CampusOS Whitepaper

# Open and Modular 5G Campus Networks:

## Use Cases, Requirements, and Architecture

CampusOS

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# Contents

# Introduction

This whitepaper provides a perspective on open and modular 5G campus networks and their use in (industrial) scenarios. Benefits of open and modular 5G campus networks and associated requirements and challenges are discussed for a representative set of use cases. A high-level architectural approach to building open and modular 5G campus networks is outlined, and further work in CampusOS and the application projects is motivated.

Before discussing use cases and their specific requirements on campus networks in terms of openness and modularity, we define the term open and modular 5G campus network and outline the ambitions of the CampusOS project and its associated application projects. The use cases studied in these projects are then introduced and key requirements and challenges for a campus network are discussed for each use case. A summary of all use cases is provided in the subsequent section. This is the motivation for the architecture approach introduced at the end of the whitepaper and further work in the context of the projects, as discussed in the conclusion and outlook.

**The CampusOS project and ecosystem**

The goal of the BMWK-funded (German Federal Ministry for Economic Affairs and Climate Action) project CampusOS is to establish a sovereign campus network ecosystem in Germany utilizing the openness and modularity of the respective elements to offer tailored solutions. For this purpose, CampusOS is assembling a "5G Technology Construction Kit" containing a catalog of verified components, architecture building blocks, and operation model blueprints. The Core Project CampusOS drives the implementation of this Technology Kit, from the perspectives of the (technology) providers ("Anbieter") and users ("Anwender") of a campus network. Six additional associated application projects complement this effort, each representing a specific vertical, by providing real world application scenarios, requirements, testbeds, and feedback.

***Visit campus-os.io for more information.***

## Ambition and contributions

Starting with 5G, cellular communication networks offer a common architecture for a wide variety of application requirements, targeting connectivity between machines and human-machine communication. The support of low latencies, high data rates, and high reliability with 5G technology enables wireless communications to be used in emerging industrial sectors, such as Industry 4.0, Telemedicine, AR/VR, and Connected Mobility. Every sector has specific requirements with respect to network capacity, reliability, resilience, security, latency, versatility, etc., which calls for customizable Campus Network solutions tailored to address the individual sector demands.

With their origin in the mobile telecommunications domain, today's campus networks are mostly provided by a few major network suppliers in the form of highly integrated monolithic solutions for high-performance mobile telecommunication systems. Monolithic solutions, however, may not always cover the complex and changing requirements of industrial use cases and the variety of business-critical requirements in the best possible way. The design, integration, deployment, and operation of custom campus networks is, therefore, emerging as a new market, which is fueled by the discussion around the disaggregation and modularization of 5G networks. Certain elements of the campus network may be virtualized so that they can run on standard, common, off-the-shelf hardware. This opens up many opportunities for German and European companies, including small and medium-sized endeavors, to participate in shaping this new market.

**Definition: open and modular campus networks**

We define the **open and modular campus network** based on the definitions of an open system. An open campus network allows third party products to plug into or interoperate with it. From the perspective of the respective use case, relevant interfaces need to be specified, documented, and made available. There are means to exchange relevant (in the scope of the use case) components of the network. "Open" in the scope of this definition does not necessarily imply "open source" or "open standards".

We refer to systems that do not follow this definition as **established monolithic integrated solutions**. Relevant components in the use case cannot be freely exchanged, leading to a lock-in for a specific vendor or solution. Additionally, access to interfaces, the ability to plug in other components, or interoperability with other components may be limited (regarding the requirements of the use case).

## Use cases and their requirements on open and modular campus networks

In the CampusOS project and the associated application projects, a wide range of use cases from different vertical domains are studied. For each use case, a brief description and a discussion of the benefits of open and modular 5G campus networks are provided as well as key aspects regarding the realization and utilization of the campus network and its modularity or flexibility. The addressed use cases are summarized in the table below, including their key aspects regarding the utilization of open and modular campus networks in the respective scenario.

*Table 1:*
*Use cases considered in CampusOS and associated application projects.*

| USE CASE | KEY ASPECTS |
|---|---|
| **Intralogistics in Industry 4.0** | Application- and customer-tailored networks , supporting scalability, manageability, and integration requirements in the respective OT environment. Reliability and availability are key concerns. |
| **Connected Mobility** | Fulfillment of specific requirements from the use case, availability of network information for tight interaction between network and application (monitoring the network state and means for influencing the network). |
| **Agriculture and Forestry** | Nomadic deployments offered on-demand and for limited periods of time, usually bundled as "Application as a Service" (e.g., sowing, harvesting, weeding); dedicated infrastructure as alternative to public network slicing, as availability or performance in rural areas might not suffice for all use cases. |

| USE CASE | KEY ASPECTS |
|---|---|
| **Construction Site** | Nomadic deployments to allow Internet connectivity for construction machines and the construction office plus partners. In addition to sensor data transmission and the exchange of design data, potentially in real-time, the (nomadic) network is used to provide position correction data (Real Time Kinematic). Complexity needs to be low along the lifecycle, and the network must integrate seamlessly with the applications. |
| **Manufacturing in SME:** Flexible Production and Mobile Manipulators | Ability to support self-contained (nomadic, spatially restricted) deployments with low complexity only for use cases and areas with clear RoI rather than as a one-size-fits-all campus networking solution. Common reorganization of cells and corresponding (automated) reconfiguration of the communication system due to reconfigurations of the shopfloor layout. Potential value-add with positioning capabilities. |
| **Manufacturing in SME:** Encapsulation of Communication within Production Processes | Enable isolation on Layer 2 (e.g., through VLAN) for different users of the communication network within one cell and across multiple nomadic cells; support for 100+ VLANs by all components. |
| **Manufacturing in SME:** Mobile Quality Measurement Cell | High data rates of captured sensor data and limited time for transmission of data in a (mobile) measurement setup require a dedicated local nomadic cell to accompany the sensor setup. The local nomadic cell should interface/coexist with existing 5G campus network (e.g., backhauling or adjustment of RF parameters). |

