Monitoring and diagnosis possible for campus operator	++	-	-	o / o
commercially available	2020	2020	2021	2022+ / 2022+

analysis of the planned use cases) for identifying the best solution for the case at hand. Furthermore, it is important to specify the degree of data security required for transmission and storing business-related data. In addition, the expenses incurred at the campus operator and the potential operator of the 5G campus in implementing and operating this type of network should not be overlooked.

To help make a selection, [6] provides the following, expandable list of questions that each potential 5G campus network user should ask himself or herself:

1. What is the maximum, acceptable round trip time for my data?

2. Is it acceptable that business-related data leave the campus or my own IT environment (that is, the data is managed by an external network operator)?

3. Is it acceptable that external service providers, such as an external network operator, knows the number and location of my devices (even if the data remain on the campus or in my own IT environment)?

4. Is device connectivity required only on the campus (and the close vicinity) or also beyond that, for example in road vehicles, trains, in other countries or even globally, in customer branch offices, etc.?

5. Are the financial resources and HR staff available to create and operate a 5G campus network in-house, or should we procure the 5G campus network as a sort of service?

6. Can appropriate guarantees for Quality of Service be bindingly stipulated and implemented (Service Level Agreements, transparency in network operation), so that end-to-end Quality of Service requirements can be complied with across all network elements (radio path, nodes, communication connections, etc.)?

The question "why" should always be addressed. In addition to obvious communications technology reasons, the acquisition of technology and market pressure may also play a role. Suppliers may find it essential that products for customers are 5G-compatible in future – even now, almost 50% of VDMA members are planning a long-term switch to 5G technology. This would make comprehensive in-house testing possible. If there is no compelling reason for 5G technologies, it is also worth considering whether it is better to wait to use 5G. In particular, it is important to remember that not all industry-relevant releases are on the market yet, and that the cost of components will go down with time. If there is no 5G expertise in-house, it is recommendable to start with suitable partners. The cost-benefit analysis should also take account of the fact that the follow-on costs of 5G will be greater than that of WLAN, for example.

4.3 Setting up and operating 5G campus networks

5G campus networks are similar to a complex IT system in the way they are introduced, implemented and operated. Table 3 in the following outlines the required tasks and the effort drivers for the campus operator (or a services provider designated by the campus operator). The tasks falling to the MNO are not included.

Table 3: Tasks of the campus operator in setting up and operation

	Separate network/ in-house operation	Virtual slice	Slice with local user plane	Hybrid
Effort drivers	dedicated, independent 5G campus network (4.2.1)	5G campus network within the public network of an MNO (4.2.2)	5G campus network with local user plane and network elements within the public network of an MNO (4.2.3)	Combination of components and services on-site (own responsibility) and provided by MNO (4.2.4) Variations*: Shared RAN / Small Cells
Identifying the application	Description of the (key) applications, including their qualitative, spatial and security requirements and the expected traffic volume			
Feasibility study	spatial, legal, organisational requirements	spatial, technical and integration requirements	spatial and integration requirements for the MNO and IT	spatial, legal and integration requirements
Legal prerequisites (acquiring a licence)	acquiring a campus licence, proof of technical knowledge and compliance with regulatory obligations	none	none	In some cases, acquisition of a campus licence, proof of technical knowledge and compliance with obligations
Contractual requirements	None for in-house operation If operated by service provider: contract with service provider	(standardised) Service Level Agreement with MNO, service agreement, monitoring agreement	Service Level Agreement with MNO, service agreement	Service Level Agreement with MNO, service agreement, monitoring agreement
Network planning	radio network, infrastructure, service architecture	integrating local systems, assistance in MNO network planning	integrating and connecting local systems and 5G components, assistance in MNO network planning	radio network, infrastructure, integrating local systems
Installation and start of operation	Pre-testing and acceptance, installing systems and infrastructure, adopting services	adopting services	Installing systems and infrastructure, adopting services	Pre-testing and acceptance of the radio network, adopting services
Integrating into company IT	services and rights management, security	rights management, connecting services	services and rights management, security	rights management, connecting services
Operation	direct access to complete FCAPS management and service monitoring	only SLA monitoring	SLA monitoring and operating local 5G components	Operation and monitoring
Support	direct access to on-site 1st and 2nd level mobile communications and services	Standard IT support, external service provider	2nd level services and 5G core, standard IT support, external service provider	Standard IT and LAN support, external service provider

*The various hybrids have different designs

Individual steps will be explained in the following chapters.

