The Application of 5G Networks on Construction Sites and in Underground Mines: Successful Outcomes from Field Trials

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The fifth generation of mobile communications 5G has been introduced to a variety of application domains enabling significant progress towards networked and adaptive systems. As the development of 5G was specifically tailored towards the requirements of industry, a broad knowledge of the technology has been built up in industrial production while also contributing to increasing the spread of data-driven technologies like machine learning. Other application domains are still lacking the widespread use and adoption of digital and data-driven technologies. The objective of the research project 5G.NAMICO is to utilize the gained expertise and knowledge from industrial production and contribute to the adoption of 5G in the application domains of construction and underground mining. We set up trail sites on a construction site and in an underground mine to determine how a 5G network must be designed to meet the domain-specific requirements. Use cases have been designed and implemented to verify the functionality as well as the benefits of the employed 5G networks. First network tests were conducted showing the potential of 5G to enable an end-to-end coverage, which provides the basis for the use of digital and data-driven technologies in the application domains of construction and underground mining.

Keywords— 5G, underground mine, construction site, field trials, radiating cables.

I. INTRODUCTION

As the first telecommunications standard specifically tailored to the needs of modern-day industry, 5G plays the role of a key enabler for the evolution of industrial production towards intelligent, networked, and digital production environments. In particular, the ability of 5G communication networks to achieve low latencies (< 10 ms), high bandwidths (up to 20 GB/s), high reliability (99.999%), and high end-user density enable the realisation of a variety of new approaches for the digital transformation of industry [1,2,3]. However, existing industrial 5G implementations are primarily installed in conventional factories, which are stationary installations operating in highly controlled production environments. In contrast, few studies have investigated the performance of 5G networks in challenging industries, such as construction and mining, where highly dynamic, harsh, and heavy-duty operating environments prevail, implying that wireless communication networks need to be more adaptable and

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flexible to meet the specific challenges of construction and mining.

The construction and mining industries are in the process of undergoing a digital transformation promising a development towards more autonomous, connected, and intelligent systems that enable more efficient and reliable processes. However, established cellular network technologies such as 4G or WiFi are unlikely to be sufficient to meet the coverage, latency, throughput, and reliability requirements posed by novel use cases and technologies to be implemented on construction sites or underground mines [4]. Both, construction sites and surface and underground mines differ significantly from traditional factories in that the project sites are non-stationary and constantly evolving, resulting in continuously changing operating environments. Operations take place in harsh, highly demanding, and limited controllable environments. Due to the uniqueness of each mineral deposit, each (underground) mine is unique in terms of key operational parameters like the extent, geometry and layout of the development and production drift/tunnel networks, as well as the host rock, ground support, depth, type of equipment, etc. Each of these parameters has implications for a cellular network's design requirements and performance characteristics.

Similarly, construction sites are also characterised as dynamic sites, as the structure and site facilities of the project are constantly evolving, affecting the network being built. The building structure and its materials, as well as site facilities such as containers, access roads or storage areas, can cause signal blockage, shadowing or reflections. Sites can be linear or punctual and are exposed to the natural environment, such as dust, vibration, and humidity. Therefore, findings, expertise, and best practices from 5G implementations in conventional factories cannot simply be transferred to these application domains. In order to advance the research and commercial implementation of 5G networks in such heavy-duty industries, it is necessary to design, plan, install and test 5G networks in real construction and mining environments.

Within the research project “5G.NAMICO – Networked, Adaptive Mining and Construction” these gaps are to be addressed. As the industrial use of 5G has its origins in industrial production, a high level of expertise and knowledge has been gained in recent years on the beneficial use of industrial 5G in production [5]. The main objective of the research project is to transfer the knowledge and expertise from production to the application domains of construction and mining. For this purpose, 5G communications networks were designed, planned, installed, and tested on the Reference Construction Site as well as in an underground salt mine. After installation and commissioning of the 5G networks, their performance was evaluated by measuring selected performance indicators (e.g., bandwidth, throughput and, latency) and by performing selected remote control and automation use cases representative for the needs of the mining and construction industry. This article provides insights into the preliminary results of the installation and performance testing phases at the construction site and underground mine and demonstrates the potential of 5G networks for demanding. In doing so, the results of the 5G.NAMICO project and this article contribute to advancing the technology readiness level of 5G applications in construction and mining.