| USE CASE | KEY ASPECTS |
|---|---|
| **Edge-controlled AMRs:** Dynamic adaptation | Control of industrial AMRs by an edge server (located at production site, rather than on the vehicle itself), requiring highly reliable, latency-restricted and upload-centric connectivity, varying over time and space. |
| **Energy management of production sites:** Dynamic adaptation | Real-time energy consumption measurements and support for energy optimization systems. Requires temporary, latency-sensitive upload data connections for selected production plants during measurement campaigns. |
| **Major damage event at a production site:** Dynamic adaptation | Enable availability of the existing campus network for prioritized utilization by authorized third entities in case of a major damage event with dangerous goods (security and rescue staff, robots, drones, etc.). |
| **Clinical and Hospital Environments** | Diverse use cases with significantly different requirements and expected functionality. For example, tracking of equipment requires localization capabilities, transmission of video data requires high data rates, wireless control of medical devices has real-time requirements. All within a challenging regulatory framework with stringent safety and security requirements for patients and clinical users. |
| **On-Ship connectivity during construction and operation** | Use of 5G for ship construction and during operation (on-ship network), with a focus on utilization of the network under changing environmental conditions (e.g., different manufacturing sites during buildup, phases of mobility, effects of harsh environments and surrounding metal). |
| **Teleoperated Control** | Focus on TSN enablement of wireless campus networks, i.e., integration of 3GPP Rel. 16 specification with IEEE 802.1Q for end-to-end TSN. |

***In the following we describe the above listed use cases in more detail in terms of benefits and requirements.***

## Intralogistics in Industry 4.0

Industrial use cases in connection with wireless communication usually relate to mobile machines. Typically, these are autonomous guided vehicles (AGVs) or other autonomous robotic systems capable of operating as independently as possible in the field. Here, a robust and reliable data connection is essential to exchange process-relevant data. Although the vehicles have a high level of intrinsic safety in accordance with the Machinery Directive[1], the need for data exchange is increasing continuously. Applications relating to camera data require a high data throughput. Once applications with real-time capability are to be generated from this data, latency becomes a key factor. Additional challenges arise in rail-guided warehousing systems, where the metallic structures can significantly impact signal propagation.

### Benefit of open and modular 5G campus networks

In industry, the introduction of 5G is stalling, because investments in new technologies normally require a quick return on investment. Powerful communication for industrial use cases is already available over Wi-Fi, so the benefit of using 5G in industry needs to be identified and explained. Today, it is mostly mid-sized or large companies that are investing in this technology for testing or for isolated applications. So, to succeed, 5G needs a wider stage so that more and more companies are interested in using it. CampusOS and 5G open campus networks are addressing this topic. 5G open campus networks take care of the real needs of customers and try to create a powerful, cost-adequate ecosystem that can be used by the full range of industrial partners. A wider choice of components will increase the options to tailor systems to specific needs.

[1] https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32006L0042&rid=6

The availability of systems is increasing with a higher number of providers, and open standards will make 5G more transparent to companies and prevent them from falling into lock-in situations. Additionally, the market for third party applications in different areas of the campus network (e.g., dedicated management or monitoring solutions, applications for RAN real-time controller, and so on) is either newly established or strengthened, which gives industrial companies the chance to gain greater control over their communication business (communication quality, maintenance, etc.).

### Key requirements and challenges

In addition to latency requirements, availability and reliability of the 5G campus network are key concerns for the intralogistics use case. One additional challenge with the introduction of 5G in this use case is the (current) cost level of components and operations of such a network. For use within a solution that is to be sold to a customer (e.g., network used within an intralogistics warehouse facility), additional challenges arise as a result of the potential coexistence of different 5G networks at a customer's facility. To ensure reliable operation of the overall system, the 5G network needs to expose all relevant monitoring and status information required for fault detection and analysis.

## Connected mobility

Mobility support is an intrinsic property of wireless communications and hence a common factor in the use cases considered in the CampusOS project. The connected mobility use case refers specifically to the automotive domain, where vehicles communicate with each other, with the infrastructure and/or with servers, for instance, to provide infotainment or to improve road safety.

Several of the connected mobility use cases are defined to operate in confined environments, such as parking lots or industrial depots as illustrated in Figure 1. Examples of such use cases are automated valet parking and teleoperation of trucks in industrial areas. These use cases require strict levels of reliability, latency, and privacy that may not be met by traditional public networks focused on mobile broadband services. Hence, the deployment of specialized campus networks is a promising solution to support connected mobility in confined areas.

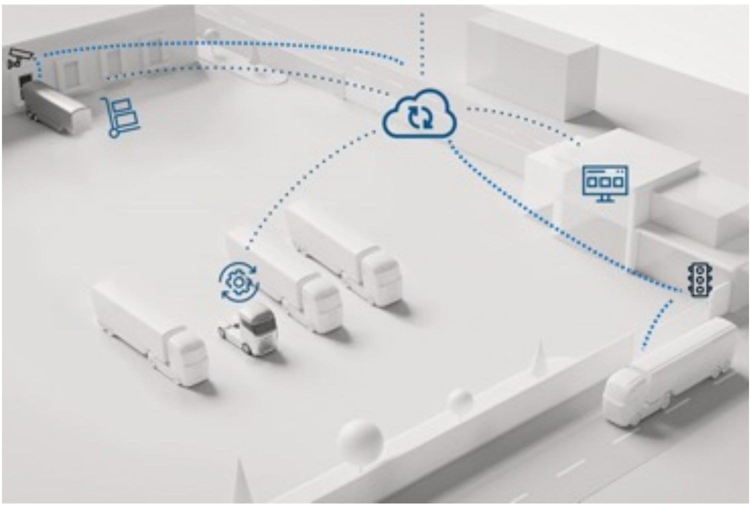


*Figure 1: connected mobility use cases in an industrial depot*

## Benefit of open and modular 5G campus networks

Established monolithic integrated solutions usually provide proprietary interfaces to the user, with limited access to network information. Hence, they prevent tight interaction between the application and the network. Moreover, the lack of modularity of these monolithic integrated solutions hinders the cost-efficient implementation of tailored systems addressing the specific requirements of the target use cases.

The concept of 5G open and modular campus networks investigated in the CampusOS and application projects attempts to overcome the shortcomings of established monolithic integrated solutions. On the one hand, the application provider can have access through standardized interfaces to detailed network information that can be used to influence the application. For instance, network monitoring can be essential to leverage the functional safety of a tele-operated vehicle. On the other hand, application knowledge can be used to influence the network operation, so that the use case performs as expected in all required areas. Additionally, the modular nature of the campus network design enables the realization and scalability of the target use cases by allowing the selection and exchange of critical functionality, when required.

