Universidade Federal da Bahia
Escola Politécnica
Colegiado do Curso de Eng. Elétrica

Luiza Souza Simões

Validation of remote-control use cases for construction and mining robots via 5G

Supervisor: Profa. Dra. Ana Isabela Araújo Cunha – Universidade Federal da Bahia
Co-supervisor: M.Sc. Sarah Schmitt – Fraunhofer Institute for Production Technology

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"Anyone who has never made a mistake
has never tried anything new".
(Albert Einstein)

Resumo

Os *use cases* remotamente controlados estão sendo constantemente utilizados na indústria atualmente. Os setores da Mineração Subterrânea e Construção exigem um tipo de comunicação confiável e de alta qualidade, que pode ser alcançado através do 5G. Esta tese surge com o objetivo de validar o trabalho e os dados extraídos em diferentes circunstâncias, analisando os seus resultados e detalhando o impacto que podem ter na indústria como um todo. Ao examinar o desempenho dos *use cases*, pretende-se demonstrar a importância da utilização do 5G, já que possui imenso potencial e contribui para o avanço do conhecimento neste campo, lançando luz sobre os potenciais benefícios e implicações decorrentes da implementação da tecnologia. Os objetivos para cada cenário são descritos juntamente com a forma como as medições foram realizadas para ambos os casos. Na Mina Subterrânea, os testes foram realizados com a rede Wi-Fi disponível localmente, enquanto na construção os parâmetros foram testados com 5G. Latência, taxa de transferência, cobertura e qualidade do sinal foram os principais indicadores para a análise e eles foram capazes de fornecer diversos *insights* para a compreensão dos cenários. Como as instalações das redes não foram concluídas a tempo para os testes, elas apresentaram resultados que não atenderam às especificações desejadas. No entanto, considerando os novos cabeamentos e antenas que estão previstos para serem implementados, espera-se que os resultados demonstrem o 5G como uma tecnologia de comunicação confiável e de alta qualidade, cumprindo a expectativa e atingindo as metas estabelecidas. Por fim, para trabalhos futuros, foi sugerido que o processo de instalação e configuração seja completamente documentado para garantir uma avaliação minuciosa da influência de cada componente envolvido, o que pode levar a uma análise e compreensão mais aprofundada do impacto que o 5G pode causar na indústria.

Palavras-chave: Redes 5G. Construção. Mina Subterrânea. Validação de Dados. Conectividade.

Abstract

Remote-controlled use cases are consistently being used in the industry today. The Underground Mining and Construction sectors require a high-quality, reliable type of communication that can be achieved with 5G. This thesis comes with the objective of validating the work and data extracted in different circumstances, analyzing their results, and detailing the impact that they can have on the industry as a whole. By examining the performance of remote-controlled use cases, it aims to demonstrate the significance of utilizing 5G, as it holds immense potential, and contributes to the advancement of knowledge in this field, shedding light on the potential benefits and implications that arise from the implementation of the technology. The goals for each scenario are described along with how the measurements were performed for both cases. In the Underground Mine, the tests were held with the Wi-Fi network available locally, while at the Construction site, the parameters were tested with 5G. Latency, throughput, coverage, and signal quality were the main indicators for the analysis and they were able to provide insights for the understanding of the scenarios. Since the network setups were not complete in time for either of the tests, they present results that would not fulfill the specifications desired. However, considering the installation of new cabling and antennas that is planned to happen, it is anticipated that the results will demonstrate 5G as a reliable and high-quality wireless communication technology, ultimately fulfilling the expectation and achieving the set goals. Finally, for future work, it was suggested that the installation and configuration process is completely documented to ensure a thorough assessment of the influence of each component involved, which can lead to further analysis and deeper comprehension of the impact that 5G can cause on the industry.

Keywords: 5G networks. Construction Site. Underground Mine. Data validation. Connectivity.

List of Illustrations

List of Tables

List of abbreviations and acronyms

1G	First Generation
2G	Second Generation
3D	Three Dimensional
3G	Third Generation
4G	Fourth Generation
5G	Fifth Generation
AR	Augmented Reality
D2D	Device-to-Device
eMBB	Enhanced Mobile Broadband
IPT	Institut für Produktionstechnologie
GUI	Graphical User Interface
IoT	Internet of Things
MC	Multi-Connectivity
MIMO	Massive Multiple-Input Multiple-Output
mMTC	Massive Machine Type Communications
MRE	Mineral Resources Engineering
NAMICO	Networked, Adaptive Mining and Construction
Ping	Packet Inter-Network Groper
PPE	Personal Protective Equipment
Q5GA	Quick 5G Analyser
R&S	Rohde & Schwarz
SMS	Short Message Service
UE	User Equipment
uRLLC	Ultra-Reliable Low Latency Communications
uHSLLC	Ultra-High Speed and Low Latency Communication
V2I	Vehicle-to-Infrastucture
V2N	Vehicle-to-Network
V2P	Vehicle-to-Pedestrians
V2V	Vehicle-to-Vehicle

V2X Vehicle-to-Everything

VR Virtual Reality

Summary

1 Introduction

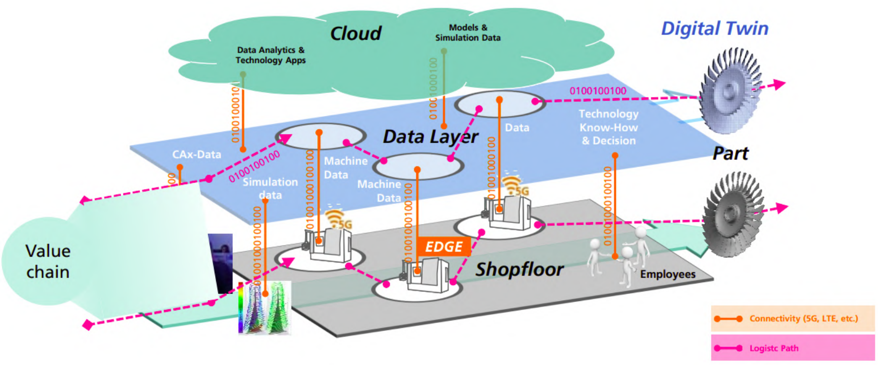
The manufacturing world is continuously evolving in the 21st century, and companies today have to combat competition, molding themselves and improving their line of work to provide the expected customer experience. Global connectivity, innovation, and disruption are all reshaping the manufacturing industry, but a world-class business platform can help companies transform operations digitally to keep up with an evermore modern world (WALLACE, 2021). As said in Küpper et al. (2016), the factory of the future is a vision for how manufacturers should enhance production by making improvements in three dimensions: plant structure, plant digitization, and plant processes.

In the Plant Structure, the idea is to develop a more flexible, multi-directional layout, with a modular line setup that provides interchangeable line modules and production machinery that can be easily reconfigured. The objective here is to also have an environmentally sustainable production process.

With Plant Digitization, the goal is to explore the field of smart and collaborative robots while implementing advanced technology and data analysis in order to enable smarter automation and promote efficiency in several ways. At the same time, by improving the Plant Processes, workers are taking lean management to the next level and exploiting its full potential.

In the day-to-day world, the exchange of information can be seen in the dynamics of the work organization. In Figure 1, it is possible to observe the flow in which data is inserted, going from the shopfloor, passing through logistic paths and data layers until it gets to the cloud. All of this relies on the connectivity provided by the network. In this thesis, the 5G connection will be explored.

Figure 1 – The factory of the future scheme.



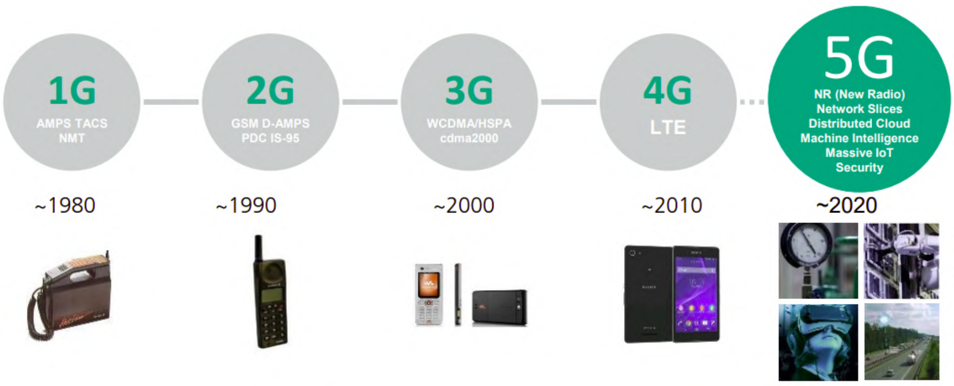
Reference: Schmitt (2022)

It is important to highlight that communication systems are the basis for the factory of the future. To realize the vision of a highly flexible and networked manufacturing complex, these systems require some specific properties such as high reliability, real-time data exchange, scalability, high data rates, high data density, and decentralization. The Fifth Generation (5G) is the first mobile communications standard to meet all of them (SCHMITT, 2022).

1.1 Evolution of Wireless Connectivity

Mobile connectivity has evolved at a rapid pace since the late 1970s due to the ongoing demand for high-speed communications across the globe (MADRONA, 2021). Figure 2 offers the visualization of a timeline resuming the main characteristics of each generation.

Figure 2 – Evolution from 1G to 5G devices.



Reference: Schmitt (2022)

In the First Generation (1G) the main features were quite basic. Phones were very practical: used only for the establishment of mobile telephony and voice calls. Speed and security were not priorities at the time.