4.3.1 Identifying the application

The first and essential step in creating a basis on which to decide which 5G campus type is suitable is to define the (key) applications, including their qualitative, spatial and security requirements as well as the expected traffic volume. Chapter 3 described some relevant application scenarios. The actual applications as considered in this section (e.g. monitoring and control of a production unit) should be identified and characterised as extensively as possible (parameters may include acceptable latency, error sensitivity, availability, robustness, traffic volume and type, and data security).

4.3.2 Feasibility study

Before a company starts using a new communication technology it is essential to conduct an comprehensive economic and technical assessment. Usually, the situation is not a greenfield scenario, which would allow for much easier planning, rather the existing infrastructure must be used.

Efforts to simplify technology are necessary, and are greatly affected by 5G. In assessing whether it makes sense to operate a 5G campus network, an extensive cost-benefit analysis and a site analysis are important aspects. This is at the heart of a feasibility study that should determine whether the legal, time-related and economic prerequisites for the desired version of 5G campus network can be satisfied:

- **Spatial requirements:** The assessment involves conditions on-site, external conditions (location, temperatures, humidity, topography, existing structures, etc.) and internal conditions (installation possibilities, business premises etc.).

- **Legal requirements:** The use of 5G technology for the planned applications must be reviewed regarding standards for security and robustness, required certification, occupational health and safety, and radio licences.

- **Organisational requirements:** How processes will change and the issues of providing personnel and creating internal know-how must be reviewed.

- **Integrational requirements:** Connecting the systems of the mobile network operator (MNO) with those of the in-house IT and of existing industrial communication networks sometimes poses very complex challenges involving standards for delay time, availability, reliability and security.

Furthermore, it is important to assess the importance of the areas to be covered. If some of these systems are relevant for manufacturing, an outage in the 5G campus network could lead to a production standstill. In such situations redundant systems are usually created, which of course means increased hardware outlays. In addition to on-site radio technology equipment, the facilities and systems must be sufficiently equipped with 5G modules. The range of systems being offered will increase significantly in the next few years.

4.3.3 Legal prerequisites (licence)

If a local radio frequency is to be acquired (see also 2.2), it must be proven that standards for necessity and availability are fulfilled (see e.g. [2] for Germany). It can be assumed that it will not always be possible to acquire a spectrum in the desired range at the desired location. For Germany an online tool is available [22] for help in filing an application with the Bundesnetzagentur. When the application has been filed and the licence acquired, the operator then has obligations to the Bundesnetzagentur to ensure that the spectrum in being properly used [2].

4.3.4 Contractual requirements

If construction and/or operation of the 5G campus network is outsourced to third parties, the contract must stipulate performance, quality, keeping deadlines etc. For separate networks, this may apply to third party providers for set-up and operation, if the 5G campus network is not operated in-house. If the 5G campus network will be partially or completely set up in the mobile radio network, SLAs with the MNO must include agreed Quality of Service of the 5G communication and monitoring possibilities for the 5G campus network operator, as well as issues of liability. SLAs are often available in standardised form. These service agreements for various levels define response time for communication outages, for example, which can have significant financial consequences for business-related processes. The SLAs to be agreed refer in turn to the application requirements agreed beforehand. They must be formulated in a manner that will help quickly identify a situation where the requirements of the applications are not being met, and then reliably store a record of the event and clearly define responsibilities.

4.3.5 Network planning

In addition to planning radio coverage, a sensitive factor in providing reliable service, planning also includes the numerous tasks of connection planning, network size and integration into existing networks. The result of network planning is a "blueprint" that can be directly used for implementation without additional detailed work. This blueprint must include at least the following aspects:

- **Radio network:** the required radio coverage is largely dependent on the applications to be used and the surroundings or facilities. If large data volumes will be transmitted, a dense network plan is required. If however there is relatively little sensor data, yet this data is time sensitive, high reliability should prevent radio disturbances. The surroundings play a role, too (plant growth, buildings), as well as the furnishings between halls and buildings (visual contact, many metal cabinets, etc.). Neighbouring 5G campus networks with local radio licences must adhere to operator agreements.

- **Infrastructure/connecting with local systems:** infrastructure planning comprises the physical and logical requirements for connecting 5G components (e.g. the gNPs and antennas), in particular also the electrical and cable network planning (security, fire protection, dimensioning, routers and switches) and the physical hardening (ruggedness, temperature areas, humidity).