### Key requirements and challenges

Major requirements and challenges of the connected mobility use cases relate to the asymmetric data rates in uplink and downlink directions, high reliability in both directions, and the need for personalized end-user network monitoring and configuration possibilities.

For use cases such as the tele-operation of vehicles, the uplink and downlink data rate requirements are significantly asymmetric[2]. In the uplink, data from multiple sensors such as video, LIDAR and GNSS impose very high data rate requirements from the vehicle to the teleoperator. In contrast, the control information provided by the remote operator to the vehicle can be transmitted in rather short messages with low data rate requirements on the downlink. Furthermore, in both directions, uplink and downlink, high reliability is required for the control loop to properly operate. If the same 5G open campus network supports additional use cases, the network orchestration needs to be analyzed to satisfy the tele-operation data rate and reliability requirements without negatively impacting other applications.

Timely access to network information from the application is fundamental to leverage the functional safety of connected mobility use cases. The network information can be used, for instance, to predict potential degradations of the communication service at the application layer, thereby enabling safety measures to be taken before harm to people or damage to property is caused. This safety measures can take place at the application, or even at the network if there are available interfaces allowing for triggering network reconfiguration by the application/end-user.

[2] 5GAA Whitepaper, C-V2X Use Cases Volume II: Examples and Service Level Requirements, Oct. 2020

## Agriculture and forestry

Open 5G campus networks are also a promising technology for agriculture use cases. For example, an autonomous system can be used to control weeds. For this purpose, an unmanned aerial vehicle (UAV) flies over the field to detect plants. The UAV sends images over the 5G network to the edge cloud, where they are analyzed, the plants detected, and their location calculated. A spraying robot is then sent to areas in the field where weeds are located to combat them. The robot itself also sends two video streams to the edge cloud for a second opinion to ensure optimal spraying, as the calculated position of the plants detected through the UAV camera can be suboptimal. A nomadic 5G network is integrated into a van and connects all elements of the process.

### Benefits of open and modular 5G campus networks

This use case requires the 5G campus networks to be available "on-demand" for a planned time span, usually a few days for sowing, harvesting, and weeding. Therefore, a nomadic network is ideal, which can be easily set up on the desired days. Another possibility is a dedicated network slice of the public network, which might not be available in the desired performance or at all at the site.

One advantage of 5G campus networks is the high data rate in a larger coverage area than WiFi can provide. This is required to be able to transmit the image material from both the UAV and the robot. To be able to interact with devices, latency is also of great importance. This makes it possible for the robot to film target plants and activate the required spray nozzles based on the data evaluated by the edge cloud co-located with the nomadic network infrastructure. It also enables the operator to intervene in the robot or UAV operations and control it in the event of an error or emergency.

### Key requirements and challenges

One of the biggest challenges in this use case is the high data rate in the upstream coupled with the demand for a large coverage area. The image signals from the drone must be uploaded live for further processing. The analyzed data are then used to calculate the optimal route for the spraying robot. Again, a high upload speed is important as the robot sends video signals. This is equipped with several cameras to determine the exact position of the weeds, and thus when the robot needs to spray. The cameras look at the spraying areas of the robot, so that there are only very short time intervals between filming and spraying.

Another important aspect is the possibility to intervene. If the drone or the robot does not move forward on its own, the operator must intervene. This requires short latency times.

## Construction site

A construction site with several machines like an asphalt paver, an excavator, dozer, or wheel loader is considered in this use case. The machines will be equipped with GNSS machine control systems, as illustrated in Figure 2. In addition to the machinery, a base station to provide RTK (real time kinematics) data for positioning is part of the use case.


*Figure 2:*
*Example of a machine being equipped with GNSS machine control systems.*

The construction site is managed by an established cloud-based software. Site information and design data should be exchanged between the machines and the cloud-based software. Also, as-built data from the machines should be recorded at the cloud-based software and be exchanged between the machines.

On more and more infrastructure construction sites, it is now necessary to have a functioning internet connection to connect construction machine control systems to the construction office or various partners outside the construction site. This serves not only to supply the machines with position correction data (real time kinematic) and exchange design data, but also for feedback of meta and as-built data collected by the construction machine control systems. For various construction processes - such as asphalt compaction - the real-time exchange of as-built data between the machines (compacting rollers) is essential to meet the high quality criteria.

## Benefits of open and modular 5G campus networks

For the use case, the plan is not to rely on ubiquitous coverage by provider networks. Therefore, for the use case it is interesting to study how a local campus network can work under construction site conditions. Open and modular 5G campus networks allow for targeted deployments for these conditions and are expected to help in scaling the connectivity solution to the characteristics of the construction site (e.g., multiple interconnected cells for larger sites, re-deployment of cells in case of changes in the site setup).

### Key requirements and challenges

Low-complexity installation/deinstallation and operation is required for provisioning of a (nomadic) network in the construction site scenario. Depending on the exact use case, different latency and throughput requirements might need to be met – for the basic case, connectivity to component and services outside of the campus network needs to be ensured. In addition, the network needs to operate under non-ideal conditions and potentially harsh environmental influences (e.g., dust, heat, dirt, and so on).

## Use cases of small and medium size enterprises in manufacturing

The needs of small/medium sized enterprises (SMEs) differ from those of larger manufacturing companies. Running network infrastructure is not their focus and core competency. Hence, they want to buy or obtain a service of connectivity that "simply works" (may it be wired or wireless or both) and fulfils their requirements, while not caring about the technology used. Typically, an automation system integrator and solution provider (third party) will run the communication system, and SMEs typically do not want to pay for a production-wide/site-wide (5G) network, as this constitutes a big financial invest, while its return on invest (RoI) appears hard to justify. As communication technology tends to be one of the larger investments, they want it to be future-proof. Consequently, they avoid committing to a single wireless technology. Instead, they keep the option of switching between technologies, i.e., they maintain resilience by diversity. Furthermore, even some large size companies share these concerns, in particular with regard to the RoI and will consider using 5G only in a locally very restricted (to the range of one base station) area and only where they really need it.

**The 5G++ FlexiCell project**

Small and medium-sized companies in particular face major challenges in the course of Industry 4.0. The „5G++ FlexiCell" project, funded by the German Federal Ministry for Economic Affairs and Climate Action, intends to use the 5G mobile communications standard as a campus network in production in order to reduce production costs. The focus lies on reducing setup times in „high-mix, low-volume" production using networking and localization technology.

