Enabling Construction Automation: Implementing Radio Frequency Communication Infrastructure on Construction Sites

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Abstract –

In the evolving landscape of global markets and technical rationalisation, the digitalisation of tools, machines and construction processes requires communication technologies that enable fast, stable and wireless data exchange on construction sites. The search for suitable network technologies that offer a wide range of options designed to meet specific needs and applications includes 5G, the fifth generation of wireless communication technologies, which offer various possibilities due to its network characteristics. This paper analyses the site-specific factors that influence and impact the installation and configuration of 5G networks. The application of these factors to the deployment of a 5G network at the Reference Construction Site in Aachen highlights the implementation of site-specific requirements. However, the presented results need to be further investigated and applied to other construction sites to assess the scalability and interdependencies of site characteristics, user requirements and network performance.

Keywords –

5G, Communication Infrastructure, Construction Sites, Automatisation

1 Introduction

The demand for networking on construction sites not only pertains to the setup and comprehensive distribution within construction site containers to ensure digital tools and communication with external project participants. Nowadays, the demand for connectivity is also extending to the outdoor area, to the area of machine operation on the construction site. As the shortage of skilled labour [1], safety requirements and the need to increase productivity demand more digitalised and semi-automated solutions for construction projects, the selection and installation of communication technologies become crucial [2]. According to SCHUH et al. 2017, six stages are defined for the successful implementation of *Industrie 4.0*: computerization, connectivity, visibility, transparency, predictability and adaptability [3]. The maturity model, which was first developed for the traditional manufacturing industry, can also be adapted for the construction industry [4, 5]. The construction sector is in the early stages of embracing Industry 4.0. In recent years, there has been a global shift towards integrating digital technologies to enhance operational efficiency and productivity in construction while *Construction 4.0* is recognized as a driving force in the ongoing transformation of the construction industry [6]. A key challenge in the construction industry is the lack of standardised processes for the exchange of information. The Reference Architecture Model Building 4.0 (RAMB 4.0) was developed based on the Reference Architecture Model Industry 4.0 (RAMI), which defines the standardization of information networking and information exchange. Key components are the integration and communication level, in which networks and communication protocols are defined to enable the operability and seamless integration of different systems and companies [7]. Yet, the focus is on creating a communication infrastructure that enables digital data transmission and processing. This requires transmission technologies that represent the technical infrastructure for exchanging data and information between individual actors [8]. The different transmission technologies offer different levels of performance to suit a wide range of site applications. In general, there are three different scenarios that require different levels of communication and network performance: Human to Human (H2M), Machine to Human (M2H) and Machine to Machine (M2M).

Typically, construction sites are dynamic environments characterised by the temporary nature of both the site and the resources. Configuration for consistent network performance in terms of coverage, latency, bandwidth and reliability are highly linked to the construction site characteristics and operating environment. Consequently, the network set up needs to be designed in close collaboration with the specific construction site and its characteristics.

Within the 5G.NAMICO – Networked, Adaptive Mining and Construction" 5G networks are set up on construction and underground mining sites to investigate the domain-specific requirements for the network.

5G, as the fifth generation of wireless communication technologies, offers various potentials due to its network characteristics [9, 10]. Wireless network is essential on construction sites for digital and automated applications. Using WLAN has the disadvantage of limited bandwidth and latency, which affects operational efficiency [11]. The adoption of 5G networks in construction sites is currently limited, but various application projects and use cases are investigating its advantages [12]. This paper provides the basis for aligning site characteristics and network configuration to demonstrate the interdependencies. It enhances the compatible set up of communication infrastructure on construction sites for H2H, H2M and communication. The underlying concept can be applied to different transmission technologies but this paper focuses on the set up of 5G on construction sites.

2 Communication Infrastructure

2.1 Communication Infrastructure Requirements for Construction Site Use Cases

The level of automation and digitalisation differs amongst construction sites and the full benefits is yet to be explored [13]. The different levels are reflected in the three types of communication: H2H, H2M and M2M (see Figure 1).