- **Connecting to and integrating local systems:** Unless it will be operated as a stand-alone 5G network, the 5G campus network must have a sufficient connection to the outside (for example to the 5G core of the MNO). Due to the high performance of the 5G components, the connection could become a bottleneck if it does not properly support the QoS mechanisms or is insufficient regarding dimensions or redundancy. Local systems (both the local 5G components and for example application servers or databases) require in particular a sufficient connection, because otherwise the advantages of 5G are not available (low latency, high throughput, high availability). In essence, here too the initial requirements list is extremely important, because over-dimensioning could lead to substantially more expense. Of course security aspects should also be taken into account, a security-related hardening of all systems should already be considered in the network planning phase.

- **Service architecture:** the 5G campus network can also provide services. 5G has a service-oriented architecture. In addition to connections, the network planning should also determine how computing resources for services and how target systems (databases or production systems) are to be addressed.

4.3.6 Network installation and start-up

Unless it is provided as a "turnkey" system for example by an MNO or third party provider, a 5G campus network is far removed from a "plug and play" network. Such 5G campus networks, if they are available at all, are still in the early phase of the product cycle, that is, that many adjustments are still necessary in set-up and implementation.

- **Pre-testing and acceptance:** due to the lack of market experience with 5G systems, it is recommendable to start as soon as possible with prior testing on a small scale. Even in the case of "turnkey" offers and light variations (such as the hybrid solutions discussed in the foregoing), these lead times should be included in planning.

- **Installation of systems and infrastructure:** When infrastructure and systems are installed and set up for the first time, companies usually already have access to extensive experience, sometimes even in-house. The time risk is therefore low with careful planning. If the 5G network is partially or entirely run on the mobile radio network, the provider's SIMS (SIM card or eSIM) must be installed or configured.

- **Adopting services:** the many possibilities provided by 5G also lead to new and additional complexity. If in particular features such as MEC (mobile edge cloud) are to be used, this could create a high time risk due to the novelty of the possibilities. Integrating the applications usually also involves process changes and as such can create a time challenge and additional effort. Extensive application-specific testing is therefore absolutely necessary.

4.3.7 Integration in the company IT infrastructure

The 5G campus network becomes a part of the company's IT infrastructure or of the previous industrial communication networks. In particular, rights and service management and the security of the 5G network require close cooperation with the existing system landscape. Rights management must integrate all new and existing network users and takes place in the 5G network in the UDM (Unified Data Management). Provisioning interfaces are to be created in the company's IT and in the 5G network.

5G campus networks provide various possibilities for services management, including communication services; in particular, certain services can be granted higher or lower priorities. Identifying and managing the (communications) services and rules (initiation, configuration, modification, termination), as well as their provisioning to the 5G campus network requires a connection to the existing company IT.

4.3.8 Operation

If the 5G campus network is to facilitate use of essential company applications, network operation will be complex:

- **Complete FCAPS management and service Monitoring:** for network management of 5G campus networks, the aspects of fault, configuration, accounting, performance and security management (FCAPS) must be taken into consideration. Operators of extensive IT infrastructures are usually familiar with this, such that the 5G campus network is often simply another component in the overall company infrastructure. However, the specific (mobile communications) challenges and the protocols to be used are new. When using the features offered by MEC (mobile edge cloud), there are new tasks involved in monitoring this distributed cloud structure, which also require close attention, due to the high performance aspect.

- **SLA monitoring:** If the 5G campus network is operated with the help of service providers, in particular MNOs, Service Level Agreement (SLAs) ensure performance requirements. SLA monitoring is then only required for monitoring compliance with the SLAs. In addition, monitoring must apply strategies determined in advance (e.g. halting production) if the SLAs are not adhered to in a specific situation. SLA monitoring usually does not go beyond pure monitoring; error detection and resolution are also the job of the service provider.

- **Operating local 5G components:** local 5G components, in particular the local UPF, can be operated either by the campus operator or by a service provider. These components involve time-sensitive and data security system components requiring close attention.

- **Operation and monitoring of the radio network:** If a hybrid network involves a network only using small cells set up locally, that however are connected to the MNO, operating this local radio network is similar to operating a local WLAN network. This means that here a pragmatic operating approach is commonly used, which tends to replace any components that are down, rather than carrying out extensive equipment inspections.

- **Maintenance/network adaptation and expansions:** regardless of whether the 5G campus network is operated in-house or using a service provider, the system components used require regular maintenance and upgrades. In particular, the very high availability times can only be achieved without using scheduled maintenance if the systems are highly redundant. If this is not desired or is not possible due to cost or complexity, maintenance should take place at regular intervals.

4.3.9 Support

Whereas the operating aspect involves infrastructure performance, the support function focuses on (human) users. It comprises user help (including hotlines and training), on-site service as well as trouble shooting, that is, extensive error analysis and resolution. This is particularly important where communication downtimes can lead to extensive effort and cost (e.g. turning off machines and interrupting processes). If the 5G campus network is operated through a service provider, the provider usually also supplies support services. The various levels of support are listed in Table 3, "1st and 2nd level mobile communications and services", "2nd level services and 5G core" and "Standard IT and LAN support".