Coming up to the Second Generation (2G), text messaging and Short Message Service (SMS) were introduced. Users were now able to make phone calls outside the geographic coverage area of a network (roaming) and there was an increase in safety and speed quality.

In the Third Generation (3G), the possibility of web browsing arose. The internet started gaining more and more popularity so the foundation of mobile broadband happened. Next, the Fourth Generation (4G) is marked by the possibility of mobile video consumption and high data speeds.

And finally, the Fifth Generation (5G) brought the digitization of the industry and the development of the Internet of Things, connecting equipment and upgrading algorithm intelligence. It is a faster, safer network that enables the communication between billions of connected devices, with the right trade-offs between speed, latency, and cost (THALES, 2022).

Up to 100 times faster than 4G, 5G is creating never-before-seen opportunities for people and businesses. It is really about connecting technology everywhere – reliably, without lag – so people can measure, understand and manage things in real-time (ERICSSON, 2020b). The knowledge about the possibilities and requirements of using 5G for wireless networking, which is gained in production, offers enormous potential to transfer to other sectors.

1.2 The Mining and Construction Sectors

Remote-controlled construction machines are increasingly being used in the construction and mining sectors, and they require reliable communication via mobile devices. Especially in these sectors, which have high numbers of industrial accidents, a functioning, and fast network is of utmost importance. The use of 5G offers new possibilities in the creation of safety concepts based on continuous real-time localization of all people and machines on the construction site or in the mine. Therefore, workplace accidents can significantly be reduced and machines be more reliably operated (IPT, 2022).

The Networked, Adaptive Mining and Construction (NAMICO) Project, funded by the State of North Rhine-Westphalia through the Ministry of Economic Affairs, Innovation, Digitization, and Energy, comes with the responsibility to develop, examine, and validate a 5G connection on a reference construction site and in an underground mine.

For that matter, at the beginning of the project, requirements for the underground and the construction site 5G networks are specified. Based on the gained results, the next step deals with its technical design. This design interconnects the identification of the entire required infrastructure and architecture as well as the essential technologies for the realization of the 5G networks, like transmitting and receiving components. In the following stages, there are the installation and testing of the planned system and optimization of its parameters to implement the previously derived requirements. Validation of the functionality takes place in the last step of the project by transferring the designed and installed 5G networks to application-specific use cases on the construction site and in the mine (RWTH, 2022).

2 Definition of the Study Problem

The networking of production using 5G has been examined in an application-oriented manner since around 2017 and is already delivering concrete progress and adding value on the way to leaner and more efficient production through networked and adaptive process chains (IEEE, 2020).

Automation on construction sites offers faster and more economical construction processes, also providing efficiency in a dangerous work area, and diminishing the high number of accidents at work. For the automation of construction processes with robot systems, all objects that are part of a construction process must be detected and analyzed. A dynamic environment such as a construction site, with many unknown objects - construction waste, tools, construction machinery, and people - poses a particular challenge for automation. In this context, a 5G network on the construction site can be used for real-time detection of its current state and real-time communication between humans and devices. Thus, machines can react more adaptively to dynamic processes and possible emergencies on the construction site, laying the foundation for the safe use of autonomous construction machines.

The automation of the mining industry faces similar challenges as automation on the construction site. Besides the opportunity to increase the safety of the people involved, this kind of automation also outlines production efficiency, cost-saving, productivity, and energy-efficiency benefits that private-network 5G-ready connectivity can deliver across different use cases (ERICSSON, 2020a).

2.1 General Objectives

In the NAMICO project, a 5G system is to be installed on a reference construction site and in an underground mine in order to make use of the advantages offered by 5G technology. From that, the network will be studied with the purpose of understanding how 5G behaves under these different circumstances. The investigations into the technical implementation promise an enormous gain in knowledge as well as the development and expansion of competence in dealing with 5G technology, thus favoring its further development and its successors.

In the second stage of the project, which is where this thesis will rely on the most, the validation of the designed and implemented 5G networks is to be performed. It is important to state that validation is carried out to get a pre-impression of if the network performance meets the requirements of the planned applied use cases, each of which includes the implementation of a security concept based on real-time communication and position detection using 5G. These use cases will be explained in the next chapters.

2.2 Specific Objectives

In order to achieve the general objective, the work will be divided into steps.

1. Conduct a bibliographic review of existing works on the subject, in order to filter what can be useful and can be applied.
2. Create and plan a setup for 5G applications in the Construction and Mining sections.
3. Validate the work and data extracted in different scenarios and analyze their results.
4. Write a detailed description of the Use Cases and Network Setup.
5. Set up a test plan to assess the 5G network performance and suitability, including measurement methods description.
6. Manage the measurements, validation, and assessment.

3 Bibliographic Review

3.1 Contextualization

In Mendoza et al. (2021), different use cases are explored for the purpose of understanding aspects related to the construction process that may benefit from the use of 5G. Likewise, reference Ericsson (2020a) does the same for the Mining area. To summarize the main points and provide a wide comprehension of the work to be done, the next sections and subsections will be organized in a way to expose them one by one. Before that, however, it is essential that some basic features are introduced to ensure the comprehension of all concepts.

3.1.1 5G characteristics and features

The 5G network architecture has been designed with three key service areas in mind: Ultra-Reliable Low Latency Communications, Enhanced Mobile Broadband, and Massive Machine Type Communications. To enable each area to operate separately within the 5G ecosystem, some other features are necessary, such as Network Slicing (ANTENOVA, 2022). In the following sections, various 5G differentials and their benefits will be presented and explained how they are going to be explored in this thesis.

3.1.1.1 Ultra-Reliable Low Latency Communications

The abbreviation *uRLLC* stands for Ultra-Reliable Low Latency Communications (uRLLC). It is one of three currently defined application profiles for 5G mobile networks. The profile is intended for time-critical applications that require minimal latency times - that is how much time it takes for a data packet to travel from one designated point to another - in the range of one millisecond or less and depend on robust, fail-safe communication (LUBER; DONNER, 2019).

Some use cases related to this application are vehicular communications and remote monitoring. Regarding the ones involving the construction and mining industries, uRLLC services can provide the capacity to remotely control drones or manage machinery at worksites (MENDOZA et al., 2021).

3.1.1.2 Enhanced Mobile Broadband

Enhanced Mobile Broadband (eMBB) defines a minimum level of data transfer rate, promising to deliver both vastly increased bandwidth and decreased latency compared to existing 4G services. This technology will enable new applications such as 8K video streaming and truly immersive Augmented Reality (AR) and Virtual Reality (VR) (GIGABYTE, 2020).

A few applications connected to the construction and mining industries that have strict requirements in terms of throughput and will benefit from this category of service are the visualization of Three Dimensional (3D) models that make use of AR and VR services and the monitoring of worksites through the use of high-quality video cameras (MENDOZA et al., 2021).

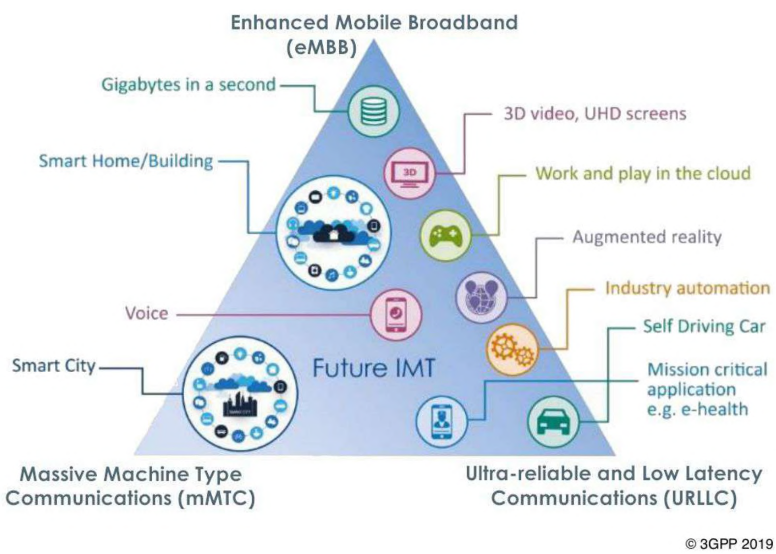
3.1.1.3 Massive Machine Type Communications

Massive Machine Type Communications (mMTC) aims to support a large number, up to 1 million end devices per km², of networked devices from the areas of machine-to-machine communication and the Internet of Things (IoT). An important requirement is high energy efficiency for mobile devices.

The possibility of integrating such a large number into a communication network enables the creation of new network types that can record and take into account all participants in the industrial environment. Hence, the typical application areas are in sensor networks, networked machines, wearables, or autonomous and networked robot technologies (DRAGER, 2021).

In Figure 3, a triangle is represented and several applications can be seen in it. Each application stands closer to the feature - uRLLC, eMBB, or mMTC - that is most important for it to run. This way, it is possible to understand how flexible 5G can be when its characteristics are differently embraced.

Figure 3 – 5G features and its applications.



Reference: Jablonski (2019)

3.1.1.4 Other 5G solutions

Besides the three main services presented in the last subsections which are focusing on the application, 5G also provides important attributes for the management of a network itself.

A relevant concept is Network Slicing. It refers to partitioning a physical network into several virtual networks, each of which can be customized and optimized for a specific type of application or subscriber. By leveraging cloud computing and virtualization technologies, the shared physical network resources can be dynamically and efficiently scheduled to logical network slices based on changing user demands (ZHANG, 2019).

This is important because network operators can now allocate the right amount of required resources per network slice. Therefore, it helps in the effective and efficient utilization of resources. For example, one network slice can be designed to deliver low latency and low data rate while another can be configured to deliver high throughput (RANTCELL, 2022).

