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Private 5G-networks in underground mines: Promising results from field trials testing radio and radiating cable setups

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ABSTRACT

The fifth generation of mobile communications, 5G, has brought substantial progress to networked and adaptive systems across various application domains. As the development of 5G has been explicitly tailored to the needs of industry, a broad knowledge of the technology has been built up in industrial production. By contrast, in industries characterised by demanding and challenging operational conditions, like surface and underground mining, the performance and potential of 5G networks have only been studied to a limited extent. Only a limited number of mine sites have tested applications, and even fewer scientific publications have presented the results. The 5G.NAMICO research project aims to bridge the gap by setting up a dedicated 5G network at an underground salt mine in Sondershausen, Germany. Its performance was evaluated using established network test protocols. Conventional radios and varying radiating cable configurations were tested in field trials. Network tests demonstrated that 5G can deliver extensive area coverage, high bandwidths, and low latencies in the trial field. Conventional radios and radiating cables produce varying signal strength, bandwidth, and coverage results, especially in different drift configurations and topographies. The results imply that combining both antenna technologies can create expansive and high-performing networks in underground mines, affirming 5G networks' potential to support network-intensive applications like real-time production monitoring and teleoperation, promoting more efficient and safe operations.

1 INTRODUCTION

The ongoing digital transformation requires a shift from static processes and rigid workflows to networked, adaptive systems that enable real-time information exchange and are the backbone of digital transformation. 5G, the first network technology designed specifically for the industry's needs, enables fast and reliable wireless communication between production participants due to its high bandwidth, ultra-low latency, and massive machine-to-machine communication. (Gundall et al., 2021; Rao & Prasad, 2018) Since around 2017, 5G has been analysed in industrial production and has already demonstrated concrete progress towards leaner and more efficient production (5G-ACIA, 2021; Janina Knußmann, 2022, 2023; Lossie et al., 2023; Temesvári et al., 2019). However, in industries such as underground mining, which are characterised by unique and complex operating environments and conditions, the potential and performance of 5G networks have not yet been sufficiently explored. Few mines have tested 5G networks, and few concrete results have been published. Meanwhile, 5G is seen as an opportunity to catalyse digitalisation in underground mining and enable new use cases for more efficient and safer operations. (Langefeld, 2018; Martin Veitch, 2023) Therefore, the objective of the 5G.NAMICO research project (funded by the State of North Rhine-Westphalia through the Ministry of Economic Affairs, Innovation, Digitalization and Energy; Grant No. 005-2108-0111) was to address this gap by testing different 5G network configurations in an operating underground mine. This study aims to present the first practical measurements of 5G network performance using different antenna technologies and enable mine operators to assess a potential implementation. The derived research investigates how different setups of private 5G networks, such as directional radio and radiating cables, impact performance metrics within underground mining environments. A private 5G network was implemented in the Sondershausen underground salt mine in Germany. The network's performance was evaluated by measuring established performance metrics, including signal strength (RSRP), upload and download throughput, and round-trip time (latency). At the same time, different radio and radiating cable configurations were investigated. This study involved three separate test phases. In phase 1, the range of a directional radio was tested underground. In phase 2, different radiating cable configurations were compared; in phase 3, directional radios were compared with a radiating cable configuration. The results of the network tests demonstrated that 5G can deliver extensive area coverage, high bandwidths, and low latencies across the entire field trial area. Conventional radios and radiating cables achieve different signal strengths, throughputs, and coverage depending on the configurations and course of the drift. The results confirm the potential of 5G networks to support network-intensive applications in underground mines and suggest that a combination of radio and radiating cable technologies will enable the full potential of 5G to be realised and facilitate the creation of extensive high-performance networks that enable real-time monitoring of underground extraction processes, and machinery; real-time analysis of the mine workings and reliable and uninterruptible teleoperation of underground machinery. 5G thus offers the potential to be the backbone of underground digitalisation, enables the automation of mass mining operations, and promotes more efficient and safer operations.

Below (cf. Table 1) are some specified terms from the field of network technology that will increase this study's comprehensibility.

