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Importance of Internet Exchange Point (IXP) Infrastructure for 5G: Estimating the Impact of 5G Use Cases (Extended Technical Report)

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Executive Summary

While the Internet is ubiquitous in most parts of the world as of today, the dominant network access technology is gradually shifting from wired to wireless connections. Notably, the ever increasing bandwidth together with reduced latency in mobile networks enables a multitude of new use cases for a range of industries. Yet, with ever increasing requirements of applications the Internet architecture needs to keep pace with the recent developments, particularly in light of the holistic approach of the new mobile communication standard 5G. In this study we shed light on the effect of 5G in the Internet's core, specifically Internet Exchange Points.

Thus, we coherently derive twelve 5G use case groups from a comprehensive picture of twenty relevant vertical indusrty and describe how they can solve current challenges. We describe these use case groups and their use cases in terms of their network implications and requirements in detail. Further, we develop and apply a methodology to qualitative assess these 5G use cases and rank them in terms of possible impact on the overall Internet traffic growth. Based on this systematic approach we find that the traffic for the use case groups Video in 5G, Health and Virtual & Augmented Reality will rise significantly. We identify a large number of other use case groups, e.g., Live Events, Tactile Internet, and Manufacturing that will contribute rather small individual fractions to the overall growth of internet traffic. However, their aggregated contribution to the internet traffic growth will be significant.

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1 Introduction

1.1 Motivation

Mobile communications and the Internet have become drivers of prosperity, economic growth, and accompany us in our daily lives [1–3]. Traditionally, the majority of Internet traffic was carried by wired connections through the access networks towards end users [4]. The increase in wireless connection bandwidths has brought a gradual shift towards mobile communications. Currently, the next generation mobile communication standard called 5G is on its way. globally [5–9]. The 3GPP is finalizing release 16 and the 5G frequency spectrum has been assigned in many countries including Germany (31.12.2018). In addition to a new radio interface, with a new frequency spectrum, 5G also embraces a new network architecture [10]. This network architecture is necessary for 5G applications to fulfill their latency requirements as low as 1ms [11, 12]. Therefore, 5G will transform the communication landscape immensely, particularly due to the inclusion of new technologies like Software Defined Networking (SDN), network slicing, cloud edge computing [13–19]. New use cases and their applications building on these technologies are already described, prototyped, and deployed across the globe.

In principle, these new applications will require a multi-access edge cloud (MEC), which is a server unit at the edge of the network, or a related ad hoc cloud or a device-enhanced MEC architecture [20,21] close to the base station or the individual users. This computing unit coordinates, operates, as well as configures network functions and network resources. At the same time, it is providing computing power and data storage capacities for different applications. This computing power and storage capacity in the vicinity of the users and their base stations in conjunction with acceleration hardware modules [22,23] and low-latency compute processing techniques [24, 25] will enable ultra reliable and low latency communication services [26–28]. Naturally, research and development has focused on changes in network architecture and its implications at the edge [29–32]. However, studies on effects of 5G at the core of the Internet, specifically Internet Exchange Points (IXPs) are missing. Most new use cases will generate massive amounts of data at the edge, which bears the question for large IXPs, like the DE-CIX, how this increase in traffic volumes and traffic flows at the edge will impact the Internet's core infrastructure. Undoubtedly, Internet traffic will increase; nonetheless, the uncertainty on the impact on the Internet core through 5G remains.

Internet Exchange Points (IXPs) traditionally enable medium and large networks, e.g., Content Distribution Networks (CDNs), as well as Tier 1 and Tier 2 Internet Service Providers (ISPs) to exchange internet traffic directly at their IXP platforms. The processing evolution of the internet and the continuous popularity for networks to connect directly amongst each other, lead to IXPs to be a core component of the internet architecture and physical infrastructure. The benefits for networks to use IXPs stem from saving transit costs and self-management of their internet connectivity, with the goal to provide reliable high-quality internet services. Constantly, IXPs evolve to match the needs of the changing internet landscape and traffic demands. This is done by continuously updating the IXP's technical components to state-of-the-art technology, by developing new technical features, and through the development of new services. Due to the significance role that IXPs play within the global internet landscape, they are also able to drive the development of new internet technologies and actively support the internet's development.

The introduction of the new 5G communication standard will result in a general change in the mobile network architecture [33, 34]. Computation and storage will be performed at the base stations of mobile networks. This will enable new use cases and applications [10]. In the past, research has primarily focused on the implications and consequences this changed architecture will have at the edge of the communication network and on the mobile networks themselves. However, systematic research on the possible effects that the introduction of 5G will have on the core of the Internet has not been performed.

In general, Internet traffic has steadily increased over the last years and is expected to continue growing [35]. While the adoption of the 5G standard leaves the current interdomain Internet architecture untouched, the overall impact on the interdomain infrastructure due to the changes in the edge network architecture has not been researched in detail and is not well understood. On the one hand, the use cases enabled by 5G focus mainly on traffic at the edge, which could lead to the conclusion that interdomain traffic will not be specifically altered. On the other hand, the overall increase in use cases and their traffic will lead to an increase in information exchanges in general, which will very likely directly affect interdomain traffic.

1.1.1 Infrastructures for Exchanging 5G Interdomain Traffic

Over time the Internet has evolved from a strict hierarchical topology to a more and more densely interconnected network of networks. This development was driven by the development of new use cases for the Internet, business decisions to reduce costs, and the need of more control of network connections to ensure a better quality of Internet services [36]. In general, the Internet interdomain traffic, which is also referred to as the core Internet traffic, is exchanged between the autonomous systems (ASs) owned by distinct organizations (i.e., the different "networks") via two main concepts for interdomain traffic: transit and peering. With the transit concept, a customer AS (network) connects to a transit provider network that abstracts all the routes and forwards all the traffic for the customer network so as to enable the full participation of the customer network in the Internet. With the peering concept, a customer AS (network) directly exchanges traffic with one or several other networks. Peering is further divided into public peering and direct peering. Public peering provides direct connections to one or several other networks at an Internet Exchange Point (IXP). Private peering provides a direct connection between two networks via a private network interconnect (PNI).

Practically speaking, large networks, such as networks of large media content providers or content delivery networks (CDNs), typically directly exchange traffic with top Internet Service Provider (ISP) networks via PNIs. At the same time, these large networks typically use IXPs to exchange traffic with a wide variety of other (small to medium) networks. In addition, networks can use transit providers to exchange traffic. Overall, the global interdomain traffic is transported via different interdomain infrastructure setups, which are mainly transit provider networks as well as IXP and PNI infrastructures. Normally, policy and business considerations determine the type of interdomain infrastructure over which the interdomain traffic is routed. In particular, the policy and business considerations of a given customer network determine the combination of interdomain infrastructures to be used and as well as the proportions and types of traffic to route over each interdomain infrastructure type.

To the best of our knowledge, a detailed study on how the global Internet interdomain traffic is distributed over and handled by the different interdomain infrastructures dose not exist. Such a study would require all interdomain infrastructure operators to cooperate and share statistics about their traffic. The common understanding of the interdomain infrastructure community appears to suggest that PNIs may exchange a somewhat higher portion of the global volume of interdomain traffic than IXPs. Nevertheless, IXPs play a critical role as interdomain infrastructure in that a large IXP forms a focal point for traffic aggregation that exchanges very high volumes of interdomain traffic on a single concentrated interdomain infrastructure [36]. In contrast, PNIs are scattered interdomain infrastructures in that the PNIs are scattered both in terms of placement on the Internet topology as well as geographical locations. To underscore the importance of large IXPs for today's Internet, in 2016, the German government declared large IXPs with more than 300 connected networks as critical infrastructures [37].

While the interdomain traffic analysis that we conduct in this study is relevant for all interdomain infrastructures, due to the concentrated focal point nature of large IXPs, this study is especially important for large IXPs. Overall, the interdomain infrastructures play an important role in supporting the 5G development of collaboration across mobile, edge, and core networks. In particular, IXPs provide centralized platforms for networks to interconnect [38–40]. Today, large IXPs interconnect up to thousands of networks, providing a rich environment of different network types which exchange combined interdomain traffic on the order of 10 Tbps. For about 10 years, the growth of traffic at IXPs has been strongly driven by an increasing demand on the Internet for content and video. Not only the size of the content and video streams has increased, but also content delivery networks (CDNs) appeared and have made extensive use of IXPs to move data closer to the users to increase the quality and efficiency of the content delivery [36, 41, 42]. If IXPs will be used similarly to the historical developments with video and content, what would be the impact of 5G for IXPs? The latest developments already point in this direction, as IXPs gain popularity for industry networks to become connected. Answering this question is specifically interesting for IXPs, as they are not directly involved in the policy and business decisions and strategic planning of their interconnected networks. Therefore, IXPs can only estimate growth from historical and current traffic monitoring. Hence, our study aims to provide an outlook onto the possible impact of 5G use-cases on the interdomain traffic that drives traffic growth at IXPs.

From a business perspective, due to their nature of being singular focal-point (concentrated) interdomain infrastructures, IXPs have to predict and prepare for an increase of interdomain traffic in advance to satisfy their customer demands. In contrast, the scattered transit and PNI interdomain infrastructures may be able to more readily absorb traffic demand changes with several small (geographically distributed) adjustments; whereas, the concentrated IXP infrastructure may require significant adjustments (in a particular single location). Therefore, a methodology to estimate the additional increase of interdomain traffic due to the 5G mobile communication standard is of interest to transit providers and PNIs, but is of utmost interest for IXPs. In particular, if some of the new use cases will increase the interdomain traffic more than others, IXPs would have an advantage, if they knew which use cases should be monitored in terms of implementations.

In this study, a joint effort of the TU-Dresden The Deutsche Telekom Chair of Communication Networks, the 5G Lab Germany, DE-CIX, and Arizona State University, we aim to evaluate the impact of 5G technologies on the Internet's core traffic, especially on IXPs. Our scientific contribution is manifold: we identify comprehensive 5G use cases, their applications, and develop a methodology to rank their impact on the overall Internet traffic. We then apply the methodology and derive a use case ranking.

1.2 Important Technologies enabling 5G Use Cases

The introduction of cloud edge computing in the network will enable different 5G use case applications and foster a shift in the network architecture. Applications can have latency requirements as hard as 1ms to 10ms. To guarantee such a round trip time computational tasks must be performed closer to the application compared to previous mobile communication technologies. If this is infeasible for any reason the delay for the end user will be too long. To address this in a straight forward manner, the computation is moved to the user equipment. However, usually the user equipment does not provide sufficient storage and computation capacities. So the task has to be performed very close to the user equipment, i.e. by the multi-access edge cloud server, which could be positioned at the base station. This MEC will provide storage, network management and also computational power for the application.

The MEC has to share its resources with multiple users, probably even hosting and coordinating different applications for each user at once. Yet its resources are not unlimited. To cope with this scarcity, the network has to coordinate traffic routes, prioritize traffic flows, as well as share bandwidth and spectrum for the applications. SDN is a new paradigm decoupling the data from the control plane in a network. Thus, a logically central component (controller) with a more global knowledge about the different network components decides which network path certain packets are using. Furthermore, the network can be "sliced", e.g. two different use cases get a separate network slice each. These slices act like a separate network, with defined parameters for, e.g. bandwidth, latency, and, resilience. Although, both slices run parallel on the same physical infrastructure.

For better understanding a short description of the underlying network technologies enabling the 5G use cases is added:

- The Multi-Access Edge Cloud (MEC) [old term: Mobile Edge Cloud]: describes an infrastructure of one or multiple servers with storage and computational capacities at the edge of the network. Applications can be transferred from one edge cloud to another without noticeable delay for the user. This makes the application seem mobile. Hence, the infrastructure is called mobile edge cloud. While some applications will run on a public MEC, other use cases will require a private MEC. This can have security or spatial reasons. For instance, emergency room applications to support surgery should run on a private MEC as any connectivity loss or delay might have life threatening implications.

- Software Defined Networking (SDN): SDN decouples the control plane of switches and routers from their data plane, enabling the control and orchestration of those devices from a central entity, e.g., SDN controlled traffic flow routing controlled by a central routing control [43–46]. That central (not necessarily one physical) SDN controller is in charge of one single network formed by several SDN switches on which softwarization takes place. SDN advocates for centralized controlled network protocols replacing the state of the art distributed protocols. The centralized approach plus the softwarization of the network protocols makes it easier to experiment with new ideas and adopt the network to specific needs and, thus, speeds up the deployment of new or upgraded protocols. SDN is a result of consequent fusion of computing and communication, or software and networking.

- Network Function Virtualization (NFV): NFV is a direct request from telecommunication operators to shorten development cycles as well as cutting costs for service deployment by replacing specialized and static hardware solutions with software on standard hardware using virtualization concepts. The softwarization fosters quick deployments of new services, while the virtualization allows relocation, live migration, upgrade, and downgrade of services wherever and whenever they are needed. Furthermore, the softwarization will cut the cost of exchanging and maintaining new services reducing the capital expenses (CAPEX) and operating expenses (OPEX) of network operators.
- Service Function Chaining (SFC): SFC allows the flexible and efficient deployment of network functions for different applications. With NFV the elements of the chain can be provisioned in virtual environments on any commercial off-the-shelf hardware. SFC facilitates practical use cases that normally require a complete network service (NS) consisting of several Service Functions (SF)s in a specific order (e.g. first a firewall then a DPI), NFV has to be capable of forcing packets to traverse through them in the predefined order. The traffic in a SF chain traverses between running SF-Interfaces probably distributed over the different physical compute nodes.
- Network slicing: The network slicing concept describes a logical segment of a physical network guaranteeing a set of Quality of Service (QoS) requirements. More importantly, they are ensured for end-to-end communication, not only at the radio access segment, but also at the network core. The whole network infrastructure needs to provide provisioning, manage the association to slices, offer interoperability and support performance and isolation. To realize the concept of network slicing in 5G systems, SDN, and NFV play critical roles. SDN contributes a control plane which has the complete view and control of network resources such as network functions and computation infrastructure to quickly set up on-demand a configurable data plane to adapt to various requirements from applications. Whereas, NFV provides tools to manage and orchestrate computation and storage resources needed to instantiate network functions.

2 Impact on IXPs

2.1 Industry Sectors for 5G Use Cases

Given the current 5G vision to become a disruptive new standard we expect a wide adoption in very different vertical industries. The holistic 5G idea supports numerous use cases. To infer the impact of 5G use case adoption on the Internet as a whole and IXPs in particular we develop a comprehensive list of all use cases in all vertical industries and group these use cases. In absence of related work, we follow a systematic approach to identify these use case groups and their use cases in the different vertical industries.

In this study, we examine and describe different levels of abstractions to identify relevant use cases and analyse them. On the highest level are vertical industries, consisting of different smaller industries and subindustries. 5G use case groups for those vertical industries describe a technology or systematic interplay of technologies in this industry. A use case group usually consists of different use cases, which are a 5G solution to a specific today unresolved problem. An example would be an autonomously driving car, navigating through a city with no human interaction. The control and steering of such cars is one use case. Another use case might be the entertainment service, e.g., a video stream, for the passengers. Both use cases are part of the use case group “Connected Cars”. This use case group is mapped to the vertical industries Transportation and Warehousing.

Naturally, new technologies will transform some vertical industries but will not impact others at large. To identify the relevant vertical industries and the relevant use case groups we apply the following structured approach: First we derive a holistic picture of all vertical industries, by applying the industry classification system of the Office of Management and Budget of the United States. In this classification system 20 industry sectors are described accumulating to a total of over 1.000 industries and subindustries. For each of these industry sectors we have scanned the literature on 5G use cases and interviewed experts on possible use cases. In the next step, we map our identified 5G use cases to the corresponding vertical industries and group them. The results are comprised in Table 1 and Table 2.

Index	Vertical Industries	Use Cases	Use Case Groups
1	Agriculture, Forestry, Fishing, and Hunting	Automated harvesting, machine automation, farming, animal tracking, ground condition tracking	Agriculture
2	Mining, Quarrying, and Oil and Gas Extraction	Machine automation, virtual assistance hardly connected area	Mining
3	Utilities	Decentralised energy grids and resynchronisation	Energy
4	Construction	Construction site virtualization, machine control, construction support	Construction
5	Manufacturing	Factory virtualization, robot control, production support	Manufacturing
6	Wholesale Trade		No 5G use case
7	Retail Trade	Advertisement, virtual reality shopping	Video in 5G, VR/AR
8	Transportation and Warehousing	Autonomous transport vehicles, connecting end users moving at high speed	Cars, Aircraft, Train
9	Information	Broadcasting news with video, information distribution via virtual and augmented reality (VR/AR)	Video in 5G, VR/AR
10	Finance and Insurance		No 5G use case
11	Real Estate, and Rental and Leasing		No 5G use case
12	Professional, Scientific, and Technical Services	Collaborative project work with video or VR	Video in 5G, VR/AR
13	Management of Companies and Enterprises		No 5G use case
14	Administrative and Support		No 5G use case
15	Educational Service	Education or training via VR /AR, practical training with haptic feedback	Tactile Internet, VR/AR

Table 1: Vertical industries from NAICS Table 1 of 2

Index	Vertical Industries	Use Cases	Use Case Groups
16	Health Care and Social Assistance	Supporting personal health sensor devices, smart ambulance, smart surgery	Health
17	Arts, Entertainment, and Recreation	Information distribution from and within live-events, AR tourism guides, VR art exhibitions, VR/AR live gaming	Live-Events, VR/AR
18	Accommodation and Food Services		No 5G use case
19	Other Services (except Public Administration)	Maintenance within the 5G context	Predictive Maintenance
20	Public Administration	Automated video surveillance, broadcast as emergency service	Video in 5G Emergency Service

Table 2: Vertical industries from NAICS Table 2 of 2

Some use cases, like virtual reality, will be relevant in different vertical industries. Some use case groups will be excluded from deeper investigation, or their use cases are discussed within other use case groups. This applies to the following use cases for the following reasons.

- Mining: The Mining use case group consists of highly specialised use cases, which usually applies to very remote areas. Underground an Internet connection will barely be available. Most computation and storage has to and will be performed locally. As a live connection via the Internet is very unlikely, data transmission will be rare or done via media devices like USB-sticks. Therefore, this use case is considered unrelevant for this study.
- Emergency Service: Assuring connectivity for multiple users under emergency circumstances is an important issue, yet highly depending on the existing infrastructure. While 5G provides the technological background for such a scenario, only one major use case is described: emergency broadcast. This use case will be triggered on rare occasions. The overall contribution to the Internet traffic of this use case group is negligible or even rarely existing in comparison to other use case groups. Therefore, this use case group is not considered relevant for this study.

This study will focus on the remaining twelve use case groups and their use cases. The use case groups and the described use cases are displayed in Table 3. A structured methodology to rate the use case groups and use cases according to their impact on the internet traffic is developed in section 2.2. The use case groups and their use cases are described rated according to our developed methodology in section 2.3. The 5G use case groups are ranked according to their rating in section 2.4. This ranking suggests which 5G use case groups is more likely to increase the overall traffic at IXPs. A detailed describtion and rating for each individual use case is found in the Annex.

2.2 Use Case Requirements - Methodology

In this section we develop and explain the methodology to estimate the impact of 5G use case groups on IXPs.

The easiest way to analyse and understand the effects of the introduction of 5G on IXPs would be an extensive measurement study comparing the change in interdomain traffic at an IXP before and after the introduction of the 5G mobile networks. Unfortunately, at the time of writing, 5G is not yet widely introduced and while mobile network equipment is available, suitable end devices can only be acquired as development samples. Additionally, a traffic measurement approach would only capture past and current changes to the traffic increase and would not uncover underlying trends causing future changes.

An alternative methodology could be to implement the various different 5G use cases on 5G testbeds, to estimate the resulting traffic at the edge and at the core of the internet. However, most 5G use cases are still in research, development, or prototype implementation phases, which makes measurements difficult, if not impossible. With these prerequisites there is close to zero available data to perform a reliable traffic estimation for the use cases.

Since traffic measurements are currently impossible, we decided to investigate, which use cases will probably have the highest impact on interdomain traffic. We developed a method that estimates the traffic of the selected use cases and provides a ranking of the use cases against each other by their probable impact on the increase of internet traffic.

Since the traffic for the 5G use cases cannot be measured yet; another evaluation method for the analysis and evaluation has to be applied. We introduce a method to analyse which use

Table 3: The twelve identified 5G use case groups with their associated 5G use cases.

Agriculture	Tactile Internet
Precision farming ground sensor networks [47–49]	Human training [50–54]
Agriculture machine automation [55, 56]	Robot assist. & skill transfer [50,53,57,58]
Agricultural object recogn. [59–63]	Movement to machine learning [50–52, 58]
Predictive maintenance [56, 64]	
Energy	Live Events
Smart energy grid home automation [47, 65–67]	Local XR support [47, 64, 67–71]
Grid control [66, 67, 72, 73]	Local information distribution [47, 64, 67, 68, 70, 71, 74]
Fault detection [64, 67, 73]	Off-premise event streaming [47, 64, 67, 71, 74]
Construction	Manufacturing
Virtualization of the construction site [67, 75, 76]	Massive sensor networks for virtualization [67, 77, 78]
Camera data for virtualization [67, 79, 80]	Camera data for virtualization [67, 78]
Camera data for object recognition [64, 67, 79, 80]	Camera data for object recognition [50, 64, 67, 78, 81]
Construction machine control & Mobility support [67, 80, 82]	Machine control & Mobility support [67, 78]
Predictive maintenance [67]	Predictive maintenance [67, 78]
Virtual & Augmented Reality	Video in 5G
360° Content [78, 83–86]	Surveillance [47, 64, 87, 88]
XR Simulations [64, 68, 84–86]	Conferencing [47, 68, 89]
6 degrees of freedom VR [83, 85, 86]	Streaming [68, 87]
XR gaming [64, 78, 84–86, 90]	Broadcasting [47, 68, 87]
Cinematic VR [78, 83, 85, 86]	
Cars	Health
Platooning [64, 91]	Wearables [92–94]
Car control [47, 64, 91]	XR surgery assistance [95]
Car coordination [47, 64, 91, 96]	Assistive robot control [95]
In-Car entertainment [47, 64, 91]	Telemedicine and rehabilitation support [67, 95]
Predictive maint. [64, 67, 91]	Smart ambulance [97]
Aircraft	Trains
Aircraft passenger entertainment [98–100]	Passenger entertainment [67, 101, 102]
Critical flight information [98–100, 103]	
Predictive maint. [98–100]	

cases will have a larger impact on the IXPs business model than others. More specifically, we have developed an analytical three step approach, including a calculation model, which enables the ranking of 5G use cases against each other to determine their impact on the interdomain traffic.

- First, the generated traffic at the edge for each use case is estimated, by analysing the requirements of the use case's connection link.
- Second, we estimate which percentage of the edge traffic will be transmitted over the internet. This can be done by analysing where the use case will compute and store data.
- Third, we use statistical data to analyse predictions on growth of the use case group and the use case implementations. This provides us with an estimation for the number of future use case implementations.

While this method does not determine the amount of data that a distinct use case generates and transfers through the internet, it enables the evaluation of the relative contributions of the different use cases to the increase of the overall internet traffic. Thus, our methodology enables a ranking of the different use cases against each other in terms of their relative contributions to the internet traffic growth. The model can be adjusted according to future changes by adjusting and refining the different parameters.

Use Case Requirements

To evaluate the impact of a given use case group on the IXP, we first evaluate each 5G use case associated with the considered use case group. The sum of the use cases for a given use case group results in its the overall impact of the vertical use case group.

The 5G standard has been shaped by the requirements of various wireless communication use cases, especially those requirements that are not met by the current wireless technologies. These requirements are well researched and standardized and can be found in the literature for most use cases.

To understand the traffic that a use case will likely generate at the edge, we consider the requirements of the use case's connection links. In particular, we analyse the following three requirements of this connection link.

- Nodes – the number of connected devices at the edge
- Bandwidth – the bandwidth that each node requires to operate
- Latency – the round trip time required between the node and the application.

Each of these requirements is evaluated independently. In order to structure the analysis for the edge traffic estimation and to help with the relative ranking of the use cases against each other, we model every requirement as belonging to one of two states. We acknowledge that in reality, there are infinitely many possibilities for each of these three requirements. However, having an infinitely fine-grained range for each requirement is not practical for the model. In order to obtain a practical, yet insightful model, we limit each requirement to two states. This modeling of the use case requirements can be differentiated into a finer grained model with more than two states for each requirement in future work.

- Nodes – Use cases which collect data from many nodes and transmit their data frequently will generate more traffic, than use cases with only a few nodes. We consider a use case to have many nodes if more the 1000 nodes are connected to one base station. The corresponding state of such an requirement is many. If an application has less than 1000 nodes connected to one base station, then the number of the nodes is low, and the corresponding state of the requirement is few.

Table 4: Definition of traffic type *T*: The number of nodes is given the highest importance, followed by required bandwidth and required latency in terms of traffic generation.

Nodes	Bandwidth	Latency	Traffic Type Factor *T*
Many	High	Low	8
Many	High	High	7
Many	Low	Low	6
Many	Low	High	5
Few	High	Low	4
Few	High	High	3
Few	Low	Low	2
Few	Low	High	1

- Bandwidth – A use case which requires high bandwidth for each connected node to run smoothly is likely to generate more traffic at the edge compared to a use case that can operate flawlessly operate with a low bandwidth per node. We associate a use case with a high state, if it requires a throughput above 500 Mbit/s per node. Use cases which can operate flawlessly with a lower bandwidth are associated with the state low.
- Latency – We consider that use cases which need low latency will transmit data more frequently than use cases which can tolerate high latency; therefore, low-latency use cases will generate more traffic at the edge. We associate a use case with the state low, if a round trip time of less than or equal to 40 ms per node is required. If the use case can tolerate a round trip time above 40 ms, then we associate the use case with the state high.

To ease the comparison of the use cases we assume that all nodes transmit data permanently with a constant throughput.

These three requirements influence the generated traffic at the edge differently. We consider the number of nodes to be more important than the required bandwidth per node; moreover, we consider the bandwidth of each node to be more important than the required latency. All states of the three requirements can be combined into a matrix, with each combination of states. We term a possible state combination as *traffic type*, see Table 4. The traffic types are ranked, so that the traffic type that is likely to generate the most traffic is at the top. Each traffic type has a *traffic type factor T*. A higher traffic type factor *T* indicates that the corresponding combination of state requirements, generates more traffic at the edge than a combination with a lower *T*. A combination of use case requirements (nodes, bandwidth, and latency) specifies a traffic type; the table orders the traffic types according to their impact on the traffic in decreasing order of contribution to the traffic.