Another significant concept is Multi-Connectivity (MC), which refers to the simultaneous use of multiple independent communication paths, nodes, access points, or base stations for data transmission to a User Equipment (UE). The MC architecture is a very promising feature for 5G as it has proved to enable the realization of high reliability, low latency, and high throughput for all the broad classes of 5G use cases. MC also enables Ultra-High Speed and Low Latency Communication (uHSLLC), representing a mix of use cases (BUSARI; MUMTAZ; GONZALEZ, 2020).

Furthermore, Massive Multiple-Input Multiple-Output (MIMO) is an extension of MIMO technology, which involves using hundreds and even thousands of antennas attached to a base station to improve spectral efficiency and throughput. This technology consists of bringing together antennas, radios, and spectrums to enable higher capacity and speed for the incoming 5G (CHATAUT; AKL, 2020).

Finally, there are also Vehicle-to-Everything (V2X) communications. Depending on the type of elements involved in the communication, information can be exchanged between vehicles, Vehicle-to-Vehicle (V2V), Vehicle-to-Pedestrians (V2P), Vehicle-to-Infrastucture (V2I), or Vehicle-to-Network (V2N). V2X communications cover all of those. The benefits of using this functionality comprise avoiding traffic congestion, reducing environmental impacts, and even avoiding accidents. However, the requirements for such communications are very rigorous in terms of latency, reliability, throughput, and accurate location. For the industry, it allows machinery to act autonomously, improving the efficiency of construction processes (MENDOZA et al., 2021).

Table 1 associates different use cases explored in the industry with the solutions explained above. In the following sections, these use cases will be hitched to Construction and Mining, and an overview will be conducted in order to highlight the importance of each one.

Table 1 – 5G solutions applied to industry use cases.

Use Case	**Challenges**	**5G Solutions**
Autonomous machinery	Low latency (1-10 ms) High reliability ($<10^{-6}$) High bandwidth (>10 Mbps) High availability of services (>99.9999 %)	URLLC eMBB Multiconnectivity Network slicing V2X communications
Health and safety at worksites	Low latency (5–10 ms) Large number of devices	URLLC mMTC Network slicing
Real-time condition monitoring	Low latency (<10 ms) Large number of devices High bandwidth (25 Mbps)	mMTC eMBB Network slicing Multiconnectivity

Reference: adapted from Mendoza et al. (2021)

3.2 Use Cases

Now that the most relevant concepts have been exposed, it is possible to describe the Construction and Mining use cases based on Mendoza et al. (2021) and Ericsson (2020a). These use cases will form a substantial basis for the objectives of the 5G NAMICO project.

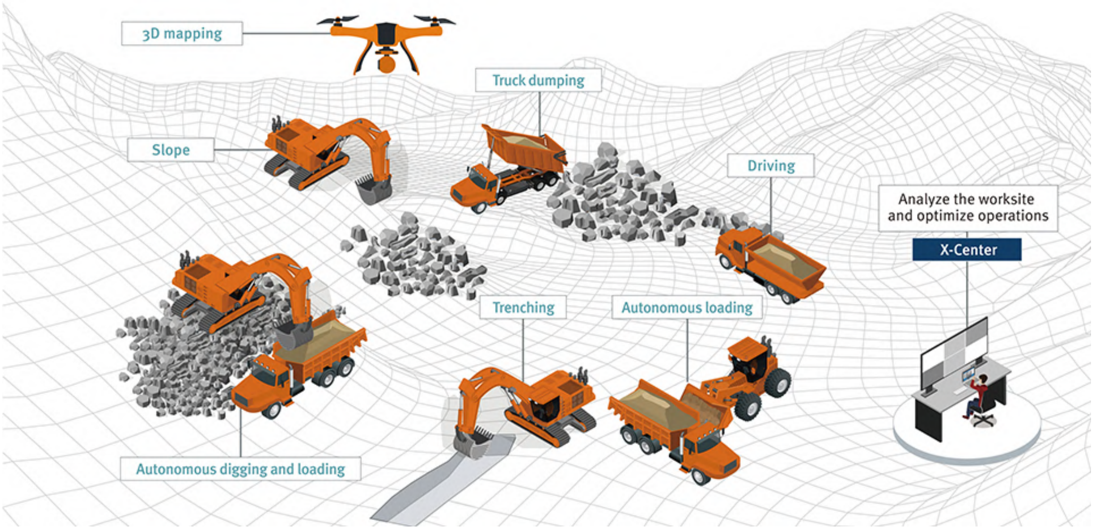
It is important to emphasize that all of them are connected at a certain level, and the discrimination of the use cases is based mainly on the goal that the process is displaying.

3.2.1 Autonomous machinery

With the help of different kinds of sensors, it is possible to collect information from an environment, such as video images and physical parameters, that can influence the decision-making process of a worksite. For autonomous machinery, there is usually a machine or a control center to manage the whole process. In the case of remotely controlled machinery, that decision is normally made by an operator.

The importance of this type of application is that autonomous vehicles can significantly improve efficiency and safety for construction and mining by allowing these operators to control machines from safe positions, as seen in Figure 4. Considering the harsh scenarios that workers are exposed to, this kind of digitization can provide safety benefits as well as a clear, positive bottom-line impact. The use of autonomous machinery avoids possible human errors and contributes towards achieving higher productivity and sustainability through energy savings and work efficiency, facilitating the coordination of all different processes.

Figure 4 – Worksite equipped with 5G technology.



Reference: Doosan (2022)

3.2.2 Health and safety at worksites

Besides having sensors to act on the day-to-day work, it is also important to have other sensors specifically to control the continuity of the tasks and the quality of the equipment.

According to an Analysis of Equipment-related Fatal Accidents in U.S. Mining Operations: 1995–2005, up to 90% of fatal mining accidents are related to equipment, at the same time that maintenance is responsible for 41% of a mine's equipment costs. On the other hand, studies say that 70% of machine-specific malfunctions could be prevented by collecting and analyzing the machine's data (ERICSSON, 2020a). A similar scenario is seen in construction sites.

5G can fill this gap. This use case operates on the idea that a digital twin map of the construction site can be generated in real-time. The map would identify high-risk areas, and the positioning of workers and machinery within the worksite aiming to monitor them and send real-time notifications. By doing that, it is possible to prevent many accidents and deaths by reducing the number of falls and the probability of being struck by machinery or other objects. As a bonus, according to Modular Mining's Maintenance Management Webinar, unplanned maintenance can be reduced by 25% (ERICSSON, 2020a).

3.2.3 Real-time condition monitoring

With the same structure as in subsection 3.2.2, now real-time condition monitoring has the objective to use real-time sensors to organize tasks and improve the efficiency and the effectiveness of processes that have an impact on the final result of the work, such as concrete setting or welding execution.

Using this kind of information, remote monitoring of progress will become possible, and more informed decision-making would facilitate time and cost reduction. Consequently, that would provide greater control over existing resources and work status, leading to an increase in productivity and in the quality of the final result, and avoiding the appearance of problems in the short and long term. This type of automation could bring actual benefits to the optimization of the supply chain.

In addition to sensors, real-time monitoring can also count on drones to monitor, inspect, and produce map settings that are potentially dangerous for workers to do, achieving results in a much faster and safer manner. Besides, thanks to the more accurate models, drones are capable of delivering, operators are able to make more accurate and cost-efficient plans that need less backfill material. All of these resources could bring a great impact on the work budget.

4 Measurements

For the application of the use case basis that has been created in this document, different parameters will be measured in the Construction Site and in the Mining. The schedule for the installation of the 5G system in the Mining is outside of this work's time frame so, because of that, the next sections will be separated into Wi-Fi and 5G measurements.

Although these are different kinds of networks in different environments, it will be interesting to analyze how data behaves according to each scenario. It will also be possible to compare the results with the expected values established in the use cases, and from that, speculate about the viability of the system and the success of the implementation.

It is important to state that the databases used in the analysis were extracted from the networks via Shell scripts or bash commands, and through different kinds of equipment, such as the ones from Rohde and Schwartz (R&S) and from Milesight. The comparisons and graphics, on the other hand, were developed with the help of the software SmartAnalytics from Rohde & Schwarz, Microsoft Excel, and the programming language Python. The respective codes for each section will be addressed accordingly in the Appendix A chapter. All of the equipment and the software necessary for this thesis were provided by the Fraunhofer-Institut für Produktionstechnologie (IPT).

The 5G parameters for the NAMICO project were defined and detailed for each use case device and can be seen in Table 2, where DL stands for Download, and UL for Upload. With the Wi-Fi results, it will be possible to compare their proximity to the expectation, as well as to draw conclusions about the success of the implementation. On the other hand, with the 5G results, it will be possible to actually analyze the performance of the network and compare it to the previous presumptions.

It is important to state that, despite the different latency or data rate requirements for the devices, if the minimum requirement is fulfilled, 5G can manage to provide unique measurements for each situation. This happens thanks to the network slicing solution, which allows the network to behave by adopting individual parameters according to each use case necessity.

In the next topics, the scenarios for the reality of 5G in the mine and in the construction site will be described, followed by the presentation and detailing of the test methodologies and obtained results.

Table 2 – Expected Latency and Data Rate Requirements.