Table 1 Glossary Network Technology

Acronym	Description
RAN - Radio Access Network	Network segment that provides access to the wireless network by establishing the connection between mobile devices and the core network.
NR - New Radio	5G wireless standard.
TDD - Time Division Duplexing	Process in which data is transmitted and received over the same frequency by time division.
RSRP - Reference Signal Received Power	RSRP is a metric in mobile networks that measures the power of a base station's received signal.
TCP - Transmission Control Protocol	Transport protocol used for the transmission of data ensuring a reliable connection.
UDP - User Datagram Protocol	Transport protocol used for the transmission of data without ensuring a reliable connection.
RTT - Round-Trip Time	The time it takes for a message to travel from a source to a destination and back to the source.
SiSo - Single Input Single Output	Technology in which both transmitting and receiving devices each use a single antenna.
MiMo - Multiple Input Multiple Output	Technology that uses multiple transmitting and receiving antennas to improve data transmission speed and reliability.
iPerf3	Tool for measuring network performance such as download and upload.
TWAMP	Tool for detailed RTT measurements.

2 METHODS AND EXPERIMENTAL SETUP

The following section describes the 5G hardware used for the investigations, the measurement methodology, the underground mine, the field trial site, and the different testThe 5G hardware used in the investigations is described below: the 5G core, the 5G radios, and the radiating cables. In Figure 1, all core elements described are marked correspondingly.

2.1 5G hardware

2.1.1 Private 5G core

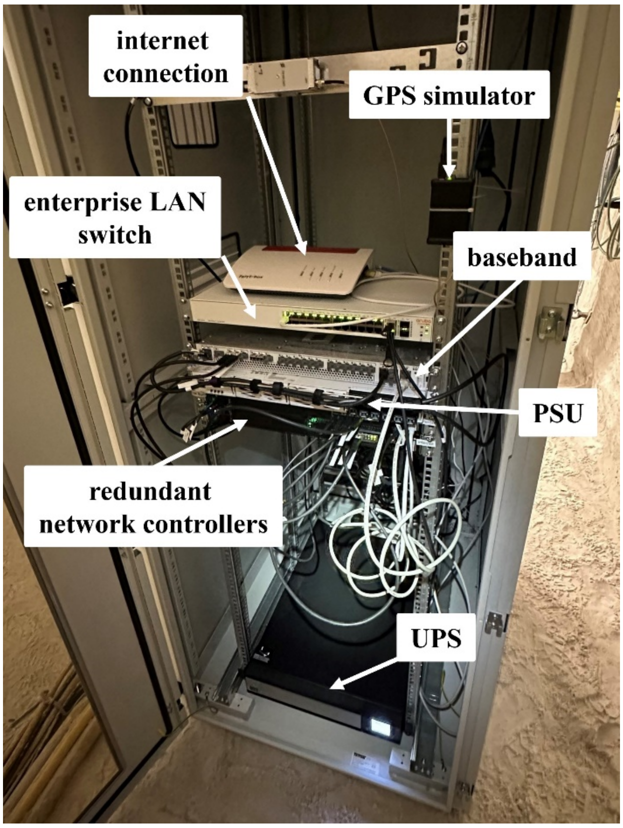

Figure 1 Private 5G core setup in Sondershausen salt mine.

The 5G network analysed is a stand-alone 5G network from Ericsson designated as Ericsson Private 5G (EP5G). 5G consists of three key components: a core network, a Radio Access Network (RAN) and an enterprise Local Area Network (LAN).

The 5G core consists of two redundant network controllers operated on a standard Dell EMC VEP4600 server. The network controller's task is, for example, network and SIM card management, increase network performance, improve communication efficiency, or provide the Quality of Service (QoS), a hierarchical structure to prioritize specific network applications. (Aijaz, 2020; Rai et al., 2023) The 5G core is powered by an Ericsson Power 6250 Power Supply Unit (PSU). The RAN is the air interface in which data is processed to signals so that the radios can distribute these via electromagnetic waves (Ericsson AB, 2020). The baseband used in this research is an Ericsson 6631. The interconnection between the baseband and the radios requires a single-mode optical fiber connection. The Enterprise LAN consists of a Level 2 switch, a MikroTik CRS328-24P-4S, which connects the 5G network to the existing Enterprise LAN. The 5G core is connected to the enterprise LAN switch via two 10 Gbit/s small form-factor pluggable (SFP+) ports to which the downstream devices can be connected via Gigabit Ethernet. Due to its architecture, 5G networks require time synchronisation. On the surface, time synchronisation is carried out via satellites, mainly the Global Positioning System (GPS). As no satellite connections are underground, the CLAW GPS simulator from Jackson Labs was used to utilise the network. An uninterruptible power supply (UPS) was installed to ensure reliable operation, enabling the network to be shut down properly even during unplanned power failures. The entire network setup was installed in an air-conditioned, dust-protected server rack to protect the components from dust, especially from corrosive salt dust.