4.4 Summary

This chapter described the various operating models for 5G campus networks and the related technology architectures and building blocks. Criteria were specified on this basis for setting up and operating 5G campus networks. It is important to mention that is in the interest of any company to first identify the use cases for networks and to then analyse the requirements. Tables 2 and 3 build on this, providing decisive and objective tips to companies when designing their own 5G campus network.

5 Outlook and further development

5.1 International 3GPP standardisation and regulation

For companies wishing to implement 5G campus networks, standards and norms are very important. The international standardisation of 5G campus networks is being carried out by the 3GPP (3rd Generation Partnership Project). The 3GPP specifies standards and requirements for network infrastructure and terminal equipment. Europe is represented in 3GPP by ETSI (European Telecommunications Standards Institute) and its members. The basic requirements and recommendations of the ITU (International Telecommunication Union) regarding spectrum and frequencies for radio transmission are implemented by the national regulatory authorities (in Germany, the Bundesnetzagentur). 3GPP Release 16 has placed vertical users more in the focus of 3GPP-5G standardisation. Technical specifications are developed in various working groups.

The services working group (3GPP SA1) looks at 5G use cases and 5G requirements for applications with complex communications requirements, very low latency and very high availability (Work Items on Communication in Automation for Vertical Domains (CAV), FS_CAV, cyberCAV, (FS_)eCAV). This includes specifications for industrial and energy automation (documents: TS 22.104, TS 22.261, TR 22.804, and TR 22.832). The performance requirements for non-public networks – the basis for 5G Campus Networks – were also formulated by this group (TS 22.261). Additional important vertical use cases are found in the medical field (TR 22.826) and the media sector TS 22.263 and TR 22.827).

The Architecture Working Group (3GPP SA2) addresses these topics in the following Work Item families: LAN for Vertical Industries (Vertical_LAN), Industrial IoT (IIoT), Non-Public Networks (NPN) and Ultra-Reliable Low-Latency Communication (URLLC). These groups also defined the concepts for Stand-Alone Non-Public Networks (SNPN) and Public Network Integrated Non-Public Networks (PNI-NPN). The various operator models in these Guidelines are based on these specifications.

Corresponding Work Item families have been created in many more 3GPP Working Groups, such as in the Security Working Group (3GPP SA3) and the Working Groups for the radio access network (3GPP RANx) and for the core network and terminals (3GPP CTx).

The ITU has been developing and coordinating the shared use of international radio frequencies in mobile communications for over 30 years. The ITU coordinates with national regulatory authorities regarding allocation and harmonisation of frequencies. For 5G there are currently three frequency bands that are of interest, with a few exceptions. Figure 11 provides an overview of selected countries across the globe. The allocation, regulation and international harmonisation of frequency ranges gives user equipment and network infrastructure manufacturers more planning certainty regarding product design, global market possibilities and also allows mobile network subscribers to use international roaming. This means that with certain user devices, a subscriber can also request 5G services in foreign networks. Companies with campus networks in various countries can connect them together and use their devices across borders.

Three frequency bands have been created internationally:

- **Low band frequency range:** in the 600 MHz range in North America and 700 MHz range in European countries.
- **Mid-band frequency range around 3.6 GHz:** the range between 3.4 and 3.7 GHz was sold in an auction in Germany in 2019. The range between 3.7 to 3.8 GHz must be applied for in an allocation

scheme. In other countries, too, local frequencies will be assigned, for example in the UK and in Malaysia. There have been some deviations globally, which must be complied with due to existing satellite or radar services.

- **High band frequency range between 24 and 28 GHz:** Frequencies in the area of 26 GHz will be used in Europe in the future – in some countries a local allotment is still being discussed. These millimeter waves have only a relatively short range (around 200 m), however, there is more than 1GHz of bandwidth available. This provides applications with either maximum data rates or very low latency.

At the World Radio Conference 2019 (WRC-29), more frequency bands were opened up to allocation to mobile communications. These are in even higher frequency ranges, that is, exceeding 30 GHz. National regulatory agencies have accordingly issued a recommendation for their national frequency plans, and 3GPP can make decisions in the coming planning and releases regarding technical specifications.