Device	**Latency Requirement**	**Expected Data Rate**
Remote Monitoring	< 10 ms	DL ≥ 1 Mbps UL ≥ 1 Mbps
Remote Control	< 10 ms	DL ≥ 1 Mbps UL ≥ 1 Mbps
2D-LIDAR	< 20 ms	DL ≥ 1 Mbps UL ≥ 1 Mbps
3D-LIDAR	< 50 ms	DL ≥ 1 Mbps UL ≥ 300 Mbps (Ouster) UL ≥ 500 Mbps (Leica)
Radar	200 ms	DL ≥ 1 Mbps UL ≥ 100 Mbps
Cameras	< 10 ms	DL ≥ 1 Mbps UL: $8 - 48$ Mbps
Voice over IP	20 ms – 100 ms	DL: $5 - 25$ Mbps UL: $5 - 25$ Mbps

Reference: MRE (2022)

4.1 Underground Mining – Wi-Fi

4.1.1 Scenario description

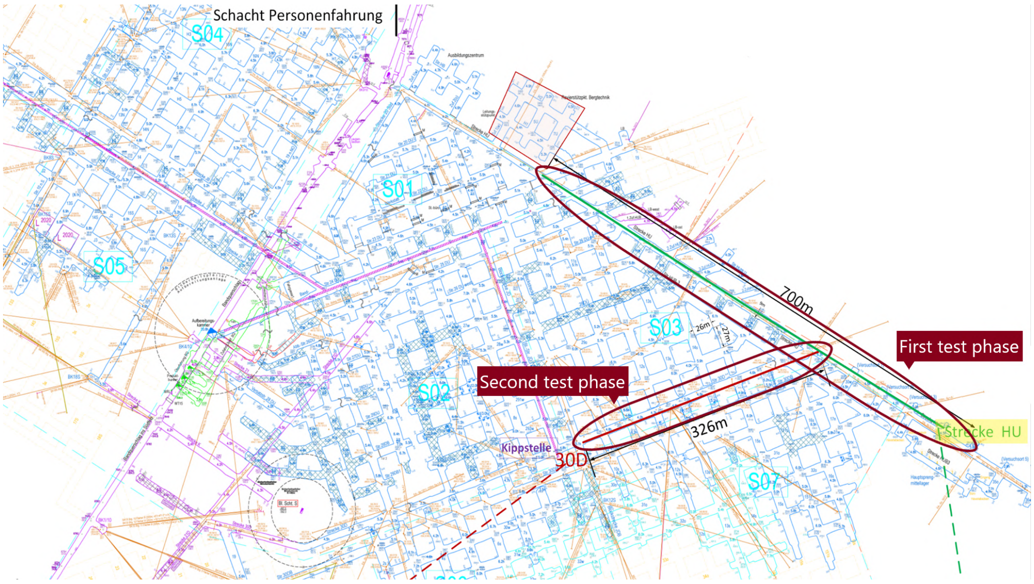
This subsection is based on the internal document IPT (2021a).

All the measurements were performed along with Johannes Emontsbotz, M.Sc. from the Mineral Resources Engineering (MRE), and Sarah Schmitt, M.Sc. from the Fraunhofer IPT.

The overall goal of the mining use case is to develop a 5G communication network for the adverse and dynamic requirements of underground mining, to install it in the *Erlebnisbergwerk Sondershausen* mine, and finally to validate the parameters based on performance measurements and the implementation of the defined use cases. For that, the project is divided into two test phases: the first one is focused on the range of the antennas, while the second one aims for the comparison between beam cables and antennas, and the implementation of use cases. The map for the mine and each test phase's location can be seen in Figure 5. In this paper, the studies will be concentrated on the first test phase because of the time frame, as commented before.

In the active context of an underground mine, three scenarios can be predicted. The first one is where nothing is on the way and there is only an empty track. This is a more ideal scenario for communication, but it is rarely seen on the day to day basis. The second scenario is where there is a static obstacle on the path, whereas the last one is where there are dynamic obstacles, just like a functioning work environment.

Figure 5 – Erlebnisbergwerk Sondershausen mine map and indication of each test phase's location.



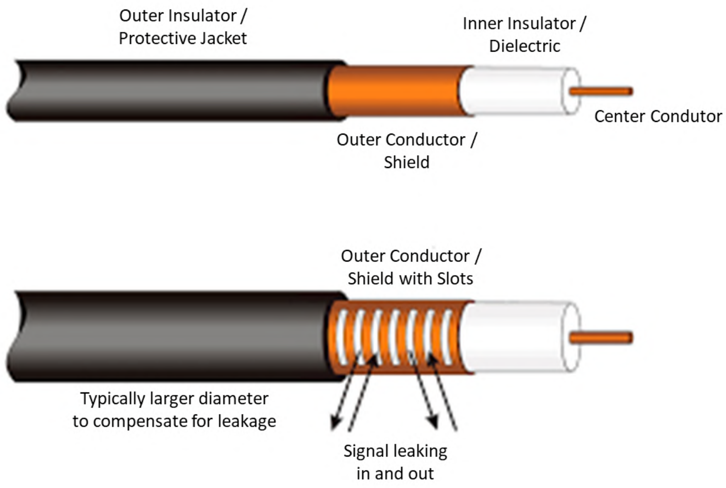
Reference: IPT (2021a) confidential.

The most important objective for the application of 5G in the Underground Mine is understanding what kind of infrastructure is required for a good quality network. This is because, in order to fully leverage the advantages that 5G can provide in such a workspace, it is fundamental to have a well-established system that can support its necessities. To get to this stage, each scenario described must be carefully explored and evaluated, taking into consideration factors such as the size and layout of the mine, the presence of challenges that could impact signal propagation, the desired coverage area, and the potential use cases for 5G technology within the operations.

To ensure the quality of this infrastructure, the mine operators need to be aware of the unique demands of the local settings and make well-thought decisions regarding the placement of base stations, antennas, and the different network components. First of all, in the *Erlebnisbergwerk Sondershausen* mine, the plan is to have a type of cable, called a Leaky Feeder cable, that can prevent the quality of the signal from dropping and maintain a good propagation. It is shown in Figure 6.

The way these cables work is similar to an antenna: with slots and gaps along their length, Leaky Feeders allow the signal to escape and radiate into the surroundings. But unlike traditional antennas, one advantage of the Leaky Feeder is that, since it is a cable, it can be distributed throughout an area, granting coverage along its entire extension. It is designed for reliable and continuous communication coverage in challenging underground settings, but it is not available at the location yet, and neither is 5G. For now, the mine only operates with regular antennas and Wi-Fi.

Figure 6 – Leaky feeder cable.



Reference: BEDFORD, M. D. et al. (2020).

In the next sections, it will be possible to understand how the Wi-Fi tests were prepared and performed. In this context, the results will be presented, revealing different parameters, such as coverage, latency, throughput, and signal quality. Furthermore, it will be described what can be expected with 5G, and how could it impact the overall mining system.

4.1.2 Methodology

4.1.2.1 Preparation

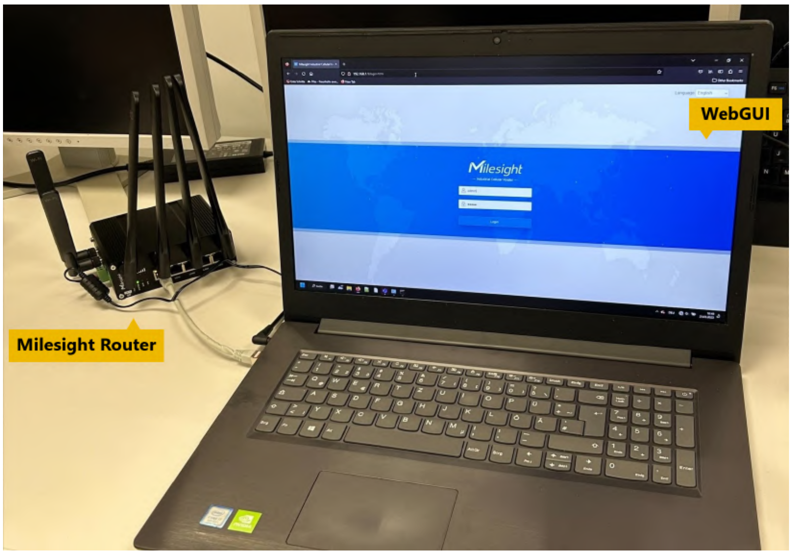
To perform the tests in the Underground Mine, a visit was scheduled for March 28, 2023.

In order to prepare for it, the Fraunhofer IPT's Wi-Fi was used to test the Milesight Industrial Router UR75 as a Wi-Fi-capable device. Therefore, the router was powered and connected to a laptop using an Ethernet cable. That done, it was necessary to adjust the Internet Protocol Version 4(TCP/IPv4) and the IP address configurations aiming to access Milesight's Graphical User Interface (GUI). Inserting the 192.168.1.1 IP in the browser, used as default, it was possible to access the desired page, as seen in Figure 7.

After the adjustments from the equipment side were done, and the Wi-Fi connection was successful, latency tests were performed in order to have a basis for what results to expect. For that, a Packet Inter-Network Groper (Ping) was chosen.

The concept of the ping test is to send small packages of data (pings) from one device to another and measure the time it takes for it to travel back to the original device, resulting in the round-trip time. It requires one computer and an IP to establish

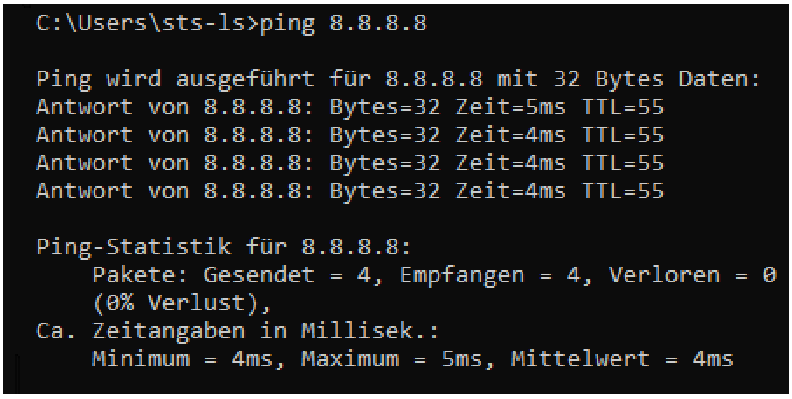
Figure 7 – Tests setup at the Institute.