2.1.2 5G radios

Ericsson 4408 5G radios were used for the investigations. The main technical features of the radio are New Radio (NR), Time Division Duplexing (TDD), and Long-term evolution (LTE) TDD. The radio is equipped with a duplex transmitter and receiver (4 Transmitters (TX)/ 4 Receivers (RX)) and offers a maximum transmission power of 5 watts per antenna. The transmission power of the radio is individually adjustable with a minimum value of 0.25 W to 5 W per antenna output. The radio complies with the 3GPP specifications for the medium-range base stations. The radio has dimensions 213 x 200 x 119 mm and weighs 5 kg. The recommended operating conditions cover a temperature range from -40 to 55 °C, and the suitable relative humidity is 5 – 100 %. The antennas used on the radio are Ericsson 6524, integrated 4x4 Multiple Input Multiple Output (MiMo) directional antennas for frequencies from 3300 to 3800 MHz.

Figure 2 Final installation of the directional radio (Ericsson 4408) in the mine workings.

The radios (cf. Figure 2) were attached to the roof using anchors and a standard TV satellite dish mount. To properly connect the radios to the 5G core, single-mode fiber optic cables were installed at all radio positions. In addition, the operation of the radios requires a 230 V Alternating Current (AC) power source. The installation considered the maximum vehicle height of the equipment used in the mine and the recommended distance to the roof by the radio manufacturer of at least 50 cm.

2.1.3 Radiating Cables

The Euracay RMC 114-G 'A' from Kabelwerk Eupen was used to investigate the performance of the 5G network emitted by radiating cables. These cables support the frequency band from 30 MHz to 3800 MHz. The longitudinal loss at 3800 MHz is 8.65 dB/100 m, and the corresponding coupling losses are C50% at 62 dB and C95% at 67 dB. With a minimum bending radius of 350 mm, the cables offer flexibility during installation. The cables have a diameter of around 32 mm and a weight of 0.79 kg/m. They are attached to the radio core using jumper cables. End resistors with 50 Ω were installed at the end of each cable.

Figure 3 Final installation of the radiating cables in the drift.

The radiating cables were installed using two parallel 300m steel cables attached to the roof using anchors along the longitudinal axis of the drift. 3 m wooden slats were attached in a parallel manner to the steel cables using ropes. The ropes made it possible to align the wooden slats horizontally to compensate for the uneven geometry of the deprived roof. Unique plastic holders for the radiating cables were attached to the wooden battens, into which the cables were clipped at a later stage. To simplify the installation, the wooden slats, cables, and plastic holders were prepared and attached to the steel cables without the radiating cables. In a further step, the cables were mounted in the brackets. Figure 3 shows the final assembly of the radiating cables.

2.2 Methodology Underground Network Measurements

The private 5G network (band n78: 3.700 – 3.800 MHz) was configured to a maximum upload bandwidth. Using TDD mode 3 (sub-mode: 3:8:3), 39 % of the total bandwidth was reserved for the upload. The test drifts were divided into measurement sections of 25 m, along the drift axis. Each section was measured using point measurements in a 3x3 matrix (cf. Figure 4) to comprehend the interaction between the network and the underground geometry. This study calculated the average of all nine measurements to one mean performance indicator.

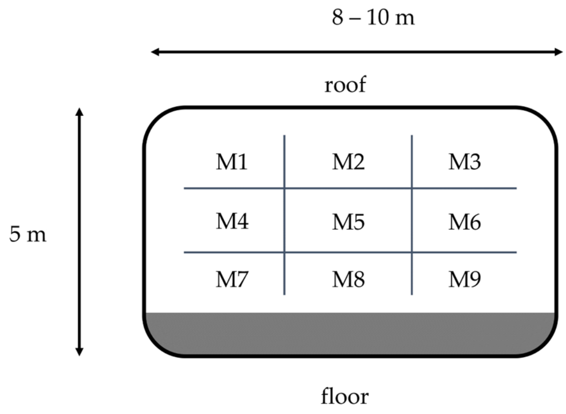

Figure 4 Schematic 5G point measurements (M1 - M9) in the drift cross-section of each measurement section.

The objective of this study is to determine the usable network performance of the 5G network and disseminate reproducible network performance parameters (signal strength, up- and download, Round-Trip Time (RTT)) for mine operators. To achieve this, four commercially available 5G routers were analysed in a preliminary test. The preliminary test aimed to identify a router that has sufficient performance reserves and reliability to carry out a 5G network evaluation, without itself being a bottleneck. The models analyzed were HMS NV1000, Milesight UR75, Amit IDG780, and Siemens Scalance MUM856-1. Based on the preliminary investigation's results, the Siemens MUM 856-1 was selected for further tests. Passive and active measurements were conducted to determine the network performance, measuring signal strength, throughput, and RTT. The throughput determination (TCP and UDP) was carried out with iPerf3. The measurement duration was 10 seconds, and three measurements were taken. The RTT measurements were done using the Linux ping tool and the Two-Way Active Measurement Protocol (TWAMP). All functions and protocols have been integrated into a software package compatible with Linux, enabling equal measurement sequences.