Traffic Transmitted over the Internet In the 5G network architecture, compute and storage tasks can be performed at the edge, i.e., computing and storage functionalities are provided by the MEC or a related ad hoc cloud or a device-enhanced MEC architectures close to the base station or the individual users, as illustrated in Figure 1. Computing and storage in the vicinity of the users and their base stations enable ultra reliable and low latency communication services. Use cases will transmit data to the MEC. Nevertheless, some data still needs to be collected at a central location. The amount of this centrally collected data will vary according

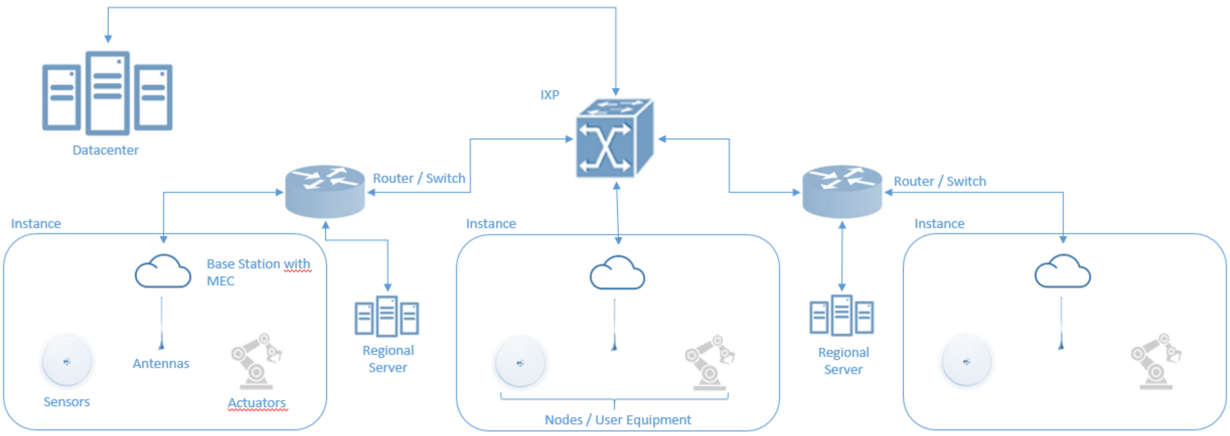

Figure 1: Network architecture: Computation and storage can be performed at the user equipment nodes, base station, a regional server, or a central data center that is reached via the IXP.

to the computing and storage requirements of the different use cases as well as the available computing and storage at the edge. To understand which portion of the edge traffic is transmitted across the internet, we analyze two parameters for each use case: network level for computation and network level for storage.

Network Level for Computation – We define the network level for computation as the point within the network hierarchy, where the majority of computational tasks of the use case are performed. This can typically either be:

- the user equipment (sensor, actuator, or mobile phone)
- the MEC at the base station receiving the data from the user equipment
- a regional server receiving data for computation from a regional close base station
- a data center receiving the data over the internet

Our general assumption is that a use case, whose computations are mainly performed closer to the user equipment will send less data via the internet than a use case with a more centralized computation.

Network Level for Storage – We define the network level for storage as the location within the network hierarchy where the collected data of the use case and its service are stored. We apply the same categories and logic for the network level of storage as we do for the network level for computation. The closer the service stores its data to the edge of the network, the less data is transmitted via the internet. As computation and storage can be performed at different hierarchy levels within the network, we associate each level with a certain percentage of the data transmitted from the edge to a data center via the internet. Table 5 shows our assumptions for modeling parameters the percentages of data transmitted over the internet, mapped to the network level for computation and the network level for storage. We emphasize that these percentages are modeling parameters. A future adjustment can be performed if measurements of the use cases are available.

We also note that these percentage may appear quite low, especially for the Data Center level. However, the user equipment will most likely only create telemetric and signalling data in

Table 5: Percentages for Internet Traffic for Different Levels of Computation and Storage

Network Point of Computation	Data in Percent	Network Point of Storage	Data in Percent
None	0.00%	None	0.00%
User Equipment	0.01%	User Equipment	0.01%
Base Station	0.50%	Base Station	0.50%
Regional Server	1.00%	Regional Server	1.00%
Data Center	5.00%	Data Center	5.00%

the Interdomain traffic. The base station will load the necessary functions or application, but will not create much more traffic. For the data center and regional server for storage, only real data will be transmitted. However, a lot of the edge traffic will also include signalling, headers, and telemetrics that will not be centrally stored. Moreover, not every traffic flow sent to a data center will be routed trough an IXP. Therefore, we consider a relative low 5% value for the data center network point.

Our third step to estimate the impact of a use case on the traffic transmitted over the internet is to incorporate the scale of the use case. The scale of the use case depends on the number of deployments or the size of the corresponding use case group. In particular, we consider the probable number of use case implementations. We describe the number of implementations as instances I. Currently, no use case is widely implemented; however, most use cases are considered to be implemented over the next years. The timescale varies between industries and use cases. To rank the use cases and industries according to their impact, we decided to estimate the scale of implementations of the use cases in the year 2025. We consider this as a compromise between statistical availability of reliable data and relevant prediction timeframe in the future for most use cases.

We obtained the number of instances I by analysing statistical data from the official sources and government statistical agency, such as the German “Statistisches Bundesamt” and performed linear prediction for each use case. We decided to limit the geographical scale to the number of implementations of use cases within Germany.

Every discussed use case is evaluated by means of the six described parameters. These parameters are depicted within the following spider diagram, see Figure 2. For each use case a spider diagram can be made. These spider diagrams are then layered upon each other for the entire use case group.

Mathematical Model

Based on the previously described parameters and the corresponding factors we can compare the impact of the use cases by calculating their impact rating (ρ) We use the impact rating ρ to rank the use cases according to their relative impact on the overall internet traffic and therefore on IXPs. The traffic type factor T implies how much traffic the use case generates at the edge of the network. The network levels for computation and storage estimate which percentages (C for computation, S for storage) of this edge traffic is transmitted through the internet. The number I of instances describes how many implementations of the use cases will be present in the year 2025 in Germany.

We multiply the traffic type factor T with the sum of the percentages $C + S$ of network level for computation and network level of storage. The result is an estimation of the relative traffic amount that a use case will probably send via the internet on a per instance basis. We multiply

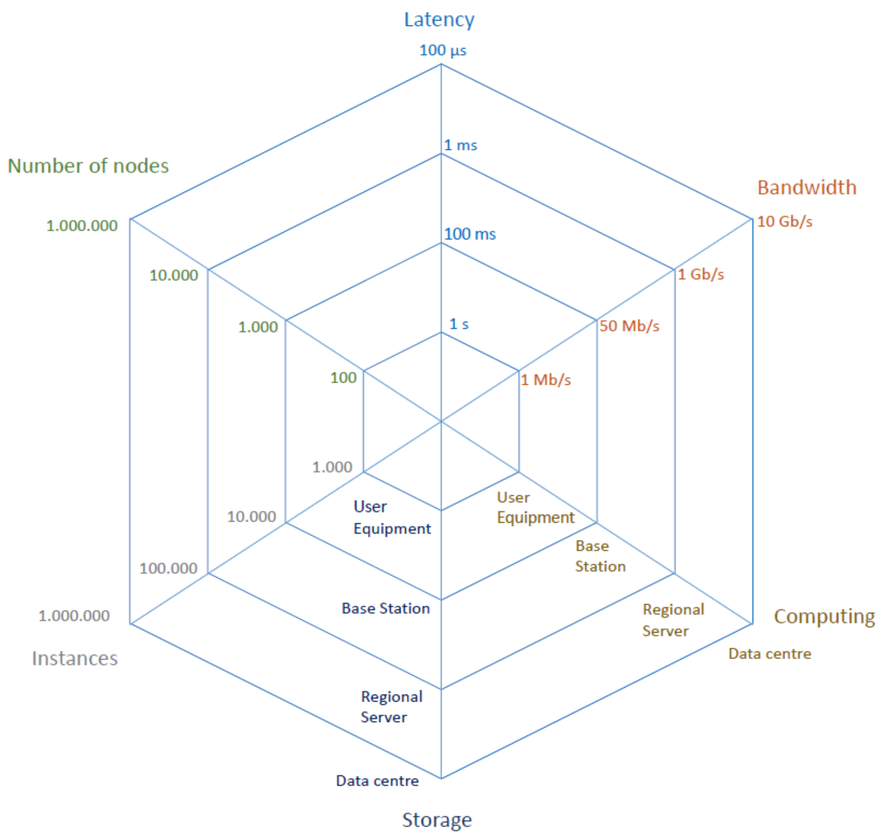

Figure 2: Spider diagram showing the impact of the six considered parameters for use case Evaluation: number of connected nodes, bandwidth, and latency, network levels of computing and storage, as well as number of instances for a given use case.

this result with the number I of instances to obtain the total impact rating ρ of the use case:

$$\rho = T \cdot (C + S) \cdot I. \tag{2.1}$$

The product of the equation, i.e., the impact rating ρ, is an indication how much impact the use case will have on the increase of internet traffic. The impact rating of a use case group equals the sum of the impact ratings of its use cases.

To give a graphical overview of the factors that influence the impact rating ρ, the factors can be shown as a spider diagram with the six described parameters, see Figure ??. Layering all spider diagrams of the use cases in a use case group on top of each other provides an indication of the factor that is the most important for the use cases in the industry.

General Assumptions Most of the use cases will be implemented in the future. Some of them will be implemented earlier and be more widespread, while others will need much longer to scale. To ease the comparison between the use cases in this study a common space and time horizon has been decided. For all use cases we estimate the possible number I of instances in Germany in the year 2025. The year 2025 is considered the most suitable time frame. Estimates for the implemented instances for most use cases and applications in the year 2025 are available. Estimates for longer time frames are considered too vague.

2.3 Evaluated 5G Use Cases

2.3.1 Agriculture

The agriculture industry is facing several challenges today, such as climate change, dramatic increase in demographics and immense consumption of food. Agriculture aims at addressing these challenging by incorporating cross-industry technologies and use cases under the name of precision farming [47, 56].

Description

The use case group Agriculture employs information and communications technology with the ultimate goal is to improve crops. It defines methods for measuring related data, analysing the measurements (in near real-time, if needed), and defining and applying actions accordingly. For instance, data about weather and soil conditions can be collected by specialised sensors, then analysed by some machine learning algorithms, to determine proper amounts of water, pesticides and fertilisers for each individual plant. In the following, we focus on four exemplary Agriculture use cases: Agricultural object recognition, Precision farming ground sensor networks, agricultural machinery automation and predictive maintenance.

Figure 3: Agriculture – Agricultural Machinery Automation

In **Agricultural object recognition**, agricultural machinery and the farm are equipped with cameras to take photos and videos for several objects like plants and crops [49, 56, 62, 63]. Another use case is the deployment of **Precision farming ground sensor networks** to provide information about current ground conditions like humidity. These sensors could be connected via LPWA technologies to a base station [48, 49, 104–106]. The **agricultural machine automation** is mainly about platooning in the context of harvesting. For instance, it can be used to enable an agricultural vehicle to follow a leading tractor. Both vehicles can synchronise, for instance, in terms of speed, position and braking [55, 56, 107]. The idea of **predictive maintenance** is to use measured data of agricultural machinery to identify as close as possible the time of upcoming failure so that preventive actions can be performed. This approach promises to decrease machinery downtime, thus maintenance costs, when compared with time-based preventive maintenance [56, 64, 67].

Deployment of the use cases above can be confronted with two challenges: First, farmers usually are not willing to upload information about their farms to external clouds, for storage and analysis, mainly for privacy reasons. As an alternative, these information can be stored either on a self-hosted server in each farm, or on a regional cluster. In addition, the data can be pre-processed using well known approaches so that both the data utility and the required privacy level are preserved. Second, access to farm-related data can be challenging in the areas where cellular network coverage is low. This challenge can be tackled with Low-Power Wide-Area (LPWA) technologies and 5G communication standards. We expand on this point below.

Agricultural platooning use cases might face additional challenges. For instance, agricultural vehicles have to avoid tracks containing crops, or other obstacles like humans, animals or trash. One possible solution is to use an autonomous drone flying several meters ahead of the vehicle to take photos. The vehicle can avoid upfront obstacles based upon analysis of these photos.

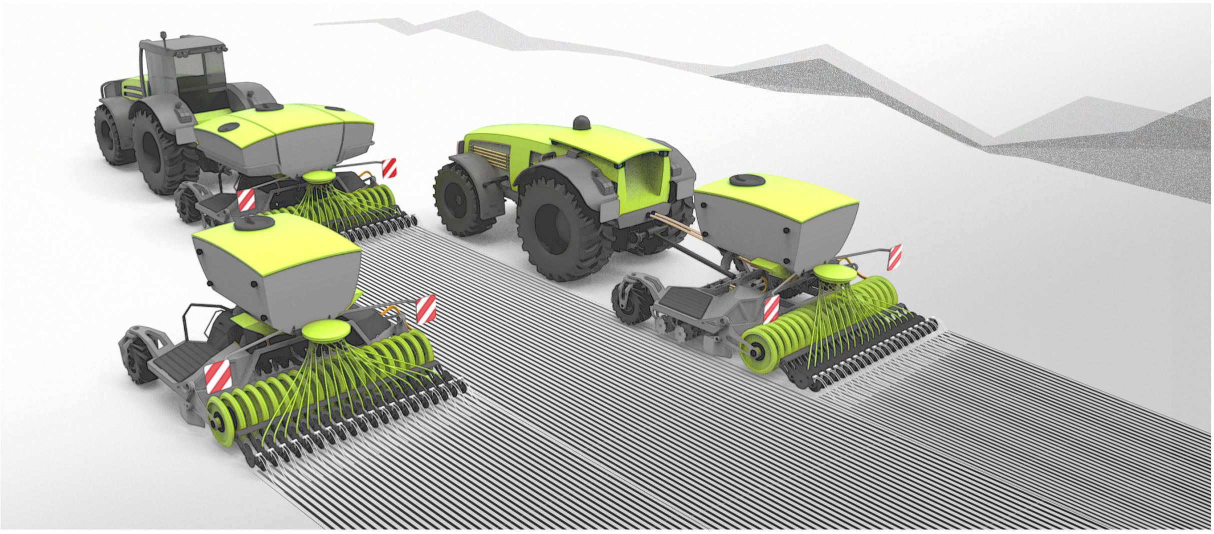

Figure 4: Agriculture – Agricultural Machinery Platooning

Network Implications

As the above discussed use cases are implemented in farming fields, establishing 5G connectivity will be difficult. This is because 5G cellular networks will likely be deployed first only in the cities. LPWA could possibly cover rural areas and used to collect latency insensitive measurements requiring small bandwidth. Still, requirements like high throughput and low latency for farm photographing or agricultural machinery automation cannot be met by LPWA technologies. More precisely, in these use case, the database and software have to be close from the agricultural machinery. This could be achieved using a nearby mobile edge cloud, e.g. installed in a cellular base station or placed along with a small base station directly on the agricultural machinery.

To summarise, Agriculture use case can be realised by equipping every farm or region with infrastructure for data collection, and offloading computation and storage. While this solution is widely accepted today, some major agricultural companies prefer to have their own infrastructure, and to develop their own services. This would give the farmer the opportunity to buy services, like crop analysis or predictive maintenance, from such companies.

Traffic Types Taxonomy

Agriculture has eight traffic types. Table 6 lists their properties, and maps them to the above described use cases.

T	Latency	Bandwidth	Connected Devices	Use Case
8	Low	High	Many	
7	High	High	Many	
6	Low	Low	Many	
5	High	Low	Many	Precision farming ground sensor networks
4	Low	High	One or few	Agricultural object recognition
3	High	High	One or few	
2	Low	Low	One or few	Agricultural machine automation
1	High	Low	One or few	Predictive maintenance

Table 6: Agriculture – Traffic Types

The mapping between traffic types and use cases can be described as follows: Farm photographing uses a few cameras requiring low latency and high bandwidth. Ground sensors are likely connected using the LPWA technology which has low data rates and can tolerate with high latency. As for the agricultural machinery automation, the platoon is rather small but requires low latency for synchronisation, while steering and control data do not require much bandwidth. Predictive maintenance does not require a low latency nor a high bandwidth.

Use Case Rating

Table 7 lists the aforementioned four use cases of Agriculture along with their ratings, while Figure 5 shows the overall use case spider diagram.

Use Case	Rating
Precision farming ground sensor networks	1.000
Agricultural object recognition	600
Agricultural machine automation	200
Predictive maintenance	1.000
Total	**2.800**

Table 7: Agriculture – Use Case Rating

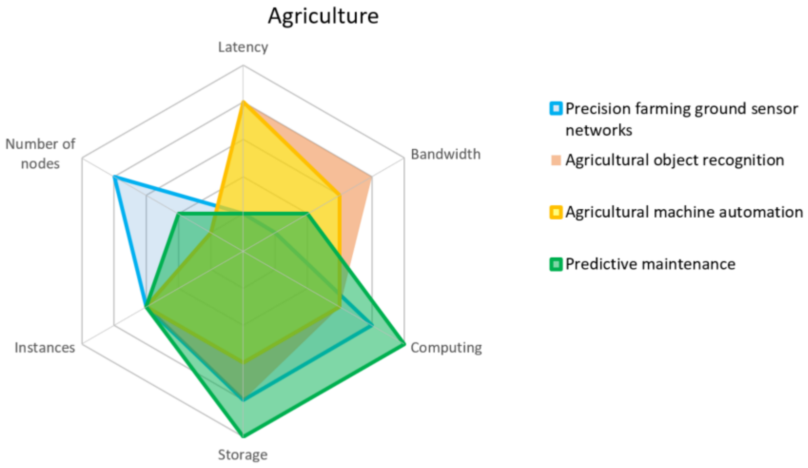

Figure 5: Agriculture – Spider Diagram

2.3.2 Energy

Energy supply has changed during the last years due to renewable energy like photovoltaic, wind energy or biomass from a centralised energy generation to a more decentralised structure, with small local power plants [108]. Additionally, to this transformation the introduction of 5G will provide the energy sector to build so called smart energy grids [66]. Smart grids will provide enhanced monitoring capabilities, a superior energy distribution as sectors can be decoupled and reconnected with the main grid thus reducing expensive energy transportation. New Storage solutions with new more efficient battery technologies, maybe based on carbon, will provide the capability to store energy generated by renewable locally and thus decrease energy transportation even further. The 5G communication standard with its focus on reduced latency will be an enabler to these new use cases in the upcoming years [64, 109].

Description

There are several use cases being enabled with the 5G communication standard currently proposed and researched for example in National 5G energy hub [110].
New communication technologies will enable wireless communication in wireless hard-to-cover areas like basements. Providing the controller to monitor and coordinate load and power generation management within a local segment, including power supply forecasts. These segments could be temporally self-supporting and become decoupled from the main grid. 5G will also enable fault detection and fault clearance within these structures due to the low communication latency. Such a structure is like a enhanced **Grid control** [73,111]. In addition to grid control faults have been detected. This latency critical **Fault detection** [73, 108, 111] in combination with grid control combine together into the **Self Organizing Virtual Power Plant** [66, 72, 108] . Another use case is the **Smart energy grid home automation** [47, 65]. Load and generation forecasts can be used to increase the use of decentralised load generation, reducing energy transportation losses.

Network Implications

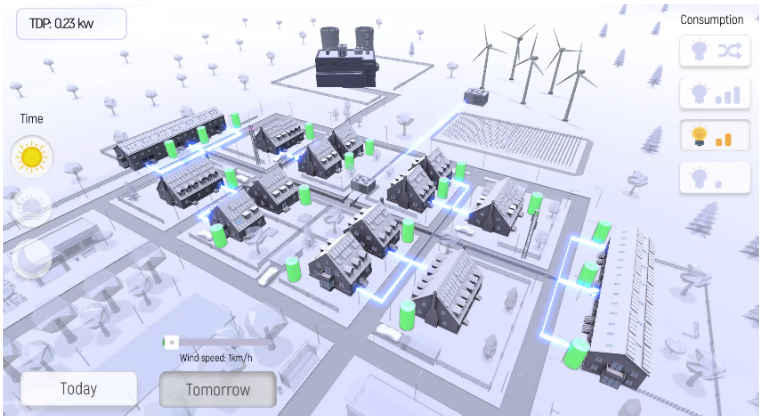

Figure 6: Energy– Virtual Power Plant Model

Energy meters will be connected to a base station or decentralised MEC infrastructure. This MEC coordinates the energy supply within an area enabling the virtual power plant. The MEC uses and updates forecasts models for load and generation management within the virtual power plant and provides the service to coordinate smart home devices.

Traffic Types Taxonomy

Energy has two traffic types. Table 8 lists their properties, and maps them to the above described use cases.

T	Latency	Bandwidth	Connected Devices	Use Case
8	Low	High	Many	
7	High	High	Many	
6	Low	Low	Many	
5	High	Low	Many	Smart energy grid home automation
4	Low	High	One or few	
3	High	High	One or few	
2	Low	Low	One or few	Self Organizing Virtual Power Plant
1	High	Low	One or few	

Table 8: Energy – Traffic Types

Use Case Rating

Table 9 lists the aforementioned two use case for Energy events along with their ratings, while Figure 7 shows the overall use case spider diagram.

Use Case	Rating
Smart energy grid home automation	5.000
Self Organizing Virtual Power Plant	11.000
Total	16.000

Table 9: Energy – Use Case Rating

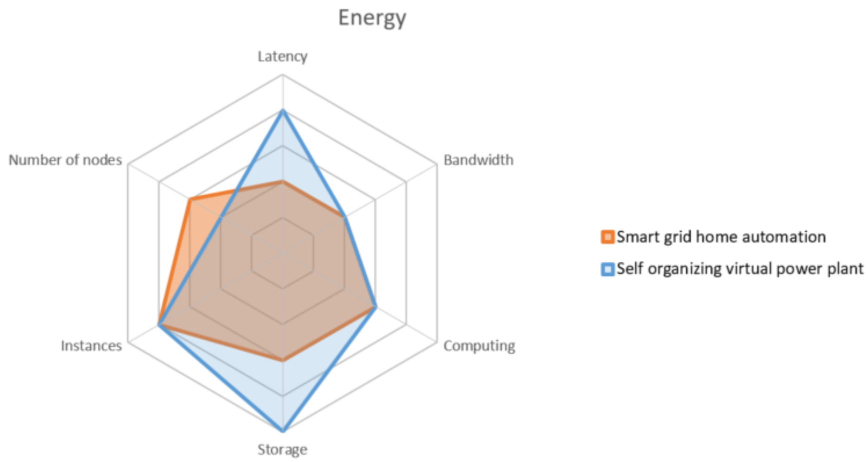

Figure 7: Energy – Spider Diagram

2.3.3 Construction

The construction industry is going through a transition. While durability of electronics in construction machinery was doubted in the past, promoting pneumatic systems, other industries have proven such concern invalid. Now the digitalization of construction machinery shall be accelerated. Also a digital model (Building Information Model - BIM) of the entire construction process has been defined. The idea is to automatically record, document and plan the projects and update the process according to the real world status. The new communication standard 5G will play an important role in this scenario due to increased throughput, resilience and reduced latency in wireless connectivity.

Description

One major use case is the creation of a digital model the **virtualisation of the construction site** and maintaining this model during the construction period. This process is summarised under the term (BIM) [67, 76, 79]. Changes should be recorded automatically, for instance via **camera data for object virtualisation** and the digital model is updated constantly [67, 79, 80]. The resulting digital model is supposed to support the building throughout the whole life cycle and will include the design, planning, actual construction and facility management. The unique character of each construction site is a challenge for this use case. In particular, during the construction phase, logistical processes (building material, construction process, machines, personnel), cost and time have to be recorded, documented, mapped and adjusted as needed. There are two possible scenarios. The first scenario is to have a real time virtualization of the construction site, the second is to have a model, which will be updated over longer periods, for example once a day. This model will be initialized at the beginning construction or maybe even at an earlier stage. All available information of the construction site will be recorded by sensors and cameras and passed on to a virtualization software. This virtualization software creates or updates a digital model. This way, construction progress and construction quality can be documented and measured. Due to the high capital expenditure, such a digital model will primarily be created for large, complex construction sites.

Besides providing a virtu model of the construction site, the automated **construction machinery control** and its **mobility support** is another major use case for 5G in the construction industry [67, 80, 82]. The automation of machines is similar, yet more challenging, than in a manufacturing, as different tasks as well as environmental influences have to be taken into account. Therefore, a different degree for automation and autonomy for every kind of machinery will be considered. Some machines, e.g. for the transport of earth, could be fully automated and autonomous, while others will only partially automated or even remotely controlled. The reasons are manifold e.g. the safety for construction workers. For a fully automated process **camera data for object recognition** is required [64, 67, 79, 80].
Independent of the virtualization of the construction site, sensor and camera data would also be used for logistic processes and managerial decisions. Most likely the majority of the collected data will be confined to the site. Yet, some data for higher level management decisions could be sent to a central server (e.g., the building company's company network or the client's server). An example would be the allocation optimization of construction machinery between different construction sites.

Predictive maintenance of construction machinery is even a relevant use case for the construction use case group.

Network Implications

In construction WLAN and the cellular network will be used to establish a reliable communication link. For the BIM the usage of Low Power Wide Range (LPWA) communication link like LORA could be implemented.

A full automation of the construction sites is aimed at certain construction machines and activities such as the loading of soil. Besides fully autonomous machines there will also be the remote control of machines or assisted machine control. For machinery remote control additional sensor data for haptic and acoustic information is required. Construction machines will be connected to a base station in the immediate vicinity. The base station or base stations will be connected to a MEC which hosts the control and steering software. Due to the latency and resilience requirements of communication link, this control loop is computed at the MEC. This MEC could be in a nearby data centre or construction site specific, depending on the computational demands regarding machinery control and construction site virtualization. While the control of construction machinery and mobility support has high requirements on latency and resilience, virtualization will probably need more bandwidth at the edge, e.g. for a camera data. Other major requirements are data security and high availability. Taking the requirements into consideration large constructions sites will likely have their own MEC. If the model is updated only once or a few times per day, it might be profitable to use a centralized simulation software for several construction sites. The collected information will be transmitted via the Internet to a server hosting the virtualization software and the virtualized construction site model will be retransmitted.