Authorship: Luiza Souza Simões. Creation date: March 21, 2023.

communication, and it is performed as an example in the command window as illustrated in Figure 8.

Figure 8 – Ping example with Google Public DNS IP address sending 32 Bytes of data.



```
C:\Users\sts-ls>ping 8.8.8.8

Ping wird ausgeführt für 8.8.8.8 mit 32 Bytes Daten:
Antwort von 8.8.8.8: Bytes=32 Zeit=5ms TTL=55
Antwort von 8.8.8.8: Bytes=32 Zeit=4ms TTL=55
Antwort von 8.8.8.8: Bytes=32 Zeit=4ms TTL=55
Antwort von 8.8.8.8: Bytes=32 Zeit=4ms TTL=55

Ping-Statistik für 8.8.8.8:
    Pakete: Gesendet = 4, Empfangen = 4, Verloren = 0
    (0% Verlust),
Ca. Zeitangaben in Millisek.:
    Minimum = 4ms, Maximum = 5ms, Mittelwert = 4ms
```

Authorship: Luiza Souza Simões. Creation date: April 13, 2023.

There were two different Wi-Fi networks available with the two main frequency bands (2.4 GHz and 5 GHz). After achieving the results from the ping test and sending them to a text file, they were plotted in Figures 9 and 10 using a software developed in Python. Its script is presented in Appendix A.2.

This software was called Quick 5G Analyser (Q5GA) and was developed based on different Python libraries. For the data analysis, *Pandas* was chosen, whereas for the data plotting and visualization libraries, *Matplotlib* was used. The Graphical User Interface was completely based on the *PyQT5* library and its features to create a user-friendly interface and manage the functioning of the front end.

Figure 9 – Result graphics from the Ping test with 2.4GHz Wi-Fi.

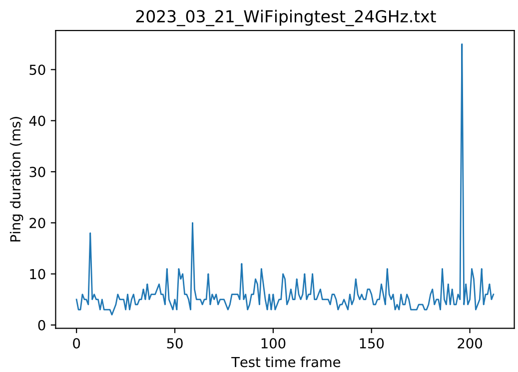
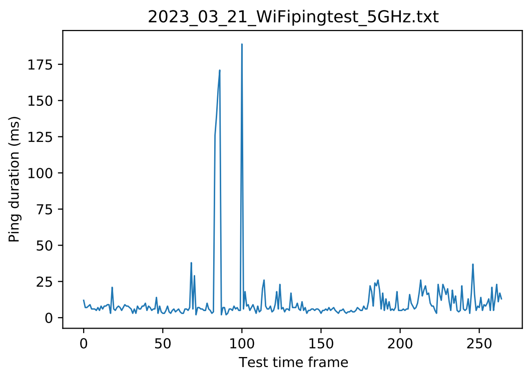


Figure 10 – Result graphics from the Ping test with 5GHz Wi-Fi.



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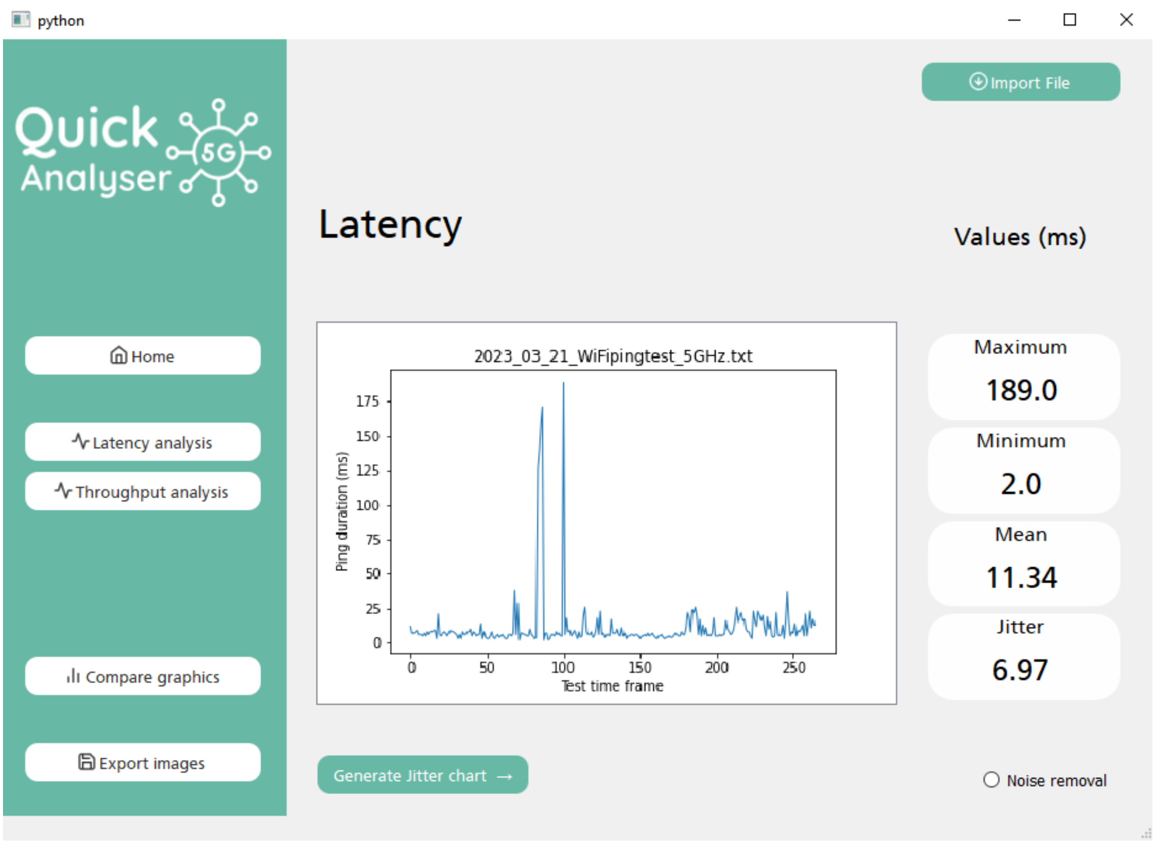
The principle of Q5GA is to get the text files extracted from performance tests and analyze them automatically, without requiring manual data analysis via Excel or coding. With its help, it was possible to rapidly get network parameters and plotting results. Figure 11 displays the interface of the software.

Figure 11 – Q5GA's interface showing the data analysis of a ping test.



Authorship: Luiza Souza Simões. Creation date: April 17, 2023

The maximum, minimum, mean, and jitter values from the tests can be seen in Table 3. The jitter refers to the variation in the time delay of a signal or data packet as it travels through a communication system. It is a measure of the deviation in the arrival time of each successive packet from the expected time of arrival. It can be calculated using the equation (4.1).

Table 3 – Main performance values extracted from the preparation Wi-Fi tests.

	2.4 GHz Wi-Fi	**5 GHz Wi-Fi**
Maximum	55 ms	189 ms
Minimum	2 ms	2 ms
Mean	5,75 ms	11,34 ms
Jitter	2,54 ms	6,97 ms

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$$Jitter = \frac{\sum_{i=1}^{n} |T_i - T_{i-1}|}{n} \tag{4.1}$$

In 4.1, T_i represents the time of arrival of the $i-th$ packet and n is the total number of packets. It calculates the absolute difference between the time of arrival (latency) of the current packet and the one from the previous packet. The summation of all differences is divided by the total number of packets to achieve the average jitter. The resulting value is a measure of the deviation and can be used to identify and diagnose issues in communication systems because excessive jitter might result in a degradation of the quality of the connection.

Regarding the results thus obtained, both networks provided excellent Wi-Fi behavior, with means below 20 ms. Usually, the 5 GHz frequency band delivers faster speeds and less interference than the 2.4 GHz band, but that was not the case. The 5 GHz Wi-Fi presented more interference and instability, which was reflected in the jitter values. This observation was probably due to the configuration or the device's own internal support system.

Moreover, spikes can be seen in both Figures 9 and 10 and they might mean temporary network congestion, background processes on the device, internal updates, or even other kinds of factors. Considering the spikes are infrequent and brief, they probably do not severely impact the overall experience. If however this became constant, it would be interesting to investigate their cause aiming to optimize the network.

At the mine, there will also be a throughput test in order to measure the maximum achievable bandwidth between two devices on the network. This test has already been performed with different devices, the codes have been prepared and their functionality has been proven. It is useful to diagnose connectivity problems, test the quality of a link, and evaluate the performance of network infrastructures such as routers, switches, and servers. It requires the Twamp Client and Responder protocol and an open-source GUI which can be acquired online (DEMIRTEN, 2022). On top of that, the WiFi Analyzer app from Microsoft will also be utilized to measure the strength of the signal quality.