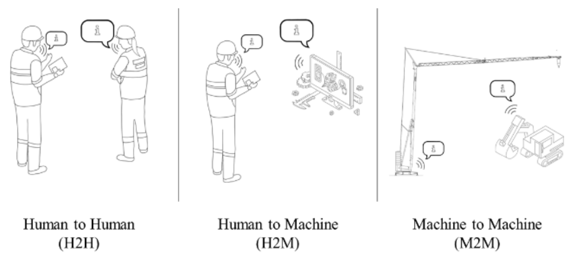

Figure 1. Three types of communication

H2H communication on construction sites, for example, shows two workers talking about the current progress or the day's tasks. H2M, on the other hand, involves the interaction and communication between users and a machine through a human-machine interface [14]. In the construction context, this could be the operation of a crane or collaborative communication using BIM software, where different stakeholders contribute and access data for efficient project management. M2M-enabled devices, capable of autonomously generating, transmitting, and collaboratively making decisions, characterize M2M communication [15]. In general, the example of communication between manufacturing machines and logistics systems can be applied here to ensure smooth production and timely delivery of materials. On a construction site, M2M communication can represent the interaction between autonomous or semi-autonomous construction machinery capable of performing tasks with minimal human intervention, controlled through programming or remote control.

Depending on the type of communication, a communication infrastructure must be established to ensure the smooth, reliable and appropriate transmission of information. The different types have different requirements for the appropriate network technology and hardware setup on the construction site, which will be displayed in the following chapters.

2.2 Different communication technologies

The search for suitable networking technologies offers a wide range of options, each designed to meet specific needs and applications. Bluetooth and BLE (Bluetooth Low Energy) are well suited for short-range wireless connections between devices, while WLAN (Wireless Local Area Network) offers wider coverage for local wireless networking. GSM (Global System for Mobile Communications), LTE (Long-Term Evolution) and the latest 5G technology excel in cellular communications, providing high-speed data transmission for mobile and IoT devices. NB-IoT (Narrowband Internet of Things) is optimized for low-power, wide-area IoT applications. LoRa (Long Range) technology specializes in long-range, low-power wireless communication for IoT devices. For industrial environments, Industrial Ethernet and various bus systems offer robust and reliable connectivity solutions tailored to specific industrial automation requirements [16]. The choice of networking technology depends on the specific use case and requirements, and this wide range of options ensures that there is a suitable solution for different applications and industries. The choice of technology depends not only on the application, but also on the environment. Fixed, indoor production facilities allow for different settings than outdoor construction sites in rural areas.

Recently, the emergence of Low Earth Orbit satellite constellations like Starlink is paving the way for satellite-based Internet access as a viable alternative to conventional fixed and wireless technologies, offering similar throughputs and latencies [17]. Satellite-based Internet access solutions offer new opportunities for providing communications in rural areas.

The following Figure 2 provides an overview of different network technologies in terms of their data rate, range and cost. It also shows a first attempt to classify the types of communication (see Figure 1) and their network requirements within the overview. The data rate of H2H communication is usually not data intensive. H2M communication in contrast, demands higher data rates and bandwidth for the communication. M2M communication itself may only require the exchange of small packets (e.g. machine control commands), but the overall application also involves sensor fusion, where image or scan data is processed to provide the fundamental basis for safe machine operation and require high data rate provision [11].

The range for all types may vary depending on the location and distances of interaction. The figure serves as a visual representation of the outcome after determining the functional dimensions for the selected use case. The following sub-chapter 4.1. will focus on that.

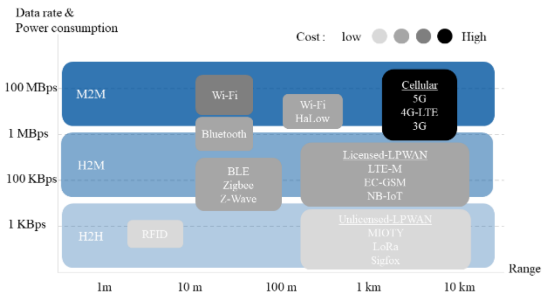

Figure 2. Overview of different network technologies and their characteristics, based on [18]

The focus of this paper is only on the benefits and integration of 5G on construction sites and the link to the hardware set up based on construction site characteristics.

5G integration is of utmost importance on construction sites due to its ability to transform communication, enable IoT devices and sensors, support automation and robotics, and facilitate augmented and virtual reality experiences. The adoption of 5G technology has the potential to enhance productivity, safety, and efficiency in the construction industry, leading to cost savings, improved project outcomes, and a safer working environment.