II. Methods and Experimental Setup

The following section describes the experimental setup of the test sites that were used to investigate, how functional 5G communication networks can be designed to enable the beneficial use of the technology on construction sites and in underground mines.

A. Construction Site

The Reference Construction Site provides a real-world setting that closely mimics the conditions, challenges, and complexities of an actual construction project. This allows for more accurate testing of equipment, processes, materials, and technologies in an environment that mirrors what would be encountered on a live construction site. The Construction Robotics GmbH opened the first large-scale testbed in 2020 to close the digital gaps in the construction industry from planning through production to implementation. 4.000 m² test ground of the Reference Construction Site in Aachen enables a faster integration of research to market. By conducting tests and trials on the Reference Construction Site, potential risks and issues can be identified and addressed in a controlled setting before they escalate on a live project.

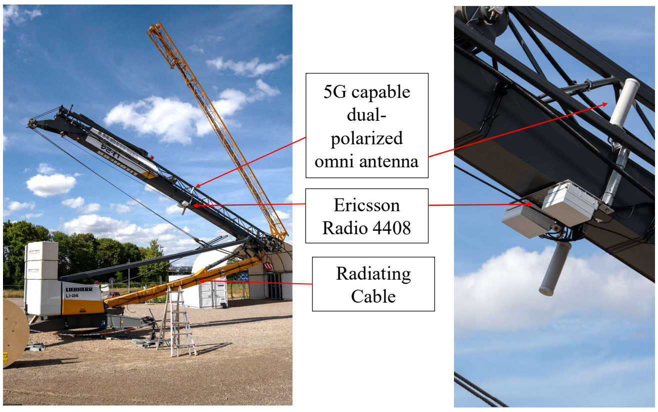

Fig. 1. Tower crane, which is utilized as a transmission tower, to which radio unit, omnidirectional antenna and radiating cables are attached.

Usually, construction sites are dynamic settings in which both the location and resources are temporary in nature. Often, small and medium-scale projects last between one to five years. Moreover, the existing resources (containers, cranes, etc.) tend to be dynamic during this period. This, in turn, causes a hindrance in the scalability or maintenance of a stable wireless network. Additionally, signal coverage is affected by the presence of the buildings <undergoing construction and large quantities of concrete and metal often found on construction sites. Thus, the natural question arises, how a 5G network, especially the radio units and antennas, can be deployed in this ever-changing working environment when the construction site consists of an open field.

1) Tower crane as a transmission tower

In this context, we utilize a tower crane as a transmission tower to which the radio units and antennas are attached

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(Figure 1). The use of heavy-payload machinery is common on construction sites. Especially the usage of cranes is predestined on construction sites to enable the lifting and movement of heavy materials and equipment with an evenly spread coverage due to its purpose. Leveraging the existing infrastructure of a tower crane provides several advantages for deploying a 5G network in such dynamic environments:

- Strategic Point:

Tower cranes are typically positioned and electrically supported at central locations on construction sites, providing an elevated and strategic point. This positioning enhances the line-of-sight communication between the radio units and antennas, minimizing signal obstructions caused by nearby structures or construction materials. This results in improved signal coverage and reliability.

- Stability and Mobility:

Tower cranes are engineered to be stable, even when carrying heavy loads. This stability ensures that the mounted radio units and antennas remain in place and operational during the entire construction process. Additionally, the mobility of the tower crane allows the network infrastructure to be adjusted or relocated as needed during different phases of the construction project.

The deployment and testing of the 5G network in this study were conducted at the Reference Construction Site located at RWTH Campus Melaten in Aachen, Germany, encompassing an area of approximately 4.000 m². Figure 2 illustrates a snapshot of the construction site at 5G-Industry Campus Europe.

Fig. 2. Reference Construction Site, conneted to 5G-Industry Campus Europe (5G-ICE).

2) Implementation on Construction Site

- Radio Unit:

The radio units used in the implementation were Ericsson Micro Radio 4408. These radio units are designed to support 5G technology, providing the necessary connectivity and communication capabilities for the network.