4.1.2.2 Onsite

After the preparation, everything was packed and taken to Sondershausen, where the Erlebnisbergwerk mine was located. The mine is approximately 685 meters below the surface, and it produces rock salt, used for a variety of purposes. Accessing it required safety instructions as well as the use of Personal Protective Equipment (PPE), including hard hats, goggles, shoes, and high-visibility clothing. This can be seen in Figure 12.

Figure 12 – Worker in personal protective equipment adhering to safety protocols.

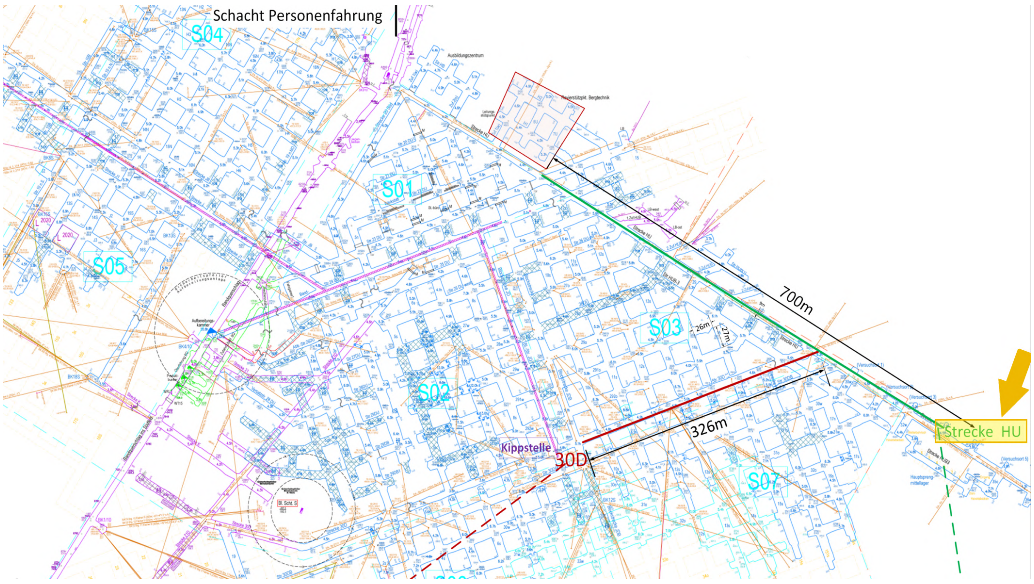
Authorship: Luiza Souza Simões. Creation date: March 28, 2023.

Subsequently, it was possible to get down and start the measurements. The Wi-Fi network was installed at the end of one of the tunnels, specifically near the bottom right corner of the map, where the "Strecke HU"is marked and flagged in Figure 13.

Once the connection was established by following the same procedure as in subsection 4.1.2.1, the test station was prepared and started. Besides the Milesight router used in the preparation, another one was also taken to the site, the BrosTrend AX1800, aiming to achieve different and more reliable results. This router is specifically used for Wi-Fi measurements and can be seen in Figure 14.

The difference between these routers is that the Milesight is an industrial router while the BrosTrend is a consumer-grade router. This reflects directly on the performance,

Figure 13 – Underground Sondershausen Mine map.



Reference: IPT (2021a).

Figure 14 – BrosTrend AX1800 Router.

Reference: Amazon (2022).

given that industrial routers are designed to be used in harsh settings, making them able to withstand challenging conditions and provide reliable and uninterrupted connectivity, whereas the BrosTrend AX1800 is designed for a typical home or small office usage scenario. Additionally, industrial routers typically have higher throughput, faster processing speeds, and more robust hardware components than consumer-grade routers. This will be proven in the results.

The tests were then conducted in the following manner: considering that the tunnel to be analyzed was approximately 700 meters long, and there was no equipment to measure the network continuously, tests were run every hundred meters to check connectivity, and latency. In each spot, nine measurements were taken with the BrosTrend AX1800 and they were divided into areas from one side of the tunnel to the other, as displayed in Figure 15. Areas 1 to 3 were three meters high, 4 to 6 were two meters high, and 7 to 9 were one meter high. The router was attached to a long metal stick so it could reach the ideal height. The setup is shown in Figure 16 along with the measurement group performing the tests.

Figure 15 – Underground Mine tunnel represented as areas.

Figure 16 – Measurement group performing the test.

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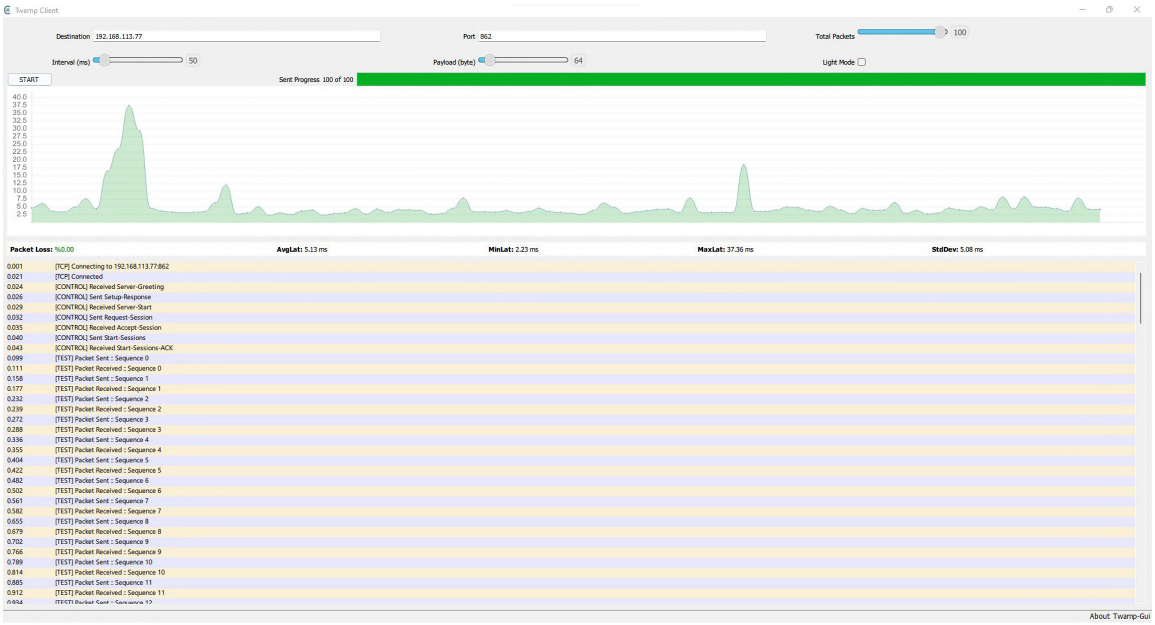
With the Milesight router, only three measurements were taken (in areas 7 to 9) since it was a heavier kind of equipment and could not be brought up and down.

4.1.3 Obtained results

After finishing the measurement phase, the test results were available for analysis. With the Milesight industrial device, the data was stored in different screenshots that displayed a chart and the main parameters needed. Figure 17 shows an example. The Twamp Client application required the destination IP, port, number of packets, payload, and interval. They were specified according to the necessity.

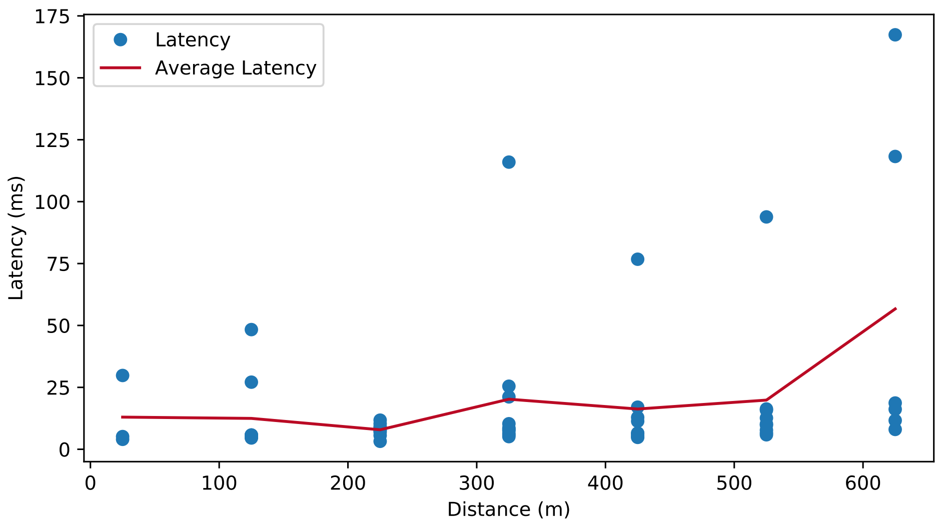
Fifty-eight tests have been performed and all of their results were saved in an Excel sheet. Overall, the results corresponded to the expectations. Figure 18 displays all of the measured points along with a line representing the mean values between them. The codes used to plot the graphics from this section are available at A.3.

Figure 17 – Screenshot of the Twamp Client application Underground tests.



Authorship: Luiza Souza Simões. Creation date: March 28, 2023

Figure 18 – Latency measurements and average line graphic for the Milesight device.