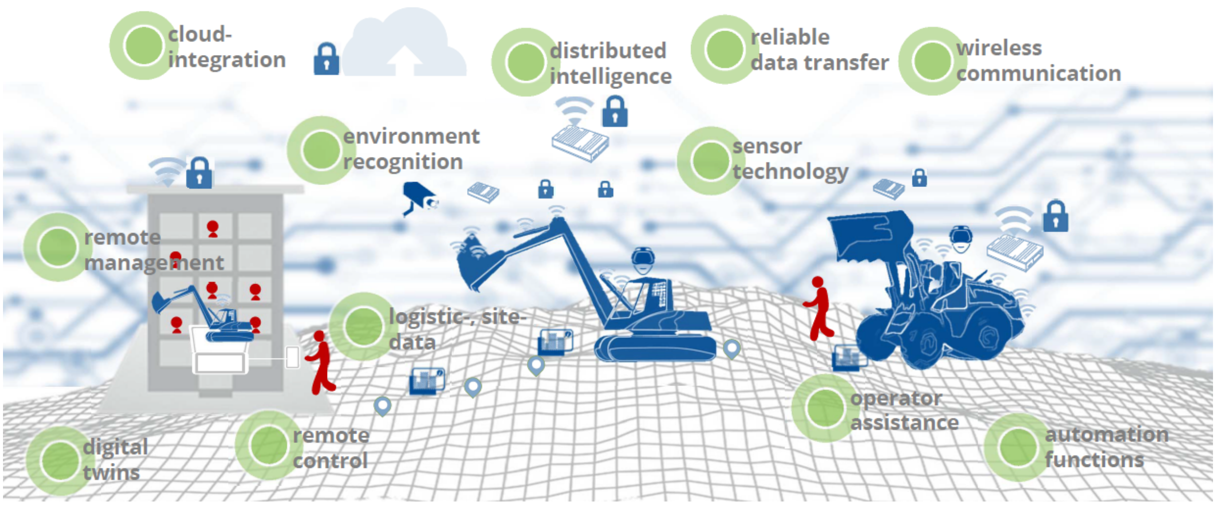

Figure 8: Construction – Overview

Traffic Types Taxonomy

There are seven applications in the construction use case group, which are mapped to the the defined traffic types in table 10.

T	Latency	Bandwidth	Connected Devices	Use Case
8	Low	High	Many	
7	High	High	Many	
6	Low	Low	Many	
5	High	Low	Many	Virtualization of the construction site Predictive maintenance
4	Low	High	One or few	Camera data for virtualization Camera data for object recognition
3	High	High	One or few	
2	Low	Low	One or few	Construction machine control Mobility support
1	High	Low	One or few	

Table 10: Construction – Traffic Types

The virtualization of the construction model can be achieved via massive sensors, camera data or the combination of both. While sensors will consist of a large number of devices requiring low latency but also low bandwidth, camera data will stem from a small number of devices but will require higher bandwidth.
The use case of construction machine control and autonomous construction machine will include a comparatively small number of devices which require control, steering data but also modal (haptic, acustic, optical) data. While autonomous construction machines usually require data transmitted in the KBit/s range, modal data for partially automated construction machines requires a higher bandwidth. All these applications are very latency sensitive and require

a very low latency.
Another traffic type for the use case of machinery automation is the object recognition from cameras for machine control. This traffic type has high bandwidth and low latency requirements.
For predictive maintenance the data will be collected from few sensors. However this data is requires neither a low latency nor a high bandwidth.

Use Case Rating

Table 11 lists the aforementioned five applications of Construction along with their ratings, while Figure 9 shows the overall use case spider diagram.

Use Case	Rating
Virtualization of the construction site	50
Predictive maintenance	1.000
Camera data for virtualization	40
Camera data for object recognition	400
Construction machine control	200
Mobility support	200
Total	**2.290**

Table 11: Construction – Use Case Rating

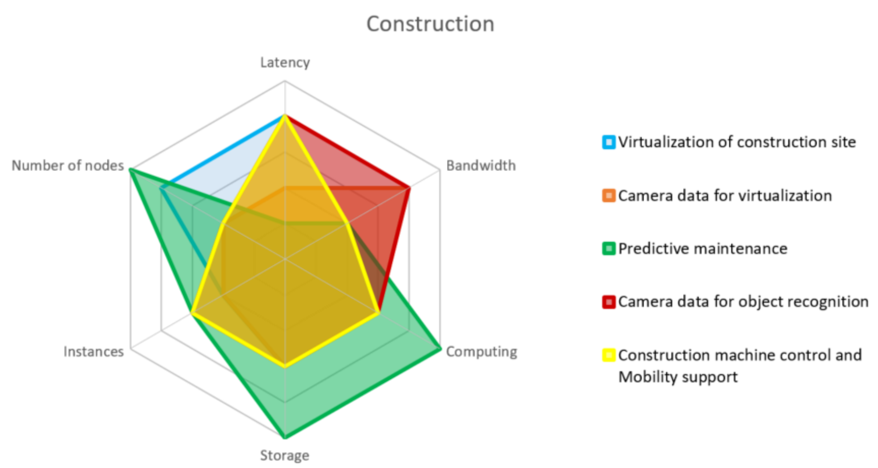

Figure 9: Construction – Spider Diagram

2.3.4 Manufacturing

The 5G standard introduces new wireless communication scenarios within the production process mostly described with the buzzword industry 4.0. Industry 4.0 is supposed to logistically connect every layer of the production. Additionally, the manufacturing industry will see a rise in wireless communication devices as 5G finally meets the robust communication requirements of the industry automation within the production process [112].

Description

We have identified five major use cases for the manufacturing industry, see Table 3, which will enable different and numerous applications. These use cases are **massive sensor networks for virtualization** of the production environment, **camera data for virtualization** of the production environment, **camera data for object recognition**, **machine control and mobility support**, and data aggregation for **predictive maintenance**. We briefly describe these use cases and explain the chosen parameters for our ranking model.

Massive sensor networks for virtualization Large numbers of sensors are deployed within the factory or production hall to enhance process control, planning, and production adjustments. These sensors could, for example, detect and transmit audio-data for failure detection and process control. The sensors will likely connect to multiple base stations in order to increase throughput, resilience and to reduce latency [77, 78]. Within a factory, process control is a critical task; therefore, real-time interaction is necessary. The collected data will be used to simulate or virtualize the production process or factory environment and to react to production changes or machine or process failures. Most likely, the virtualization will be performed on a server at the factory premises [77,113]. As the name already suggests a massive number of sensors will connect to the network. The amount of data per sensor transmitted in the network will be small, so a low bandwidth is sufficient [78, 113]. However, real-time virtualization will likely require low latency.

Camera data for virtualization For the virtualization of the production process and the process control, video data from cameras will be used as well. The cameras could monitor the production process similar to the sensor network and transmit the data to a server [78]. On the server, an object recognition algorithm will support the virtualization of the process. Camera data is usually large and requires a high transmission bandwidth; yet, typically only a few cameras will be installed. The data for the cameras requires low latency as it is critical for the production process [67, 113].

Camera data for object recognition In the future, visual camera data will be utilised to determine the position of an object for a robot or the position of an AGV [50,78,113]. This camera data has to be transmitted and analysed within the network in near real-time to avoid collisions and accidents. Therefore, the camera data has to be computed on a server at the edge [67]. Although contextual camera data (pre-filtered with low resolution) can be used for such tasks, the required bandwidth is still high.

Machine montrol and mobility support Machines will produce most goods in Industry 4.0 factories and autonomous vehicles will transport equipment and goods. In both use cases, machine control and mobility support, a very low latency is required, as failures could be expensive [81]. Compared to the numbers of sensors, the numbers of machines and automated guided vehicles (AGVs) in a factory will typically be low. While low latency is critical for these use cases, they do not require large bandwidth, as control and steering data is rather small [67, 113].

Predictive maintenance Sensors integrated on robots and industrial machines within the factory will collect various data about the machines and robots. This data will be provided to predictive maintenance algorithms. For the predictive maintenance use case, latency and bandwidth are not critical [67]. The data will be collected at the factory and then sent to a third party for analysis to identify and provide predictive maintenance services [113].

Network Implications

Within an industry 4.0 factory the communication network needs to support diverse use cases. Each of these having different requirements regarding latency, throughput, reliability etc. Facilitating all requirements at reasonable costs will be possible only in a heterogeneous communication environment. To establish a wireless communication link WLAN, industrial wireless IoT and the cellular network will coexist within the factory. Cellular network and WLAN are supposed to provide the main support in the wireless communications. For security, reliability and performance reasons the factories will deploy their own base stations. The quantity of the base stations can vary, depending on the factory scale and performance requirements. In extreme cases, the radius of cells will comprise just tenth of meters requiring hundreds of base stations being deployed. The cost of the base stations will be reduced through the Cloud RAN idea. With Cloud RAN the signal processing is moved to the MEC. These base stations, also called as Remote Radio Heads, will be more like antennas. The unprocessed or partially processed base band signal will create a significant traffic between the Remote Radio Heads and the MEC. Considering the high requirements (Transmission Time Interval [TTI] of 5 to 10 microseconds; tolerated transmission failure of 10-6 to 10-9) for the communication link part of the industry is applying for a distinct licensed frequency spectrum. A distinct frequency will reduce interference with other communication devices and enable more possible wireless devices as well as lower implementation costs.

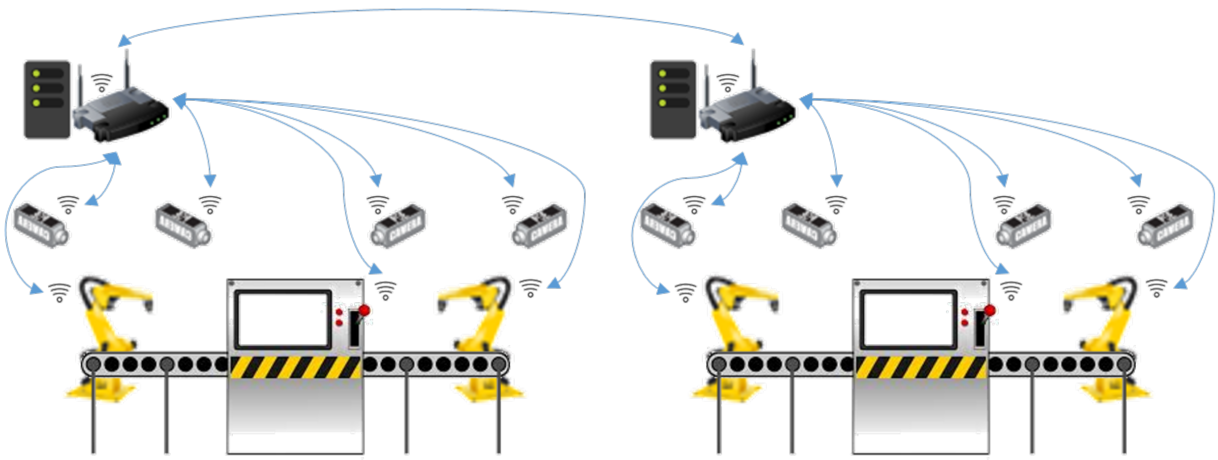

Figure 10: Manufacturing – Example Network Architecture

This proposed 5G communication network will not only include the traditional communication devices like base stations, routers, firewalls, switches but also a virtualized infrastructure of the storage and computation resources. Most likely a factory will have a private MEC allocating network resources, performing computation and storing data. Taking data ownership and privacy into consideration this probably will be the solution most companies will opt for. However, considering factory size, production process latency requirements, security requirements, software specialisation and other boundary conditions, some smaller enterprises might outsource the MEC tasks to a nearby data centre or specialised company.

Traffic Type Taxonomy

There are six use cases in the Manufacturing use case, which are mapped to the the defined traffic types in Table 12.

T	Latency	Bandwidth	Connected Devices	Use Case
8	Low	High	Many	
7	High	High	Many	
6	Low	Low	Many	Massive sensor networks for virtualization
5	Low	High	Many	
4	High	Low	One or few	Camera data for virtualization Camera data for object recognition
3	High	High	One or few	
2	Low	Low	One or few	Machine control Mobility support
1	High	Low	One or few	Predictive maintenance

Table 12: Manufacturing – Traffic Types

The virtualization of the production process can be achieved via massive sensor networks, camera data or the combination of both. While massive sensor networks consist of a large number of devices requiring low latency but also low bandwidth, camera data will stem from a small number of devices but will require higher bandwidth.
For the use case of machine control and mobility support there will be a comparatively small number of devices which only require control and steering data, usually transmitted in the KBit/s range. However these use case are very latency sensitive and require a very low latency. Another traffic type for the use case of machine control and mobility support is the object recognition from cameras for object recognition. This traffic type has high bandwidth and low latency requirements.
For predictive maintenance the data will be collected from few sensors. However this data is requires neither a low latency nor a high bandwidth.

Use Case Rating

Table 13 lists the aforementioned six use cases of Manufacturing along with their ratings, while Figure 11 shows the overall use case spider diagram.

Use Case	Rating
Massive sensor networks for virtualization	900
Camera data for virtualization	600
Camera data for object recognition	600
Machine control	200
Mobility support	200
Predictive maintenance	1.000
Total	3.500

Table 13: Manufacturing – Use Case Rating

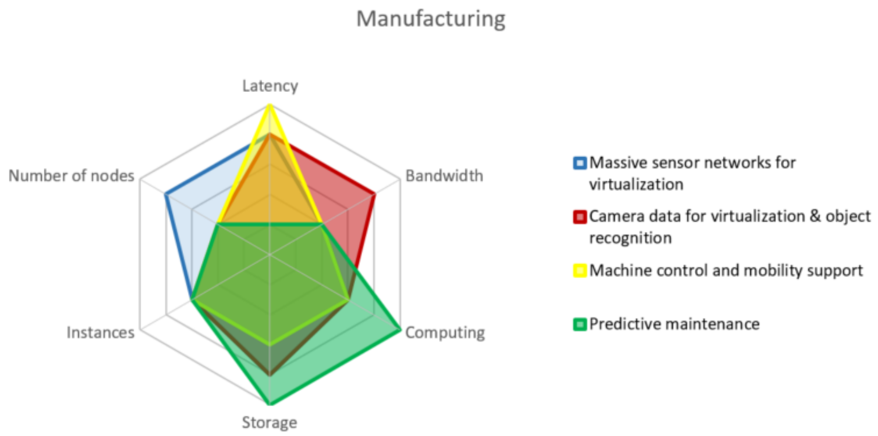

Figure 11: Manufacturing – Spider Diagram

2.3.5 Live Events

Innovative large-scale live events use cases, like AR/VR viewing and event streaming, have special latency, bandwidth and other technical requirements. 5G communication standards can be exploited to fulfil these requirements. This will improve live events use cases and the experience of their users, in stadiums, concerts and other places hosting large events [47, 64, 67].

Description

We focus on three exemplary live events use cases: Local XR support, local information distribution and off-premise event streaming. In **local XR supports**, on-premise audience (e.g. in a stadium) share photos and videos, receive and post information, or use XR to view additional information about some ongoing event. Such use cases require a temporary supply of high bandwidth [68–71, 114, 115]. However, the audience can tolerate to some delay. In **local information distribution**, a large number of on-premise users send and receive information among each others [68, 70, 71, 74, 115]. This type of use cases does not require low latency nor high bandwidth.

Users of off-premise use cases do not attend the event. Instead, they connect to the Internet to send or receive information about the event while it is taking place. In the **off-premise event streaming** use cases, the users are provided with video, AR, or VR streams. In popular events, high bandwidth becomes mandatory for these use cases, but low latency is not required [71, 74, 116]. In this use case, neither high bandwidth nor low latency are required.

Network Implications

Figure 12: Live Events – Exemplary Network Architecture

AR/VR and video events can be sent to a mobile edge cloud to be first processed and enriched with useful related information, and then redistributed (e.g. via a broadcast). Base stations are used to transmit the information. The information generated by phone camera or head-mounted devices needs to be rendered very quickly on the viewing surface. Ergo, it would benefit from local processing.

Transmitting live events information over the Internet requires to establish highly resilient connections with large bandwidth. Latency is not a major concern in this case as users outside the premise will not recognise delays. Depending on the expected demands, the information will be either redistributed via a single connection per stream using CDN or via multicast to different networks.

Traffic Types Taxonomy

Table 14 lists the properties of different traffic types, and maps them to the above described use cases.

T	Latency	Bandwidth	Connected Devices	Use Case
8	Low	High	Many	
7	High	High	Many	Local XR support Off-premise event streaming
6	Low	Low	Many	
5	High	Low	Many	Local information distribution
4	Low	High	One or few	
3	High	High	One or few	
2	Low	Low	One or few	
1	High	Low	One or few	

Table 14: Live Events – Traffic Types

The mapping between traffic types and use cases in Table 14 can be described as follows: On-premise (i.e. local) users see the events live, thus do not require low latency. However, to ensure the best support for AR, VR and video contents, high bandwidth should be provided. As for off-premise use cases, it is essential to have consistent uninterrupted information flow, in order to achieve a very positive user experience. More precisely, the event streaming use cases require high bandwidth to cope with massive amounts of information. In contrast, distribution use cases deal with small amounts of information, and only require low latency.

Use Case Rating

Table 15 lists the aforementioned four Live Events use cases along with their ratings, while Figure 13 shows the use cases spider diagram.

Use Case	Rating
Local XR support	7
Local information distribution	5
Off-premise event streaming	70
Total	82

Table 15: Live Events – Use Case Rating

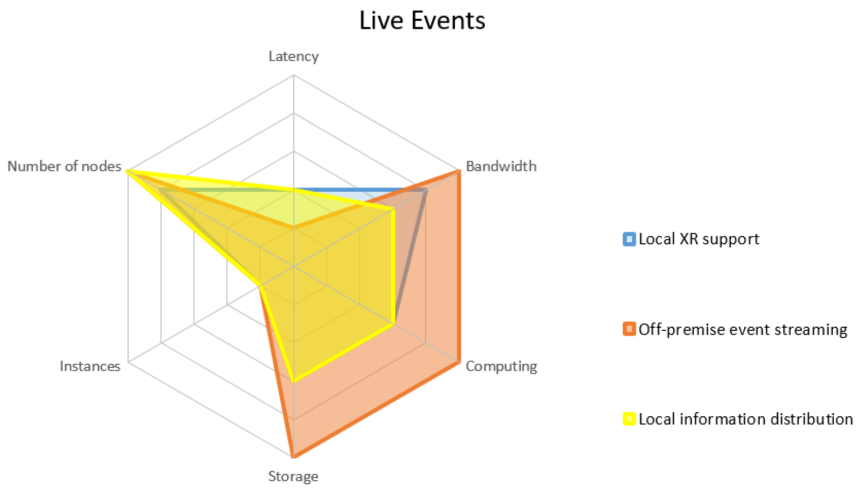

Figure 13: Live events – Spider Diagram

2.3.6 Cars

In the future, autonomous connected cars will be vital part of everyday traffic. These vehicles will require suitable sensors, suitable communication technology and control algorithms. The next mobile communication standard 5G will be of particular importance for various scenarios. While communication and control must always be guaranteed in areas with high traffic volumes, so-called platoons could be formed on motorways. Such a platooning is planned for trucks on motorways in particular, as CO2 savings and economic advantages appear to be the greatest [47, 64, 67].

Description

Various communication scenarios for controlling vehicles with regard to resilience, latency and bandwidth are currently being discussed. A specific technology has not yet been established. With 5G the autonomous driving and autonomous **car control**, which requires no human interaction to steer, or navigate the car shall be enabled [91, 117, 118]. **Car coordination**, which describes the navigation of multiple cars and other participants of the traffic to avoid accidents and ensure the safest and fastest route for everyone is another use case enabled by 5G [91, 96, 117, 118]. One way of controlling cars is a direct communication between vehicles (V2V), which is possible at a short distance. A variant of the car control sceanrio is forming platoons, **platooning** of cars, on motorways [91, 119]. Theoretically, this communication is possible without base stations. However, without a base station several issues have a negative impact on the communication link. First, the communication channel could be jammed if a certain amount of vehicles are connected to each other. Second, a direct communication between the first car and the last car of a platoon may be difficult due to the distance. This would require the message to hop, which increases latency. Additionally, the car in control of the platoon is not defined. Still car manufacturers consider this scenario a viable option, as the control hard- and software will be stored directly inside the car, providing them reliability. The other option for controlling vehicles is establishing a communication link with a base station V2X. Base stations could be located approx. 20 - 50 km apart. Exchanged information could be speed, position, acceleration, loading or other. This scenario solves the issues of a vehicle to vehicle communication, but contains its own technical challenges. As the distance to the base station is much longer than to the next car, a low latency for the data transmission must be ensured via an apt network slice.

Each car generates gigabyte of data volume per day through its sensors, controls, and so on. This data is supposed to contain error messages that are to be transmitted to the car manufacturers and suppliers for **predicitve maintenance** services. It is to be decided whether this data is transmitted on a daily, during maintenance, maybe on a real-time basis, or only when necessary, like in case of an error [67, 91].
In cities, the connection to several base stations is likely to become even more important due to the higher number of road users. As several base stations are required for complete coverage, overlaps will occur. This makes data exchange with the Edge server particularly important. From the perspective of traffic engineering, high density maps needing gigabyte of data are created. Since some road users will establish a connection to different base stations, traffic control and regulation must take place on a central server. All data converges on this server. Such a car coordination can also occur on a nationwide level.
The introduction of 5G and the breakthrough of autonomous vehicles will enable drivers and

Figure 14: Cars – Platooning

passengars to use of **In-car entertainment** services such as video streaming, VR, gaming while driving. On the one hand this option stems from the larger bandwidth of 5G and on the other hand a quality of service through network slicing is adapted to the respective software use case [91]. Car control requires a more resilient and latency sensitive connection, yet has a lower throughput than entertainment services. The resulting data traffic for entertainment services will also access data outside the edge, i.e. the servers of streaming service providers, content networks, etc.

Standardization

A final long term prediction of the network architecture of connected cars is difficult. There could be a communication link between vehicles without any information being passed to the base station. There could be a communication link between vehicles and a base station without and vehicle to vehicle communication or a mixed form of both. Neither automotive manufacturers nor automotive and network equipment suppliers have agreed on common standards, common interfaces or common software. This could result in each car manufacturer creating a proprietary system for controlling autonomous vehicles and platoons. However, it is likely that either an industry standard will prevail or that few large alliances between automotive manufacturers will be formed. It remains unknown whether the control software is running in the car itself, on an edge server in the base station or more centralised. Also it is not defined, whether one or more car control use cases will be needed, where they will be stored and when they will be transferred to the edge. However, as memory is comparatively cheap, it is very likely the control software will be available on every edge cloud server. Regulatory concerns such as the permissibility of streaming videos by the driver of autonomous driving cars, have not yet been clarified.

Network Implications

From the network architecture point of view, the position of the MEC with the control software and the handover of the autonomous vehicles from one base station to the next must still be structured. The MEC could be in the base station. This scenario is very likely, especially for highways and the control of platoons. Vehicles currently only have a connection to one base station, however multi-connectivity is an option as well. If a car enters the area of one base station and it is predictable that it will leave the coverage area of its currently connected base station, all data necessary for further control must be transmitted to the new base station. Transmission could be from base station to base station directly or via a server in the background. The use case for the car control will be vertically integrated in the network. One part will be the vehicle control at the edge. This could be a computation per crossroad or even a city part. There will also be a higher level control use case appointing paths to the desired destination for the city or the country, thus avoiding traffic jams or traffic congestion as well as optimising traffic.

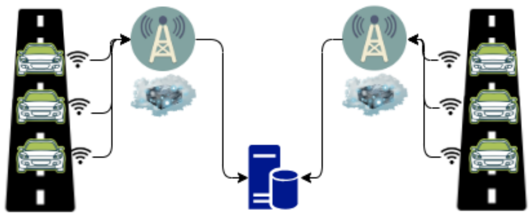

Figure 15: Cars – Mobility Support

Vulnerable road users, e.g. pedestrians without smartphones, will be recognised by video cameras. The video data is evaluated and included in the traffic control. This evaluation requires considerably more computing power than traffic control. At the same time, the evaluation of the video data must be transferred to the control server at the edge. The two use cases (video analysis and traffic control) can probably run on one server at the edge.

Due to the large number of users and the large amount of information as well as the necessary processing of video data, it is expected that amount of generated data in cities will be significantly higher than on the motorway. Data exchange will be predominantly decentralized; however, this will likely lead to a hierarchical structure of the control software on several levels. At the lowest level, only a small geographical area, e.g. a crossroads, would be controlled. The edge server at the next higher level, e.g. district, receives all relevant control information for higher-level traffic optimization, destinations etc.

Traffic Types Taxonomy

There are five use cases in the cars use case group, which are mapped to the the defined traffic types in Table 16.

T	Latency	Bandwidth	Connected Devices	Use Cases
8	Low	High	Many	
7	High	High	Many	
6	Low	Low	Many	Mobility support - car control
5	High	Low	Many	
4	Low	High	One or few	Platooning
3	High	High	One or few	In-car entertainment
2	Low	Low	One or few	
1	High	Low	One or few	Mobility support - car coordination Predictive maintenance

Table 16: Cars – Traffic Types

Whether car platooning and autonomous cars there will be an unknown number of vehicles connecting to a base station. Consider this studies time horizon it is likely only around 100 vehicles will connect to one base station at a time. For this steering use case low latency is required. Control can or must happen with low bandwidth.
Entertainment in the car is only for one or few users and will require high bandwidth. This use case can tolerate high latency.
The use case predictive maintenance and car coordination work with high latency and low bandwidth as data rates will be low. Also there are only a few devices connected to a base station in these use cases.

Use Cases Rating

Table 17 lists the aforementioned five use cases for the cars use case group along with their ratings, while Figure 16 shows the overall use case spider diagram.