2.3 Underground Mine and Test Phases

This chapter describes the underground mine in which the investigations took place. The investigations were divided into three individual phases.

2.3.1 Underground Mine

The field trials were conducted at "Glückauf Sondershausen Entwicklungs- und Sicherungsgesellschaft mbH" (GSES) in Thuringia, Germany. The mine extracts food-grade salt and grit. Furthermore, the mine serves as an underground landfill for non-recyclable waste materials. The mine workings are located at a depth of 65 to 750 m and cover an area of around 32 km² with 80 km of open mine workings. During the investigations, the average temperature was 25 °C with a relative humidity of 30 %. The mining method used is room and pillar, where the layout of the mine is characterised by a series of parallel drifts arranged in an orthogonal manner.

2.3.2 Field Trial Site

A schematic representation of the 5G field trial site at the intersection of Drifts A and Drift B at the -700 m level within the underground mine is shown in Figure 5. Drift A and Drift B feature a rectangular cross-section with dimensions of 5 m in height and 8 m in width. From the intersection, Drift A extends in a linear trajectory, with slightly vertical undulations, covering a distance of 600 m before reaching the mine shaft that connects the underground mine workings with the surface infrastructure. Drift B, branching off from Drift A at approximately 45 °, extends for 350 m to terminate at a crushing station, demarcating the boundary of the trial area. This depiction outlines the trial field's spatial configuration within the underground mine environment. Various radiating cable configurations, including 4x4 MiMo (four parallel cables), 2x2 MiMo (two parallel cables), and 1x1 SiSo (single cable), are investigated in the setup. The schematic drawings are provided for illustrative purposes and do not represent precise scale proportions.

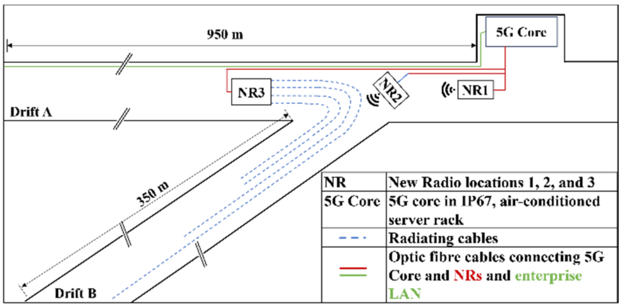

Figure 5 Schematic representation of the 5G field trial site in the Sondershausen mine.

2.3.3 Test Phases

This chapter describes the objective and design of the three test phases that were used to investigate the performance of 5G in underground mines using directional radios and different radiating cable configurations.

Phase 1 - Determining the Range of a Directional 5G Radio Used Underground

In the first test phase, the potential range of a 5G radio is determined. The investigation is conducted in Drift A using directional radio NR1 (cf. Figure 5). The drift is level and flat, with a dip from 140 m to 200 m behind antenna NR1.

Phase 2 - Comparison of Different 5G Radiating Cable Configurations

In the second test phase, the network performance of 4x4, 2x2 MiMo, and 1x1 SiSo radiating cable configurations are analysed using active measurements. The investigation aims to compare relative 5G network performance and identify the most suitable radiating cable configuration for using 5G underground. The investigations were carried out in drift B with radio NR3 (see Figure 5).

Phase 3 - Comparison of directional 5G radio with radiating cable configurations

In the third test phase, the network performance of the 2x2 MiMo Radiating Cable configuration is compared to a directional 4x4 MiMo radio. The investigation was conducted in Drift B, including radio NR2 and NR3.

3 RESULTS AND DISCUSSION

3.1 Phase 1- Determining the Range of a Directional 5G Radio Used Underground

The signal strength (Reference Signal Received Power (RSRP)) emitted by radio NR1 decreases with increasing distance, ranging from -110 to -95dBm at the end of the drift at measurement point HU38, 935 m behind NR1 position (cf. Figure 6). At HU07 (160 m), HU10 (235 m) and HU19 (460 m), outliers from the signal characteristics can be recognised. Within the initial 350 m of Drift A (junction to Drift B), the signal strength reaches a peak of -88 dBm. Beyond approximately 600 m, the average signal strength dips below -100 dBm. From HU36 (885 m), the signal strength increases from -110 dBm to -98 dBm for the last two measurement points.