5.2 Overview of 3GPP Releases

Due to the large number of use cases to be considered, and the new global frequency spectrum to be agreed on, the standardisation procedure became very

Figure 11: Global overview of all 5G frequencies (already allotted and planned)

Source: IC4F Consortium

complex and resulted in a new standardisation programme in several phases (see Figure 12):

The first phase concentrates on EPC, the existing core architecture, and deployment of new 5G radio access technology, especially when using frequencies below 6 GHz. This phase (3GPP Release 15) will also introduce 5G radio via the Dual Connectivity mode with LTE as an anchor (5G NSA) and create the basis for an independent option (5G SA). However, forward compatibility with the future 5G core is ensured and the following releases will be backward compatible with 5G Phase 1. Use cases focus on broadband access with greatly increased data rates (eMBB).

In Phase 2 with 3GPP Release 16, requirements for sensitive MTC use cases will be fundamentally fulfilled, that means that latency-sensitive or high reliability use cases are addressed (URLLC), and basic functions for real-time applications are standardised with TSN (Time Sensitive Networking). Some vertical solutions and their respective use cases will be supported in the standard. For campus networks, 3GPP Release 16 also describes the end-to-end solution for non-public 5G networks, that is, private 5G networks.

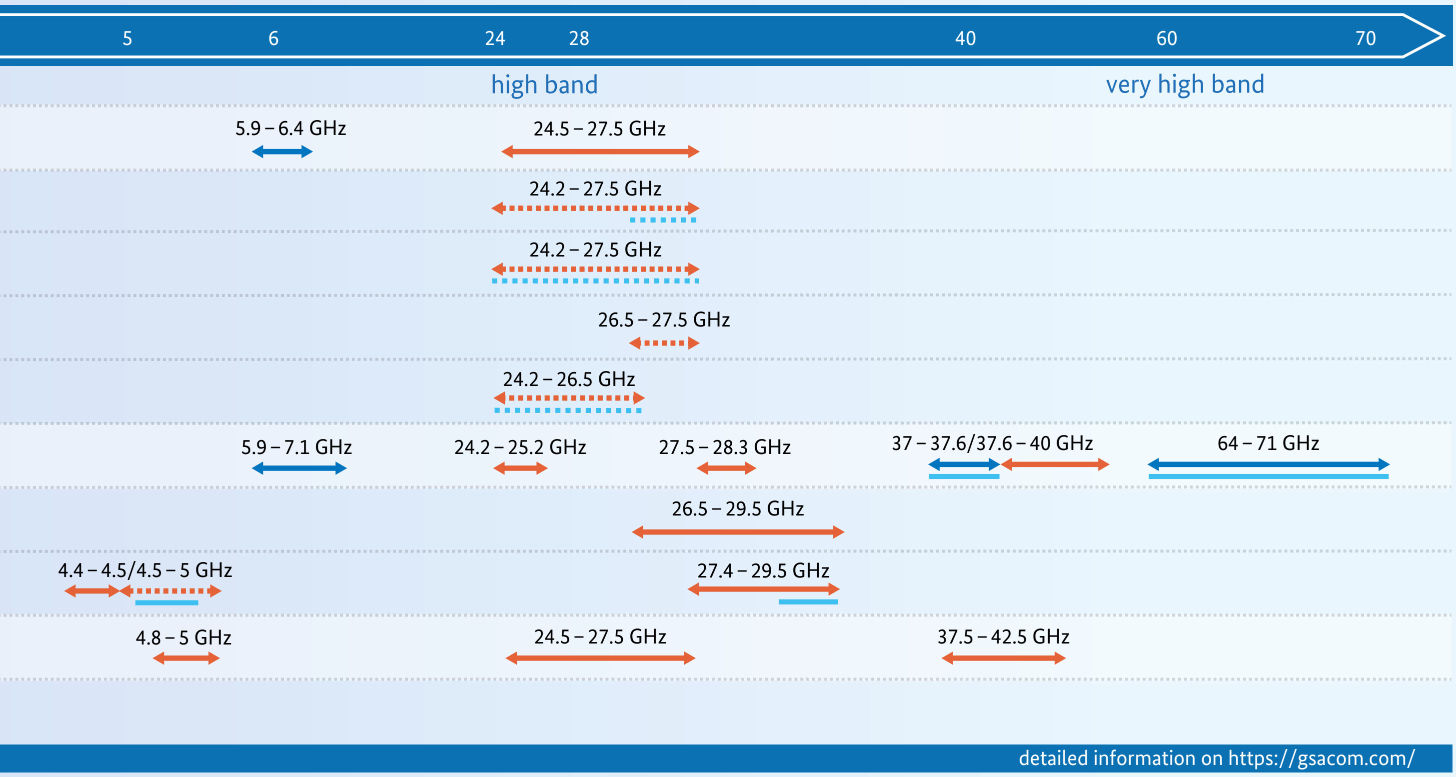
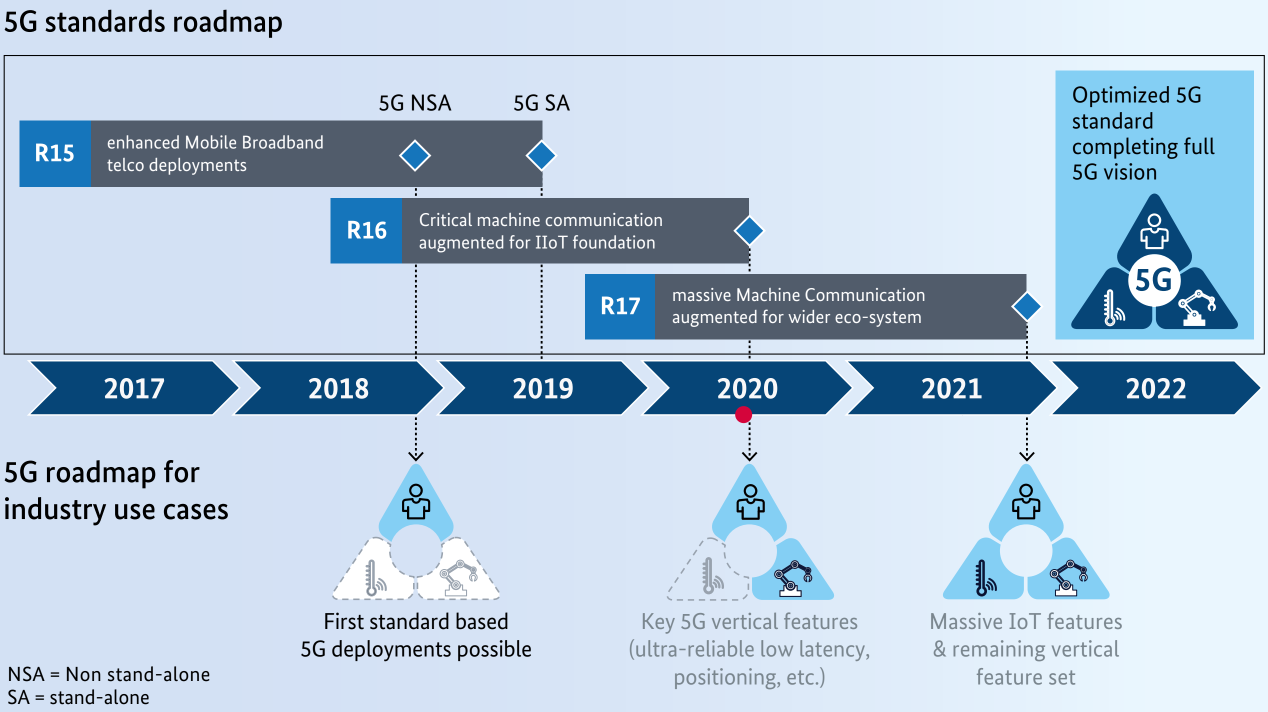