Some studies already show the potentials and successful implementation of 5G in outdoor as well as the construction context. [12] summarizes 5G solutions for construction industry use cases in terms of challenges and 5G services, such as Ultra-Reliable Low-Latency Communication (URLLC), Enhanced Mobile Broadband (eMBB) and Massive Machine Type Communication (mMTC). In rural areas, both agriculture and construction operate in outdoor environments, which is reflected in the challenges of harsh weather conditions and difficulties in network deployment. An experiment in the south of Denmark demonstrated that 5G has the potential to support data-driven agriculture and applications related to the Internet of Food (IoF) [19]. The paper [20] introduces a digital monitoring system designed for asphalt road construction, based on real-time monitoring enabled by a 5G network. [21] shows an unmanned bulldozer designed for automated construction and equipped with an earthworks monitoring system based on 5G technology.

3 Construction Site Infrastructure

Construction sites are very dynamic and individual environments. There are different types of construction sites (Track / Line, Point, and Tunnelling Construction Sites) which, at the top level, influence the configuration of the network on the site (see Figure 3).

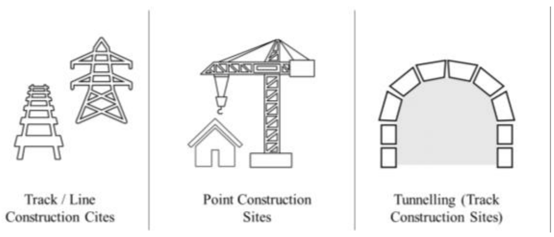

Figure 3. Overview of different construction site layouts

Construction projects, regardless of their size or complexity, are subject to various constraints that can significantly affect their planning, execution and successful completion of network integration. The following Figure 4 summarises the characteristics of construction sites that give rise to requirements that need to be considered when defining and configuring the system architecture of the network. As the site layout evolves over time, development and change must also be incorporated into the ongoing configuration and optimisation of the network.

Features	Impact
"Global" location	Technology deployment and regulations
Building typology	Impact of construction progress on network coverage
Structure Material	Impact of material blockage
Number of devices	Impact on network performance for simultaneous and reliable use by all devices
Distribution of network devices	Impact of construction progress on network coverage
Media supply (e.g. internet / phone etc.)	Interference and co-existence with other communication technologies
Environment (e.g. Dust exposure)	Impact on choice and design of hardware as well as technology
Time	Set-up time in relation to rapid commissioning of the network and temporary construction time
Budget	Trade-off between use case demand and budget for network set up

Figure 4. Overview of construction site characteristics and the impact on network choice

4 Methodology

In the following, the required functional dimensions of the network, assessing the suitability of data transmission technologies and designing the communication network for different site applications, that need to be determined are listed. It then categorises and analyses the impact of network deployment on construction sites, presenting different scenarios in order to thoroughly understand their implications. Finally, this methodology is applied to a 5G testbed, the Reference Construction Site in Aachen to validate the findings and assess the practical feasibility of the proposed network design strategies. In addition to the aforementioned methodology, the establishment of large-scale 5G testbeds is proving to be beneficial for the evaluation of deployment requirements, network performance and the practicality of 5G integration on construction sites. Evaluating 5G performance on the Reference Construction Site in Aachen provides valuable insights into its strengths, weaknesses and areas for improvement, enabling stakeholders to make informed decisions for the deployment of robust and efficient 5G networks. Based on the 5G.NAMICO project, the results are focused on the implementation of a 5G network, but are applicable to other communication technology deployments and need to be further integrated into other testbeds and construction sites to evaluate the deployment factors.

4.1 Determination of functional dimensions

Determining the required functional dimensions of the network is used to assess the suitability of data transmission technologies and the design of the communications network for different applications on site. Various parameters play a decisive role in optimizing network performance and meeting user requirements [16].

1. Determine data rate needs to size network capacity and avoid bottlenecks.
2. Define transmission reliability, especially for wireless tech, to ensure consistent communication.
3. Decide between wired and wireless links, considering minimum wireless distance.
4. Establish connection range for network coverage within specific geographical areas.
5. Consider data packet size to enhance transmission efficiency and data flow control.
6. Account for latency requirements based on application needs.
7. Specify device density to influence network capacity and performance.
8. Define network size to plan infrastructure and ensure coverage in a specific geographical area.