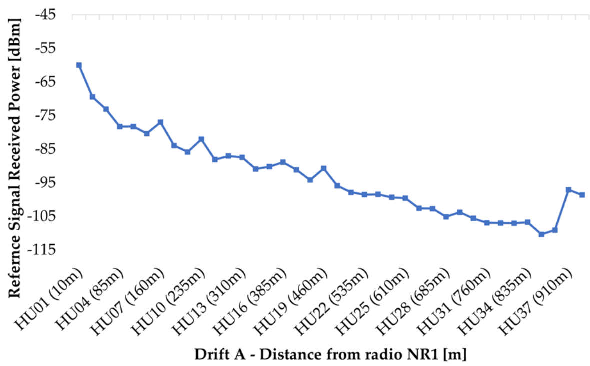

Figure 6 Signal Strength (RSRP) emitted by directional radio NR1 in Drift A.

The active measurements to determine the up- and download throughput using User Datagram Protocol (UDP) (cf. Figure 7) show an initial download performance of 503.1 Mbit/s, which rises to its global maximum of 541.5 Mbit/s at HU03 (60 m). The download performance then decreases under fluctuations with a standard deviation of 34.6 Mbit/s to 430.5 Mbit/s before becoming relatively homogeneous from HU09 (210 m); the standard deviation is 22.4 Mbit/s up to HU28 (685 m). From this point to the end of the drift, the download has a standard deviation of 18.4 Mbit/s until a final download performance of 341 Mbit/s is reached at HU38 (935 m).

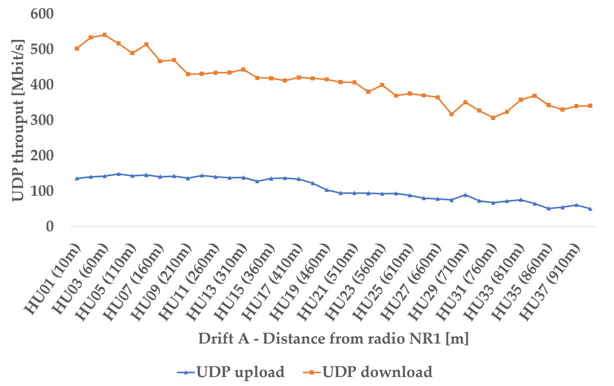

Figure 7 UDP up- and download measured in Drift A, using radio NR1.

The UDP upload has a global maximum of 148.8 Mbit/s at HU04 (85 m). Up to HU18 (435 m), the upload shows a homogeneous trend with a standard deviation of 6 Mbit/s. The absolute upload performance at HU18 is 122.9 Mbit/s. Between HU18 and HU19 (460 m), the upload performance decreases by 19.3 Mbit/s, reaching a final value of 103.5 Mbit/s. Afterwards, it steadily drops to a minimum of 50.4 Mbit/s until the end of Drift A. The RTT measurements using TWAMP (cf. Figure 8) show RTTs between a minimum of 15.09 ms at HU13 (310 m) and a maximum of 16.46 ms at HU22 (535 m). The standard deviation of the RTTs, considering the total length of drift A, is 0.30 ms.

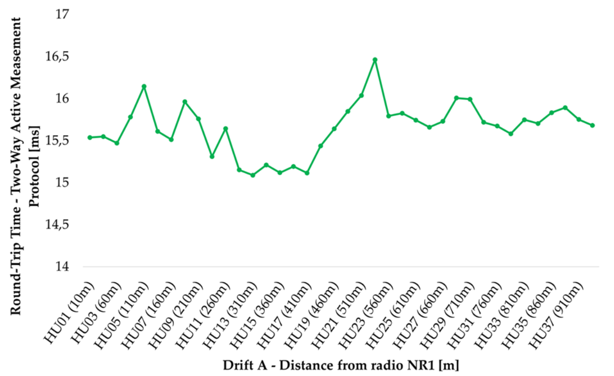

Figure 8 TWAMP round-trip times measured in Drift A.

Examining the signal strengths of radio NR1 (Figure 6), it is evident that the signal strength increases again from HU36 (885 m). One possible explanation for this is the end of the drift, which leads to a 90-curve and thus increases the reflection surface for the electromagnetic waves. Figure 9 shows the corresponding local conditions.

Figure 9 End of the field trial (Drift A), 935m behind directional radio NR1.