Figure 12: Development of the 3GPP standard for 5G technologies



Source: 3GPP and Nokia

In Phase 3 with 3GPP Release 17, the new 5G Core will also efficiently support massive MTC applications and it will be possible to use the 5G radio standard to operate a very highly-scaled number of IoT sensors and actuators together with the machines using the user equipment ecosystem available by then. The functions for real-time applications using TSN will be expanded, enabling latency that was previously only attainable with wired systems.

In the next phases of standardisation, 3GPP Release 18 will incorporate the initial know-how attained with commercial networks and further additions to vertical requirements are expected. This applies for example to use cases such as radio communications with and between vehicles and vehicle platoons (platooning) and more flexible concepts for TSN.

5.3 Future aspects of 5G

The first 5G networks use higher frequencies than those of 3G and 4G, spurring research on functions that significantly improve reach and, accordingly, radio coverage, in particular very large service radii outside the proximity area and radio signal strength deep inside buildings. IoT services will accordingly become more reliable, as will voice services, which are still very important. Standardisation also deals with new frequency bands in the millimeter wave range, e.g. the globally harmonised frequencies around 26 GHz, 39 GHz or above 66 GHz. For industrial IoT use cases, user equipment is moving to the focus as a study from Release 17 is continued on ‘NR lite’ – basically, simplifying functions and reducing user equipment complexity, at the very least to reduce costs.