- Antennas:

For the antennas, a 5G-capable dual-polarized omni-antenna is employed. This antenna is designed to offer omnidirectional coverage, meaning they can transmit and receive signals in all directions. The dual-polarized feature enhances the efficiency of signal transmission and reception, improving the overall performance of the network. Additionally, radiating cables are installed. These radiating cables offer an alternative to conventional antennas and can be employed in scenarios in which antennas do not provide sufficient coverage (e.g., in tunnels, or mines)

- Radiating Cables:

In addition to the antennas, radiating cables were also installed on the crane to provide homogeneous and continuous RF-coverage in confined areas. The EUCARAY RMC 78-G "A" Series cables were selected for this project since they support the frequency range between 75 – 4300 MHz which is ideal for 5G applications. Additionally, they have a minimum bending radius of 350 mm which allows for them to be routed along the crane without causing damage.

- Installation:

The crane's stability, weight capacity and height are crucial to ensure that the mounted network equipment remains steady during the construction activities and adverse weather conditions. The crane's weight capacity should be sufficient to support the additional load of the radio units and antennas without compromising its safe operation. In this project, the tower crane from Liebherr L1-24 is selected considering the abovementioned aspects and the total coverage of the Reference Construction Site.

First, the Ericsson Micro Radio 4408 units are securely mounted on the tower crane's structure. Especially, it is ensured that the units are properly fixed and protected against any potential vibrations or movements caused by the crane's operation.

The 5G-capable dual-polarized omni-antenna is then attached next to the radio units on the crane. Here, the antenna is positioned to provide optimal coverage in all directions. The selection of this antenna type is motivated by its dual-polarized functionality, which optimizes signal transmission and reception efficiency. This attribute significantly enhances network performance, particularly in scenarios where the crane is executing rotational manoeuvres during its operational phases.

Proper cable management is essential to ensure tidy and safe connections between the radio units, antennas, and fibre cables. Significant focus is directed towards acknowledging the fragile attributes of the fibre cables, necessitating their precise attachment to the structural framework of the crane. This pre-emptive action is undertaken to prevent any potential disturbances to the crane's manoeuvrability and to diminish the likelihood of safety risks. Especially noteworthy is the tower crane's capability to fold up or down in response to changing wind conditions. To accommodate this feature, jumper cables are employed in the region of the crane where folding occurs, specifically in relation to the fibre.

- Use Case Description:

Digitizing the processes on a construction site, often involves deploying multiple sensors and or automating heavy construction machinery [6]. Data and control commands are then streamed between these sources and an on-site control centre. To evaluate the performance of the network on the

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construction site, a setup was designed that emulates this data communication. The communication between a 5G capable WNC router (connected to a Linux laptop) and a server (connected to a private Ericsson 5G core) placed in the control room as illustrated in Figure 3 was established. The packets to and from the laptop are routed through the radio on the crane directly to the baseband of the 5G core, while the communication with the server is routed through the RWTH Campus Network. The 5G core includes the network controllers, the baseband, the indoor radio units and a GPS synchronization.

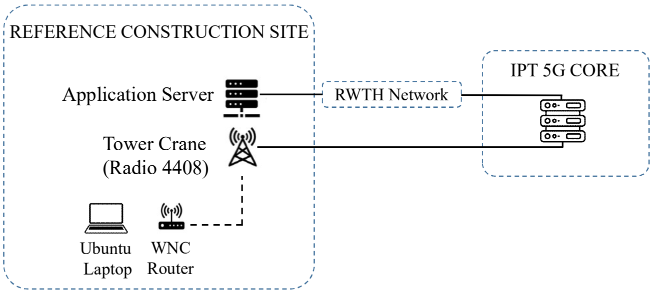

Fig. 3. Schematic of the non-standalone 5G network setup on the construction site.

B. Underground Mine

The field trials for the underground mining use cases were conducted at *Glückauf Sondershausen Entwicklungs- und Sicherungsgesellschaft mbH (GSES)*, an underground salt mine in Sondershausen, Germany. The mine operates using the room-and-pillar mining method at a depth of 650 to 750 metres, with temperatures around 24°C and a relative humidity of 30%. As is typical of room-and-pillar mining, the mine extends over an area of 32 km² with a drift layout characterised by a series of parallel drifts crossed perpendicularly at regular intervals by crosscut drifts, resulting in a chequered drift pattern. The following sections first present the field trial site within the underground salt mine and introduce the different test phases (section 1). The key network components, i.e. the 5G core, the 5G radio and the radiating cable setup, are then introduced. The measurement system used is then briefly introduced.