Use Case	Rating
Platooning	4
Mobility support - car control	60
In-car entertainment	3.300
Mobility support - car coordination	20
Predictive maintenance	10.000
Total	13.384

Table 17: Cars – Use Case Rating

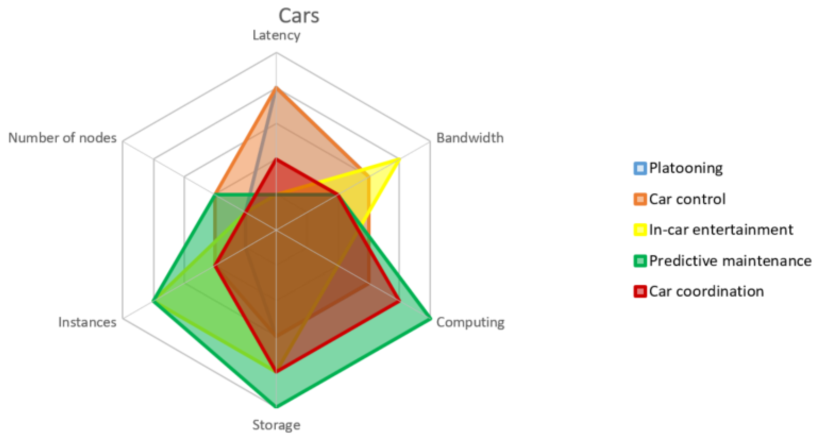

Figure 16: Cars – Spider Diagram

2.3.7 Aircraft

Description

The new cellular communication standard 5G will enable civil aviation to implement connectivity with similar requirements as mainland cellular networks. An aircraft can establish a communication link either via satellite connection or via a dedicated cellular network. Such a network is currently implemented [120, 121]. There are different kinds of information traffic with diverse requirements for the aircraft to ground communication. Flight data, like flight analysis, geographic positioning and route updates, which can be summarised as **critical flight information** need ultra-high reliability, low latency and low throughput [98–100]. While consumer data for **aircraft passenger entertainment** like web-browsing or video streaming require high throughput but have laxer requirements for latency and resilience [98–100, 103]. Aircraft maintenance is of major importance for airlines interested in **predictive maintenance** data and information about component durability [98–100]. Such data will be collected via sensors and can add up to multiple terabytes in volume. However, this data will probably be transmitted at the ground once the aircraft has landed and established a connection to a regular network.

Figure 17: Aircraft – Cellular Network

Network Implications

To establish a connection a geostationary or low earth orbit satellite can transmit and receive signals from the aircraft and communicate with a base station on the ground. While this approach offers global connectivity, even over oceans, bandwidth and latency requirements especially for passenger entertainment probably cannot be met. A communication link via a cellular network offers connectivity only when the aircraft is above the mainland. Such a dedicated cellular network might require base stations every 70 to 100 km apart from each other. However, in combination with new air interface of the 5G communication standard, this approach can offer acceptable levels of throughput, latency and resilience. The cellular network will regard the aircraft as one single, very fast moving entity connected to the network. If the aircraft leaves the coverage of one base station and connects to new base station a handover of the states and requests, maybe even pre-caching will be implemented. Due to the large distances it is imaginable that these state handovers are transmitted over an IXP. This is probably even more valid, when the aircraft crosses borders.

Traffic Types Taxonomy

There are three use cases of the Aircraft use case group, which are mapped to the the defined traffic types in Table 18.

Use Case Rating

Table 19 lists the aforementioned three use cases of the Aircraft industry along with their ratings, while Figure 18 shows the overall use cases spider diagram.

T	Latency	Bandwidth	Connected Devices	Use Cases
8	Low	High	Many	
7	High	High	Many	
6	Low	Low	Many	
5	High	Low	Many	Predictive maintenance
4	Low	High	One or few	
3	High	High	One or few	Aircraft passenger entertainment
2	Low	Low	One or few	Critical flight information
1	High	Low	One or few	

Table 18: Aircraft – Traffic Types

Use Case	Rating
Predictive maintenance	50
Aircraft passenger entertainment	15
Critical flight information	20
Total	85

Table 19: Aircraft – Use Case Rating

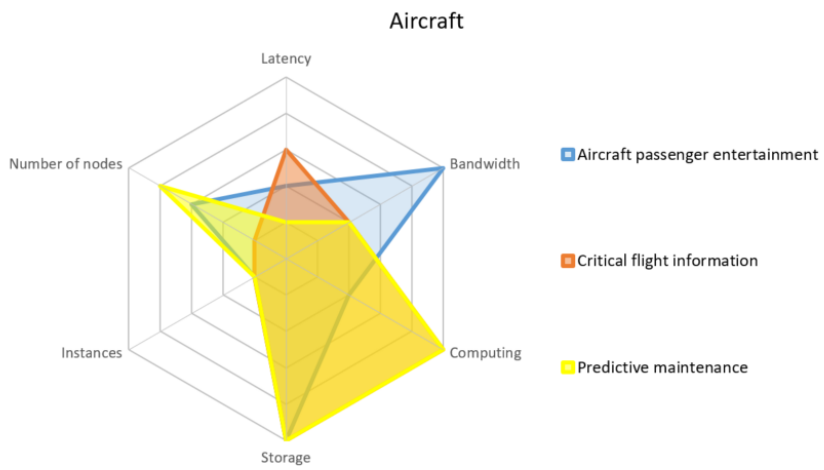

Figure 18: Aircraft – Spider Diagram

2.3.8 Trains

Description

For trains the new communication standard 5G will become important as customer demands drive connectivity expectations when travelling by train. **Passenger entertainment** will be the prevalant use of 5G as passengers want to be connected to the Internet, work or use entertainment services. The difficulty is providing a stable connection throughout the journey, with high bandwidth and an acceptable latency at speeds up to 500km/h. This challenge must take into account, that while the train is regarded as one connection to the Internet, services for up to 1.000 passengers on the train must be provided [67, 101, 102, 122].

Network Implications

High speed trains will need multi-connectivity to many base stations along the rail-road and will change the base station they are connected to rapidly. The main problem for this use case to keep a stable connection to the Internet, as trains move too fast to be keep a long connection to one base station. Therefore, a secure and reliable handover of the trains Internet connection from one base station to another must be assured. A solution to this issue is currently researched. An idea would be to track the trains position and transfer data to the train via the UDP-protocol and network coding [123–128]. Predictive caching at the base station or radio tower could provide a stable data transmission.

Traffic Types Taxonomy

There is only one use case in the High Speed Train use case group, which is mapped to the the defined traffic types in Table 20.

T	Latency	Bandwidth	Connected Devices	Use Case
8	Low	High	Many	
7	High	High	Many	Passenger entertainment
6	Low	Low	Many	
5	High	Low	Many	
4	Low	High	One or few	
3	High	High	One or few	
2	Low	Low	One or few	
1	High	Low	One or few	

Table 20: Train – Traffic Types

The train will have multiple, up to 1.000, passengers requiring an Internet connection; therefore, many devices will be connected. There is a demand for high bandwidth; yet, latency is not critical and even difficult to achive.

Use Case Rating

Table 21 lists the aforementioned one use case for High Speed Trains along with their ratings, while Figure 19 shows the overall use case spider diagram.

Use Case	Rating
Passenger entertainment	357
Total	357

Table 21: Trains – Use Case Rating

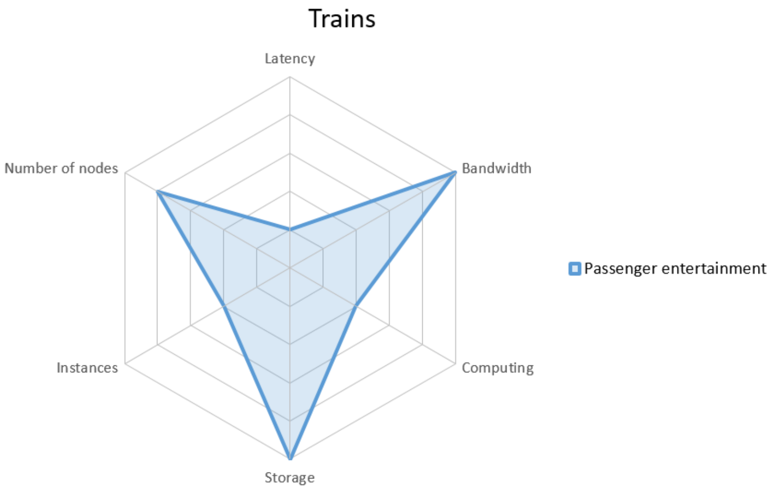

Figure 19: Train – Spider Diagram

2.3.9 Video in 5G

Description

Studies have estimated that video-on-demand for mobile and stationary clients will be responsible for the majority of the Internet traffic. The proportion of video traffic on the Internet is projected to increase from approximately 66% today to 83% in the year 2021 [35, 129]. The rising Internet video consumption and the steadily increasing demand for mobile video distribution puts a lot of pressure on carriers, service providers, and Internet core services, such as IXPs. 5G supports the network structure to ease access and distribution of mobile video on demand at the edge. Generally, video-on-demand is already an established technology [130–134] and not a 5G use case in itself. However, there are some use cases for video content which will be enabled or become more widely available due to new 5G communication standard and infrastructure [135–138].

Several use cases have been described in various papers for video streaming in the 5G context, the most prominent use cases are already available today:

Video surveillance
In the upcoming years, the demand for mobile video surveillance could massively increase. Also, use cases for video surveillance will become smarter. The amount of video data will not only be used to investigate a scene afterwards, but also to enable live interactions. Therefore, smart algorithms have to proof camera data autonomously and demand human interaction only if necessary. Such algorithms will run at the MEC. [47, 64, 87, 88]

Video Conferencing
Video is increasingly becoming a means of social communication, whether in business or private. Video conferencing and video calls are becoming more important every day. 5G will support this trend by providing more bandwidth and lower latency at the edge while performing video de- and encoding at the MEC, relieving stress on user equipment processors. This will lead to longer battery life, which will further increasing mobile video conference usage. Additionally, high resolutions video calls will be available everywhere. [47, 68, 89]

Video Streaming

Mobile video streaming will increase in the upcoming years, especially videos will be transmitted with a higher resolution. These videos will require better encoding and decoding to reduce the amount of transmitted data to the MEC. This coding algorithms can be implemented at the MEC [139, 140]. 5G will provide the required bandwidth and technology for the streaming demand. [68, 87, 115]

Video Broadcast

With 5G, broadcasts in the cellular network will be possible. While typical broadcast use cases, such as TV, will be distributed in the network, local broadcasts, such as ads, could be distributed. There are two different video broadcasting use cases in 5G. One wide-range broadcast, which will probably only operate in the downlink, and a more spatial broadcast use case with feedback possibility. Videos for local broadcast will be stored at the MEC and distributed or broadcasted on demand. [47, 68, 87, 115, 129]

The increase in bandwidth is supposed to lead to more video conferencing, video broadcast on demand, and the distribution of live video streams.

Network Implications

The technologies currently researched and described under Points 1-4 will be widely introduced once MEC becomes available. These technologies are currently already implemented.

Video content is currently supplied primarily either via content distribution networks (CDN) or by the content providers themselves. As the demand is growing, video storage becomes more distributed and decentralised. With the introduction of MEC, video storage and distribution will probably move even closer to the edge to meet the required quality of service.

Video content delivery will likely use these technologies in the future:

1. Encoding and decoding are the most compute intensive parts in video delivery. With the introduction of the MEC the computational power at the edge could be used for video encoding and enhance the quality of experience, this will also save energy. This concept could decrease storage capacities at the CDN, as videos will only be stored in the optimal resolution.

2. Predictive content distribution, also known as predictive caching, is currently researched and even adopted, e.g. by Netflix. The idea is to cache the most frequently requested videos at central or even edge nodes in advance, so latency and delay for the user will decrease. Predicting videos to be cached in advance is done via big data analysis and machine learning.

3. Although limited, MEC provides storage capabilities. A current research topic is storing and loading video content from the nearest MEC. Thus, using the MEC infrastructure as a distributed storage. Video content can be distributed and shared between locally close MECs, instead of being loaded from a data centre in the backbone. This will relieve traffic from the backhaul links.

4. In cases where video content is not stored at the MEC, but instead loaded over the Internet, link RAN-Aware Video Optimization could be a favourable technology. The MEC informs the video content server of the available channel capacity and condition so radio resources can be fully utilised.

Traffic Type Taxonomy

Video in 5G has four traffic types. Table 22 lists their properties, and maps them to the above described use cases.

T	Latency	Bandwidth	Connected Devices	Use Case
8	Low	High	Many	
7	High	High	Many	Surveillance
6	Low	Low	Many	
5	High	Low	Many	
4	Low	High	One or few	Conferencing
3	High	High	One or few	Streaming Broadcasting
2	Low	Low	One or few	
1	High	Low	One or few	

Table 22: Video in 5G – Traffic Types

For the video surveillance use case, camera data from multiple sources will be autonomously analysed. While the transmission does not require low latency, high bandwidths are necessary. The same applies for video broadcasting. Local video broadcasting has similar requirements, yet fewer devices will request such a broadcast. For video conferencing, especially mobile video conferencing, low latency and high bandwidth are required to enable social interactions. The number of devices per use case is limited.

Use Case Rating

Table 23 lists the aforementioned four use cases of Video in 5G along with their ratings, while Figure 20 shows the overall use case spider diagram.

Use Case	Rating
Surveillance	700
Conferencing	2.200
Streaming	300.000
Broadcasting	300
Total	**303.200**

Table 23: Video in 5G – Use Case Rating

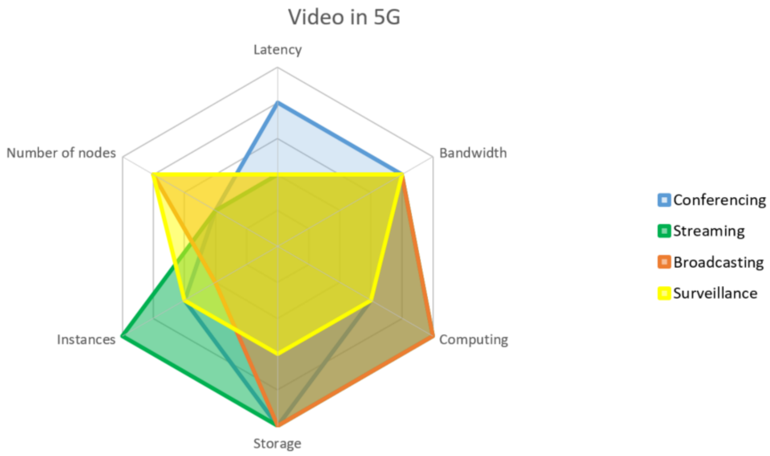

Figure 20: Video in 5G – Spider Diagram

2.3.10 Virtual and Augmented Reality

One upcoming technology within the next five to ten years will probably be the massive consumer market and industry implementation of virtual and augmented reality (VR / AR = XR) use cases. Standalone wireless head-mounted displays (HMD) are already available at a reasonable price. XR is a hot topic in research and development. First pilot use cases have been coded and tested and the market is to be expected to have massive growth rates in the upcoming years. The market size in Europe will is projected to increase nearly fivefold from 3,1 billion € in 2018 to 15 billion €or more in 2020 citeBeze2017VR. With the introduction of 5G communication standard and general network architecture, XR use cases will probably be adopted widely [78, 86].

Description

Figure 21 gives an overview of the interesting areas and corresponding companies for use cases in this use case group VR and AR use cases can be used in Industry and Engineering, for example to visualize 3D Data, 3D CAD structures and other environments; thus, enabling a new form of collaborative interregional prototyping. Another major industry use cases is VR training, e.g. VR maintenance training in complex industrial factories and on complex industrial machinery can decrease downtime, reducing costs while enhancing user satisfaction.

In architecture and interior design, VR solutions offer new possibilities to investigate the final building or interior fittings upfront. In combination with the BIM, VR models could be created swiftly. Also, such an approach allows for rapid design changes and testing without creating small mock-ups of the buildings citeMeixner2018VR.

Use cases in education and culture range from pre-booking hotel tours, information broadcasting, virtual museum tours, and local advertising. Information could be displayed in AR displays providing visitors and interested user with information, also improving local orientation. Other more straightforward use cases are **VR and AR gaming (XR gaming)** [64, 78, 84–86, 90], social XR, and adult VR.

Use case in VR and AR can be distinguished by content type. Two major content types are **cinematic VR** [78, 83, 85, 86] and **VR and AR simulations (XR simulations)** [64, 68, 84–86]. They can be further distinguished by the Degrees of Freedom (DOF), meaning the range of

Figure 21: Virtual and Augmented Reality – Use Cases from [Bezégova 2017]

possibilities in which the user can interact. The range for interaction spans from one dimension where a movie is shown similar to a TV screen, to **VR 360° content** [78, 83–86] which include head rotation, to movies and simulations with **6 DOF XR** where the VR user can move within the provided content. VR and AR content, especially with 3 DOF or 6 DOF, generate massive amounts of data [83, 85, 86]. For instance, a 360 ° 6 DOF video with a 2-foot VR range equals 10,8 TB data per minute.

Network Implications

What makes VR and AR special in regards of network architecture are the quite unique requirements [67]. XR content does need a high bandwidth and a very low latency if the use case has at least 3 DOF. Additionally, with user interactions, information is transmitted from and to the HMD. User movements, such as head movements and body movements have to be tracked via sensors, transmitted to the MEC, computed, and the results have to be transmitted back to the HMD. VR is especially prone to motion sickness; therefore, a low latency is critical. VR movies will require a high bandwidth for transmission to the HMD; however, computational tasks and responses to body movement could be performed at the MEC and the HMD. This is due to the trade-off between latency and HMD weight. The 5G communication standard will be important in this context as VR movies will require much more data volume being transmitted than traditional videos. The HMD will receive the data from a nearby computer via cellular, WLAN, or even cable connection or will make use of multiple connections simultaneously.

Simulated software for the VR and AR content will need very powerful computation, thus it will probably be computed at the MEC or a nearby PC.

Especially AR use cases will require interactions between the position of the user, the line of sight, and possibly augmented objects, and all of these components will influence the HMD projected information.

The distribution of VR content will share similarities with the distribution of video content, whether it be movies or simulation software.

VR and AR use cases will not only require high bandwidths at the edge, but also within the Internet, as, depending on provided resolutions and DOF, VR and AR content is much larger than movies.

Traffic Type Taxonomy

The Virtual and Augmented Reality use case group consists mainly of the six use cases which have been rated as in table 24:

T	Latency	Bandwidth	Connected Devices	Use Case
8	Low	High	Many	
7	High	High	Many	
6	Low	Low	Many	
5	High	Low	Many	
4	Low	High	One or few	VR 360 ° content XR simulations Six DOF VR XR gaming
3	High	High	One or few	Cinematic VR
2	Low	Low	One or few	
1	High	Low	One or few	

Table 24: VR and AR – Traffic Types

As mentioned, most XR use cases share requirements for very low latencies and high bandwidths. However, for cinematic VR, VR 360 ° content, as well as 6 DOF VR , only one device will be connected. However, there will be multiple users streaming VR content in parallel. Simple VR movies can be treated like video-on-demand, tolerating high latency due to buffering. For XR simulations and XR gaming there could be a connection of multiple devices to a base-station sharing the same immersive experience [141].

Use Case Rating

Table 25 lists the aforementioned seven use cases for Virtual and Augmented Reality along with their ratings, while Figure 22 shows the overall use case spider diagram.

Use Case	Rating
VR 360° content	22.000
VR simulations	400
AR simulations	400
Six DOF VR	4
VR gaming	8.000
AR gaming	8.000
Cinematic VR	3.000
Total	41.804

Table 25: VR and AR – Use Case Ratings

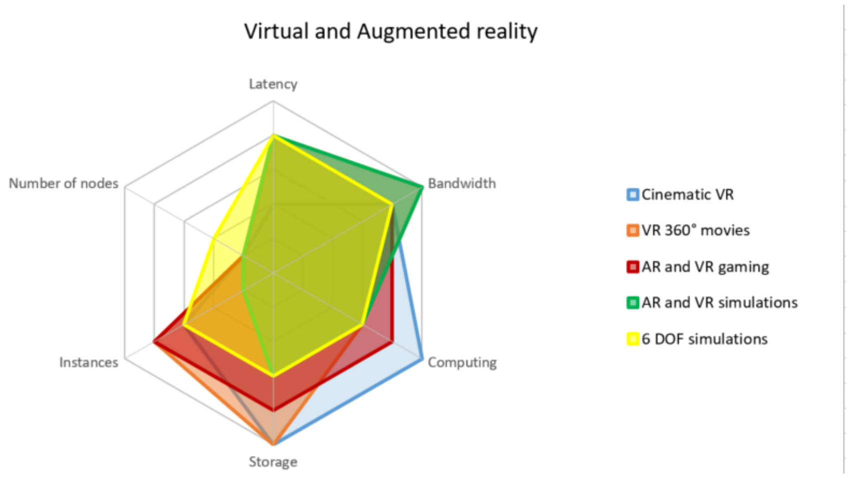

Figure 22: VR and AR – Spider Diagram

2.3.11 Tactile Internet

The 5G communication standard enables the tactile Internet to emerge [51]. The tactile Internet enables multimodal human-machine interactions with a latency as low as 1 ms. In this study, the tactile Internet subsumes all use cases, which make use of human-machine interactions based on learning, evaluatings and assisting movements. The tactile Internet use case group is supposed to propose multiple use cases across different fields. One example would be robot control in industry environments.

Description

Movement to machine learning Multi-modal sensor data and video information will be used to capture and record human movements. These movements combined with machine learning algorithms and semantic training will provide robots with any kind of human expert knowledge on movement for different tasks. These robots will be trained to assist or even take over such tasks [50–52, 58].

Human training: To enhance the task capabilities of robots, the learned movements can be performed while an expert gets full audio-visual and haptic feedback via smart wearables. The expert can evaluate robot movement performance, show improvements or simply experience the task.
Also, a user can perform the tasks and semantic algorithms evaluate the user movement in comparison to expert movements. The performance of the trainee can be evaluated and feedback for improvement can be provided [50–54].

Robot assistance and skill transfer: Human movements and expert knowledge on different tasks is essential, for instance, in high quality patient care and medical training. With the support of virtual reality, multimodal sensors and haptic feedback devices, such as gloves, clinicians can learn and train different tasks for single or multi-user minimally-invasive surgery, trauma operation, and ICU.
Similarly, movement evaluation tasks can be learned by a user via smart wearables; thus, enabling the exchange of expert knowledge for human movements via the Tactile Internet [50, 53, 57, 58].

Figure 23: Tactile Internet – Use Case Examples

Network Implications

Robot learning, evaluation, and assistance will be computed at the MEC. Also, the control functions will be stored very locally due to the low latency requirements. Most task evaluations will be conducted by experts on a local level. The MEC will be a private unit for critical tasks, such as surgery or industrial use cases. In education and assistance environments, a public

MEC will perform the necessary computations. As for the communication, most likely WLAN or cellular can be used.

The network structure will be based on one or multiple base stations receiving sensor data and sending feedback. A close-by MEC will run the necessary control loop and feedback use case. Besides the fact that knowledge acquisition and machine-type training are highly latency-sensitive tasks and will be performed locally, software updates, software maintenance and data exchanges in terms of software and knowledge-databases will be performed over the Internet. While most of these use cases are currently researched, the knowledge database once established as state-of-the-art will be stored in a decentralised manner and will be continuously updated and improved at multiple locations.

Traffic Types Taxonomy

There are three use cases in the Tactile Internet use case group, which are mapped to the the defined traffic types in Table 26.

T	Latency	Bandwidth	Connected Devices	Use Case
8	Low	High	Many	
7	High	High	Many	
6	Low	Low	Many	Human training Robot assistance and skill transfer
5	High	Low	Many	Movement to machine learning
4	Low	High	One or few	
3	High	High	One or few	
2	Low	Low	One or few	
1	High	Low	One or few	

Table 26: Tactile Internet – Traffic Types

While tasks for tactile internet use cases require low latency and high bandwidth, only a small number of devices is connected. These devices include sensors and smart wearables for haptic and multimodal feedback. For robot learning, the latency requirements can be relaxed as capturing the movements for computation is more important than instant feedback.

Use Case Rating

Table 27 lists the aforementioned three use cases for Tactile Internet along with their ratings, while Figure 24 shows the overall use case spider diagram.

Use Case	Rating
Human training	50
Robot assistance and skill transfer	60
Movement to machine learning	60
Total	170

Table 27: Tactile Internet – Use Case Rating

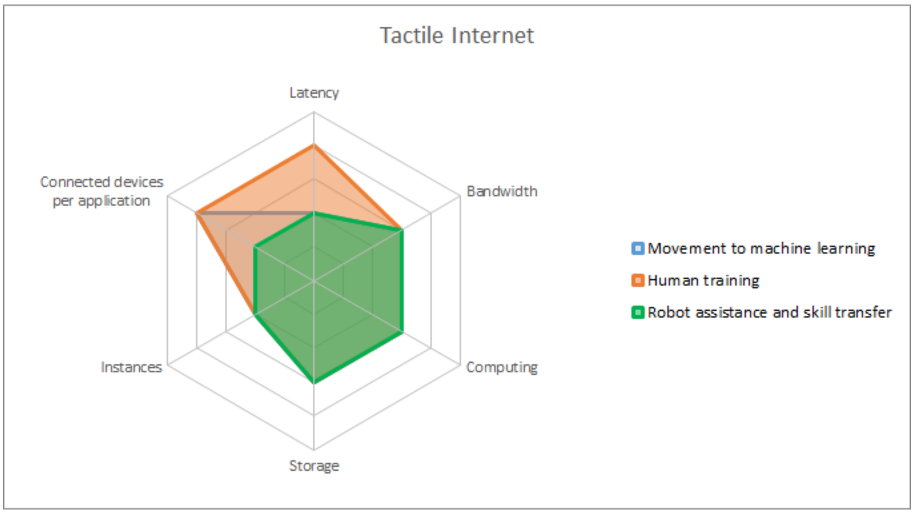

Figure 24: Tactile Internet – Spider Diagram

2.3.12 Health

Description

One major use case for 5G in Health is the large scale data collection by sensors and wearables, followed by the decentralised analysis of the personal health data at the MEC or the cloud. Health information will be analysed regularly. At the indication of an possible disease, treatment could be suggested or in the case of an emergency the wearable could autonomously call an ambulance.
A smart ambulance could support multiple sensors that send relevant information about the transported patient to the destination hospital, thereby optimising the preparation of the patient intake. Health information, e.g. blood pressure, oxygen–saturation, or x-rays can be transmitted to the hospital and provided to clinicians so an immediate anamnesis can be created prior the patient's arrival. Relevant collected data from the wearables could be included in the transmission.
Within the hospital, surgery will be performed and assisted by robots. Context-aware real-time use case of medical skills for computer and robotic assistance could be used in real surgeries. Surgeons will use XR for surgical assistance. This requires real-time control and low-latency communication networks, nearly real-time analysis and knowledge-based interpretation of sensor-data with machine-learning methods, as well as near-to-eye (augmented) display terminals with appropriate visualisations. Big data analysis will be performed at the MEC during surgeries analysing patient health data and providing assistance if required.