Overall, these functional dimensions are indispensable parameters to be considered in the design and optimization of communication networks in order to ensure efficient and reliable data transmission and to meet the increasing demands of users. The aforementioned studies by Aktas et al. [2] and Schulze et al. [22] provide important insights and foundations for the development of suitable network concepts.

4.2 Categories and impacts of network set up on construction site

Following the described factors influencing the network configuration on construction sites (use case, network choice and construction site characteristics) Figure 5 demonstrates the categories which have to be taken into account for designing the hardware set up of the network components.

Category	Details
Construction Site Layout	Linear / point construction site
Location of Antenna	Crane, container, other fixed points
Fixed construction site facilities	e.g. containers, crane in relation to construction etc.
Dynamic construction obstacles	e.g. trucks, temporary storage, material transport, etc.
Construction progress	Change of antenna position in relation to construction progress
Construction material	Influencing signal strengths based on material
Requirements of use cases	Different use cases require different network performances

Figure 5. Overview of categories for designing

hardware set up and network configuration on site

In general, the construction site layout has an impact on the location and amount of hardware used on site. In relation to the construction progress, it has to be investigated, if there are positions that are relatively fixed and centrally located, which can serve as a mounting point. At the beginning of the project, during the excavation task, there is rarely a crane, which is centrally located and could serve as a mounting option for the antenna. During that phase, another fixed location, such as a stable tower or a container, would be able to be the carrier for the antenna and the radio unit of the 5G network (see Figure 6). As the position may not be centrally within the excavation pit, it needs to be analysed if the coverage is sufficient for the specific use case, e.g. H2M or M2M communication.

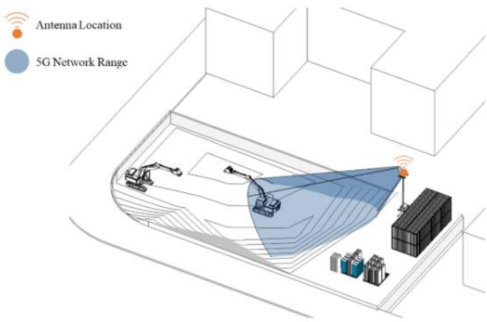

Figure 6. Antenna position during first phase of construction

Once the crane is installed on the construction site, the hardware can be mounted on the crane. As the crane is centrally located, the network's range cover the area of the site where the network is required for the applications (see Figure 7). A distinction can be made between dynamic and static installation points when selecting a crane as a set-up point. Top-Slewing cranes have fixed towers, Down-Slewing cranes have dynamic towers, impacting the choice of hardware in terms of antenna configuration. Omni-directional antennas radiate 360° whether directional antennas radiate mainly in one direction.

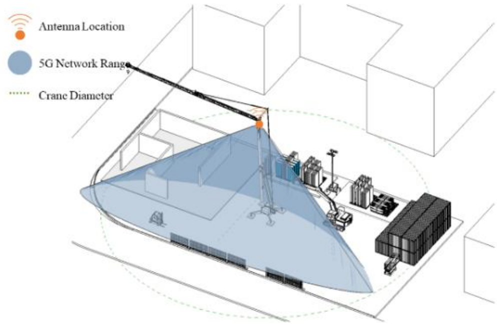

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Figure 7. Antenna position on crane during construction

In addition, there is also the possibility to install radiating cables which also radiate in one direction (see Figure 8). The choice of hardware must therefore be based on the installation point, the location of the structure and the radiating technology.

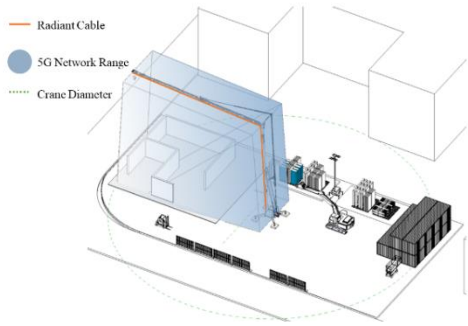

Figure 8. Radiating cable on crane

As discussed previously, there are multiple installation points for the network hardware. Installing the hardware on the container (see Figure 9) would result in range limitations on the site due to the distance between the application location and the hardware installation. This option must be selected with respect to the container and site location if the network requirements for the application can be met.