1) Field Trial Site and Test Phases

Figure 4 shows a schematic drawing of the 5G trial field located at the junction of Drift A and Drift B at the -700 m level (drawing not to scale). The drifts have a rectangular cross-section (height × width: 5 × 8 m). From the junction, Drift A continues in a straight, vertically slightly undulating course for 600 m until it reaches the mine shaft that connects the underground mine with the surface facilities. Drift B branches off from Drift A at an angle of ~45 ° and runs for 350 m to a crushing station that marks the trial area's end.

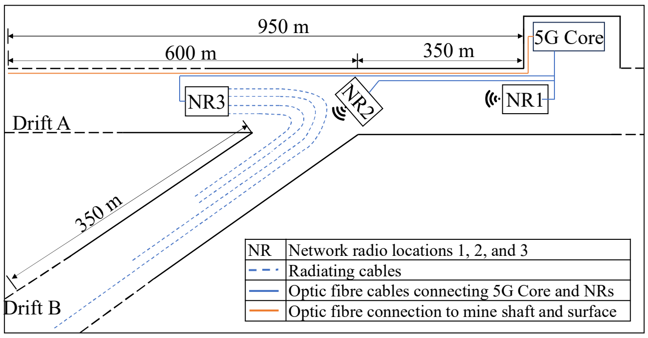

Fig. 4. Schematic drawing of trial field located at junction of Drift A and B in the underground mine. Radiating cables configurations include 4x4 MiMo, 2x2 MiMo and SiSo. Drawings are not true to scale.

Throughout the test programme of the field trial, different 5G radio positions (cf. section 2) and radiating cable setups (cf. section 4) were tested (cf. Figure 4). For Phase 1, the radio was installed on the roof of Drift A with the antenna facing towards the mine shaft. For Phase 2.1 the radio was again installed on the roof of Drift A with the antenna pointing towards Drift B. Finally, in phase 2.2, different radiating cable setups were tested. In all test phases, the performance of the network was measured by testing selected parameters (i.e., latency, two-way active measurement protocol (TWAMP) round-trip-time, TCP and UDP throughputs) at specified length intervals along the full lengths of Drift A (950 m) and Drift B (350 m). TWAMP is an open-source protocol to measure IP performance between two devices, providing a more detailed look at the round-trip time than other methods due to the use of time stamps for a signal travelling between two entities [7]. The network performance evaluation was conducted using a test setup consisting of a Siemens MUM 856 router, a Linux laptop running iperf3 (separate up- and download throughput using TCP and UDP, measurement time 10 seconds per test, n = 3,) and customized TWAMP software. Phase 1 investigated the performance and coverage of the 5G network along the entire length of Drift A (950 m), intending to draw conclusions on the network's maximum 'usable' coverage. Phase 2 focused on characterizing the performance of different radiating cable setups and comparing them with a conventional 5G radio setup in Drift B.

2) 5G Core

The 5G Core network was installed in a minimal setup (redundant network controllers and enterprise LAN switches) adjacent to the mine's power control substation in a separate fenced bay of Drift A, located 350 m from junction Drift A/Drift B. The 5G Core was connected to the surface facilities and the Internet via optic fibre cables that ran from the surface facilities through the vertical mine shaft and Drift A to the 5G Core. (cf. Figure 4 and 5)

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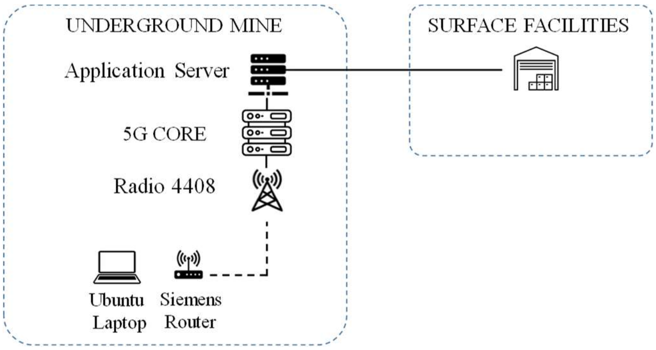

Fig. 5. Schematic of the standalone 5G network setup in the underground mine.