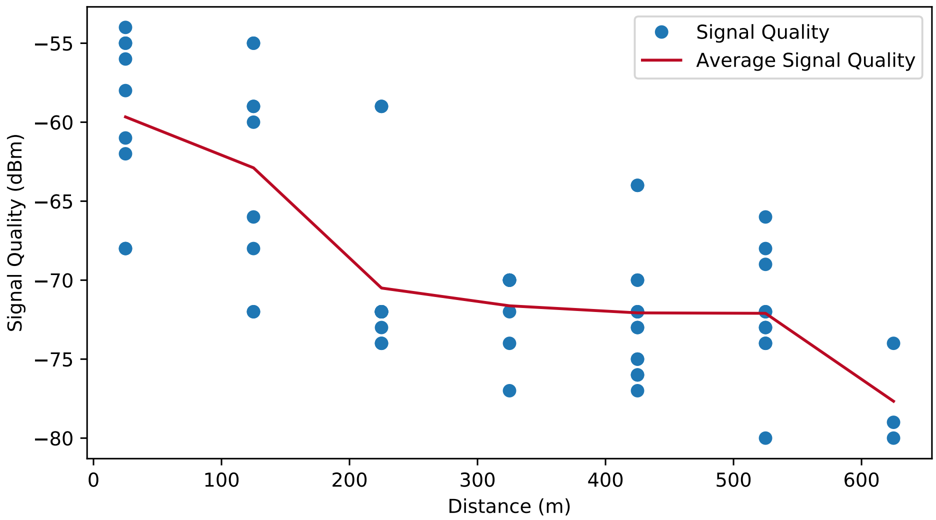
Authorship: Luiza Souza Simões. Creation date: May 17, 2023

Notably, the latency started with satisfactory values, coming from an average of 12,98 ms and even reaching 7,88 ms. However, as the tests moved further away from the router and the distances were longer, the signal dropped and the latency results started to rise. This is the major problem that is expected to be resolved with the implementation of the new Leaky Feeder cables: maintaining a high-quality network throughout the entire tunnel.

With the BrosTrend devices, the results were written in a notebook and then imported into Excel. For this one, there were 69 measurement tests, and the outcomes were more detailed since they covered a larger area of the mine.

With this device, it was actually possible to get signal quality data and plot it, as illustrated in Figure 19. One can note that the quality deteriorated the further the tests were from the central Wi-Fi router. It started with an average of -59,67 dBm - which is considered good and reliable - until it got to -77,67 dBm, close to an unstable connection network parameter (NEWTH, 2021). Again, this is something to be improved with the usage of the Leaky Feeder cables and 5G.

Figure 19 – Signal quality measurements and average line graphic for the BrosTrend device.



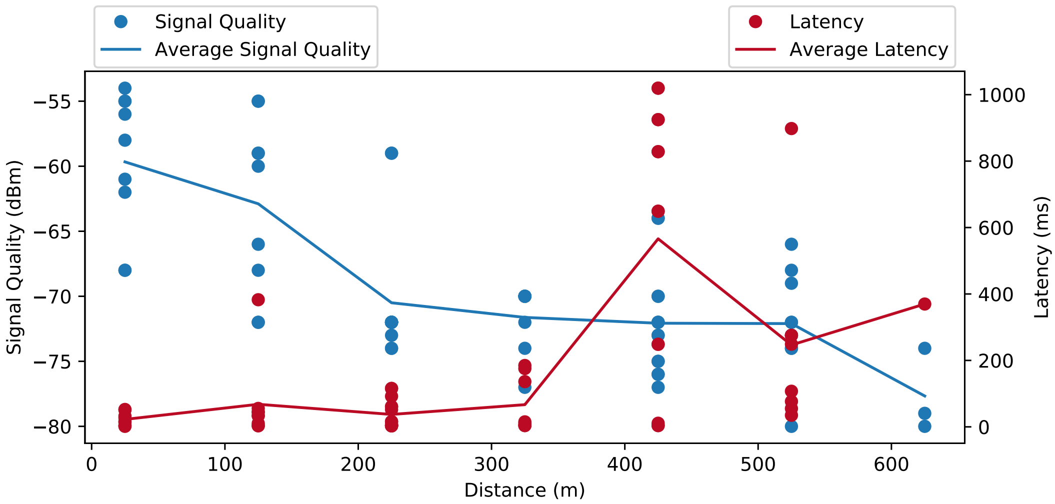
Authorship: Luiza Souza Simões. Creation date: May 17, 2023

Along with that, the BrosTrend latency showed similar results when compared to the Milesight, rising to higher values when distant from the router. This behavior is a clear reflex of the signal quality since these two parameters vary in different senses: the lower the signal quality the higher the latency. At the lowest point, latency time is approximately 22,44 ms - higher than the results obtained from the Milesight device because, as explained before, the BrosTrend is a consumer-grade router, while the Milesight is an industrial router.

This effect is also seen in throughput, which varies in the same sense as signal quality. In this case, the lower the signal quality, the lower the throughput. Figures 20 and 21 illustrate these affirmations, respectively. Throughput is highest at the beginning, with 21,52 Mbits/s, and decreases until it is insignificant.

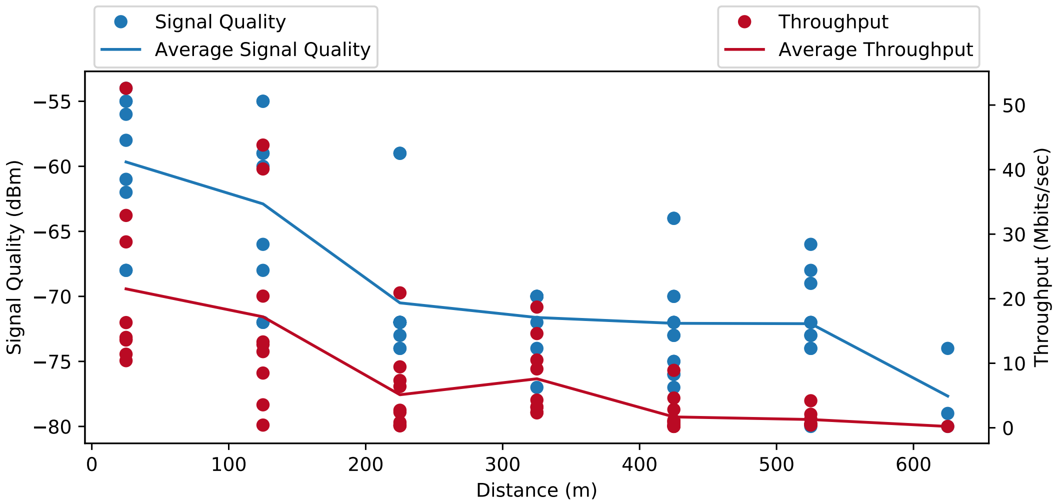
Although the charts do not present themselves as perfectly linear, that was an expected response, as variables do not behave exactly as theory suggests. It is necessary

Figure 20 – Signal quality and latency measurements along with their average line graphics for the BrosTrend device.



Authorship: Luiza Souza Simões. Creation date: May 22, 2023

Figure 21 – Signal quality and throughput measurements along with their average line graphics for the BrosTrend device.