***More information: https://www.flexicell.eu/en***

### General requirements and challenges for a flexible 5G Cell

As a possible solution to these points, the availability of open and modular 5G campus network components allow for the design of a flexible 5G cell. This cell implements a 5G base station plus 5G core (operating in the campus network/local spectrum) utilizing different modules within one device. The cell can be deployed in a nomadic fashion only where it is needed and where a RoI is feasible. This cuts down capital expenditures (CapEx) as well as operational expenditures (OpEx) as a smaller network requires less maintenance effort. To avoid a technology lock-in, the flexible cell integrates additional (wireless and wired) communication technologies as well as (indoor) localization solutions. The goal is end-to-end optimization across the applications. This means that the technologies and their components used in the cell will be open in that sense that they provide known and accessible interfaces to adjust communication parameters (see below for examples).

Multiple flexible 5G cells should be able to "federate", i.e., they can interconnect to build a bigger network, which even supports handover between individual cells, keeping the existing connection context. As a service provider serves multiple sites and multiple tenants, the system will be open to support on-site and remote monitoring, management, and orchestration of multiple FlexiCells (and their components), in particular its 5G RAN components and its 5G core(s) across multiple sites and by multiple tenants.

***The following three sections describe more specific SME-related use cases and detail the requirements on openness.***

## Flexible production and mobile manipulators in SMEs

Consider, for example, an automotive supplier producing vehicle components. In Germany, at least, a large number of these are SMEs. Contracting typically requires the supplier to be able to manufacture spare parts over more than 20 years, starting from mass production/production lines (just-in-time delivery) and ending in single piece production, i.e., high mix, low volume. This means, in addition, high OpEx in intra-logistics, hence further automation is a must. Automated guided vehicles (AGVs) can help here; however, staff are still required to load and unload machines. For this final stretch, mobile manipulators, i.e., AGVs with a collaborative robot mounted on top, can be used instead. They need to precisely localize and then position themselves and their grip arm depending on the current task.

### Benefit of open and modular 5G campus networks

Particularly the high-mix, low-volume scenario forces a supplier to re-organize the production into a matrix production, where machines are re-used for multiple products for high equipment utilization. That also means that the layout of a shop floor may be re-arranged multiple times a day, every time the produced goods change. Open and modular 5G nomadic campus networks will allow SMEs to further automate their spare sparts production and this enables them to further reduce OpEx.

For positioning in the final stretch, 5G positioning is beneficial as it does not require additional infrastructure like positioning anchors and allows existing infrastructure to be reused. However, the RF-based 5G localization system – with today's degree of precision – can only be used on a large scale. Open and modular 5G campus networks not only allow 5G positioning to be integrated with other localization technologies like ultrasonic localization; sensor fusion is then possible to permit even more precise positioning information.

## Key requirements and challenges

Every re-arrangement can also mean that the use of the flexible 5G cell will change with all its parameter adjustments like in the RAN. This re-configuration will be performed automatically following a trigger, for example, by the central production planning system (typically enterprise resource planning, ERP, together with manufacturing execution system, MES). Hence its components will be re-configurable in an automated fashion, for example, by providing application programming interfaces (APIs).

The 5G positioning system must be open in such a way that other more precise localization solutions (e.g., based on ultra-sound) can interact with each other. Ideally, positioning data of multiple sources can be merged to achieve higher precision. Moreover, multiple FlexiCells are required to cover the area of a production line such that a seamless handover must be possible - at least on OSI layer 3. Hence, the system must be open in such a way that real-time requirements (depending on the speed of movement of the robot arm and AGV base as well as on the corresponding safety requirements) can be fulfilled. In many cases it may be necessary to keep parallel links to multiple flexible 5G cells, maybe even using different wireless technologies, for example, one link via 5G and one using Wi-Fi 6/7.

## Encapsulation of communication within production processes

The number one rule (not only in SMEs) is that production process stability is paramount: Production must not stop. In order to achieve this, production management typically organizes production lines in encapsulated (virtual) networks: If one machine gets compromised, for example, by being infected with a virus, this network is shut down or isolated such that it no longer threatens to destabilize the other production lines (also cf. IEC 62443 „Industrial communication networks – Network and system security“). Ideally, encapsulation/isolation should take place on the physical layer, which is impractical for wireless connections. Hence, companies resort to encapsulation on the lowest possible layer, i.e., using layer-2 virtual network technology, mainly virtual local area network (VLAN) according to IEEE standard 802.1q.

### Benefit of open and modular 5G campus networks

Open and modular 5G campus nomadic networks can provide one connectivity solution to many communication requirements. However, the 5G user plane interfaces to other networks by the IP on layer 3.

### Key requirements and challenges

To maintain process stability, all network components will be open in such a way that they ideally support transparent layer-2 communication using more than several hundred VLANs within the range of one base station. The system will be open to creating own VLANs, even across multiple FlexiCells (i.e., 5G core networks) and logically separating them from each other.

## Massive wireless low latency data communication within mobile quality measurement cell

The flexible 5G cell is considered in a third use case, here for high-quality measurements within production lines: A high-precision wireless sensor (a point cloud sensor, say) measures, for example, the surface quality of produced goods (e.g., vehicle hood). To capture all quality features, the sensor is mounted onto a robot tip. Typically, multiple robots move within one quality measurement/production cell. The quality measurement cell is mobile in that sense that it can be moved by a forklift; hence it supports a scenario similar to the flexible production mentioned earlier.

*Figure 3: Example of a mobile quality measurement cell equipped with 5G FlexiCell. © ZEISS Group*

The quality process typically requires taking multiple measurements at multiple positions within a production clock cycle of some 30 seconds. Within this time, the measurement data must be analyzed in real-time, which is computationally very heavy, before moving to the next measurement position. This leaves little time for the transmission of several hundred megabytes of point cloud data and requires a latency of less than 20 ms per measurement/data transmission.

## Benefit of open and modular 5G campus networks

Currently, only 5G can fulfill the application requirements on communication data rate and latency.

## Key requirements and challenges

As the measurement cell is mobile and an existing 5G network cannot be assumed to be present in all cases, the measurement cell will integrate a flexible 5G cell in nomadic mode to allow independent operation. Still, the system should be able to coexist with a 5G campus network that might be operated in vicinity of the measurement cell in order not to disturb other processes. Hence it must be open to cooperating with the existing network, for example, by integrating as a wireless backhaul or by spectrum sensing and automated adjustment of its RF parameters.