The 5G Core was installed in an IP67-rated, air-conditioned server rack. The 5G core consisted of a baseband, 2 network controllers and an uninterruptible power supply (UPS). As it is impossible to receive a live GPS signal in an underground mine but necessary to synchronize the 5G network, a GPS simulator was installed and used to emulate the signal.

3) *5G Radio*

A 5G radio (model: Ericsson 4408) was used for the field trials and installed at three different network radio locations (cf. NR1, NR2, and NR3 in Figure 4.). The radio was mounted on a pedestal and then bolted to the drift roof (see Figure 6). The radio was connected to the 5G Core via a single-mode optic fibre cable.

Fig. 6. Installation of 5G radio (NR2) in junction Drift A /Drift B, oriented to drift B (see Fig. 4).

4) *5G Radiating Cable Installation*

The radiating cables were installed in such a way that they started at radio position NR3 in Drift A and were routed around the corner into Drift B at the junction (see Figure 7). Starting from NR3, metres 0-100 were set up with 4 parallel radiating cables (4x4 MiMo (Multiple Input, Multiple Output)), metres 100-200 as 2x2 MiMo and metres 200-350 with a single (1x1 SiSo) radiating cable. To achieve a stable, rigid, and uniform installation, the fibre cables were clipped into cable clamps which were screwed to wooden planks at 0,5 m intervals. Ropes were used to tie the wooden planks to hooks previously bolted to the roof at specified intervals. The use of ropes made it easy to adjust the height and the angle of the wooden planks to suit the often-uneven shape and structure of the roof.

Fig. 7. Radiating cable setup at junction drift A, drift B in the underground mine site.

III. RESULTS AND DISCUSSION

A. *Construction Site*

In previous research the performance of WiFi for sending and receiving RGB-D camera data for a robotic application was tested. The results show the limitations in terms of bandwidth and latency. One way of overcoming these shortcomings and meeting the criteria for remote-controlled construction machines is to use the 5G mobile network standard [8]. After the first set up of the 5G Network, preliminary tests were conducted with manual iperf3 and ping test scripts as well as with the professional measurement equipment TSMA6B Scanner from Rohde & Schwarz. To get a first impression of the coverage and signal quality of the respective 5G solution (omni-antenna versus radiating cables) an automated channel detection (ACD) test was conducted. The setup not to be measured was switched off for this purpose. In Figure 8, the assignment of the cell ID for the respective 5G setup can be seen. The omni-antenna has the cell ID 17, while the radiating cable has the cell ID 18. During the measurements the crane was folded and not in operation.

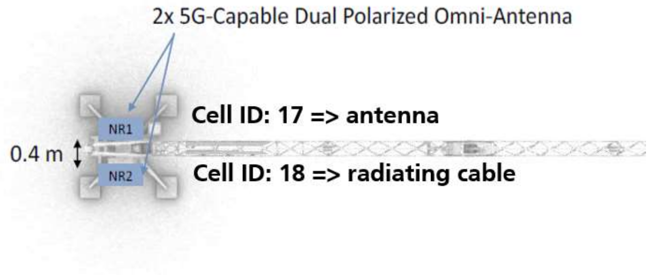

Fig. 8. Cell IDs for the two possible 5G setups at the construction site.

While walking along a predefined path the GPS antenna of the system tracked the actual positions of the testing. The test starts at the controlling centre, heads towards the crane, makes several laps around the crane and finally ends at the controlling centre again. As shown in Figure 9, the antenna setup provides an overall better coverage, with mainly -75 to -50 dBm (90,1%), as the radiating cable setup with distributed values between -50 to -110 dBm. Most of all Cell

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18 values (48,4%) are between -85 dBm to – 75 dBm. The signal quality of the omni-antenna setup is stable along the whole measurement path only showing a slight drop at the left side of the crane. In comparison the radiating cables have a good signal quality around the crane but decrease in performance with increasing distance to the crane.