This will make it possible to migrate 4G-based sensor networks to 5G and to benefit from 5G technology in the radio system as well as in the central core network functions. An important topic of standardisation also includes positioning methods that may improve device localisation three-dimensionally and at the cm-level accuracy.

This includes furthermore work areas, from operating drones (UAV) or drone applications (UDC) to expanding 5G coverage beyond terrestrial networks. Here, the approaches are linked to various flight elevations, e.g. high altitude, Low Earth Orbit (LEO) or High Earth Orbit (HEO).

When implementing all of these aspects in 5G, small and medium sized enterprises stand to benefit greatly in the context of campus networks. Furthermore, campus networks are set up technologically neutral for regulatory reasons. This makes it possible to integrate supplementary systems using 5G or to continue using existing systems in mixed operation with 5G, and to optimise them. One example for this type of island operation within a campus network is the UWIN technology that has been further developed in IC4F for real-time connection of sensors and actuators at the field level. At the same time, systems that can be integrated using standardised interfaces such as the Non-3GPP Inter-Working Function (N3IWF) are also possible.

5G Campus Networks will be characterised by a high degree of complexity and an extremely broad spectrum of functions. Planning, setting up and operating such networks must be automated as much as possible, because many 5G Campus Networks are operated by institutions that, unlike network operators, do not have the necessary telecommunications expertise (for example, schools, hospitals or factory operations). This is a major challenge that must be met in order to satisfy the basic requirements for broad use of 5G Campus Networks. This applies in particular to Industrie 4.0, where production modifications and constant changes in the environment require a high degree of adaptability and flexibility.

In order to reliably automate or simplify important processes such as planning, configuration and optimisation in 5G Campus Networks, artificial intelligence (AI) will increasingly be used. AI is promising, because 5G Campus Networks generate immense amounts of data, and AI methods can be used to extract useful information from these data sources and others (e.g. context or production data), and to make robust decisions based on this data. In this way, efficiency can be vastly improved, for example, or planning and configuration automated. AI will also make it possible to predict critical situations by monitoring end-to-end (E2E) the critical parameters of Quality of Service (e.g. data rate, latency), and to proactively optimise resources and networking. Many applications, whether in autonomous transport vehicles or mobile robotics, are evidence of high dynamics and interaction with the environment. At the same time, these applications require high standards of real-time capability, reliability and availability of the entire system. Critical situations in 5G Campus Networks, undefined system conditions or extreme disruptions must therefore be predicted with reliability before they occur, in order to take countermeasures on time (e.g. providing additional or alternative communications resources).

It is generally expected that AI will gain in importance in the area of 5G Campus Networks and will become an integral part of them. AI will be necessary to give even non-experts control over the complexity and the large scope of functionality. New online AI methods will have to be developed for some applications, so that robust results can be attained even with relatively small amounts of data. To this end, it is essential to use domain knowledge (for example, models and correlations) in order to develop hybrid AI methods that are based not only data but also domain knowledge. In addition, methods for distributed training and learning with restrictions on communication for analysing large volumes of data will be required (new functional architectures will also be needed). Finally, the resulting algorithms must have a low level of complexity and be suitable for implementation with low latency (for example, with massive parallelism).

5.4 Conclusion

5G technologies facilitate communication between man and machine – to put it simply. Business requires this development and will also provide impetus to the digital transformation in Germany. The basic network technology can serve use cases in the traditional cellular network context as well as special scenarios and areas of application in factories or industrial facilities and beyond. In the future, technological boundaries will be moved out even further. Sensible management of resources and energy efficiency will become even more important. Open systems – such as open-source systems for further development of functions and the secure handling of data – will play an increasingly important role. Cellular network structures will be enhanced with demand-driven network configurations.

5G campus networks will establish themselves as a fixed component of the infrastructure for private, non-public and completely secure company communication.