## Dynamic adaptation of campus networks and applications in industrial use cases

As one of the leading paradigms of digitization in the context of industrial production, "Industrie 4.0" has been used in the real world for some time now. In contrast, adoption of 5G for production environments, though rated as leading-edge wireless networking technology by experts and widely rolled out in public network infrastructures, is still in an early stage.

CampusDynA aims to demonstrate the added value of open and modular 5G campus networks by implementing three industrial application scenarios, sourced from the domains of autonomous mobile robotics, resource efficiency of production plants and civil safety of production environments.

The “Edge controlled automated mobile robots (AMRs)” application scenario is designed to explore the value of overcoming throughput limitations of statically configured 5G campus networks by RAN configurations that are flexible in time and space, hence adapting better to the needs of mobile user equipment. Users benefit from improved versatility of the AMRs based on autonomous navigation in known environments. This is achieved by capabilities such as sensor-based map generation and software functions for self-localization and dynamic path planning. Enhanced sensor technology such as 3D scanning will enable improved safety and value-added functions such as semantic mapping or digital twins.

**The CampusDynA project**

CampusDynA aims to realize applications in the fields of autonomous mobile robotics, resource efficiency of production facilities and civil security of production facilities with the help of open 5G campus networks. It contributes to an evaluation of the concrete added value of this technology for industrial application scenarios, which is critical for user acceptance. The focus is on aspects of the reciprocal dynamic adaptation of network and application behavior. The implications for performance improvements and innovations on both the user and provider side are analyzed, as well as the impact on society in terms of sustainability and civil security.

***More information: https://campusdyna.de/***

In this context, the execution of these software functions on a powerful edge computer rather than on an onboard system mounted on an AMR, opens a path to unified, vendor-agnostic system architectures and open interfaces. Moreover, compute-intensive value-added functions are freed from restrictions imposed by the onboard hardware. In turn, the need for continuous transmission of AMR sensor data (laser scans, RGB images, point clouds) from vehicle to edge server and of control commands from edge server to vehicle, results in high bandwidth requirements (in particular, in upload direction) combined with low latency to ensure real-time vehicle control. And as AMRs typically operate in fleets, these requirements scale with the number of units in operation, and with their density in a particular network coverage area.

Besides the spatio-temporal dynamics of bandwidth requirements, there is a similar dynamic regarding network latency. This will be investigated in the "optimization of energy consumption of production plants" application scenario. As a result of the ongoing restructuring of energy production in Germany, large consumers such as industrial production sites increasingly need to contribute to the stability of power supply networks. Hence, the prediction of available power peak rates is increasingly limited to smaller time frames. In parallel, the flexibilization of production, in accordance with the "Industrie 4.0" paradigm, may require the largest energy consumers to more frequently change their position on the campus. To avoid distortion of the overall power supply and, consequently, loss of production, real-time monitoring, and the implementation of an energy management feedback loop for large consumers will be unavoidable. For the 5G network, this application scenario focuses on dynamic adaptation of network latency, supporting real-time data provision and processing by AI applications for critical production plants and process phases when and where required.

The “major damage event” application scenario aims to complement the above scenario with the aspect of prioritized network usage by third parties. In case of a major damage caused, for example, by an accident with dangerous goods in an industrial plant, a fast reaction is indispensable to avoid severe impact on humans and the environment. Currently, this requires an evacuation of the area and the engagement of security and rescue forces who must bring and deploy their own communication and data processing infrastructure. While in this phase regular production is shut down, the existing campus network infrastructure remains widely unused. Making it available to the security and rescue forces in a fast and simple way, for example, for control and data transmission of disaster discovery robots and drones, could be a key factor in saving lives.

### Benefit of open and modular 5G campus networks

Current campus network designs hardly anticipate as-yet unknown application requirements. Established methods of network planning may struggle, for example, with the bandwidth-hungry introduction of edge-controlled AMRs, since a static distribution of AMRs over space and time does not match the requirements of flexible production, and over-provisioning of RAN is, from a monetary perspective, not the preferable option compared to an adaptive network control that matches network capacity and user demand intelligently.

With open interfaces, data, and service models, modular campus networks provide the means for a tighter coupling of network and application behavior. Network traffic prioritization cannot just be achieved by established 5G mechanisms such as QoS-based traffic steering or network slices, but also in a highly dynamic manner by ad-hoc prioritization of UE data connections for specific areas and/or time slots, complemented by additional measures such as application controlled deprioritization of other UEs' traffic, swapping of UEs to neighbor cells or dynamic transmission power control for individual radio cells. This can be achieved, for example, by development of suitable xApps, rApps or other SMO building blocks that interact with network controllers such as Near Realtime RIC or Non Realtime RIC on the network side and application and process management systems on the industrial production side.

## Key requirements and challenges

The acceptance of open, modular 5G campus network for industrial production sites depends, among other things, on successful implementation and testing of applications that are relevant to practice and demanding in terms of network performance, under real life conditions. "Success" may be measured not only in terms of required network KPIs such as throughput, latency, or packet loss rate, but also in metrics of application-specific KPIs that are better suited to assessing a potential business impact of the open, modular 5G campus network.

Examples of application KPIs for the "Edge-controlled AMRs" scenario are route performance (from start to destination) or handling performance of safety-critical situations (e.g., circumventing or stopping in front of obstacles), but also vehicle control performance at high traffic density or performance of AI-based environmental semantic object recognition (pedestrians, factory assets, etc.).

The "Optimization of energy consumption of production plants" scenario may benefit from improved application KPIs such as the time resolution of measuring points or the need to conduct a measurement campaign at an arbitrary location on the production shopfloor.

Similarly, for the "Major damage event" scenario, the amount of time needed for provisioning the communication infrastructure for the security and rescue forces, the performance of sensor data transmission from robot to edge server, and the quality of the generated maps may be primary application KPIs for network impact assessment.

While the mapping between network KPIs and application KPIs requires a lot of (variable) context information such as the number and distribution of application specific user equipment over time and space, chosen sensor technology and its configuration, application architecture and deployment of building blocks, concurrent network usage by other applications, etc., the common denominator regarding the key requirements on the network is to deliver a defined network performance to an application's UE(s) dynamically in time and space upon adhoc request, with a focus on reliable upstream data transmission with low and bounded network latency.