Within the hospital, rehabilitation and other tasks, such as drug transport, will be performed by autonomous robots.

Network Implications

The described use cases will differ in terms of their network requirements.
Wearables will have very high security requirements and will communicate with a public MEC. Computations may be performed locally; however, as this data will be needed for big data analysis and machine learning tasks in order to be optimised, storage will not be local [92–94,142].

Figure 25: Health – Wearables

The **smart ambulance** will carry multiple sensors which will communicate with public base stations in order to transmit data. For such a use case, high resilience of the used network slice is of major importance [97].
For **assistive robot control** and surgical robot assistance, sensors and actuators will communicate with base stations and private mobile edge servers on the hospital premises, because these are life critical tasks which will run on a separate hospital internal infrastructure [95,142].
Also **surgery XR assistance** will be computed locally as it requires low latency [95, 142].
The computations and control for **Telemedicine and Rehabilitation support** and other assistive infrastructure devices could be conducted within the local infrastructure on a separate, less prioritised network slice [67, 95, 143].

,

Traffic Types Taxonomy

There are five major use cases in the Health use case group, which are mapped to the the defined traffic types in Table 28.

Health wearables will involve connections of usually one device and possibly multiple devices per person. Neither latency nor bandwidth are critical for health wearables. Within a small ambulance there will be multiple sensors collecting and transmitting information. The transmission to the hospital will require higher bandwidth but can tolerate high latency. Surgery assisting systems, such as surgery robots or XR, require extremely low latency and high bandwidth but connect very few devices. The same applies for telemedicine and rehabilitation assistance except that a lower bandwidth would suffice in this use case.

Figure 26: Health – Assisted Surgery

T	Latency	Bandwidth	Connected Devices	Use Case
8	Low	High	Many	
7	High	High	Many	
6	Low	Low	Many	
5	High	Low	Many	Wearables
4	Low	High	One or few	XR surgery assistance Assistive robot control Telemedicine and Rehabilitation support
3	High	High	One or few	Smart ambulance
2	Low	Low	One or few	
1	High	Low	One or few	

Table 28: Health – Traffic Types

Use Case Rating

Table 29 lists the aforementioned five use cases of Health along with their ratings, while Figure 27 shows the overall use case spider diagram.

Use Case	Rating
Wearables	275.000
XR surgery assistance	400
Assistive robot control	40
Telemedicine and Rehabilitation support	40
Smart ambulance	45
Total	275.525

Table 29: Health – Use Case Rating

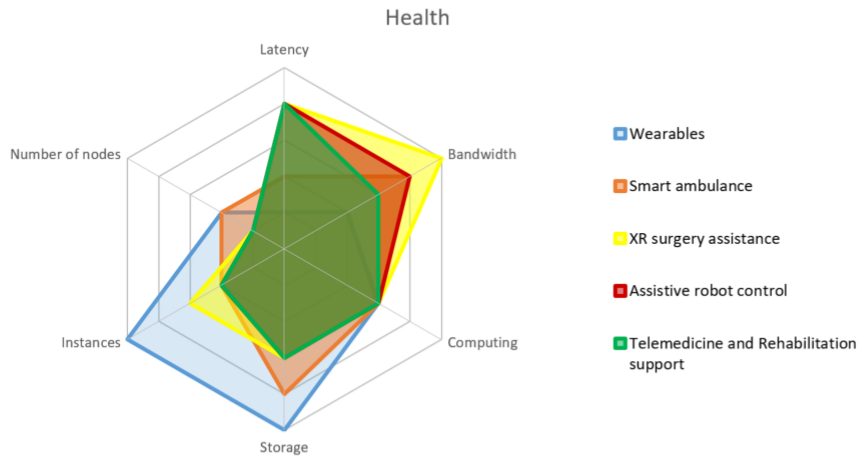

Figure 27: Health – Spider Diagram

2.4 Ranking

The use cases described and rated in the previous sections can be ranked. The 5G use case groups with the highest rating are more likely to have an large impact on the increase of overall Internet traffic until the year 2025.

The following Table 30 lists all use case groups, their ratings according to the methodology developed in chapter 2.2 and their rank.

Rank	Use case	Rating
1	Video in 5G	303.200
2	Health	275.525
3	Virtual and Augmented Reality	41.804
4	Energy	16.000
5	Cars	13.384
6	Manufacturing	3.500
7	Agriculture	2.800
8	Construction	2.290
9	Trains	357
10	Tactile Internet	170
11	Live Events	142
12	Aircraft	85

Table 30: Use Case Ranking

Some use cases in use case groups are rated especially high. These use cases are more interesting; therefore, we rank every use case with a rating higher than 10.000 in the Table 31 below.

Rank	Application	Rating	From Use Case
1	Video on Demand	300.000	Video in 5G
2	Wearables	275.000	Health
3	VR 360 ° Content	22.000	Virtual and Augmented Reality
4	AR and VR Gaming	16.000	Virtual and Augmented Reality
5	Predictive Maintenance	13.050	Agriculture Construction Manufacturing Cars Aircraft
6	Self Organizing Virtual Power Plant	11.000	Energy

Table 31: Applications Rated above 10,000 Points

3 Conclusion

In light of an access technology shift from fixed network towards mobile communication technologies in combination with the upcoming implementation of holistic 5G network architecture at the edge we expect the core network to adopt and, thus, undergo significant changes. While kind and scale of the changes is matter to future research, this study particularly asks how the significant identified 5G use cases will affect the traffic level at the core internet, especially at IXPs.

To anticipate these changes, we describe and analyse important 5G use case groups, further we determine and estimate specific parameters like the use case requirements. With these parameters we developed a methodology to derive the estimated impact of each 5G use case on IXPs for a given spatial region and a given period. The methodology enables us to rate the use cases against one another; thus, supporting a systematic approach and covering a wide set of industry sectors. Consistently, the use cases are ranked with the expected impact on the overall Internet traffic.

The results show three use case groups: Video in 5G (rating 303.200), Health (rating 275.525) and XR (rating 41.804) having the largest impact on the Internet traffic and IXPs until the year 2025. Two other use case groups, Energy and Cars have a significant impact as well. All other use case groups have been rated below 10.000 points. This low rated use case groups will probably have a negligible impact on the overall Internet traffic.

The use case groups Energy and Cars could have a larger impact after the year 2025 as their acceptance and prevalence could rise drastically. These use case groups, once widely adopted, provide major advantages in terms of cost and time reduction for industry sectors and end-customers. In contrast, the impact of spatially confined use case groups, like Manufacturing or Live events, is likely to stay negligible because the sum of data transmitted via the Internet will remain relatively small.

Each use case group consists of a range of use cases. Looking into the use cases contributing to the high rating of the most significant use case groups, video streaming via mobile devices has the largest impact. For Health Wearables have the largest rating, due to the large number of instances of this use case. Although the data of this use case will be stored in a centralized manner and has to be transmitted via the Internet, we consider this rating result too high as the single data points tend to be rather small. The impact of the XR use case group on the overall internet traffic depends mostly on its user acceptance. Although XR use cases are new and require more data than video applications their future dissemination is questionable. The applications 360 ° content and XR gaming contribute to the high rating of this use case group. If this technology makes a major market breakthrough until 2025, resulting in a massive increase in the number of instances a re-evaluation of this use case group would be necessary. In the case of a market breakthrough of XR the impact on the Internet traffic could become higher than the impact of the Video in 5G use case group.

IXPs can conclude several findings from this study. First, 5G use cases and use case groups will contribute to the steady growth of the Internet traffic up to 2025 and beyond. Second, the use case groups with the highest rating - Video in 5G, VR and AR, Health, Energy and Cars - probably contribute to the majority of this growth and their development in terms of market share and implementation progress by users should be monitored closely by IXPs.

While the applied evaluation and rating methodology is holistic and structured, the used rating factors can only be rough estimates and must be refined in terms of granularity in the future. Also the methodology leaves room for optimization. For example, the impact of the number of instances on the rating seems higher than other factors. While the approach to identify use cases was structured and logical, it cannot be assured that all important use cases have been identified. Future work could also include additional use cases. The methodology only provides a framework for assessment. Once the use cases have transitioned from research to concrete application, a more detailed analysis and possible calculation of the amount of data transferred could follow, resulting in an even more precise use case comparison.

4 Annex 1: Use Case Rating

This annex goes into detail by describing the six parameters for each use case in each use case group. The use case scenario is shortly characterised and the parameter selection is substantiated. The traffic tape parameters have been defined in cooperation with experts working on projects in the field or by literature review.

For the use case rating the equation 4.1 from Chapter 2.2 is used. The classification of the parameters was done only approximately along the dimensions, shown in Figure 28.

$$\begin{aligned}\text{Use Case rating } (R) = {} & \text{traffic type factor } (T) * \text{number of instances } (I) \\ & * (\text{percentage for computation } (C) + \text{percentage for storage } (S))\end{aligned} \quad (4.1)$$

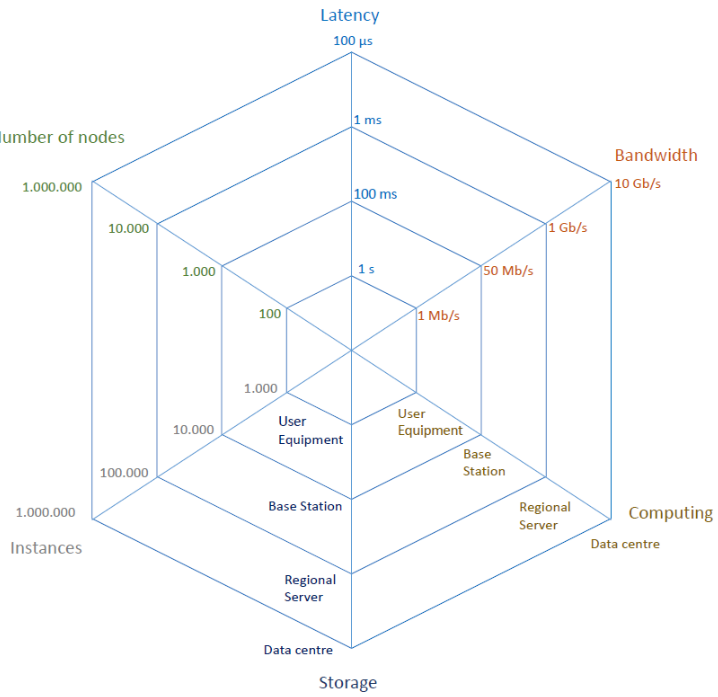

Figure 28: Use Case Groups and Use Case Evaluation – Parameters

4.1 Agriculture

4.1.1 Number of Instances

The Agriculture use case group is by large still a field of research, where pilot testsides are currently set up; therefore, a transition for this use cases from a research topic into the market will take time. While data on farms is available it is unknown which percentage will of farms will have implemented the use cases presented in this use case group. The statistic "Number of Agricultural Companies in Germany from 1975 to 2017" from the Statistisches Bundesamt show roughly 267.800 farms in Germany in 2017, see Figure 29. Considering the ongoing decline in the number of farms during the last years and a 5% implementation rate of this use case group, the number of instances in 2025 will be around 10.000 [144].

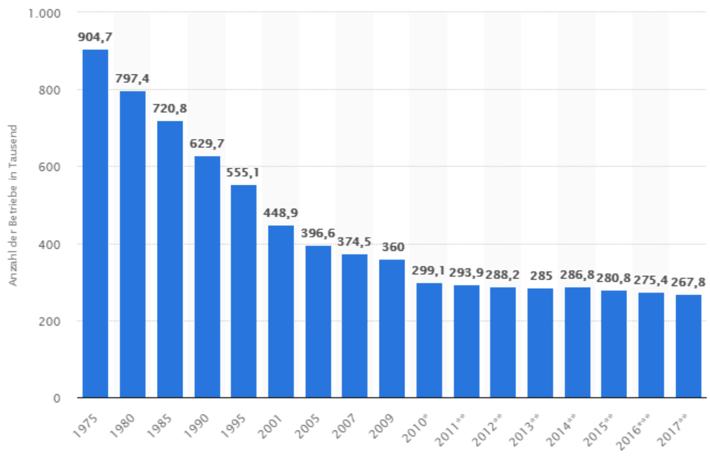

Figure 29: Agricultural Companies in Germany

4.1.2 Precision farming ground sensor networks

On a farm, a massive amount of cheap ground sensors will be distributed over a large area and collect and transmit data, e.g. on ground humidity. These sensors usually communicate via an LPWA (Low Power Wide Area) technology. There is no requirement for low latency nor high bandwidth. We assume a typical farm will have around 1.000 ground sensors.
The traffic type for this use case is T5: high latency, low bandwidth, massive connected devices. The data collected by these sensors needs a central location, like a server on the farm, for storage and analysis.

The use case rating, equation 4.2, and the spider diagram, Figure 30, are below:

$$5 * 10.000 * (0,005 + 0,01) = 750 \tag{4.2}$$

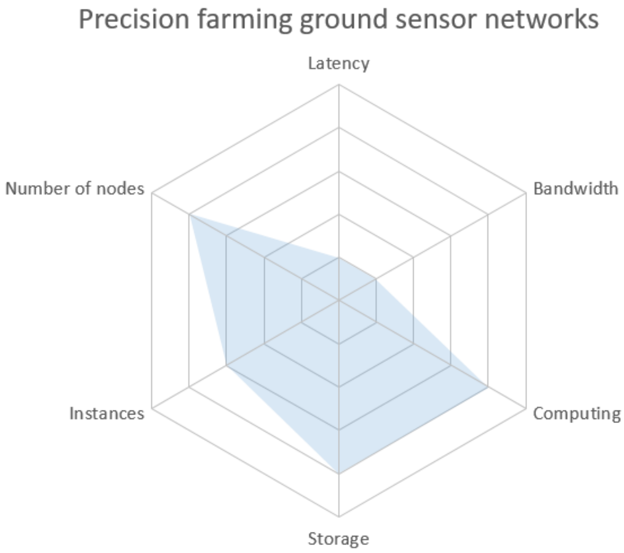

Figure 30: Precision farming ground sensor networks – Spider Diagram

4.1.3 Agricultural object recognition

As every single plant fertilisation has to be documented individually, precision farming is applied. For farm photographing camera data needs to be analysed rapidly and control mechanisms need to be applied. The rapid analyses require the communication link to have low latency while the usage of cameras requires a high bandwidth. Typically, an agricultural machine e.g. a harvester, will support around 10 cameras.
The traffic type for this use case is T4: low latency, high bandwidth, few connected devices.
On a field the mobile coverage maybe difficult, so either a dedicated network is used or the computation is performed on the agricultural machine. As the plant fertilisation has to be documented the data will be stored at a centralised location.

The use case rating, equation 4.3, and the spider diagram, Figure 31, are below:

$$4 * 10.000 * (0,005 + 0,01) = 600 \tag{4.3}$$

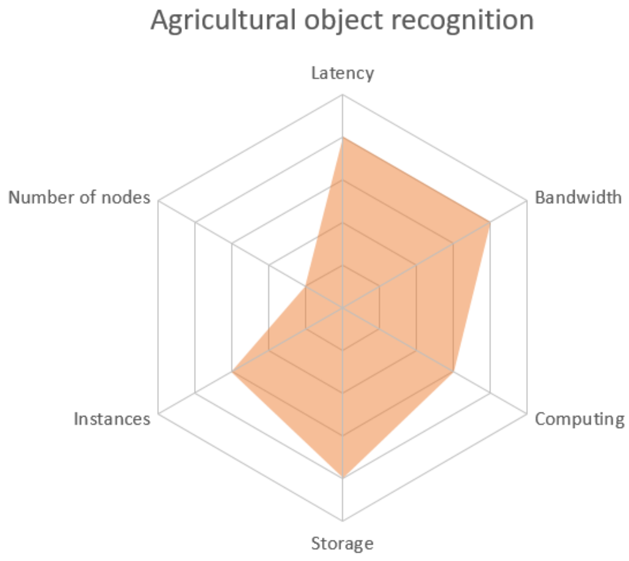

Figure 31: Agricultural object recognition – Spider Diagram

4.1.4 Agricultural Machine Automation

Harvesting and other heavy machinery operations will be performed by autonomous machines, with none or minimal human interaction. For most tasks a small platoon of machines will be coordinated. Exact positioning and near real-time communication are necessary for this use case. However, the transmitted data to control and steer such a platoon can be handled with a rather small bandwidth. The number of machines in such a small platoon is around 5. The traffic type for this use case is T2: low latency, low bandwidth, few connected devices. The computation and storage of the control data is performed at the MEC, which will probably be placed on a machine of the platoon.

The use case rating, equation 4.4, and the spider diagram, Figure 32, are below:

$$2 * 10.000 * (0,005 + 0,005) = 200 \tag{4.4}$$

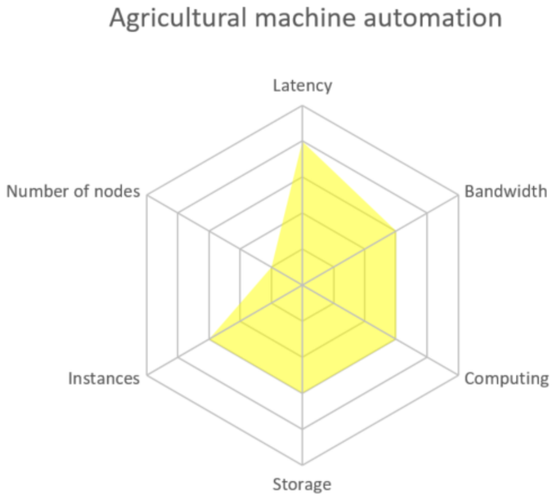

Figure 32: Agricultural Machinery Automation – Spider Diagram

4.1.5 Predictive Maintenance

Unexpected agricultural machine downtime is very expensive; so, predictive maintenance services are very important in this use case group. Machine data will be collected on the machine during the "work time" and transmitted to a central server. Neither low latency nor high bandwidth are critical for this use case. As this use case is largely researched we assume around 100 sensors collecting data on an agricultural machine.
The traffic type for this use case is T1: high latency, low bandwidth, few connected devices.
The data will be stored and computed at a data centre.

The use case rating, equation 4.5, and the spider diagram, Figure 33, are below:

$$1 * 10.000 * (0,05 + 0,05) = 1.000 \qquad (4.5)$$

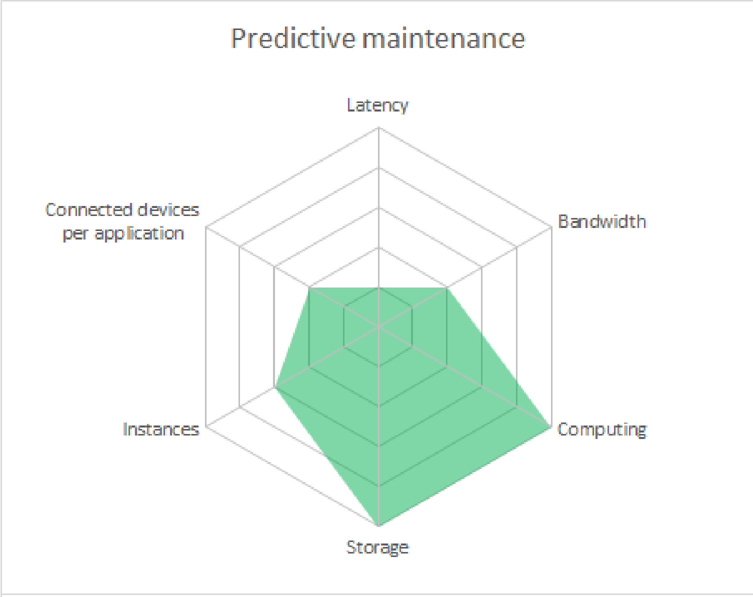

Figure 33: Predictive Maintenance – Spider Diagram

4.2 Energy

4.2.1 Number of Instances

There are around 19.000.000 living buildings in Germany [145]. An additional approx. 2.700.000 industry buildings [146]. While self organizing virtual power plants can be implemented with 10 or less units. Although the implementation could save a lot of energy and money, the energy sector slow to adopt new technologies. Stability gets prioritised over innovation in the energy industry. It is estimated that only 5% of all possibly cells will have an implementation of the described use cases resulting in 100.000 instances for this use case.

4.2.2 Smart energy grid home automation

Smart home use cases are adopted widely, yet infrastructure to reduce and optimise energy consumption according to power production forecasts and energy pricing is not widespread. With the decentralised self coordinating cells this will change. Smart home devices will connect to the MEC and will be turned on or off depending on the market price for energy, current local production and demands. Neither latency nor bandwidth are especially critical as the devices are usually sluggish themselves. Within a cell of 10 units we estimate a MEC will support up to 1.000 smart home devices. The traffic type for this use case is T5: low latency, high bandwidth, many connected devices.

The use case rating, equation 4.6, and the spider diagram, Figure 34, are below:

$$5 * 100.000 * (0,005 + 0,005) = 5.000 \tag{4.6}$$

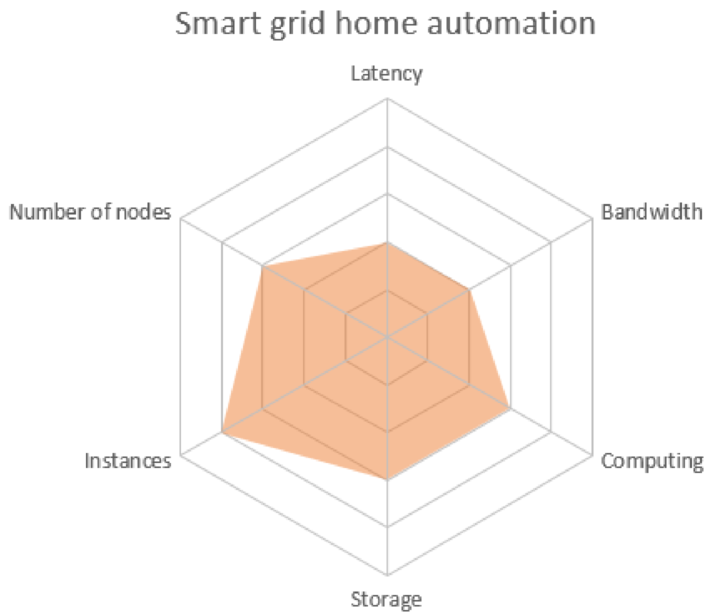

Figure 34: Smart energy grid home automation — Spider Diagram

4.2.3 Self Organizing Virtual Power Plant

Small power generation facilities like photovoltaic power plants, wind turbines etc. produce energy. Instead of satisfying the local power demand this energy is injected into the main energy grid. A self organizing virtual power plant establishes a communication between the decentralised power plant infrastructure and the consumers, balancing supply and demand in a way that power supply from the main grind is minimised. This virtual power plant can dynamically include new users depending on the optimal overall infrastructure, demand/production forecasts and real time power metering. For this use cases latency is critical, while the bandwidth needs to be sufficient. The traffic type for this use case is T2: low latency, low bandwidth, few connected devices. The computation for this use case will solely take place locally, while the data will be transmitted to a regional server or data centre to improve algorithms and forecast models.

The use case rating, equation 4.7, and the spider diagram, Figure 35, are below:

$$1 * 100.000 * (5,0 + 5,0) = 10.000 \tag{4.7}$$

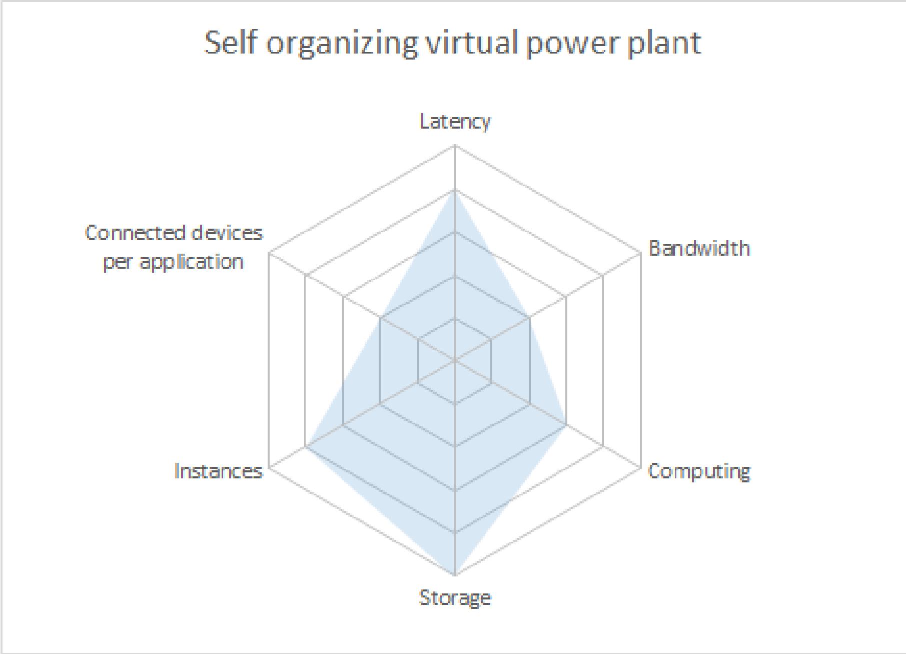

Figure 35: Self Organizing Virtual Power Plant — Spider Diagram

4.3 Construction

4.3.1 Number of Instances

The construction use case group and its use case will be implemented on large construction sites. Some use case like remote machine control are probably implemented on smaller construction sites too. To estimate the number of construction sites we utilised the statistics "Construction permits" [147] and "Constructions sites on Motorways 2019" [148].