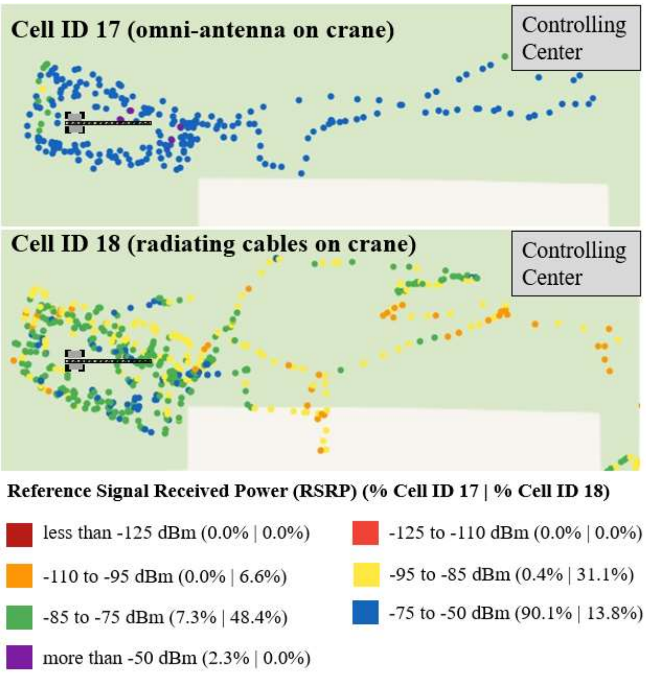

Fig. 9. Signal Quality Measurements with TSMA6B ACD for the two setups omni-antenna (Cell ID 17) versus radiating cable (Cell ID 18) on the Reference Construction Site

For a first evaluation of latency and throughput of the 5G network a ping and iperf3 test was conducted with a WNC router connected to a Linux Laptop. The average Round-Trip-Time (RTT) latency of one device at the construction site to the controlling centre is 11,2 ms. The distribution of the latency values can be seen in Figure 10. For device-to-device communication the RTT average value is 18,4 ms.

Initial throughput measurements with iperf3 TCP measurements on the WNC router and Linux Laptop towards the controlling centre showed an average of 74 Mbits/s uplink and an average of 810 Mbits/s downlink.

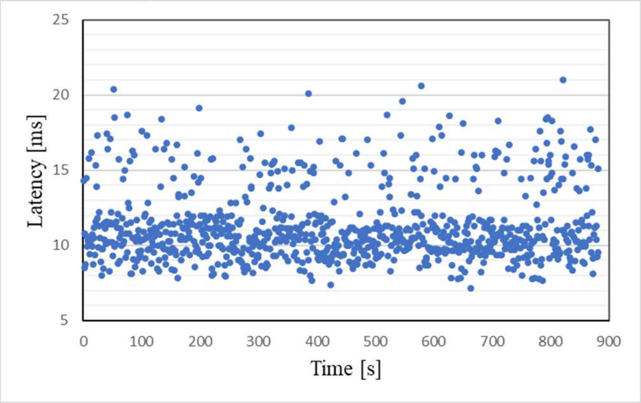

Fig. 10. RTT latency for device to controlling center in the omni-antenna setup (device attached to Cell ID 17)

The overground Reference Construction Site is part of the Industry Campus Europe in Aachen. As it is designed as a private outdoor 5G network, the frequency spectrum is limited by the Federal Network Agency (Bundesnetzagentur) to 3.7 - 3.8 GHz (100 MHz). General construction sites are embedded in an area with multiple surrounding network that cause interference to the private 5G network. Furthermore, there are limitations on TDD pattern which define the uplink and downlink configuration. In the construction site, the uplink speed cannot be increased to the maximum default 5G capacity which affects the use cases implemented with the communication technology. For example, lidar or big video and image data gathered on site need to be pre-processed locally before they can be uploaded for further use.

The omni-antenna setup on the Reference Construction Site covers the whole area with great signal quality. 90 % of all measured values are in the range of -75 up to -50 dBm. In comparison the radiating cables have a good signal quality around the crane but decrease significantly in performance with increasing distance to the crane. Around the crane the signal quality is -85 to -75 dBm. First throughput measurements of the omni-antenna setup showed an average TCP downlink of 810 Mbits/s and an average TCP uplink of 74 Mbits/s. Due to the outdoor situation on the construction site an adaption of the TDD pattern to industrial uplink - heavy was not possible. The RTT latency average is around 11.2 ms and 18.4 ms for device-to-device communication.