## Use Cases from clinical and hospital environments

The feasibility of an open and modular 5G-based network architecture in hospitals is evaluated with medical technology, biosensor technology and clinical applications. A clinical 5G test field will be set up using the developments from the CampusOS projects with a two-stage strategy. The use cases are selected in such a way that they reflect a wide range of 5G performance parameters: From high bandwidth and low latency to high subscriber numbers and very low power consumption. Due to the close integration of the consortium with the CampusOS project, requirements can be reflected at an early stage and new developments can be tested. The pilot applications are each developed by an industrial partner and a university partner and evaluated together with the hospital IT and external experts. In addition to technical applications, the focus is also on risk assessments, eligibility for regulatory approval, and possible operator models.

The following use cases are addressed in the context of clinical and hospital environments:

- Tracking of medical equipment within the hospital premises
- Wireless transmission of video data in compliance with medical requirements (lossless information transmission, very low latencies, high resolution)
- Biosensor technology for location-independent patient monitoring
- Wireless control of medical devices with real-time requirements

### The KliNet5G project

In the KliNet5G project, the feasibility of a purely 5G-based network infrastructure based on Open RAN in hospitals is being evaluated. The project connects end-user equipment manufacturers, clinic operators and medical users. Among other things, concepts for the future design of the infrastructure and the associated changes in workflows are being developed. In addition, practical clinical applications of logistics and patient care are combined and implemented in order to make processes in the clinic more flexible and continuously optimized. For example, mobile patient monitoring as well as tracking of devices and equipment can be practically realized. The project aims to integrate existing 5G know-how and 5G technology into existing medical products and applications to support the application of this future technology.

***More information: https://klinet5g.de/***

## Benefit of open and modular 5G campus networks

Available powerful networking technologies are a driver for the development of mobile applications in hospitals. At the same time, the trend within the clinics is towards making the work environment more flexible and thus toward changing requirements for the infrastructure provided. 5G technology covers the new requirements for innovations in both the hospital and medical technology and IT markets. The companies involved in the project are developing their products substantially to better meet the new requirements of the market and to gain a competitive advantage. It can be assumed that the concepts of KliNet5G can also be transferred to other areas, for example, care centers, mobile patient care or nursing. The high requirements and the complexity of the infrastructures are enormous hurdles for the establishment of 5G in the healthcare sector. The concepts and applications in KliNet5G are a decisive impetus for the transformation of the healthcare market toward the use of modern open and modular communication technologies. This transformation will sustainably increase supply and demand for innovative medical technology solutions and open up long-term market prospects for companies.

### Key requirements and challenges

The introduction of a new communication infrastructure is a major challenge in the medical context. Due to the high demands on security and stability combined with the increasing need for flexible networks, adjustments can only be made in close cooperation with clinic operators, manufacturers of medical products and the providers of the network infrastructure. The use of mobile radio technology within clinics opens up new possibilities for the flexible use of rooms and new medical technology applications. In addition to strengthening technological sovereignty, the use of open modular campus networks also enables greater flexibility in the selection and use of network components. As a result of the project, the technologies will be integrated into the hospital infrastructure using demonstrators and evaluated together with the various stakeholders. Furthermore, guidelines for manufacturers of medical products and for clinic operators are being developed.

## On-Ship connectivity during vessel construction and under harsh operational conditions

Wireless connectivity, for example in the form of (industrial) wireless LAN or other common wireless communication technologies often does not work well in harsh industrial settings where the environment changes over time. This can be found, for example, in the ship-building industry where the environment is the ship under construction together with the sites where the construction takes place—and both change frequently during the whole construction process. Depending on the ship's size and purpose, hundreds of workers may be present on and around the ship, surrounded by metal surfaces and heavy machinery. In such environments, 5G campus networks have the potential not just to outperform other wireless technologies, but also to enable new use cases and to allow for a network where the radio units do not need to move or be readjusted while the ship takes shape and moves from dry dock to landing stage and back.

**The MAVERIC project**

The MAVERIC project will develop a mobile 5G campus network system with a special focus on automated deployment, monitoring as well as flexible and digitally sovereign in-network computing. The main use cases within the project are processes and tasks on shipyards. This environment is particularly harsh and has very high requirements regarding availability, security, and confidentiality.

***More information: https://www.maveric-project.org/***

## Benefit of open and modular 5G campus networks

Whether open or not, there are expected benefits of 5G campus networks over other wireless technologies. This includes coverage and penetration, for example. Higher permittable transmit power, for example, to wireless LAN results in better coverage for large areas such as a dockyard but it also means the wireless signal can penetrate objects better, allowing for coverage on and under deck with significantly fewer radio units. Furthermore, the spectrum used is not shared by other technologies, which results in higher reliability overall and interference-free operation with the installed base.

Finally, 5G has built-in support for handovers, and more recent features such as localization have been added, allowing for entirely new use cases.

Openness in such settings primarily allows for a high degree of digital sovereignty, which is an important consideration for most classes of ships above a certain size and of a certain type. Openness also means that vendor lock-in effects are less of an issue and a high degree of freedom regarding vendors and service providers guarantees future flexibility regarding the network and leverage over providers.

## Key requirements and challenges

In particular, the on-ship network comes with challenges due to the continuous changes in the shape of the ship during the build process, the changing location of the ship itself, and the build materials of the ship's hull and superstructure. Continuous monitoring of the network is therefore required. Several use cases also require high data rates, for example, for AR applications, which can be challenging to achieve in parts of the ship. Careful design, continuous monitoring, self-* capabilities (e.g., self-healing, self-configuration, self-optimization, and self-protection) and computing at the edge are requirements that make connectivity in harsh changing industrial environments a reality.

## Teleoperated control via 5G-TSN campus networks

To enable deterministic communication required in some teleoperated control scenarios, time-sensitive networking (TSN), a set of IEEE standards, needs to be integrated into 5G campus networks. In addition, device-to-device (D2D) communication can be utilized. Campus networks will experience notable advancements in security, reliability, and resilience, while also enjoying reduced latency. Anticipated in the long run, the integration of TSN is set to supplant proprietary fieldbus systems with standard Ethernet connections. This integration of TSN and 5G will further enable the wireless deterministic transmission of data within the network, leading to enhancements in bandwidth efficiency, reduced link losses, and the establishment of additional communication pathways. Emphasizing the utilization of open standards and open-source implementations, the platform will provide application developers with seamless integration of new use cases into the campus infrastructure.