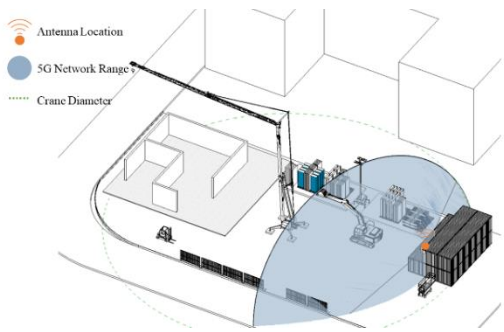

Figure 9. Antenna position on container

Given the multitude of fixed and variable objects such as machines, built structures, and storage at construction sites, it is crucial to recognize their potential impact on network performance, necessitating careful consideration in network configuration and ongoing adaptation. Furthermore, the construction progress and the materials may affect hardware installation location as it may lead to blockage and signal reduction (see Figure 10).

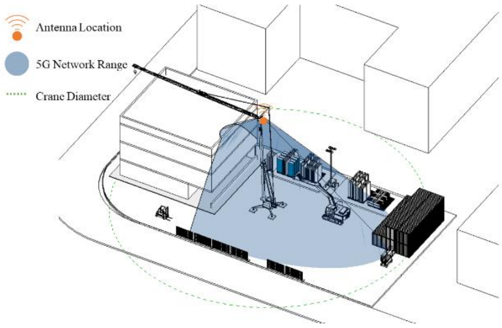

Figure 10. Antenna position on crane during construction progress

Finally, in addition to the characteristics of the site where the network is required, the use case for 5G technology must also be taken into account when configuring and installing the network. 5G offers unparalleled speed, reliability, and low latency, enabling a wide range of applications that can enhance productivity, safety, and communication on construction sites. However, before configurating the network the specific application (H2H, H2M and M2M) need to be analysed to define the network requirements such as latency, jitter, coverage, bandwidth or parallel user in the network.

4.3 Evaluation

A consequently step, the network needs to be evaluated, to test and align the use case requirements with the hardware set up and configuration on site. The evaluation involves two phases: one before implementing the use case to assess the network's performance, and another after implementing the use case to validate its performance. Key network indicators include Coverage, Latency, Packet Loss, and Reliability, which can be tested using methods such as *Ping* Test and *Iperf3* Test [23]. Upon application of the use cases, a performance assessment can be conducted to analyse how the use case aligns with the network indicators.

5 Implementation

5.1 Hardware Set up on Reference Construction Site

In 2020, Construction Robotics GmbH, Aachen, Germany, opened the first large-scale testbed, the Reference Construction Site in Aachen, aiming to bridge digital gaps across the construction industry, encompassing planning, production, and implementation. Covering 4,000 square meters, this test ground facilitates the transition of research findings to market integration. Equipped with cranes, containers, and demonstrator structures the Reference Construction Site serves as a controlled environment for testing and trials, allowing the identification and resolution of potential risks and issues before arise on real projects.

The 5G.NAMICO project provides the first implementation of a 5G network on the Reference Construction Site. Based on the previous categories, the network was set up as follows (see Figure 11):

- Radiating cable along the entire crane (tower and boom)
- Dual-polarized omni-antenna and radio units on crane tower

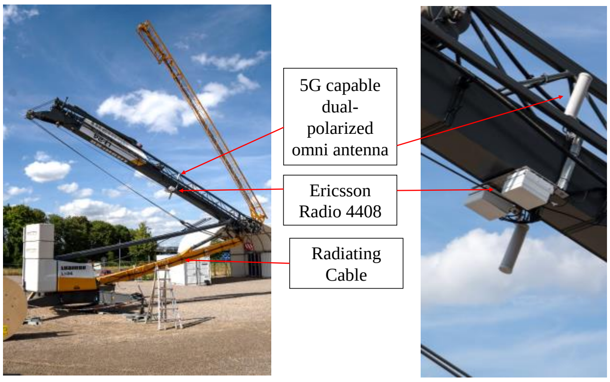

Figure 11. Tower crane with Ericsson radio unit, omnidirectional antenna and radiating cables [24]

The dual-polarized antenna is designed for omni-directional coverage and is able so send and receive signals in any direction. In addition, radiant cables are installed on the crane. These radiating cables provide an alternative to traditional antennas and can be used in situations where conventional antennas do not provide adequate coverage, such as tunnels or mines. First test with both hardware set up were conducted on the Reference Construction Site. The omni-directional antenna configuration provides extensive coverage with excellent signal quality, with 90% of the readings falling within the -75 to -50 dBm range [24]. Conversely, the signal quality of the radiating cables is robust in the vicinity of the crane, but degrades significantly as the distance from the crane increases.