6 Notes

6.1 Abbreviations and important 5G terminology

2/3/4/5G	2nd/3rd/4th/5th mobile communications generation
3GPP	3rd Generation Partnership Project: organisation that creates global standardisations for mobile radio networks (radio network, core network, services and integration)
5G-ACIA	5G Alliance for Connected Industries and Automation: international alliance for supporting 5G in industrial automation and communication
5GC	5G Core network
5GC-CP	5G Core network Control Plane: control and management functions of the 5G network in the 5G core network
AGV	Automated Guided Vehicle: autonomous, driverless transport vehicle
AI	Artificial Intelligence
AR	Augmented Reality
BNetzA	Bundesnetzagentur: German federal regulatory authority for electricity, gas, telecommunications, postal services and rail transport
CAV	Communication in Automation for Vertical Domains: 3GPP work on use cases and service requirements for automation applications
eMBB	enhanced Mobile Broadband: very high data transmission rates (1 Gbps and more)
FCAPS	Fault, Configuration, Accounting, Performance, Security: managing errors, configuration, accounting, performance and security, the various areas of communication networks management
GHz	Gigahertz: unit of measurement for frequency range
gNB GPS	next generation Node B: 5G base transceiver station
GPS	Global Positioning System
IC4F	Industrial Communication for Factories: a research project sponsored by the Federal Ministry for Economic Affairs and Energy on 5G communication in the industrial setting
ID	identifier
IIoT	Industrial IoT: 3GPP term for industrial communication requiring high and special standards, for example time synchronisation
IoT	Internet of Things
IP	Internet Protocol
IT	Information technology
ITU	International Telecommunication Union : United Nations agency responsible for issues concerning information and communication technologies
LAN	Local Area Network
LTE	Long Term Evolution: 4th mobile communications generation
MEC	Mobile Edge Cloud or Multi-Access Edge Cloud
Megahertz	unit of measurement for frequency range
MES	Manufacturing Execution System
MIMO	Multiple Input Multiple Output: radio interface with several controlled receiving antennas and with several controlled transmitting antennas

mMTC	massive Machine-Type Communications: high density of IoT terminal equipment per km^2
MNO	Mobile Network Operator (of a public mobile network)
MTC	Machine-Type Communication: communication between machines, sensors, actors, etc.
NFV	Network Function Virtualization
NPN	Non-Public Network: 3GPP terminology for private networks
NR	New Radio: new 5G radio technology
NSA	Non-Stand-Alone: 5G mobile radio network architecture with 5G radio communication and LTE core network
PNI-NPN	Public Network Integrated Non-Public Networks: 3GPP terminology for private networks that are integrated into the public mobile radio network (e.g. hybrid operator models)
QoS	Quality of Service
RAN	Radio Access Network : radio-based network of the mobile radio network on-site
SA	Stand-Alone: 5G mobile radio network architecture with 5G radio communication and 5G core network
SA	Services and Architecture: technical specifications group of 3GPP for services and architecture of 3GPP communication networks
SDN	Software-defined Networking
SIM	Subscriber Identity Module: hardware module for user identity and 3GPP security certificates (SIM card or eSIM)
SLA	Service Level Agreement: agreement between the network operator and the network user
slice	virtual 5G network with defined features, e.g. part of an MNO network
SME	small and medium-sized enterprises
SNPN	Stand-alone Non-Public Networks: 3GPP terminology for separate private networks (in-house operated)
TR	Technical Report: informal technical report issued by 3GPP
TS	Technical Specification: normative technical standard issued by 3GPP
TSN	Time Sensitive Networking: collection of IEEE 802.1/3 standards for time synchronisation and time-based communication, for example are required by industrial communication
UAV	Unmanned Arial Vehicle (aircraft or drone)
UDM	Unified Data Management: user data management
UE	User Equipment
UPF	User Plane Function: interface for user data
URLLC	Ultra-Reliable Low Latency Communication: mobile radio communication with very high reliability and availability (99.999%) and very low latency (1 ms)
UWIN	Ultra-reliable Wireless Industrial Network
VDMA	Verband Deutscher Maschinen- und Anlagenbau: German Mechanical Engineering Industry Association
VR	Virtual Reality
WLAN	Wireless Local Area Network: based on IEEE 802.11

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6.3 Links to projects, organisations and initiatives

3GPP 3rd Generation Partnership Project: global cooperation between standardisation bodies for standardising radio communications,
https://www.3gpp.org/

5G-ACIA 5G Alliance for Connected Industries and Automation: International alliance for supporting 5G in industrial automation and communication,
https://www.5g-acia.org/

IC4F Industrial Communication for Factories, flagship project of the Federal Ministry for Economic Affairs and Energy: the goal is to develop secure, robust and real-time-capable communications solutions for the manufacturing sector,
https://www.ic4f.de/

NGMN Next Generation Mobile Networks: projects of mobile radio companies and mobile radio equipment suppliers for developing the next mobile radio generation,
https://www.ngmn.org/

VDMA Verband Deutscher Maschinen- und Anlagenbau e.V.: German Mechanical Engineering Industry Association, Europe's largest industrial association, based in Frankfurt am Main,
https://www.vdma.org

ZVEI Zentralverband Elektrotechnik- und Elektronikindustrie e.V.: Central Association of Electrical Engineering and of the Electronics Industry, an association representing the interests of the electronics industry in Germany and abroad,
https://www.zvei.org/

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