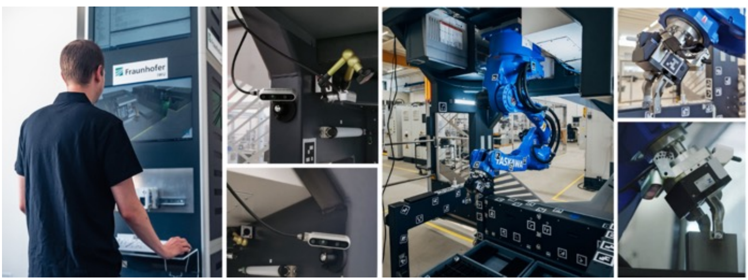
### The TICCTEC project

TICCTEC investigates the conjoint use of time-sensitive networking protocols and 5G mobile communication networks via TSN translators. The aim is to realize deterministic communication from the edge cloud to the device for tele-operated robot and vehicle control. In addition, the integration of D2D communication in such an architecture is being investigated to increase reliability and decrease latency in difficult wireless links.

***More information: https://ticctec.org/***

Three use cases will be considered. The first use case involves enabling remote control and real-time data display for a mobile robot cell, such as the Robo Operator®, allowing operators to move a robot arm from a distance over 5G-TSN if collisions or errors occur. This function enables the manufacturer to debug mobile robot cells from a central remote-control desktop without a physical presence of their service employees. Thus, machine downtime and service costs can be minimized. More precisely, remote control means moving axes of the robot arm into initial homing positions by continuously pressing relevant axes control buttons, known as continuous jogging. If the buttons are released, the robot must stop its movement immediately. To guide the remote operator, full camera feedback of the robot workspace is necessary. For this use case, the control signals of the robot (i.e., position values or stop commands) require a low-latency data transmission with minimal data loss from the remote desk to the robot controller. In contrast, the high payloads and irregular data peaks of the camera streams are challenging.

The figure below shows details of the Robo Operator. From left to right: (i) An operator controls the Robo Operator from a remote-control panel; (ii) the Intel RealSense™ cameras for visual feedback are captured; (iii) The Yaskawa robot is shown in the robot cell; (iii top) The Yaskawa jaw gripper module is shown in detail; (iv top) The Yaskawa jaw gripper holds a workpiece.



In addition to the remote control of the robot cell, a second use case deals with sending complete process images of servo motors in a test bench to reduce hardware costs in robotic applications.

A third use case demonstrates the autonomous navigation and material transportation capabilities of an Automated Guided Vehicle (AGV) within an industrial environment via 5G-TSN connectivity. The AGV use case benefits from edge cloud offloading of complex computational tasks, such as object detection and path planning. Offloading can lower the required hardware on the AGV and therefore lower the required battery capacity. This can in turn save energy. At the same time, shared resources from the 5G edge cloud can be used by multiple AGVs, thereby enhancing resource utilization. However, the AGV control communication places high requirements on the communication channel. 5G-TSN integration offers extensions to meet these requirements. Furthermore, with direct device-to-device communication, poor cell coverage in large warehouses can be mitigated by offering multipath communication to enhance reliability and lowering the latency at the same time.

### Benefit of open and modular 5G campus networks

The use of a conventional wired connection is not viable in an industrial production facility with mobile robots due to mobility limitations. Here, 5G-TSN emerges as a promising solution for a flexible, real-time-capable data transmission, i.e. for the continuous jogging of mobile robot cells from a remote-control desk. The decision regarding 5G-TSN adoption depends on various factors, including the diverse requirements of the data streams regarding data throughput and latency tolerance as well as the overall infrastructure cost and integration complexity. Ensuring security and privacy is crucial, and this can be achieved through robust encryption and authentication mechanisms. By making well-informed choices, the production facility can achieve optimal performance and efficiency, while also paving the way for future technological advancements.

With open and modular 5G campus networks, existing communication infrastructure, for example, fieldbus or wireless LAN, can be integrated more seamlessly. Factory communication, for example, process automation or system control, places high demands on the 5G system. Every component must be configured optimally to provide guarantees for data transmissions. Open interfaces allow the optimization and integration of existing appliances, modular systems enable fine-tuned deployments for specific use cases. For instance, a trimmed-down 5G system with TSN support can provide lower latencies, less variation, and enhanced reliability, if fewer components are involved, which are also located close to data source and destination.

## Key requirements and challenges

The convergence of automation and network technology will be advanced with the integration of TSN in 5G campus networks. For this purpose, new components in the form of software modules will be developed and tested. Likewise, TSN in 5G campus networks will be extended with D2D communication to enable additional communication paths. The main challenges are to integrate the 3GPP specifications, to fill the „up to the implementation" gaps with specific solutions, to find hardware that supports time-sensitive communication, and to meet application requirements end-to-end. New hardware is necessary, support from manufacturers for deep integration and optimization required, and more detailed specification from 3GPP and IEEE welcomed.

## Architecture approach for open and modular 5G campus networks

Based on the functional requirements of the use cases detailed within the projects and introduced in this whitepaper and related campus network architecture work studied within the CampusOS flagship project, we propose an initial reference architecture for open 5G campus networks. This initial architecture is motivated by previous findings in the IC4F project (e.g., iRefA[3]) and the platform-centric approach also proposed by FabOS[4] in its reference architecture. Regarding the 5G system and underlying hardware and virtualization platform, respective standardization activities in 3GPP, ETSI, and O-RAN Alliance are considered, although specification of detailed interfaces is not yet required at this stage. The architecture depicted in Figure 3 consists of three layers: user applications, platform services, and hardware and virtualization platforms and additionally includes the cross-layer topics monitoring and security. The modularity of the functional components (e.g., modularity of a 5G RAN) is not explicitly shown in this overview, meaning: each individual box can still consist of a combination of (modular) components or single, integrated solutions. The realization options are discussed in more detail in upcoming technical whitepapers on the CampusOS component catalogue and the reference testbeds and demonstrators, as discussed in the conclusion section of this whitepaper.