B. Underground Mine

The signal strength of the transmitting radio NR1 decreases with increasing distance from it and ranges between -110 and -95 dBm after approx. 935 m (Figure 11). The TCP up- and download are, on average, 353 and 73 Mbit/s, respectively (Figure 12). In the first 350 m of drift A signal strength is achieved with a maximum of -85 dBm and average upload and download speeds of 392 and 129 Mbit/s, respectively. After approx. 600 m, the average signal strength drops below -95 dBm, with the upload and download rates remaining relatively constant from this point until the end of drift A, with average absolute deviations of 38 Mbit/s (300 Mbit/s) and 16 Mbit/s (58 Mbit/s), respectively. The signal of antenna NR1 also covers route B over a length of approx. 120 meters, whereby the signal strength decreases to -110 to -125 dBm after approx. 30 m. Here, the usable upload speed drops after an additional 100 m from 30 Mbit/s to less than 1 Mbit/s.

The network generated by antenna NR2 in drift B exhibits between -50 and -75 dBm in the first 150 m of the drift (Figure 11), and after 300 m, it decreases to a range from -95 to -110 dBm. At the ends of drift A, a signal strength of -110 to -125 dBm is measured. The first active measurements showed an average minimum throughput of 150 Mbit/s for downloads and 60 Mbit/s for uploads.

Figure 13 shows the TWAMP round-trip time (TWAMP) of the entire drift A. It ranges between 14 and 16.5 ms on average. There is one outlier at drift length 110 m.

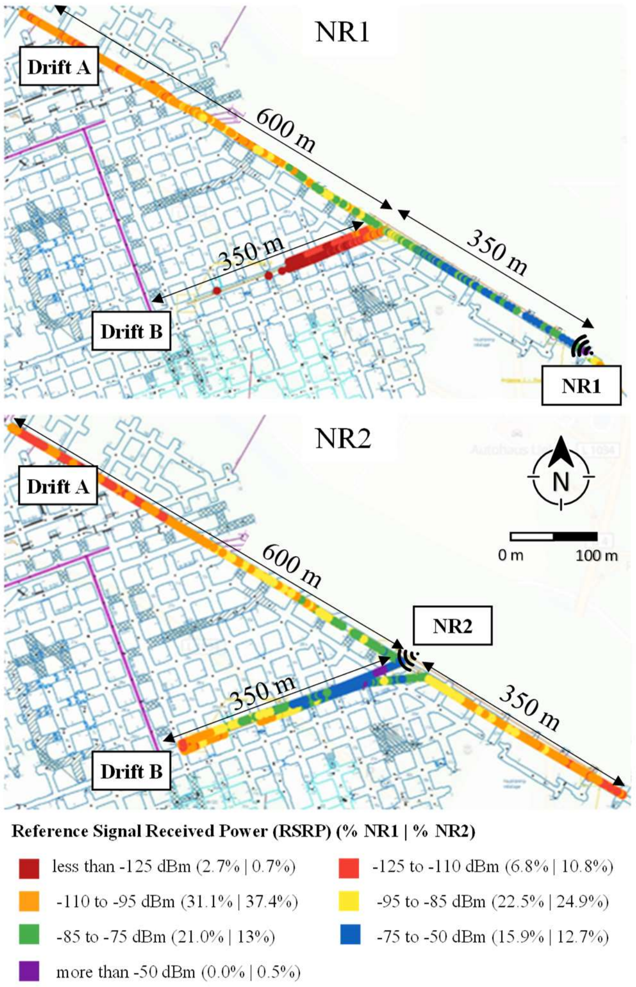

Fig. 11. Signal Quality of drifts. (top) drift A covered with NR1 (bottom) drift A and B covered with NR2 (NR2 aligned in the direction of drift B).

The different site characteristics of underground mines and construction sites have significant implications on the network setup, configuration, and achievable performance. This is also demonstrated by the results of the field trials within the 5G.NAMICO project. Compared to the construction site, the mine offers the advantage that the TDD patterns of the 5G network can be tested more variably. There are no competing networks or frequencies underground, so that no neighboring frequencies can be interfered with. The upload with TDD Mode 3 (sub-mode: 3:8:3) could be maximized to 39% of the total throughput. In addition, various transmission powers of up to 18 W can be tested at low thresholds, as no other networks are affected. Installation of the antennas is facilitated by easy access to the ridge. Only the maximum vehicle height must be considered. In the present configuration, it should be noted that the radiating cables would not be feasible in real operation as they would have to be removed regularly (approx. 6-8 weeks) for operational safety reasons (scaling). For this reason, different configurations (4x4, 2x2, and 1x1) are being analyzed to be able to develop different final implementation strategies.