5.2 Application

The digitisation of construction site processes often involves the use of multiple sensors or the automation of heavy construction machinery. Data and control commands are then transmitted between these sources and an on-site control centre. In order to assess the performance of the network on site, a set up was established on the Reference Construction Site to model the data communication.

5G and other network technologies for communication may have two different applications on construction sites. Locally, the network is required to enable the automation of construction processes in terms of H2H, H2M and M2M communication. This can be realized with a private and closed 5G network, solely open to participants and users on site.

Based on previous research [12], various use cases and challenges of *Construction 4.0* can be addressed by 5G, such as remotely controlled and autonomous machinery, health and safety at worksites, 3D models, construction processes' management or emissions and waste management.

In addition to local applications, 5G can also be used to connect the construction site to the outside world. Planning and scheduling data can be exchanged seamlessly between different stakeholders. Real-time data transmission enables efficient collaboration, monitoring, and decision-making between local and global resources.

6 Discussion

The integration of new communication technologies in construction offers benefits such as increased efficiency, improved safety and enhanced project management capabilities. However, challenges include initial investment costs, potential resistance to change from workers, and the need for comprehensive training programmes to ensure successful adoption and use of these technologies. Balancing these benefits and challenges is critical to effectively integrating and maximising the potential benefits of new communication technologies on construction projects. Training requirements for site personnel include comprehensive programmes focused on the use of new communication technologies, emphasising practical skills and theoretical understanding. Strategies to promote the adoption of these technologies can include hands-on workshops, educational seminars, and incentives for successful implementation, fostering a culture of innovation and competence among construction teams.

Although the research focuses primarily on the Reference Site in Aachen, the need for more diverse case studies is evident. Including additional case studies from different geographical locations and project types could improve the generalizability. While the project aimed to deploy a generic 5G network to understand its limitations and challenges, further research should prioritize the exploration of other construction site locations to assess the scalability and adaptability of 5G technology in different contexts.

Furthermore, while the research focused on 5G for construction, it is clear that not every communication use case requires 5G and is also realizable with 5G due to conflicts between regulations and application requirements. An example of this is the TDD patterns that make it difficult to adapt uplink and downlink rates in the outdoor sector in Germany [24]. Future research should focus on identifying the most appropriate communication technologies for different applications in (partially) automated construction. By exploring a wider range of technologies, it is possible to better understand their respective strengths and limitations, and thus make more informed decisions when adopting communication solutions tailored to specific construction needs.

7 Conclusion and Outlook

In the development and implementation of *Construction 4.0*, with the intention of automation and digitalisation, the focus is on creating a communications infrastructure that facilitates digital data transfer and processing. The choice of transmission technologies and the correct hardware configuration in relation to the characteristics of the site are crucial, as they provide the technical basis for the exchange of data and information between the various parties involved. With different technologies providing varying performance levels, the construction site context often necessitates tailored solutions. Broadly categorized into Human to Human (H2M), Machine to Human (M2H), and Machine to Machine (M2M) scenarios, these diverse communication requirements underscore the need for adaptable and efficient network solutions to cater to the distinct demands of each context. To ensure practicality and widespread use on construction sites, it is essential that the network is easy and quick to set up and maintain. Moreover, the systems must embody reliability, incorporating redundant components to ensure that the construction site doesn't come to a halt in the event of a failure in any network system component. Within the TARGET-X project (funded by the Smart Networks and Services Joint Undertaking (SNS JU) under Horizon Europe (funding number 101096614)), the research focus is on using the 5G network for deconstruction use cases to analyse the impact of site characteristics on network performance, such as material and construction progress or number and type of users. The limitations of this paper, identified in the discussion, will be investigated in further projects. Amongst others, the EConoM project is investigating how 5G campus networks with AI and edge computing applications can provide a robust and nomadic processing and network infrastructure in constantly changing environments, with changing participants.

8 Acknowledgements

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