[3] https://edocs.tib.eu/files/e01fb23/1853507466.pdf
[4] https://www.fab-os.org/

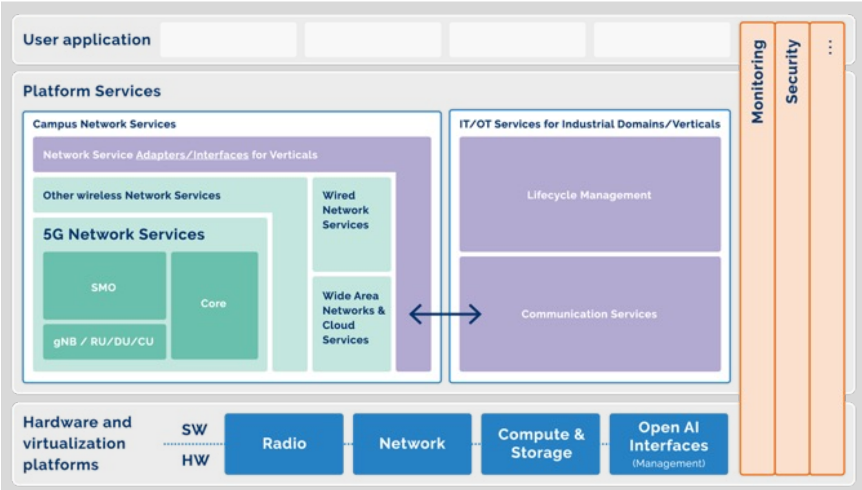



*Figure 3: CampusOS high level reference architecture.*

**User applications** rely on the campus network and its platform services to realize their functionality. To this end, applications formulate requirements and constraints (or intents) towards the campus network via the respective platform services, which are discussed in the following sections. In addition to realizing the functionality of a given use case, applications can also provide additional services such as visualization (live and historical) of a use case. Applications shall be able to utilize the lifecycle management and virtualization/compute functionality offered as part of the platform services of the campus network.

**Platform services** are divided into two main areas: campus network services and IT/OT (Information Technology/ Operational Technology) services for industrial domains/verticals.

**Campus network services** bundle functionality that relates to the operation of a specific network type (5G and other wireless networks, wired networks, wide-area networks), usually being offered via a service management and orchestration functionality (SMO). For 5G and according to the Open RAN concept, services are further broken down into SMO, core, and gNB-related functionality. Depending on the level of disaggregation, the gNB might further be split into radio unit (RU), distributed unit (DU), and central unit (CU) functionality.

Interaction with specific network services within a campus network can be offered via special network service adapters or interfaces for verticals, as introduced in the figure. These provide the means to utilize dedicated functionality such as slicing, QoS, redundancy, or data traffic management. Adapters can be tied to a single network service type (5G, wireless, wired, wide area) or can span multiple network service types. Additional interfaces and adapters for inter-technology management allow further coordination between different network service types in the campus network.

**IT/OT services for industrial domains/verticals** rely on the adapters and interfaces to provide end-to-end functionality for applications. Two groups of platform services are proposed in this area: communication services and lifecycle management. Communication services form the bridge between IT/OT services and the campus network services by enabling end-to-end network-related functionality across multiple network types. Such functionality includes application layer QoS, reliability and isolation, ability to translate between different (application) protocols and overall orchestration of the network, interfacing with different SMO services via the inter-technology management function. In addition to connectivity, data-centric communication capabilities (e.g., broker-based, and broker-less publish/subscribe, event-based communication) are provided to applications. The second set of services relates to lifecycle management and includes functionality to place application components utilizing the campus networks' virtualization capabilities, as well as campus network device management and services for maintenance.

The overall campus network is realized on one or multiple **hardware and virtualization platforms**, including compute and storage capabilities (datacenter and edge/local), network elements (e.g., routers, switches used in the RAN), and radio elements (e.g., radio units, access points, user equipment). Some or all capabilities of the hardware and virtualization platform are exposed via management interfaces, allowing their utilization by a network service SMO or a communication / lifecycle management service.

Additional services and functionality required in the respective domains and use cases may span multiple of the layers: monitoring and security-related aspects are therefore shown as vertical boxes, and additional functionality might be identified in this regard.

## Conclusion and outlook

This whitepaper presented use cases from the CampusOS ecosystem and outlines the benefit of open and modular 5G campus networks in the respective use cases. Key requirements and challenges for each use case were presented, highlighting the need for specialized and tailored solutions.

In diverse industries, such as agriculture, construction, and healthcare, the necessity for seamless integration with existing systems and technologies is paramount. The openness of 5G networks ensures an increasing compatibility, fostering interoperability critical for heterogeneous industrial environments. Modularity is the key to tailoring the network infrastructure to specific industry requirements. The dynamic nature of industrial operations demands an adaptable network architecture. Modularity enables industries to accommodate changes with minimal disruption, ensuring the agility required in rapidly evolving sectors.

Infrastructures need to adapt to future requirements and should exploit ICT innovations. Open and modular architectures mitigate the risk of technology obsolescence, allowing industries to exercise digital sovereignty by avoiding vendor lock-in and seamlessly incorporating future technologies or functionality such as localization and sensing.

Operational resilience in dynamic industrial environments, such as construction sites or shipbuilding, is achieved through the flexibility offered by modular 5G cells. These cells can be deployed where needed, ensuring connectivity under changing conditions without the need for extensive production-wide networks. Cost-effectiveness and return on investment (ROI) considerations are critical, especially for small and medium-sized enterprises (SMEs). Open and modular networks offer a cost-effective solution by allowing SMEs to deploy 5G infrastructure where ROI is feasible. This pragmatic approach maximizes operational efficiency without significant capital expenditure.

Open interfaces in modular 5G networks empower end-users to configure parameters such as radio access, ensuring that the network aligns precisely with the specific needs of the industry. This customization enhances operational efficiency and network performance, providing industries with the tools to optimize their processes.

In industries characterized by a multitude of applications, each with distinct requirements, open and modular architectures encourage innovation in the whole ecosystem. By providing a versatile platform for the integration of new use cases, open and modular 5G campus networks promote experimentation and flexibility in adapting to specific requirements and needs. In the coming months, additional results from the project ecosystem will be published. These include a detailed look at operating roles and models for open and modular 5G campus networks, more details on the component catalogue, and insights from reference test-beds and demonstrators.

**We invite you to contribute to the CampusOS ecosystem and join the discussions – visit campus-os.io for more information on how to participate!**

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