Considering the active throughput measurements, there is an increase in downstream of approx. 10 Mbit/s, while no parallel increase in the upstream is detectable. Including the RTT (cf. Figure 8), the trend mentioned above can be recognized by a reduction in RTT from 15.89 ms at HU36 (885 m), via 15.75 ms at HU37 to final 15.68 ms at HU38 (935 m) behind radio NR1. No direct correlation between signal strength and throughput and RTT can be derived from the data. The trends in the curves are similar, but an in-depth investigation is required in the future to determine the exact relationship between the signal strength and the active measurement data.

3.2 Phase 2 - Comparison of Different 5G Radiating Cable Configurations

Primarily, active measurements were carried out to evaluate the radiating cable configurations, as there is no clear correlation between signal strength and usable throughput. Successive active network measurements were carried out with one cable (1x1 SiSo), two parallel cables (2x2 MiMo), and four parallel cables (4x4 MiMo). Figure 10 shows all results in one plot.

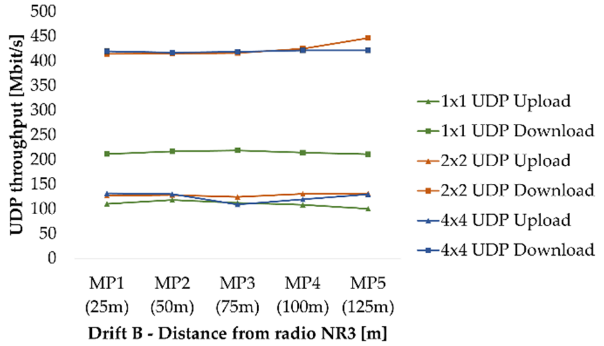

Figure 10 Active UDP throughput measurements using 1x1, 2x2, and 4x4 radiating cable.

Regarding the download, the 1x1 configuration has an average of 214.1 Mbit/s. For all measurements over the first 125 m of Drift B, the standard deviation of the downstream is 3 Mbit/s. The 2x2 and 4x4 radiating cable configurations achieve an average downstream of 423,1 Mbit/s and 419,4 Mbit/s respectively over the first 100 m of the drift, with a standard deviation of 12,2 Mbit/s and 1,8 Mbit/s. The last measurement MP5 (125 m), the 2x2 configuration shows the global maximum in downstream, with 446,4 Mbit/s compared to 421,4 Mbit/s in the 4x4 configuration. Considering the averaged measurements of the individual configurations, the upload performance of all configurations is relatively similar. However, the 1x1 configuration has the lowest performance, with an average upstream of 109,8 Mbit/s. In contrast, the 2x2 configuration achieves the highest performance, with an average upstream of 128,3 Mbit/s. The 4x4 configuration lies between the 1x1 and 2x2 configurations, with an average upstream of 123,8 Mbit/s.

These results imply that the number of parallel cables in the configuration significantly influences the throughput. A higher number of cables results in better upload and download performance. Comparing the standard deviation of the 2x2 and 4x4 configurations (12.2 Mbit/s and 1.8 Mbit/s) suggests that the 4x4 configuration creates a more stable network. However, the results do not show any further significant improvements in network performance when more than two radiating cables are used. Regarding performance results, capital expenditure, and installation effort, there is a clear trend towards a 2x2 configuration in underground mines.

3.3 Phase 3 - Comparison of directional 5G radio with radiating cable configurations

Based on the outcomes of phase 2, the comparative investigations of radiating cables with the directional radio were carried out using a 2x2 radiating cable configuration. The passive network measurements show a continuous decrease in signal strength throughout Drift B (cf. Figure 11).

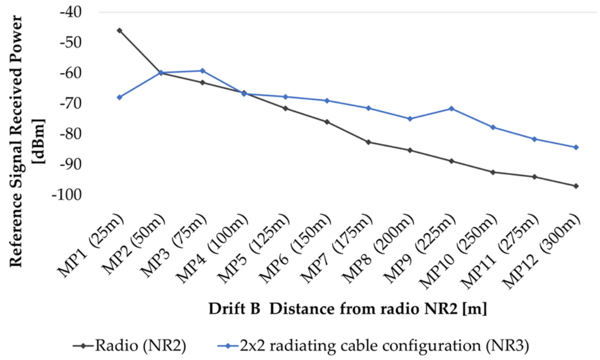

Figure 11 Signal Strength (RSRP) emitted by the directional radio and the 2x2 radiating cable configuration in Drift B.