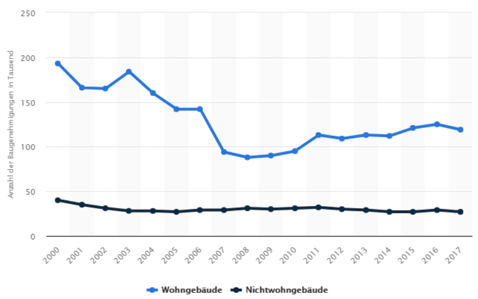

Figure 36: Statistic for Construction Permits

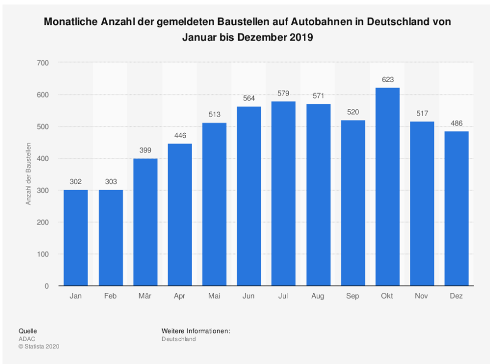

Figure 37: Statistic for Construction Sites on the Motorway 2019

According to these statistics from 2011 on there have been around 150.000 to 160.000 construction sites per year. As the implementation of these use cases will probably happen slowly and mostly for large construction sites, we estimate only 1% of the construction sites, round 1.000, will be supported. However, autonomous and remote control machines will also be needed at smaller construction sites and much more often. We estimate 10.000 remotely controlled or autonomous machines working in the construction industry in Germany in the year 2025.

4.3.2 Virtualization of Construction Site

The virtualization of the construction site will be performed under the building information model (BIM). This model will be created from sensors information and camera data. Assuming the sensor data is be required to update to digital twin of the construction site to be updated. As the computation is performed daily latency is unimportant. The network on the construction site will support up to 1.000.000 sensors sending small amounts of data, like position or audio data. For this bandwidth a small bandwidth is sufficient.
The traffic type for this use case is T5: high latency, low bandwidth, many connected devices.
The MEC near the construction site will run the software necessary for updating the digital twin, the data will probably be stored at this MEC as well.
The use case rating, equation 4.8, and the spider diagram, Figure 38, are below:

$$5 * 1.000 * (0,005 + 0,005) = 50 \tag{4.8}$$

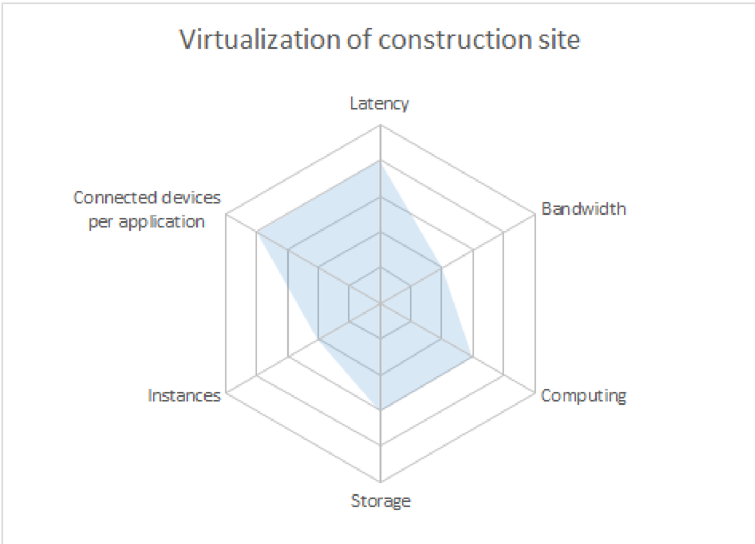

Figure 38: Virtualization of Construction Site – Spider Diagram

4.3.3 Predictive Maintenance

Small sensors in the machines, vehicles and the building will collect data and transmit this data for further analysis. This data will be used to provide in-depth analysis of the machine and building status. There could be up to 1.000.000 sensors in total on a construction site; however, they have minimal requirements concerning bandwidth and latency.
The traffic type for this use case is T5: high latency, low bandwidth, many connected devices.
The data will be stored and computed at a data centre and will is very likely to be send over the Internet.
The use case rating, equation 4.9, and the spider diagram, Figure 39, are below:

$$5 * 10.000 * (0,05 + 0,05) = 5.000 \quad (4.9)$$

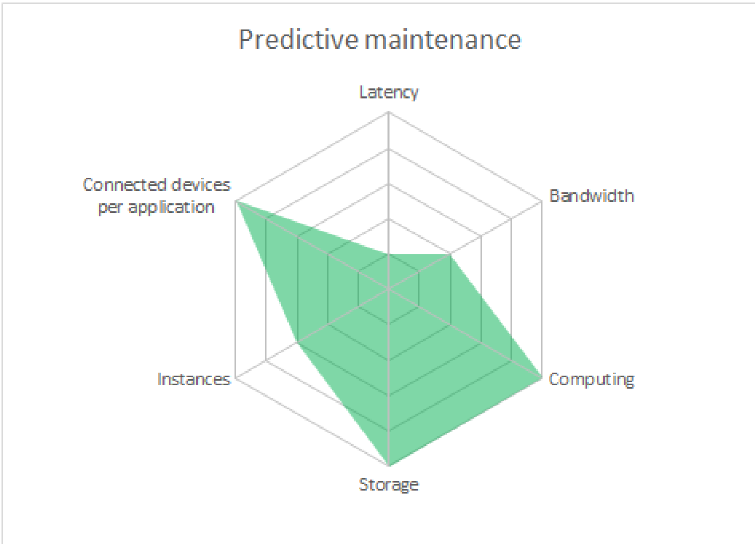

Figure 39: Predictive Maintenance – Spider Diagram

4.3.4 Camera Data for Virtualization

The visual data from cameras for virtualization and update of the digital twin of the construction site needs to be transmitted to the MEC. However, if the update happens daily, latency can be high. As visual data is rather large the cameras will need high bandwidth. We estimate the number of around 1.000 cameras on the construction site.
The traffic type for this use case is T4: low latency, high bandwidth, few connected devices.
The MEC near the construction site will run the software necessary for updating the digital twin, the data will probably be stored at this MEC as well.
The use case rating, equation 4.10, and the spider diagram, Figure 40, are below:

$$4 * 1.000 * (0,005 + 0,005) = 40 \tag{4.10}$$

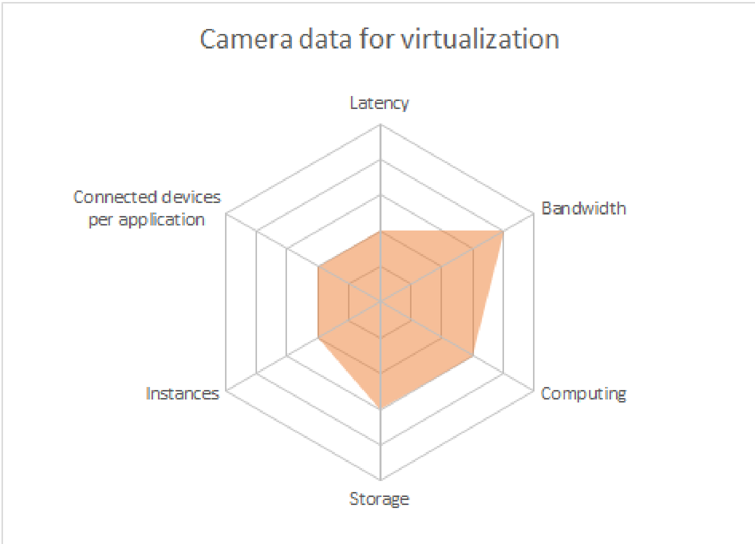

Figure 40: Camera Data for Virtualization – Spider Diagram

4.3.5 Camera Data for Object Recognition

Cameras will be implemented on the construction site for other tasks than virtualization of the construction site model. Use Case are object recognition and machine control. Visual data will be utilised to identify objects on the construction site for autonomous construction machines. This data will require low latency and high bandwidth in order to ensure a secure environment. The cameras will only be installed when necessary or are placed at the construction machines; therefore, only a few additional cameras will be needed. We estimate around 100 cameras for this use case on the construction site.
The traffic type for this use case is T4: low latency, high bandwidth, few connected devices. The computing and storage of the data will be performed at the MEC at the base station.

The use case rating, equation 4.11, and the spider diagram, Figure 41, are below:

$$4 * 10.000 * (0,005 + 0,005) = 400 \tag{4.11}$$

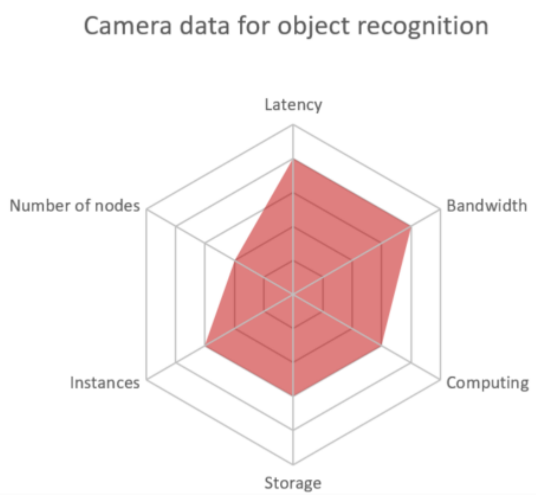

Figure 41: Camera Data for Object Recognition – Spider Diagram

4.3.6 Construction Machine Control and Mobility Support

On the construction site there will be autonomous or remotely controlled construction machines as well as small vehicles performing autonomous transportation tasks. Controlling such machines via a wireless communication link requires very low latency. As the computation is performed locally an a MEC, the required bandwidth for the use case data is low. We estimate around 100 machines for each use case.
The traffic type for this use case is T2: low latency, low bandwidth, few connected devices.
The control data will be stored at the MEC at the base station.

The use case rating, equation 4.12, and the spider diagram, Figure 42, are below:

$$2 * 10.000 * (0,005 + 0,005) = 200 \tag{4.12}$$

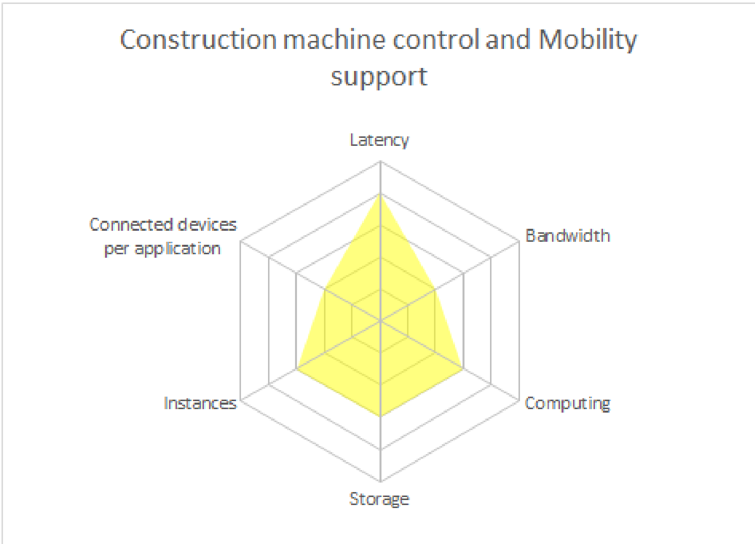

Figure 42: Construction Machine Control and Mobility Support – Spider Diagram

4.4 Manufacturing

4.4.1 Number of Instances

To estimate the number of factories having implemented the manufacturing use cases in 2025 the statistic of "New build factories and workshops between 2001 and 2017" from the Statistisches Bundesamt is utilised, see Figure 43 [149]. According to this statistic every year around 3.000 factories and workshops are build. We assume that half of these buildings are actually factories and the number of newly build factories will be constant until 2025, which leads to 9.000 factories being build between 2019 and 2025. The majority of these factories will implement these use cases. Additionally, existing factories will be renewed and implement the use cases as well. We estimate around 1.000 factories will be upgraded; therefore, around 10.000 factories will implement manufacturting use cases. These factories will differ a lot between each other; however, to rate the use cases we assume an average factory.

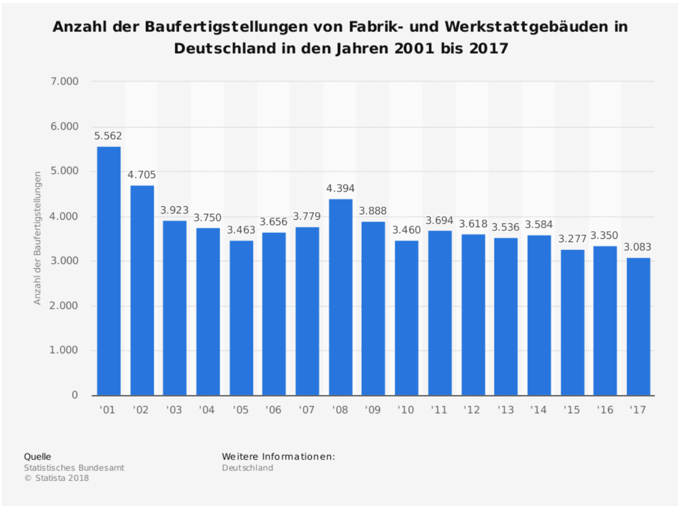

Figure 43: Statistisches Bundesamt: Construction of Factories and Workshops

4.4.2 Massive Sensor Networks for Virtualization

The virtualization of the production process will be performed by a massive network of sensors. These sensors could detect audio-data and transmit it for failure detection and process control. Within a factory process control is a critical task; therefore, real-time interaction is necessary.
To achieve this use case requirements very low latency with a round-trip time of 1 ms is required. Each individual sensor requires a small bandwidth, but many sensors are required for the analysis. We assume this use case needs up to 10.000 devices.
The traffic type for this use case is T6: low latency, low bandwidth, many connected devices. The process control is time critical; therefore, the computation has to be performed very decentralised, yet combining all sensor data. A MEC at the base station would fit this requirement. However, the data can be stored more centralised, e.g. at a regional server, for deeper analysis and improvement.

The use case rating, equation 4.13, and the spider diagram, Figure 44, are below:

$$6 * 10.000 * (0,005 + 0,01) = 900 \tag{4.13}$$

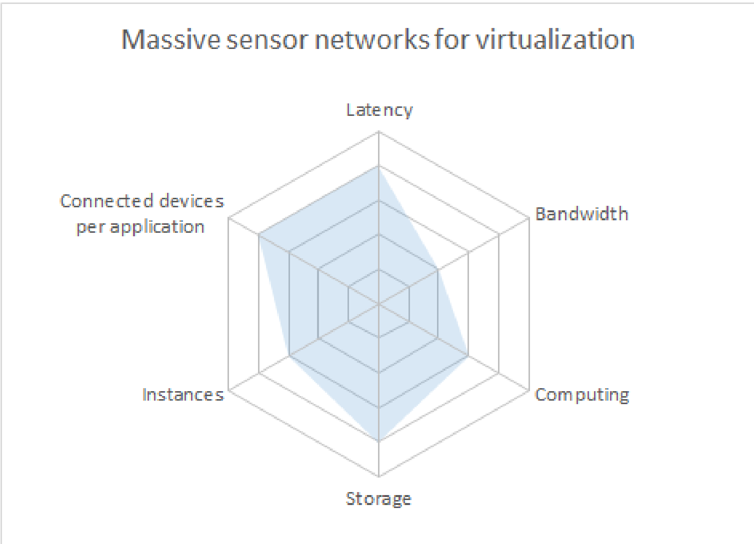

Figure 44: Massive Sensor Networks for Virtualization – Spider Diagram

4.4.3 Camera Data for Virtualization and Object Recognition

The virtualization of the production process and the process control will also be performed by video data from cameras. The cameras will monitor the production process and send data to the MEC, where a software will analyse the production process and allow for process control. Robots have different sensors to recognise the position of objects. In the future visual data from cameras will be utilised to determine the position of an object for the robot. The camera data for both use cases requires low latency as the imagery is necessary to control robots or the production process in the factory. Camera data itself requires high bandwidth. The number of cameras installed in the factory will be around 100.
The traffic type for this use case is T4: low latency, high bandwidth, few connected devices.
As these use cases require a very small round trip time, the computing will be done at a MEC near the base station. The data will be stored more centralised, e.g. at a regional server, for deeper analyses and improvement.

The use case rating, equation 4.14, and the spider diagram, Figure 45, are below:

$$4 * 10.000 * (0,005 + 0,01) = 600 \tag{4.14}$$

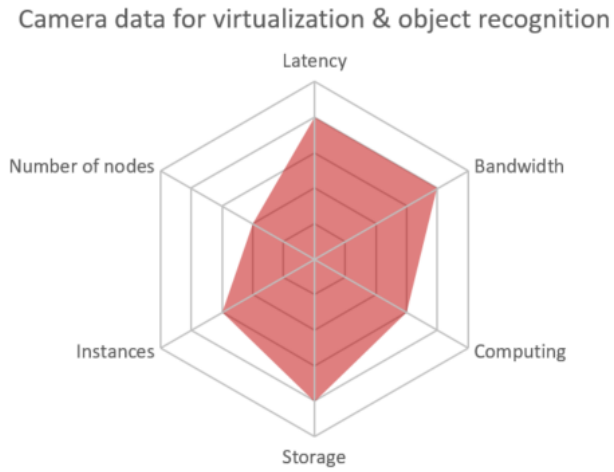

Figure 45: Camera Data for Virtualization and Machine Control – Spider Diagram

4.4.4 Machine Control and Mobility Support

Robots will produce most goods in factories and autonomous vehicles will transport equipment and goods. Both use cases, robot control loop and mobility support, require very low latency as a failure could be expensive. We estimate around 100 robots and transport vehicles per factory. The analysis for the movements, the trajectories, the control and steering data is computed at the MEC.
The traffic type for this use case is T2: low latency, low bandwidth, few connected devices.
The computing and the storage of the data will be done at MEC at the base station.
The use case rating, equation 4.15, and the spider diagram, Figure 46, are below:

$$2 * 10.000 * (0,005 + 0,005) = 200 \quad (4.15)$$

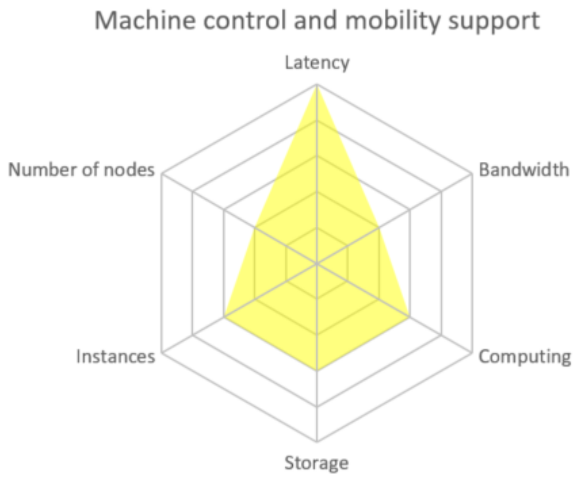

Figure 46: Macine Control and Mobility Support – Spider Diagram

4.4.5 Predictive Maintenance

Sensors integrated on robots and machines within the factory collect various information on the machine status. This data is used for predictive maintenance. For this use case latency and bandwidth are uncritical. The data will be collected at the factory and the send to a third party for analysis and predictive maintenance services. Within the factory we estimate around 100 robots and production machines.
The traffic type for this use case is T1: high latency, low bandwidth, few connected devices. The collected data will be transmitted to a data centre, where a specialised software will analyse it.
The use case rating, equation 4.16, and the spider diagram, Figure 47, are below:

$$1 * 10.000 * (0,05 + 0,05) = 1.000 \tag{4.16}$$

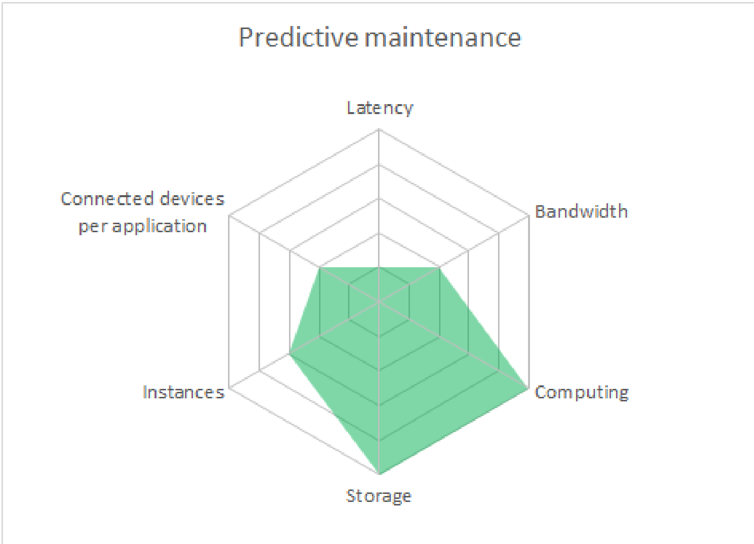

Figure 47: Predictive Maintenance – Spider Diagram

4.5 Live Events

4.5.1 Number of Instances

It is assumed that 5G support for live events will be available at stadiums, major concerts and other big events. To estimate the number of instances it is assumed that every stadium with 15.000 or more spaces will support this use case group [150]. In Germany there are around 100 stadiums which fulfil this requirement. Other events like big concert acts will should also be included; however, their number is comparatively small.

4.5.2 Local XR Support

Within a stadium event participants (users) want to receive information about the event on their HMD, if possible in real time. To support this kind of content a high bandwidth is important. For HMD movements have to be taken into account.
The traffic type for this use case is T7: high latency, high bandwidth, many connected devices. The computing and storage of the information for the HMD will be performed locally at the MEC at the base station.

The use case rating, equation 4.17, and the spider diagram, Figure 48, are below:

$$7 * 100 * (0,005 + 0,005) = 7 \tag{4.17}$$

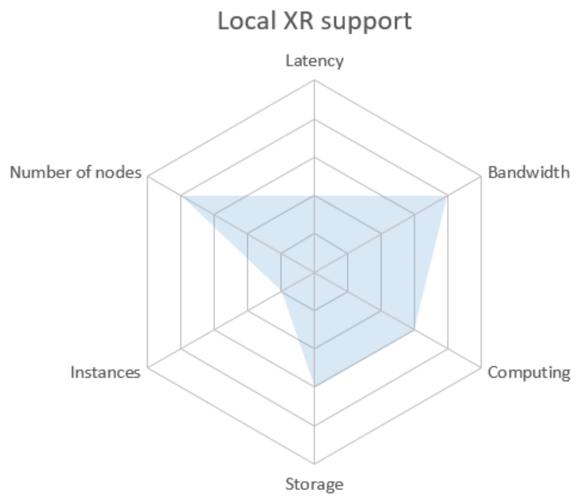

Figure 48: Local XR Support – Spider Diagram

4.5.3 Local Information Distribution

Besides AR support, the distribution of local information must support a multitude of devices as users want to receive and send data. However, neither low latency nor high bandwidth are necessarily required for this use case.
The traffic type for this use case is T5: high latency, low bandwidth, many connected devices.
The information will be supplied localy; therefore, most of the computation and storage will be at the MEC at the base station.

The use case rating, equation 4.18, and the spider diagram, Figure 49, are below:

$$5 * 100 * (0,005 + 0,005) = 5 \tag{4.18}$$

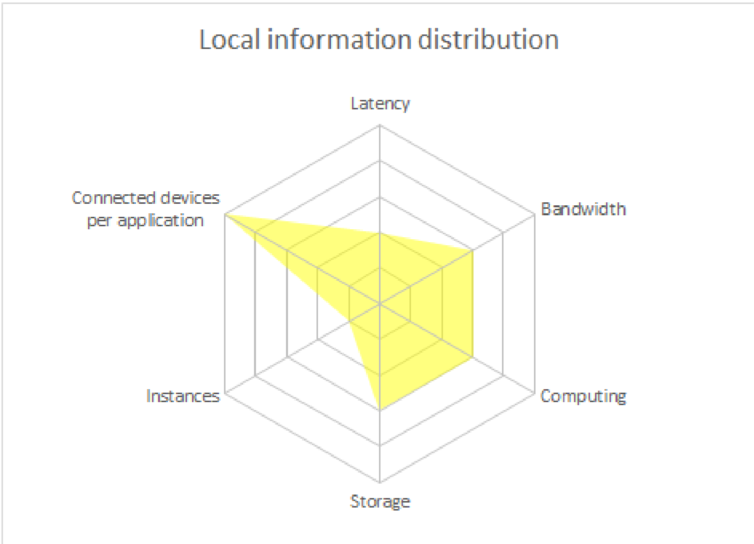

Figure 49: Local Information Distribution – Spider Diagram

4.5.4 Off-premise event streaming

There will be a large fan group not having the possibility to participate the event on premise but via the Internet. For these users a video stream of the event is supported. This stream could be video, AR or even VR data giving fans the feeling of live participation. This kind of content requires a large bandwidth. Latency is not an important issue. Depending on the demand and popularity of the event, this stream could be requested and received by millions of users at once.
The traffic type for this use case is T7: high latency, high bandwidth, many connected devices. The data will be transmitted over the Internet to the demanding users; therefore, computing and storage will be performed at the data centre.

The use case rating, equation 4.19, and the spider diagram, Figure 50, are below:

$$7 * 100 * (0,05 + 0,05) = 70 \tag{4.19}$$

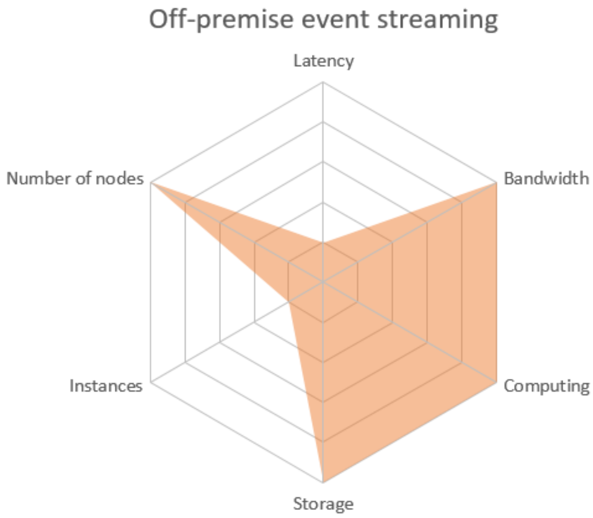

Figure 50: Off-premise event streaming – Spider Diagram

4.6 Cars

4.6.1 Number of Instances

Although connected cars are one the most researched topic today receiving significant public interest, major implementation of autonomous driving cars will not occur within this study's period of consideration. An current estimate suggests around 15 mio. autonomous driving cars until the year 2025 worldwide [151]. The majority of these cars will drive in China and the USA. However, other studies argue for a much later development of autonomous cars [152,153]. As no comprehensive picture could be found, we estimate around 100.000 active autonomous driving cars in Germany, form a total of around 50. Mio cars [152], in the year 2025. In this use case group the number of instances varies between the possible use cases.
Platoons on high speed motor ways, steering cars close to each other at high speed to save energy, will be rare as most autonomous cars will drive in cities. Therefore, we estimate around 100 platoons in total. The maximal distance for a car control server is around 25km or smaller, otherwise the latency requirements will be nearly impossible to meet. Considering this limitations, the minimum number of car control servers in Germany could be around 600, which will be rounded up to 1.000.