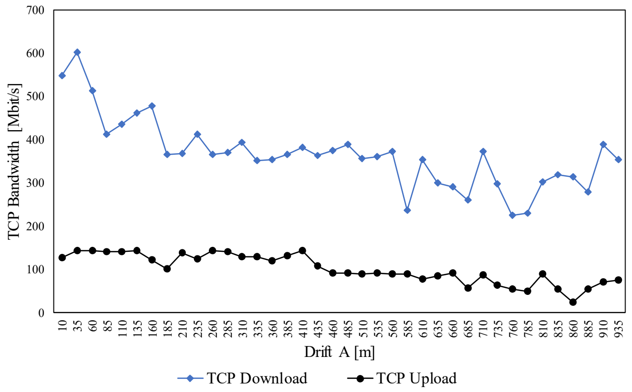

Fig. 12. Development of TCP up- and download throughput in Mbit/s along the length of drift A.

Fig. 13. Development of TWAMP round-trip times in Mbit/s along the length of drift A.

Only a few previous studies investigated the performance of different wireless network types in underground mining environments. Min and Jinhao (2021) conducted tests with WiFi 6 in an underground coal mine and reported throughput falling below 100 Mbit/s after 200 meters in the drift [9]. Kennedy and Bedford (2014) trialed a WiFi 4 network (at 2.4 GHz and 5 GHz) in an underground gypsum mine. They reported a maximum network range of 600 m, with the useable throughput dropping below 100 Mbit/s after 322 meters [10]. While a direct, in-depth comparison of different studies is limited due to significantly different experimental setups and test environments. For instance, Samoylov and Samoylov (2021) found that the propagation of radio waves is significantly influenced by the type of material [11], implying that different network performances, such as throughput and range, could be achieved in different mines. However, the results of the present field trials demonstrate that 5G offers approximately twice to four times the throughput at a distance from the antenna, as well as a range that is 2 to 5 times greater than reported by previous studies on WiFi 4 and 6 [9,10].

The results of the present field trials indicate that the network latency is sufficient for use cases such as teleoperation. According to Moniruzzaman et al. (2022), the first impairment of teleoperators begins at a latency of 10 - 20 ms [12]. As the latency times measured in this field trials (i.e., <16.5 ms) are within this range, it is believed that safe teleoperation is feasible. However, it should be noted that the latency measurements were carried out without further bandwidth utilization, with more realistic network utilization, the latency time is negatively influenced.

IV. CONCLUSION AND OUTLOOK

This study investigated the performance of 5G networks in a real underground mine and construction environments by testing different 5G antenna and radiating cable setups and performing established passive and active measurements (Reference Signal Received Power (RSRP), TCP up- and downloads, TWAMP round trip time). The 5G.NAMICO project's initial tests in mining and construction sites showcase the communication potentials and highlight the impact of specific site characteristics on network performance and configuration.

The results of the first test of the 5G network on the crane show the characteristics of each hardware component. The stable signal quality of the omni-antenna setup along with the measurement path outperforms the radiating cables, which exhibit good signal quality around the crane but decrease in performance with distance. The results form the basis for further research into harmonising the network configuration with the use cases in the construction industry.

In the underground mine, network performance decreases along the drift. While this general trend is in line with expectations, the network still achieves remarkable 353 Mbit/s upload and 73 Mbit/s download speeds and a TWAMP < 16.5 ms after 935 m down the drift. The lateral coverage achieved by the NR2 radio position suggests that it could effectively cover the entire trial area. Such insights are vital for developing optimised radio allocation strategies that allow to reduce network infrastructure costs and improve maintenance efficiency in underground mines.

Further research will focus on the assessment of technical, economic as well as ecological impacts of the implementation of 5G use cases in the domains of construction and mining. In this aspect, the question of which technical, economic, and ecological advantages can be exploited through the use of 5G and how these advantages compare to other industrial applications of 5G (for instance in manufacturing) is of particular interest. For this purpose, the maturity of the described use cases needs to be increased so that transparency on the use cases' value proposition is enabled.

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