The directional radio has a maximum signal strength of -46.0 dBm at MP1 (25 m). At the same measurement point, the 2x2 radiating cable configuration has a signal strength of -67.9 dBm. From MP2 (50 m), the signal strength of the directional radio drops to -60 dBm; simultaneously, the signal strength of the radiating cable configuration increases to the same value. As Drift B progresses, the signal strength of the directional radio continues to decrease until an average signal strength of -97.1 dBm is detected at MP12 (300 m). From MP4 (100 m) onwards, the signal strengths of the two antenna technologies continue to drift apart, with the 2x2 radiating cables always having a higher signal strength. The absolute difference between the two signal strengths increases from 3.8 dBm at MP5 (125 m) to a maximum of 17.3 dBm at MP9 (225 m). At the end of drift B at MP12 (300 m) the absolute difference of the antenna technologies is 12.7 dBm.

The active throughput measurements (cf. Figure 12) show that the download performance of the directional radio is higher than that of the 2x2 radiating cable configuration over the entire Drift B. The maximum download rate of the directional radio is 539.3 Mbit/s, and the maximum download rate of the radiating cable configuration is 446.4 Mbit/s. The minimum download is 410.0 Mbit/s or 386,2 Mbit/s respectively. Considering the entire Drift B, the download performance of the directional radio has a standard deviation of 42.1 Mbit/s, and the 2x2 radiating cable configuration of 17.1 Mbit/s.

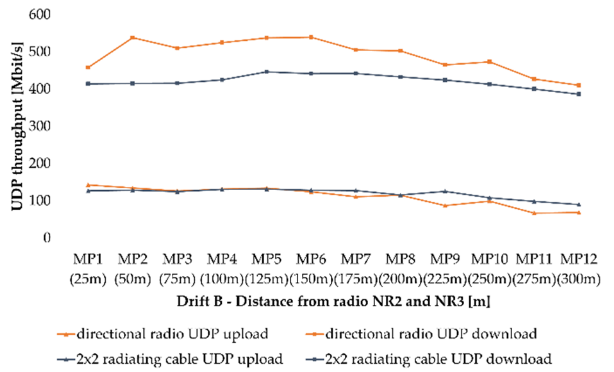

Figure 12 UDP up- and download performance of directional radio and 2x2 radiating cables.

The upload performance of the radiating cable configuration and the directional radio show similar performance. Over the first eight measuring points, the standard deviation of the directional radio is 9.8 Mbit/s. In comparison, the standard deviation of the radiating cable configuration is 4.9 Mbit/s. After MP8 (200 m) to the end of Drift B, the radiating cables, with an average upload of 105.3 Mbit/s show a higher performance than the directional radio with 80.4 Mbit/s. The maximum and minimum upload performance of the directional radio is 66.8 Mbit/s and 99,0 Mbit/s. In comparison, the radiating cable configuration has a maximum upload performance of 125,0 Mbit/s and a minimum performance of 89,9 Mbit/s.

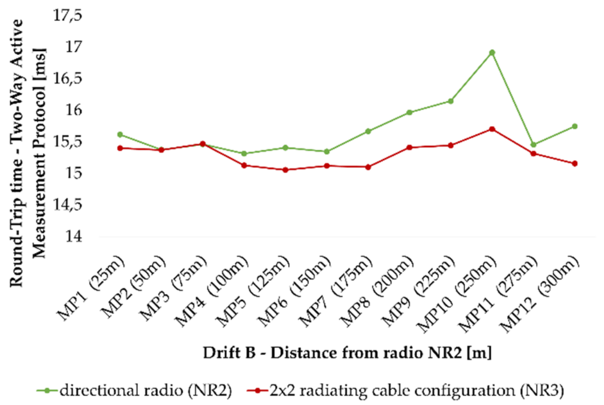

Figure 13 TWAMP results from directional radio and 2x2 radiating cable configuration.

The TWAMP measurements (cf. Figure 13) show a global maximum at MP10 (250 m) of the directional radio of 16.91 ms. The highest RTT of the 2x2 directional radio configuration is 15.7 ms, correspondingly at MP10 (250 m). The global minimum of the RTT measurements is reached with 15.06 ms achieved by the 2x2 radiating cable configuration at MP5 (125 m). The standard deviation of the directional radio over the entire test drift is 0.44 ms, and that of the radiating cable configuration 0.19 ms. The signal strength analysis shows that the network emitted by the 2x2 radiating cable configuration after an initially weaker signal strength at MP1 (25 m) always provides a higher signal strength. The signal strengths of the directional radio and the radiating cables drift further apart until the end of the drift. Focusing on the topographical profile of Drift B, a dip extends from MP4 (100 m) up to and including MP8 (200 m). The dip results in loss of Line of Sight (LOS) between the router and the directional radio NR2 and is a possible explanation for this phenomenon. This circumstance is where the radiating cables show their strength, as there is no loss of LOS due to the installation on the roof. An additional examination of the active measurements, in particular the RTT (cf. Figure 13), also shows that the two performance curves drift apart from MP4 (100 m) onwards, which also indicates an influence of the dip on the achievable network performance. The active throughput measurements showed that the download of the directional radio is above the performance curve of the 2x2 radiating cable configuration. It should be noted that four antenna connections are available per radio unit. At the same time, only two are used in the 2x2 radiating cable configuration. Therefore, another pair of radiating cables can be connected to extend the 5G coverage to another drift. The relative difference in performance between a total radio usage and a 50% usage is max. 17.23 % in the downstream and averaged over the entire drift 14.18 %. The analysis of the upstream does not show any significant differences, as the transmission power for sending data into the network originates from the router and not from the 5G network. However, the 2x2 radiating cable configuration achieves an average upload of 119.5 Mbit/s, which is a better upload performance compared to the directional radio with an average upload of 111.6 Mbit/s.