4.6.2 Platooning

Platooning autonomous connected cars on high speed motorways is considered to reduce the clearance between cars to an absolute minimum. To ensure the safety low latency is crucial. The bandwidth can be low as control data is small, to ensure resilient and fast communication. As autonomous driving cars will predominately drive in cities, the platoons will be rather small. The traffic type for this use case is T4: low latency, high bandwidth, few connected devices.
Either cars communicate between each other or the communicate with a nearby base station. The use case rating, equation 4.20, and the spider diagram, Figure 51, are below:

$$4 * 100 * (0,005 + 0,005) = 4 \tag{4.20}$$

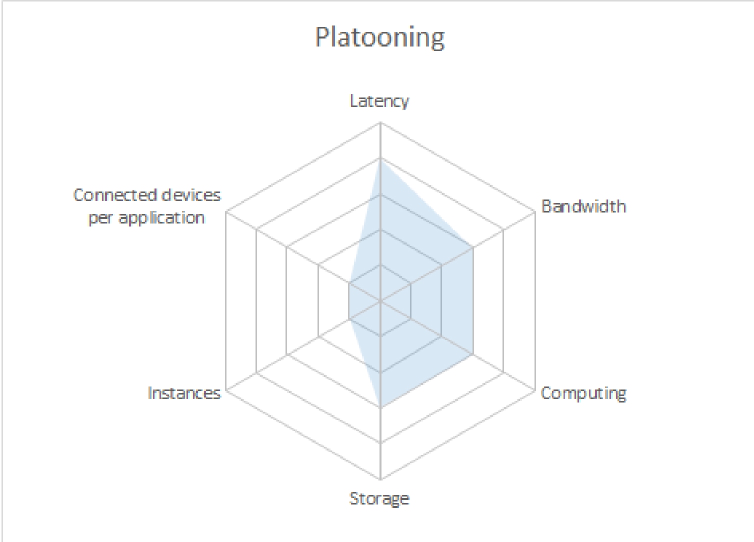

Figure 51: Platooning – Spider Diagram

4.6.3 Car Control

Autonomous cars will drive safely through the cities without human interaction, they will accelerate, break and stop on their own. To ensure this scenario without accidents network connection and V2X communication will be essential. Within the range of a base station or mobile communication cell many cars need to be connected and coordinated at a different levels. Controlling these cars needs minimum latency and enough bandwidth to ensure immediate reaction to the changing circumstances of the traffic environment.
The traffic type for this use case is T6: low latency, low bandwidth, many connected devices.
The computing of the car control algorithms and storage of the data must be performed close to the base station.

The use case rating, equation 4.21, and the spider diagram, Figure 52, are below:

$$6 * 1.000 * (0,005 + 0,005) = 60 \tag{4.21}$$

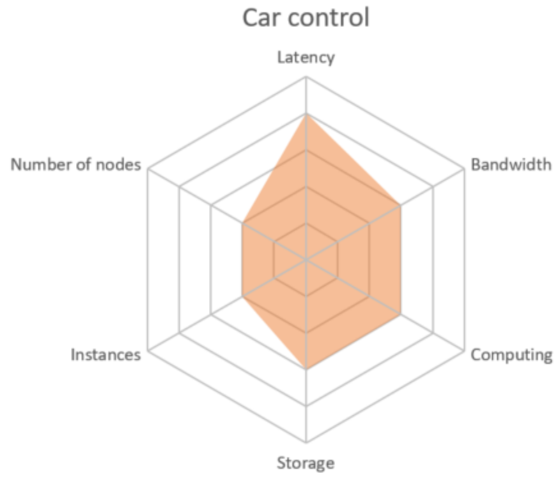

Figure 52: Car Control – Spider Diagram

4.6.4 Car Coordination

All the autonomous cars will be routed through the city on the optimal route considering different parameters like energy consumption, time, total traffic etc. These routes have to be optimised including whole city parts, cities or even regions avoiding traffic jams or street congestions. This coordination will probably be optimised at a regional server. For this coordination neither latency nor bandwidth play a vital role.
The traffic type for this use case is T1: low latency, low bandwidth, few connected devices.
The use case rating, equation 4.22, and the spider diagram, Figure 53, are below:

$$1 * 1.000 * (0,01 + 0,01) = 20 \tag{4.22}$$

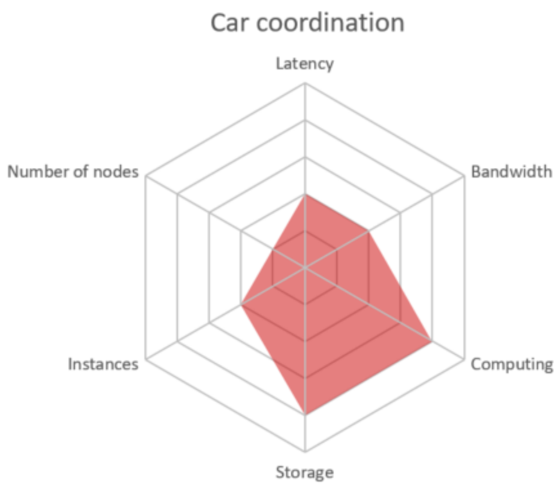

Figure 53: Car Coordination – Spider Diagram

4.6.5 In-car Entertainment

Autonomous cars will enable the driver to consume entertainment content or perform other tasks while travelling. Network slicing will ensure a reliable connection for the control of the car and simultaneously consuming web content. Latency is not crucial for this use cases but the bandwidth must be large enough to ensure a high quality user experience.
The traffic type for this use case is T3: low latency, high bandwidth, few connected devices. Most of the computing will be performed in the car, while the content will be delivered from a regional server or data centre.

The use case rating, equation 4.23, and the spider diagram, Figure 54, are below:

$$3 * 100.000 * (0,001 + 0,01) = 3.300 \tag{4.23}$$

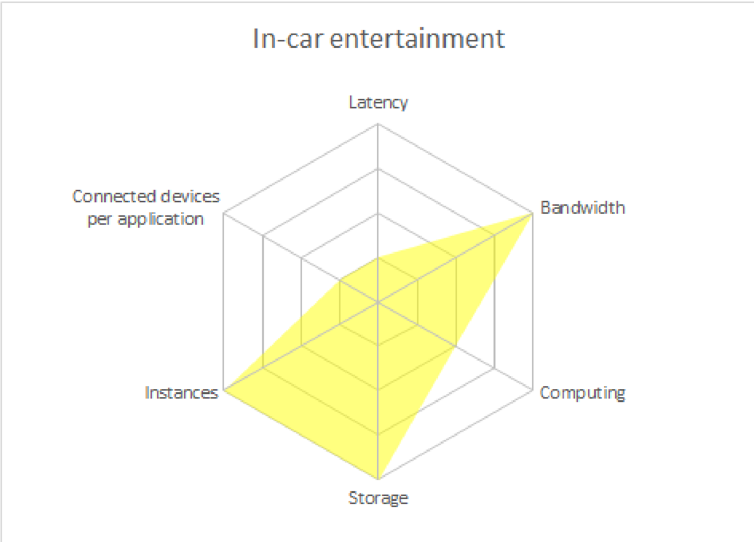

Figure 54: In-car Entertainment – Spider Diagram

4.6.6 Predictive Maintenance

Car manufacturers retrieve information on the car maintenance status. For the transmission of this information neither latency nor bandwidth are important, as the data will be collected in the car and the send to car manufacturer once a day or on demand. The number of connected devices are all sensors of a car. This use case includes the transmission of live updates for car firmware. They will be downloaded by the car and installed by the driver on demand.
The traffic type for this use case is T1: high latency, low bandwidth, few connected devices. The data will be stored and computed at the data centre of the car manufacturer.
The use case rating, equation 4.24, and the spider diagram, Figure 55, are below:

$$1 * 100.000 * (0,05 + 0,05) = 10.000 \tag{4.24}$$

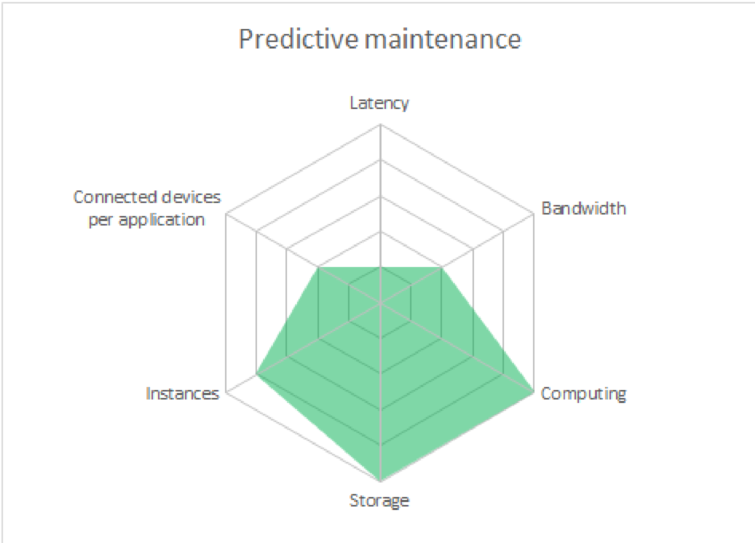

Figure 55: Predictive Maintenance – Spider Diagram

4.7 Aircraft

4.7.1 Number of Instances

Aircraft connectivity is assumed to be widely available by the year 2025 due to consumer demand. The number of flights over Germany during the year 2019 was 2.200.000 [154]. On average, 365 days a year with 24h each day, this results in around 250 simultaneous flights every hour. Only a part of this are passenger flights; therefore, we estimate the number of flights for this use case group will be around 100 [1].

4.7.2 Aircraft Passenger Entertainment

Planes will provide their passengers with a stable high bandwidth connection to the ground for entertainment or work. Within the plane there will be approximately 100 to 1.000 passenger devices connected at once using the communication link to the ground. On the one hand consumers will tolerate a high latency; on the other hand they will demand enough bandwidth. The traffic type for this use case is T3: high latency, high bandwidth, few connected devices. Most of the computing will be performed at the user equipment, while the content will be delivered from a regional server or data centre.

The use case rating, equation 4.25, and the spider diagram, Figure 56, are below:

$$3 * 100 * (0,001 + 0,05) = 15 \tag{4.25}$$

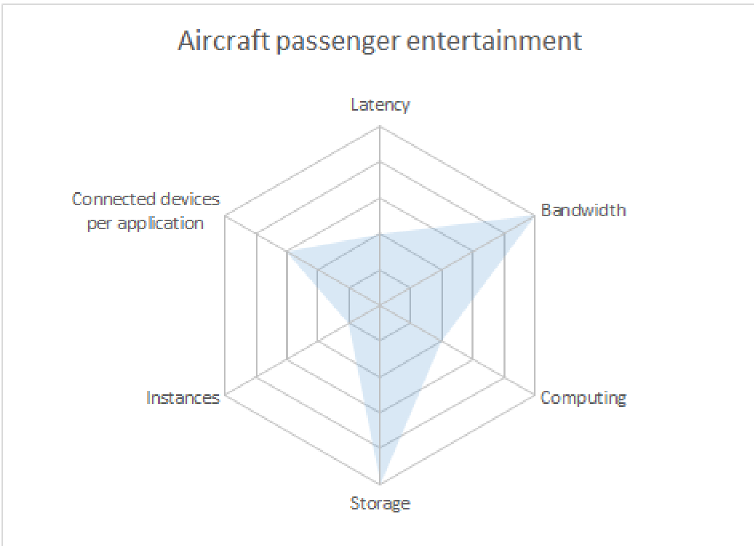

Figure 56: Aircraft Passenger Entertainment – Spider Diagram

[1] Please not, these numbers are prior the 2020 pandemic and the possible change in aircraft traffic. Unfortunately it is not possible to project an increase or decline in future aircraft traffic as a result of the pandemic. For the purpose of this study, no change is assumed.

4.7.3 Critical Flight Information

Crucial information about the flight or information for the pilot including routes, changes in landing times or destination need a separate network slice as they require more resilience than passenger entertainment. Low latency will be important. However, due to the long distance between the aircraft and the base station a delay of up to 100 milliseconds is still expected. This information usually does not require high bandwidth.
The traffic type for this use case is T2: low latency, low bandwidth, few connected devices.
The computing of the information will be performed at the aircraft and while the data will be stored at a data centre.
The use case rating, equation 4.26, and the spider diagram, Figure 57, are below:

$$2 * 100 * (0,05 + 0,05) = 20 \tag{4.26}$$

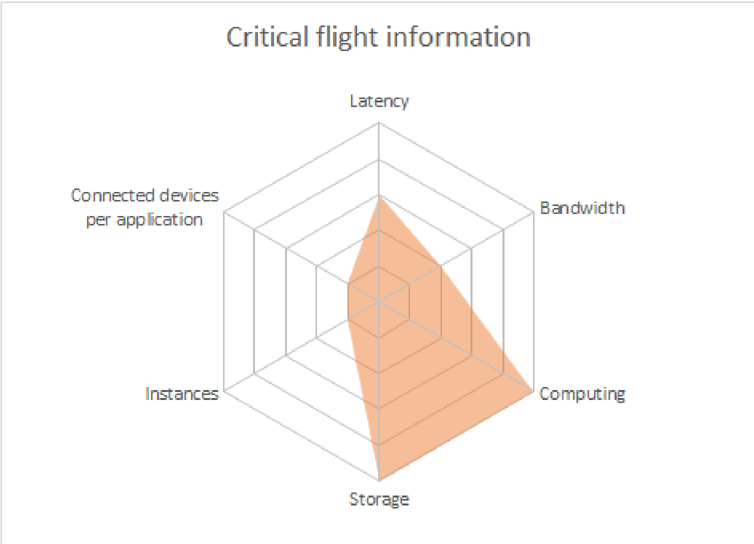

Figure 57: Critical Flight Information – Spider Diagram

4.7.4 Predictive Maintenance

A multitude of sensors will collect status information of the aircraft before, during and after the flight. This information is used for regular maintenance and predictive maintenance and can take up terabytes in volume. Latency and bandwidth are uncritical as the data will be collected at the aircraft and only transmitted at the ground.
The traffic type for this use case is T5: high latency, low bandwidth, many connected devices. The data will be stored and computed at a data centre.

The use case rating, equation 4.27, and the spider diagram, Figure 58, are below:

$$5 * 100 * (0,05 + 0,05) = 50 \tag{4.27}$$

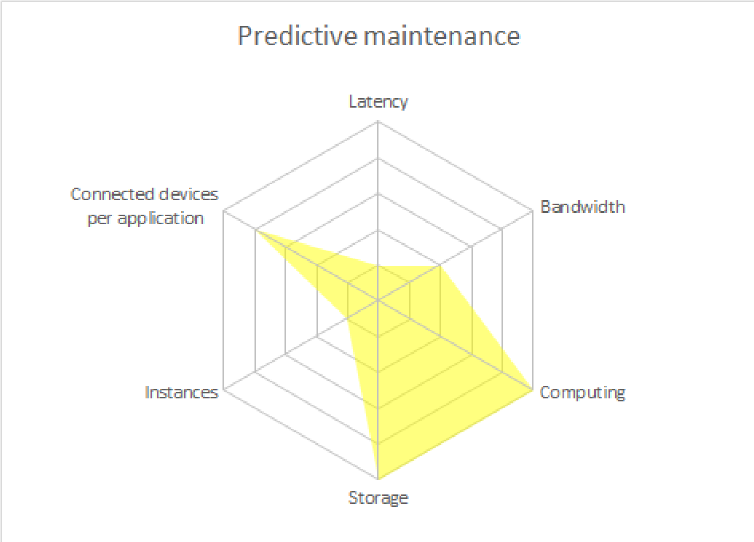

Figure 58: Predictive Maintenance – Spider Diagram

4.8 Trains

4.8.1 Number of Instances

Connectivity everywhere will be important; therefore, even on high speed trains a stable Internet connection is desired. There are around than 24.000 trains in Germany every day in 2019; therefore, we estimate around 1.000 trains every hour on average [155].

4.8.2 Passenger entertainment

Passengers want to be connected to the Internet, to work or use entertainment services. The passengers will connect their devices to the train network expecting acceptable latency and bandwidth. So the train network must allow for seamless connectivity for more than 1.000 passenger devices at once. The computation of the data will be performed at the user equipment level; however, the data will come from a data centre.
The traffic type for this use case is T7: high latency, high bandwidth, many connected devices.

The use case rating, equation 4.28, and the spider diagram, Figure 59, are below:

$$7 * 1.000 * (0,001 + 0,05) = 357 \qquad (4.28)$$

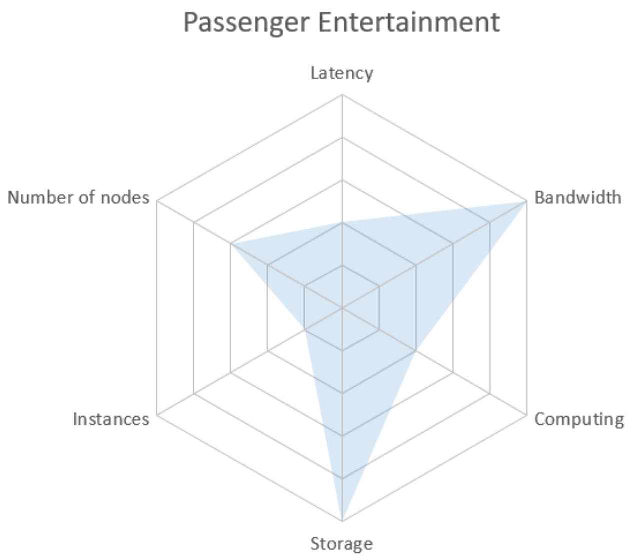

Figure 59: Passenger Entertainmeint – Spider Diagram

4.9 Video in 5G

4.9.1 Number of Instances

Video traffic is supposed to be the major contributor to Internet traffic in the next years. There is no reliable statistic available on the number of video conferences per day or video streams. 83 per cent of germans are using video streaming services daily [156]. Video conferencing has spiraled to new highs in 2020 with Zoom reporting 200 mio. users daily [157]. However, no absulote numbers on could be researched, so the number of instances for 5G video use cases has to be estimated. We assume 10.000 parallel instances for video conferencing and video surveillance and 1.000 instances for video broadcasting. Video on demand will probably exceed the scale of this study so we estimate the highest number of instances, 1.000.000, for this use case.

4.9.2 Surveillance

Public and private cameras will monitor places of interest for security and safety reasons. The cameras will send their data to a MEC where a specialised software will analyse it and decide, whether to forward video data to a human for closer inspection or not. The video data of the survailance cameras requires high bandwidth to transmit the required solution; however, the latency can be rather high, as data transmittion is not critical in the ms range. The number of video cameras transmitting their data to the MEC for one surveillance instance can vary a lot. We estimate that up to 1.000 cameras could be surveying an area.
The traffic type for this use case is T7: high latency, high bandwidth, many connected devices. Most of the computing, en- and decoding of the video data will be performed at the cameras or at the MEC. The data will be stored at the MEC and only be inspected and uploaded higher into the network if necessary.

The use case rating, equation 4.29, and the spider diagram, Figure 60, are below:

$$7 * 10.000 * (0,005 + 0,005) = 700 \tag{4.29}$$

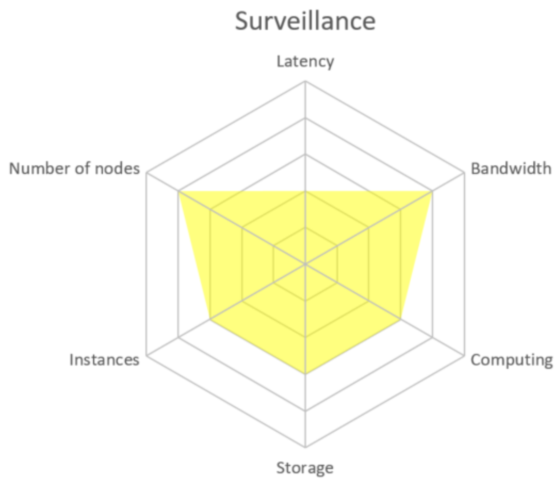

Figure 60: Surveillance – Spider Diagram

4.9.3 Conferencing

Groups and single live video conference calls on mobile devices will be enhanced by the larger bandwidth 5G provides for mobile devices. To guarantee a positive user experience for video conferencing the latency needs to be low. Additionally, a large bandwidth is needed to stream high resolution videos. Most computing, including the en- and decoding can be performed at the user device or the MEC. However, the video data needs to be transmitted to the other video conference participants.
The traffic type for this use case is T4: low latency, high bandwidth, few connected devices.
The use case rating, equation 4.30, and the spider diagram, Figure 61, are below:

$$4 * 10.000 * (0,005 + 0,05) = 2.200 \tag{4.30}$$

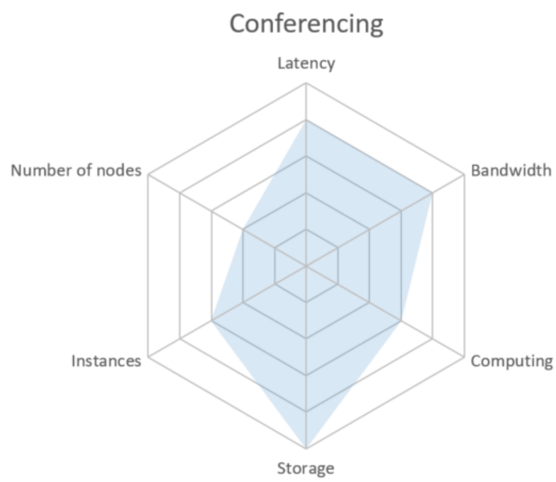

Figure 61: Conferencing – Spider Diagram

4.9.4 Broadcast

Videos will be broadcasted into the cellular network, so multiple users can receive the same video at the same time in high resolution. This could be a television channel or an emergency video broadcast. The users will demand high resolution of these videos on their mobile devices; therefore, the bandwidth has to be high. A small delay can be tolerated as the video can be buffered at the user equipment. The use cases can be requested by multiple devices at once. The traffic type for this use case is T3: high latency, high bandwidth, few connected devices. Computing, e.g. encoding will be performed at the data centre storing this video.

The use case rating, equation 4.31, and the spider diagram, Figure 62, are below:

$$3 * 1.000 * (0,05 + 0,05) = 300 \tag{4.31}$$

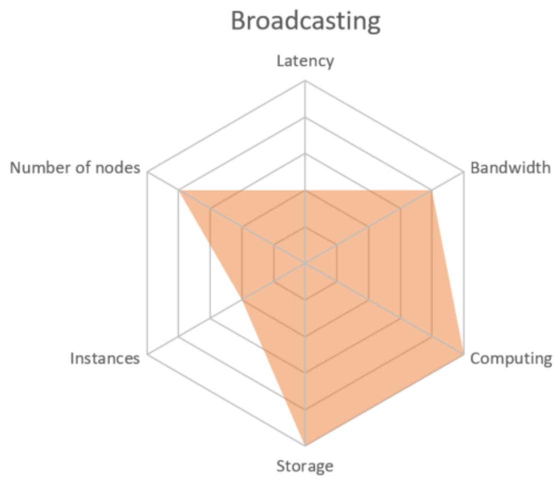

Figure 62: Broadcast – Spider Diagram

4.9.5 Streaming

Streaming videos on demand to mobile devices will be the largest contributor to the overall Internet traffic in the upcoming years. The 5G mobile communication standard with its specification for larger bandwidth and the possibility for massive device in dense area support will contribute to this development. For video distribution predictive caching will probably be used vertical within the network, from the user equipment up to the data centres, depending on the customer demand for a specific video. Streamed videos can be cached at the user equipment to avoid delay, which could be necessary considering the high resolutions users will demand. The traffic type for this use case is T3: high latency, high bandwidth, few connected devices.

The use case rating, equation 4.32, and the spider diagram, Figure 63, are below:

$$3 * 1.000.000 * (0,05 + 0,05) = 300.000 \tag{4.32}$$

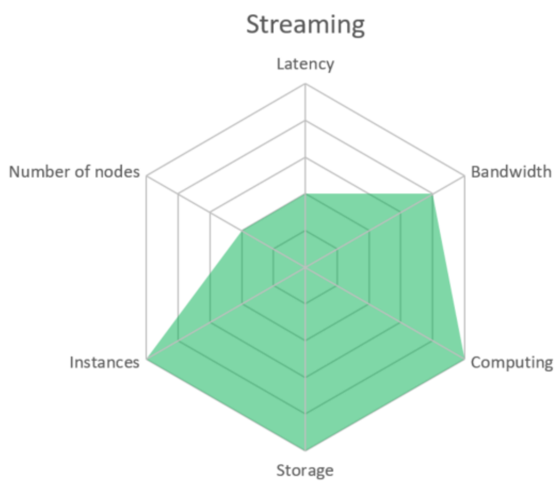

Figure 63: Streaming – Spider Diagram

4.10 Virtual and Augmented Reality

4.10.1 Number of Instances

Augmented and virtual reality are technologies which could bring a major shift how we interact in the future. It is estimated that AR and VR will be widely adopted by 2025; thus, having an impact on global Internet traffic. Estimates assume a global sale of 76,6 mio XR devices by 2025, with a market estimation of 6,2 billions of US$ by 2023. Statistics on users per use case are not yet available. Therefore, we have to estimate the number is instances per use case. For the use cases cinematic VR, AR/VR simulations we estimate 10.000 users on average in the year 2025. For the use case of 360 ° cinematic VR and AR /VR gaming we estimate around 100.000 users. Video gaming is asumed to be the leading market for XR [158]. Cinematic 6 DOF movies is considered a niche use case probably only 100 users, due to total film production and computation cost. All use cases require high bandwidth to support the demanded high graphic resolution.