4 CONCLUSION AND OUTLOOK

This study investigates the performance of 5G networks in a real underground mine by testing various 5G directional radio and radiating cable configurations. The study employs established passive and active measurements, such as RSRP, UDP up- and downloads, and TWAMP round-trip time. The initial investigation, conducted within the 5G.NAMICO project in the underground mine demonstrates the communication potential and highlights the influence of specific site characteristics on network performance and network configuration. In Phase 1, network performance declines along the drift. While this general trend is in line with expectations, the network still achieves a remarkable download performance of 353 Mbit/s and an upload performance of 73 Mbit/s, TWAMP-RTTs are below 16.5 ms after 935 m down Drift A. Initial simulations predicted a range of around 700 m; these expectations have been exceeded. In addition, the final range of the directional radio is likely even higher, but this could not be investigated further due to local conditions. These measured performances correspond to approx. 63 % of the initial maximum downstream, and 34 % of the maximum upstream and thus offer large reserves for future applications. The comparison of the radiating cable configurations in phase 2 clearly shows that the 2x2 configuration is superior to the 4x4 configuration in terms of network performance, installation effort, and expansion costs. The achievable network performance of the 2x2 configuration is on par with and, in many situations, even higher than that of the 4x4 configuration. The 1x1 configuration offers lower throughput than the 2x2 and 4x4 configuration and the lowest capital expenditure. The results have shown that a 2x2 radiating cable configuration provides the best overall performance underground and is therefore the most suitable radiating cable configuration. In phase 3, the upload throughputs measured in Drift B favour the radiated cable configuration, where the achievable throughput is 14.2 % higher than the directional radio, again due to better coverage and a continuous LOS. The continuous LOS is therefore also partly responsible for the fact that the achievable TWAMP-RTT of the 2x2 radiating cable configuration is 2.7% lower on average over the entire test drift. In particular, the 2x2 radiating cable configuration only occupies two of the four antenna connections of a radio device. Thus, the possibility exists to equip another 2x2 configuration to the radio unit and thus double the network coverage. The only downside is, that the download performance is lower by 17.2 % compared to the directional radio. The results show that 5G underground is suitable for providing high bandwidths and low latency over long distances. In the context of increasingly digitalised raw material extraction and growing demands on network technology as the backbone of digitalisation, use cases such as real-time 3D scans of the drifts or machine data reading can be carried out in real-time. In addition, upcoming 5G technology releases will offer functions such as native real-time positioning of all participants in the network, which will make a decisive contribution to mine safety. The main advantage of 5G lies in its mobility. Several cells can be connected to form an overall network, and the handover of a subscriber from one cell (radio) to another can be explicitly controlled. This technique leads to superior reliability, especially in latency-critical applications such as the teleoperation of equipment. In addition, 5G offers the possibility of integrating different Quality of Service levels that enable a hierarchical structuring of applications in the network and can be prioritized accordingly so that, for example, safety or production-critical processes do not compete with other applications. The initial results indicate that a holistic network design must combine the advantages of directional radios and radiating cables to create a robust and cost-efficient network. Further research should be carried out on radiating cables, especially on heavily used drifts and topographically uneven mine workings. It is also necessary to investigate in more detail real-time positioning underground based on 5G. Nevertheless, the 5G network resources must also be managed smartly. Practical investigations with 3D lidars have shown that data streams can deplete the bandwidth of 5G, so compression algorithms and sufficiently detailed network architecture are required to create a real-time environment that can act as the backbone of underground digitalisation — enabling autonomous excavation processes, reliable teleoperation, real-time monitoring of personnel, machinery, and the mine workings, and therefore promotes a more efficient and safer operation.

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