4.10.2 VR 360° Movies

In contrary to classical VR movies, 360° enable user interaction via head movement. To avoid motion sickness a very low latency is required.
The traffic type for this use case is T4: low latency, high bandwidth, few connected devices.
While computing of the video data will be performed at the base station or user equipment, the video will be stored at a data centre and transmitted to the user.
The use case rating, equation 4.33, and the spider diagram, Figure 64, are below:

$$4 * 100.000 * (0,005 + 0,05) = 22.000 \tag{4.33}$$

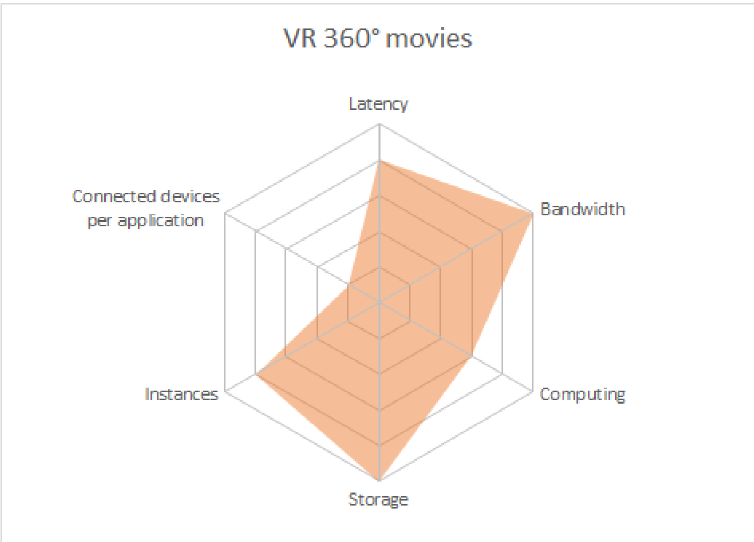

Figure 64: VR 360° Movies – Spider Diagram

4.10.3 AR and VR Simulations

AR/VR simulations use cases allow for more multiple users interacting with a model or environment and cooperate with each other. These use cases require low latency and will run on a local PC or MEC. The use case itself will be stored locally and only interaction data will be transmitted.
The traffic type for this use case is T4: low latency, high bandwidth, few connected devices.
There is also the possibility of running such an use case in the cloud and simply let users connect with it. However, this requires a stable bandwidth and will probably result in delays.
The use case rating, equation 4.34, and the spider diagram, Figure 65, are below:

$$4 * 10.000 * (0,005 + 0,005) = 400 \tag{4.34}$$

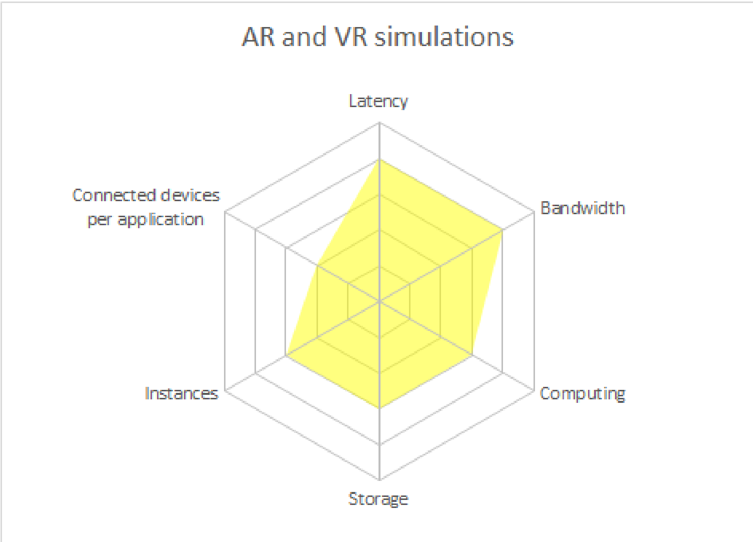

Figure 65: AR and VR Simulations – Spider Diagram

4.10.4 Six Degrees of Freedom Simulations

While 360° VR movies only allow for head movement, 6 DOF movies allow for complete user movement in the movie environment. Logically low latency as a must for this use case. 6 DOF movie files are large even by movie file standards and must probably be stored at the MEC or the user equipment prior to viewing.
The traffic type for this use case is T3: low latency, high bandwidth, few connected devices.
The use case rating, equation 4.35, and the spider diagram, Figure 66, are below:

$$4 * 100 * (0,005 + 0,005) = 4 \tag{4.35}$$

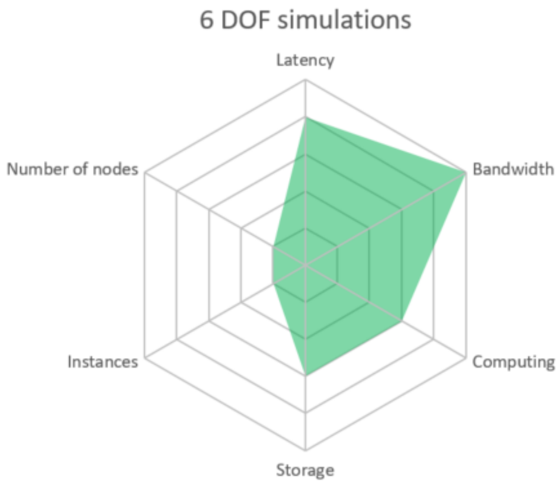

Figure 66: Six Degrees of Freedom Simulations – Spider Diagram

4.10.5 AR and VR Gaming

Like simulations, AR and especially VR gaming connect multiple users; therefore, a very low latency is a central component of this technology.
The traffic type for this use case is T4: low latency, high bandwidth, few connected devices.
For real time VR gaming, latency is such a critical factor that long distance VR gaming is likely to be not possibly in 2025. Therefore, computing and storage of the VR game will be performed at a regional server.
The use case rating, equation 4.36, and the spider diagram, Figure 67, are below:

$$4 * 100.000 * (0,01 + 0,01) = 8.000 \quad (4.36)$$

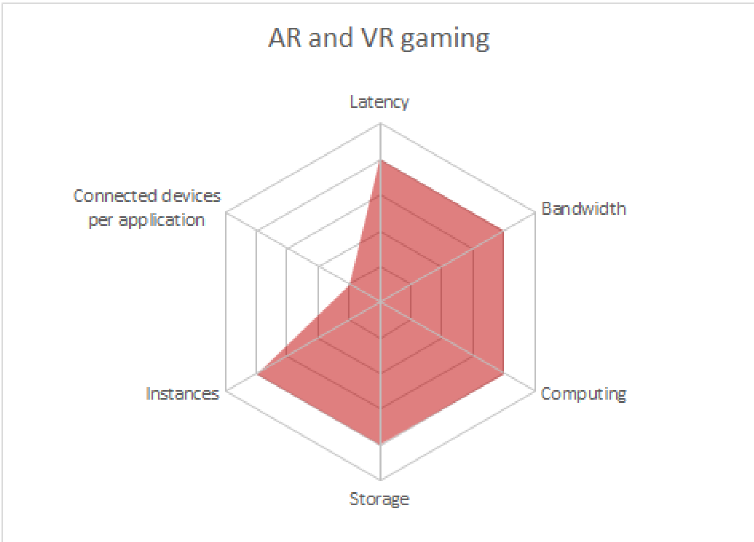

Figure 67: AR and VR Gaming – Spider Diagram

4.10.6 Cinematic VR

Viewing movies with a HMD is quite similar to video on demand streaming, except a higher resolution is necessary. As the data can be cached and user interaction is not required latency can be high.
The traffic type for this use case is T3: high latency, high bandwidth, few connected devices.
The computing and storage of the movie will occur at the data centre.
The use case rating, equation 4.37, and the spider diagram, Figure 68, are below:

$$3 * 10.000 * (0,05 + 0,05) = 3.000 \tag{4.37}$$

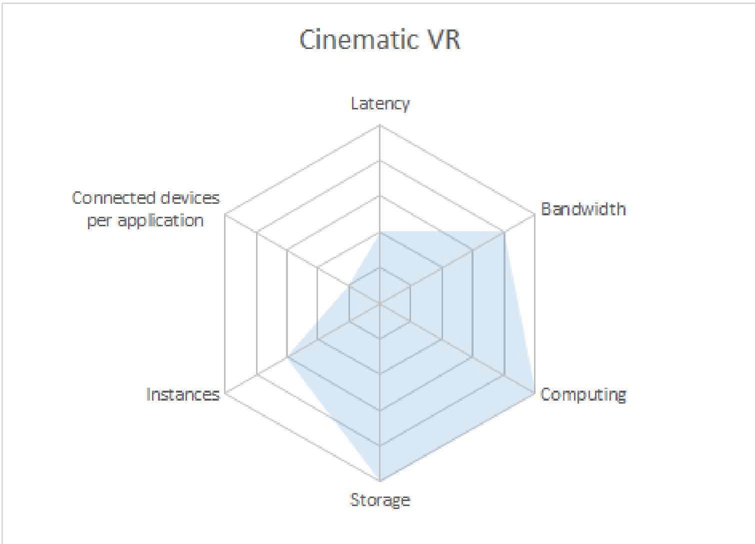

Figure 68: Cinematic VR – Spider Diagram

4.11 Tactile Internet

4.11.1 Number of Instances

The use cases for Tactile Internet are quite new and could be a centre of research interest in the upcoming years. Estimates on the number of instances on the use cases of this use case group are very difficult. Experts estimate overall 1.000 instances of these use cases in Germany in the year 2025.

4.11.2 Human Training

Some skills require repetitive training to become experts. The Tactile Internet training systems will enable to practise these skills in a VR or AR environment with multimodal feedback. Human movements are transferred to the MEC. The multimodal feedback allows for the feeling of movements and material resistance. This requires low latency. The required bandwidth for this use case is in the 50 Mb/s range. (VR data is included in equation 4.35.
The traffic type for this use case is T6: low latency, low bandwidth, many connected devices. the computation and storage of the data will be performed at the MEC at the base station.

The use case rating, equation 4.38, and the spider diagram, Figure 69, are below:

$$6 * 1.000 * (0,005 + 0,005) = 60 \tag{4.38}$$

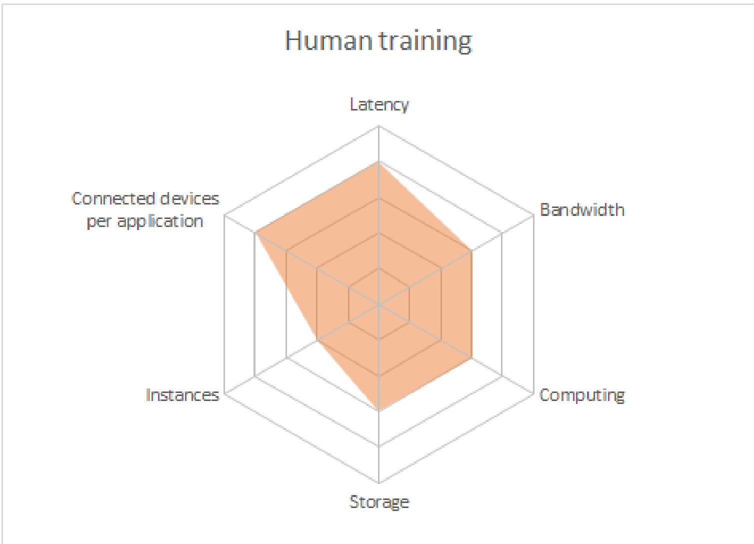

Figure 69: Human Training – Spider Diagram

4.11.3 Robot Assistance and Skill Transfer

Besides capturing human expert skills to train others, it is also possible to transfer these skills to machines in order to fulfil human work e.g. in dangerous environments or assist humans. For human-machine interaction robots need to understand human movements. Also in such environments low latency is crucial. Massive sensors need to track the robot and the human movement in order to perform the necessary robot control algorithms. The bandwidth per device however is rather small.
The traffic type for this use case is T6: low latency, low bandwidth, many connected devices.
The use case will run on a local server or MEC; therefore, the computation and storage is performed at the edge of the network.

The use case rating, equation 4.39, and the spider diagram, Figure 70, are below:

$$6 * 1.000 * (0,005 + 0,005) = 60 \tag{4.39}$$

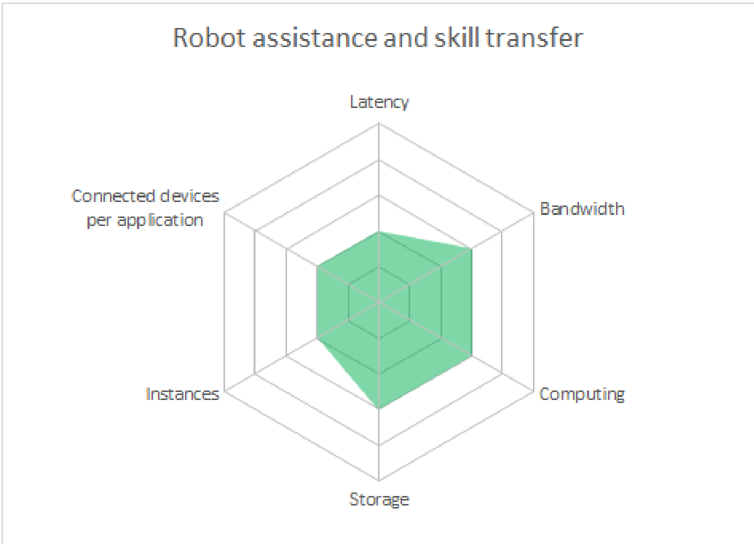

Figure 70: Robot Assistance and Skill Transfer – Spider Diagram

4.11.4 Movement to Machine Learning

In the future humans will teach movements to machines. The human will wear a suit, gloves and similar devices carrying a multitude of different sensors for multimodal movement tracking. For a live interaction the latency has to be low; however, most use cases will not require live interaction and as long as all movements are recorded correctly. The bandwidth to transmit the multimodal data is similar to the first use case.
The traffic type for this use case is T5: high latency, low bandwidth, many connected devices.
Most of these use cases will run on a local server or MEC; therefore, the computation and storage is performed at the edge of the network.
The use case rating, equation 4.40, and the spider diagram, Figure 71, are below:

$$5 * 1.000 * (0,005 + 0,005) = 50 \tag{4.40}$$

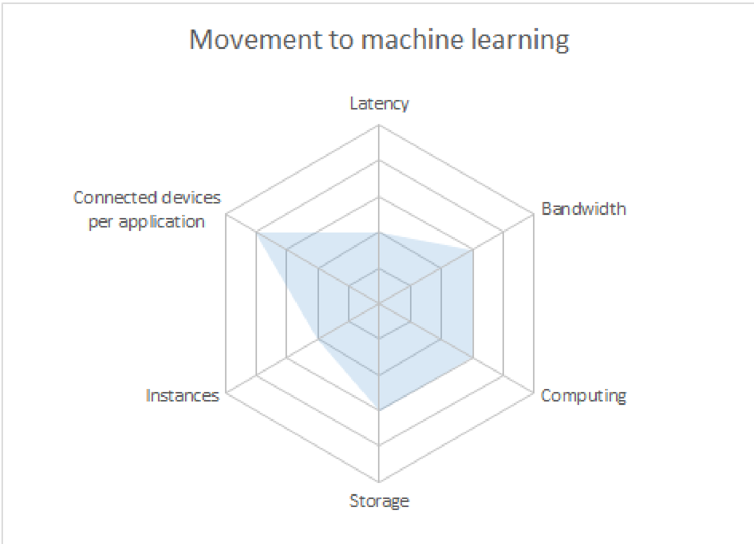

Figure 71: Movement to Machine Learning – Spider Diagram

4.12 Health

4.12.1 Number of Instances

The health sector will be supported by various use cases each varying in traffic type requirements and number of instances.
Most people will wear small personal devices, probably smart watches, which collect and analyse data on their health. The total number for smartwatches and for activity tracking devices in Germany is allready beyond 1 mio. devices [159]. It is assumed to increase until 2025.
Another use case is the smart ambulance which transmits patient data to the destination hospital prior to the arrival. In the year 2016 there have been around 12 mio. patient transportations by ambulances, see Figure 72 citeKW2020. Assuming an equal distribution throughout the year and the daytime there have been approximately 1.250 patient transports per hour. As this is live critical we assume nearly all ambulance will support this use case in the year 2025; therefore, the number of instances is 1.000.
Robots will assist humans in surgery in the year 2025. In Germany there are around 9.000 operating rooms [160]. Robot assistance will not be as common as AR assistance, due to the higher costs. Also more surgeries profit from AR support than from robotic assistance. Therefore, it is assumed that only 10% of all operation rooms will have assisting robots, leading to an estimate of around 1.000 instances.
Surgery can profit a lot from AR support, as critical information or pictures can be displays live to the surgeon. We consider most of the operating rooms in Germany will support AR in 2025 we estimate the number of instances to around 10.000.
The last major use case for this use case group is rehabilitation support for humans. Robots will assist patient in the rehabilitation process if possible. Currently around 1.000 rehabilitation centres operate in Germany [161]. We assume this use case will be a standard and available in every rehabilitation centre at least once; so, the number of instances is around 1.000.

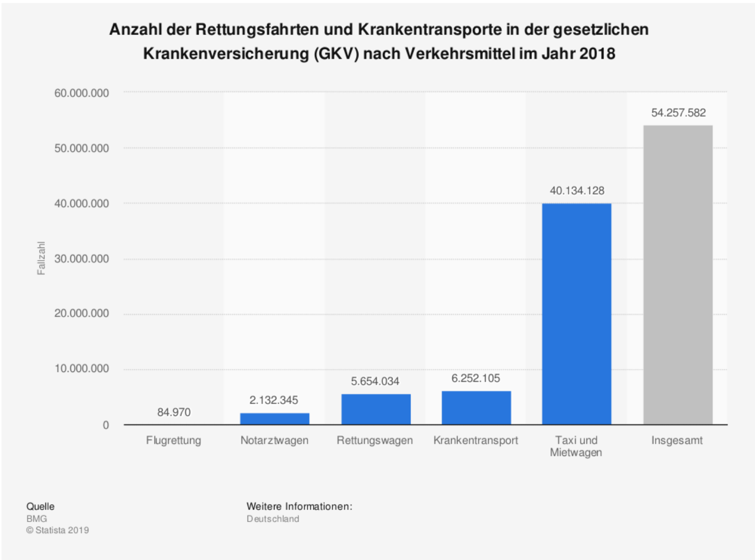

Figure 72: Statistics: Patient Transport Vehicles

4.12.2 Wearables

E-Health wearables are supposed to accompany most users in everyday live to monitor and analyse their vital functions. Neither a low latency not a high bandwidth are important, as the data collected and transmitted by wearables is comparatively small. The number of devices per user is also very low; however, the number of devices within the range of a base station could be quite high.
The traffic type for this use case is T5: high latency, low bandwidth, many connected devices.
Most of the computation of the health data will be performed at the MEC at the base station; however, if data privacy issues are cleared then storage will probably happen at a central server for an in depth analysis and algorithm improvement.

The use case rating, equation 4.41, and the spider diagram, Figure 73, are below:

$$5 * 1.000.000 * (0,05 + 0,05) = 275.000 \tag{4.41}$$

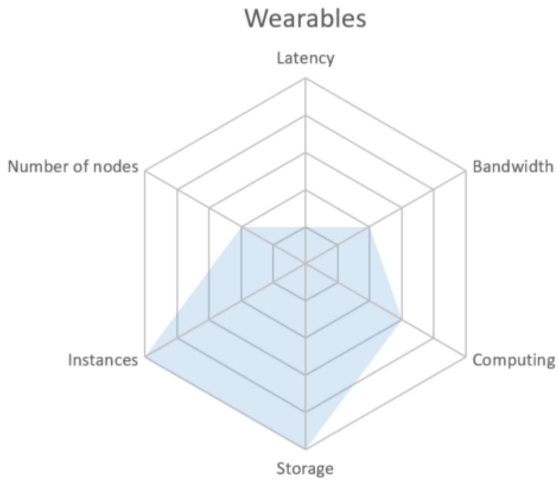

Figure 73: Wearables – Spider Diagram

4.12.3 XR Surgery Assistance

AR surgery assistance can provide critical information to the surgeon and be supportive in many ways. This use case requires near real-time feedback for the surgeon; therefore, low latency and high bandwidth are essential for this use case.
The traffic type for this use case is T4: low latency, high bandwidth, few connected devices.
The computing and storage will be performed at the base station.
The use case rating, equation 4.42, and the spider diagram, Figure 74, are below:

$$4 * 10.000 * (0,005 + 0,005) = 400 \quad (4.42)$$

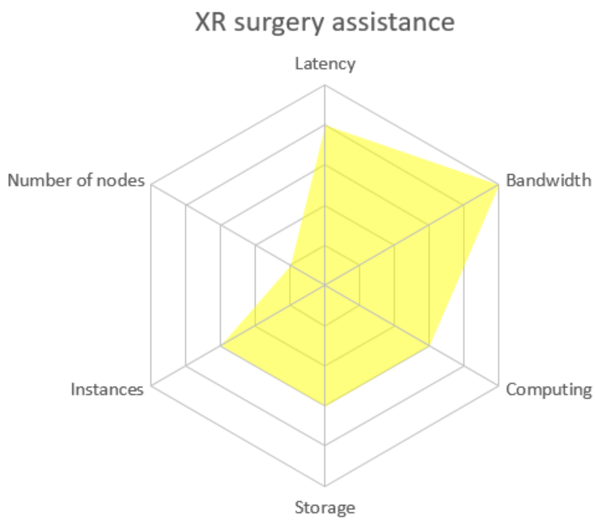

Figure 74: XR Surgery Assistance – Spider Diagram

4.12.4 Assistive robot control

Robotics assisting or even performing surgeries is a major field of research and will probably be excelled with the MEC architecture of 5G. Low latency, high bandwidth and visual support are essential for this use case. However, only few devices will be connected.
The traffic type for this use case is T4: low latency, high bandwidth, few connected devices.
The computing and storage will be performed at the base station. The use case rating, equation 4.43, and the spider diagram, Figure 75, are below:

$$4 * 1.000 * (0,005 + 0,005) = 40 \tag{4.43}$$

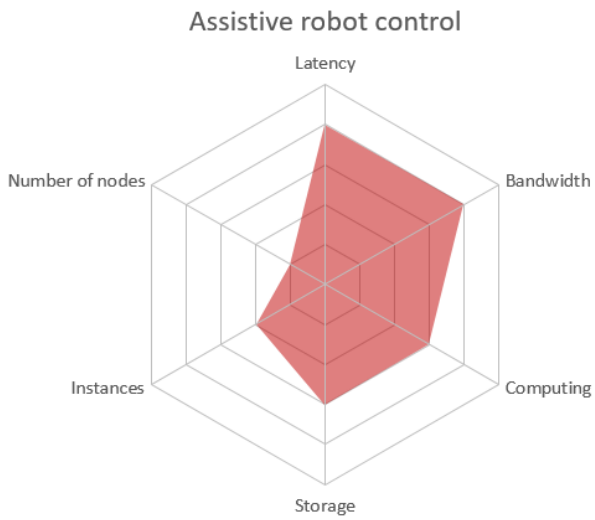

Figure 75: Assistive robot control – Spider Diagram

4.12.5 Telemedicine and Rehabilitation Support

Telemedicine and Rehabilitation support will most likely be performed by assisting robots, which have learned specialised routines necessary for the task. The use case requirements are similar to the robot assisted surgery use case.
The traffic type for this use case is T4: low latency, high bandwidth, few connected devices.
The computing and storage will be performed at the base station.
The use case rating, equation 4.44, and the spider diagram, Figure 76, are below:

$$4 * 1.000 * (0,005 + 0,005) = 40 \tag{4.44}$$

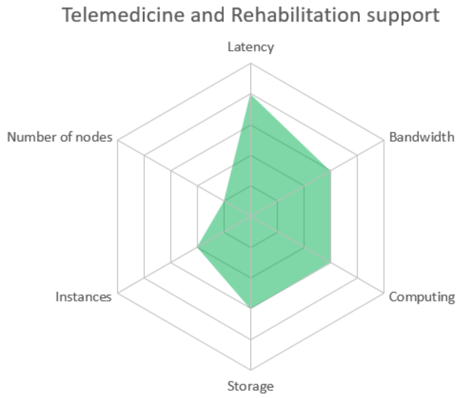

Figure 76: Telemedicine and Rehabilitation Support – Spider Diagram

4.12.6 Smart Ambulance

To improve patient care and increase survival rates ambulances will be equipped with sensors, which collect and transmit data to the destination hospital. There will be multiple sensors collecting information; however, it is likely that the count will stay above 100. A low latency is not necessary for this use case as the travel time for the ambulance is measured in minutes. The collected data will also require only medium bandwidth.
The traffic type for this use case is T3: high latency, high bandwidth, few connected devices.
The computing and storage of the data will be performed locally at the ambulance or at the private hospital MEC. The use case rating, equation 4.45, and the spider diagram, Figure 77, are below:

$$3 * 1.000 * (0,005 + 0,05) = 45 \tag{4.45}$$

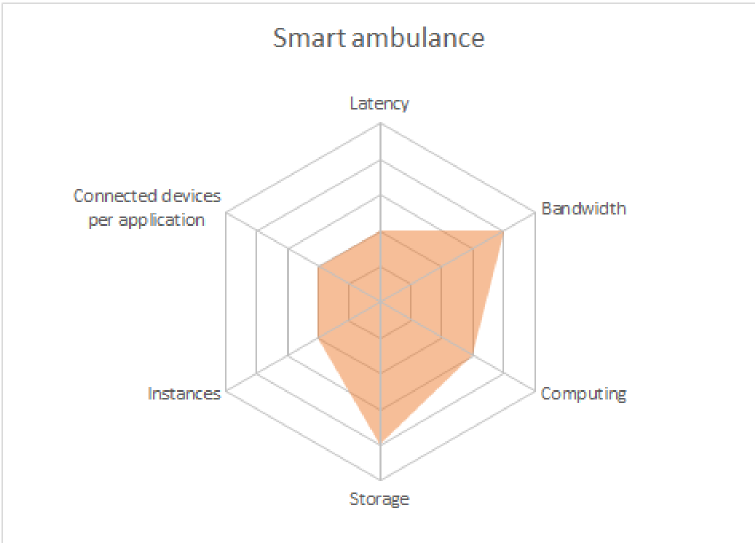

Figure 77: Smart Ambulance – Spider Diagram

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