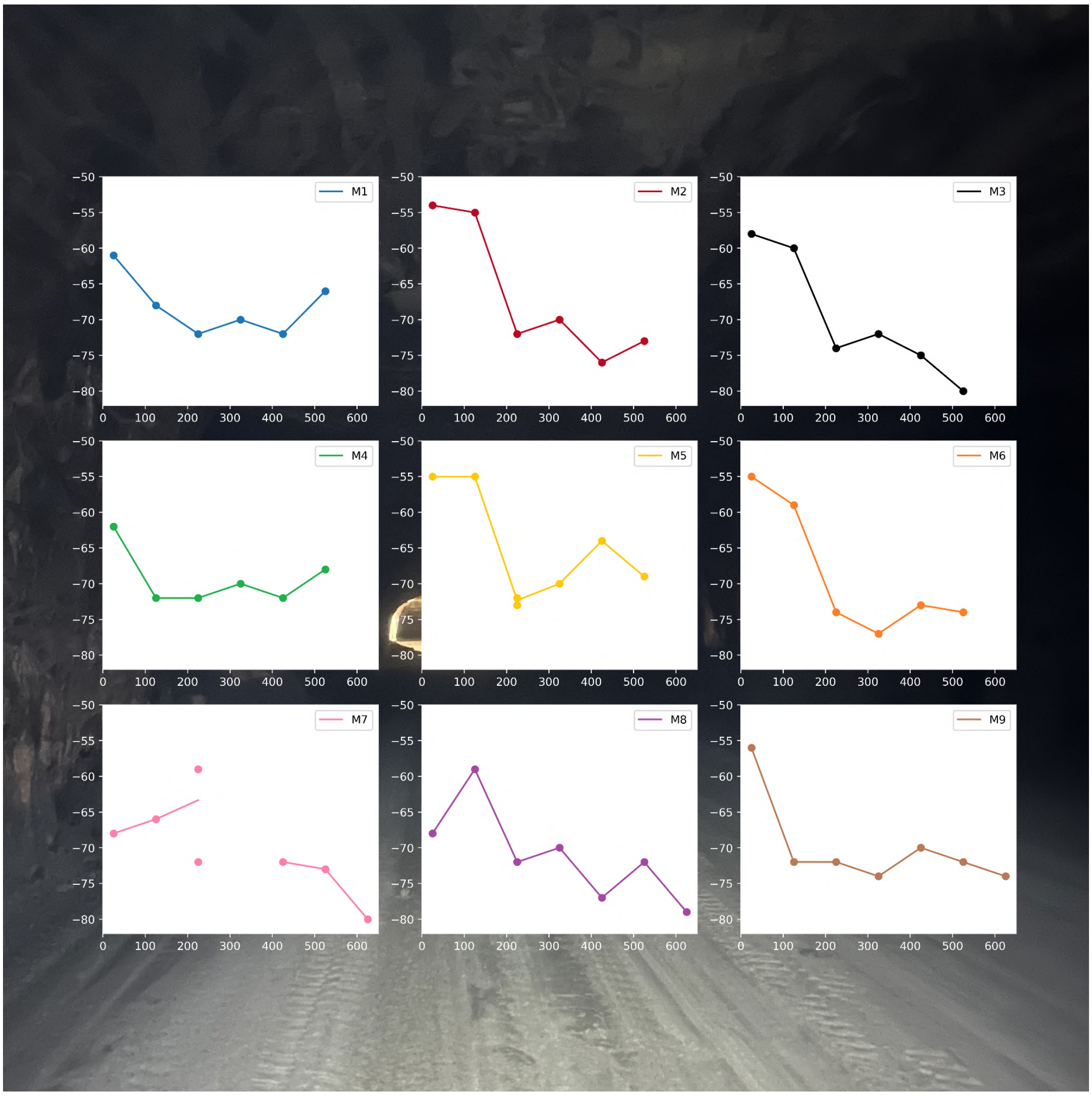


Authorship: Luiza Souza Simões. Creation date: May 22, 2023

to take several properties into consideration to determine the performance of a signal. The peak in the latency chart (x = 425m) from Figure 20, for example, was due to a physical barrier that obstruct the path during the time of the test. In the overall scenario, nevertheless, the graphics outputs show a coherent pattern.

Furthermore, one must be aware of the measuring zones, depicted in Figure 15. Since the measurements were sectioned, it is feasible to evaluate how the signal operates in each area. This is relevant because this kind of understanding could help determine where to locate future routers, antennas, or even the Leaky Feeder cables. Figure 22 presents the charts for signal quality in each section discussed.

Figure 22 – Signal quality performance in the Underground Mine tunnel represented areas.



Authorship: Luiza Souza Simões. Creation date: May 22, 2023

It is important to state that the y-axis in each graph represents the signal quality in dBm, and the x-axis represents the distance from the test location to the router in meters. Empty spaces indicate that measurements could not be taken in that specific location.

By analyzing these results, it is notable that the M1 and M4 sections were the ones less affected by the distance and were able to maintain the greatest consistency. On the other hand, in general terms, M5 presented a higher level of quality and is probably the area that offers the best connectivity, based on the mean value it exhibits, -64,83 dBm. The sections on the right are the ones with the worst performance, presenting low values throughout the entire test, except when really close to the router.

The reason why signal quality demonstrates this form of distribution could be associated with several parameters. First, the router was located in an office on the right side, thus perhaps the walls in the mine stood as a barrier for the signal to propagate on this side, giving the left side an angle advantage. Additionally, the geometry of the walls and the roof could also be more favorable to one side than the other, since physical barriers, such as rock formations and soil, can limit the coverage of wireless signals. On top of that, underground mines often contain metallic structures, machinery, and equipment that can cause signal interference. These elements can reflect, scatter, or absorb the 5G signals, leading to signal degradation and reduced network performance.

There are many other points to be examined in order to obtain a full understanding of the system, such as penetration loss, multi-path fading, and even power constraints. However, for that, it would be necessary to perform multiple tests in the mine applying different scenarios to see how the network would behave, including measurements with machinery and people along the tunnel, which will probably be seen on a day-to-day basis.

Anyway, bringing this kind of comprehension to the use cases makes it possible to understand which areas would be the ones with stronger connections and better communication. In that sense, machinery would provide faster and more precise data when their sensors are standing in the M1-M4-M5 region, considering the current network system.

Reviewing the expected requirements exposed in Table 2 and comparing them to the results acquired, it is safe to conclude that the latency parameters would not fulfill the necessity of the Use Cases using this Wi-Fi network at the mine. Although it stood low at the beginning, it was not capable to maintain an average below 10 ms so it would not provide smooth and trustworthy communication with the remote mining, the remote control, and the camera devices. Furthermore, at the spots along the tunnel where the latency was worse, it would be difficult to meet nearly any requisites.

In contrast, most time the data rate would actually be enough to meet the criteria, with the exception of the 3D-LIDAR Ouster and Leica equipment. Since the parameters did not demand such high values, Wi-Fi would provide an acceptable alternative where the network is capable of going. At the end of the tunnel, however, where signal quality is weak, it would also reach critical capacity and fail.

In conclusion, installing the 5G network in the Underground Mine promises to be very advantageous since, when compared to Wi-Fi, it has the capability to provide greater coverage, lower latency, higher data transfer speeds, improved reliability, enhanced security, and many other advantages. All this is due to the combination of technological advancements that assures a more suitable and efficient connectivity solution in such an environment, filling the gap left by the Wi-Fi system.

4.2 Construction Site – 5G

4.2.1 Scenario description

This subsection is based on the internal document IPT (2021b).

The construction industry has always been resistant to change. The reason is that there are several challenges to establishing a stable network connection on construction sites.

First off, all existing resources, such as containers and cranes, are usually dynamic. This makes it difficult to install a larger network and to have full control of what is happening in the process. Furthermore, the buildings undergoing construction and the large quantities of concrete and metal found on construction sites often negatively affect the quality of the signal coverage. Moreover, this poor signal coverage leads to poor communication of sensor data over wireless networks, hence mobile robots are almost rarely used in daily activities on the site.

Currently, 5G enables the digitization of various industrial applications, as it has been developed aiming to meet those industrial requirements. Its service-based architecture offers customization potential once modifications allow users to take a variety of distinct requirements of use cases into consideration, especially regarding URLLC, eMBB, and mMTC.

The 5G NAMICO project aims to trial and validate 5G technological and architectural features in the construction site domain. In this context, a 5G network provides opportunities to set up a robust visual feedback loop of the work environment, including 3D information and additional operator support through an intelligent system based on its time-critical functionalities.

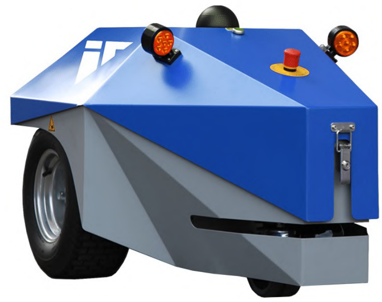
The specific Use Case adapted to this scenario is the Autonomous Machinery, mentioned in 3.2.1. Here, it involves a deconstruction machine, called BROKK, seen in Figure 23, and a mobile robot, INNOK, seen in Figure 24. Both of them are connected to the 5G network through wireless links whereas the control center is going to be connected to the network by a wired link. This does not bring any trouble to the context, because the idea is exactly that the workers do not have to move or endanger themselves to coordinate the construction site. Therefore, a wired connection does not affect the operation.

The task for the INNOK is to approach the BROKK from a safe distance, in a way that the correct perspective for mapping and viewing the operation is provided. INNOK's sensor can then transmit the data via the wireless 5G network to the control center, where the operator will get a visualization of the construction site situation. Once this person understands the environment and decides on the next steps, the necessary remote control movements will be displayed, and the command inputs will be transmitted to the BROKK,

Figure 23 – Deconstruction machine, BROKK.

Reference: Brokk (2022)

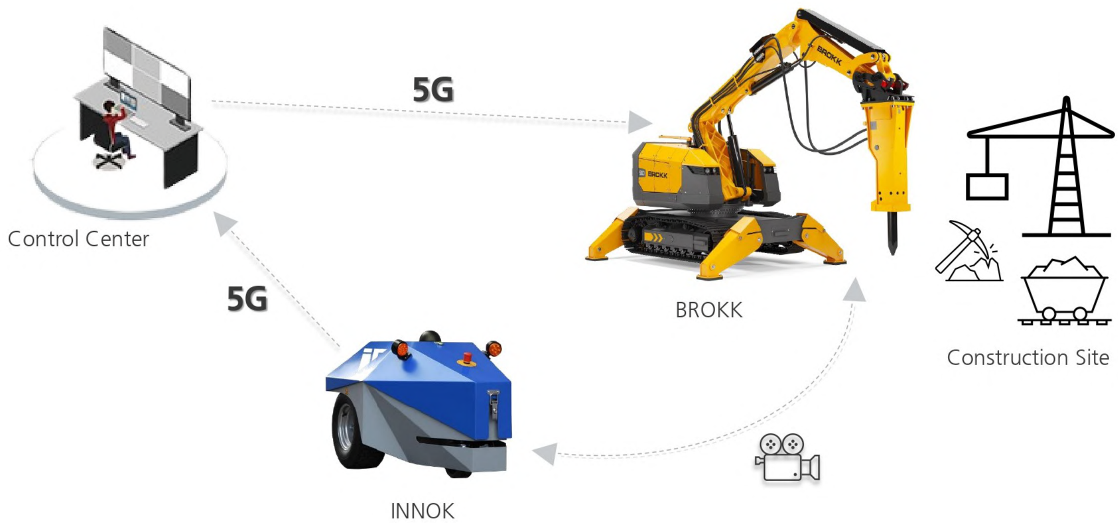
Figure 24 – Mobile robot, INNOK.



Reference: Robotics (2022)

making it move accordingly. Figure 25 shows a simplified summary of what has been described.

Figure 25 – Scheme of how the communication network will function.



Reference: Doosan (2022), Brokk (2022), Robotics (2022), and Microsoft (2023)

Moreover, safety monitoring features can also be added to the system. An example is the one where the operation is interrupted in case there are people or potential obstacles in the safety zone. Thus, the process would only continue after the area is cleared and safety requirements are met again.

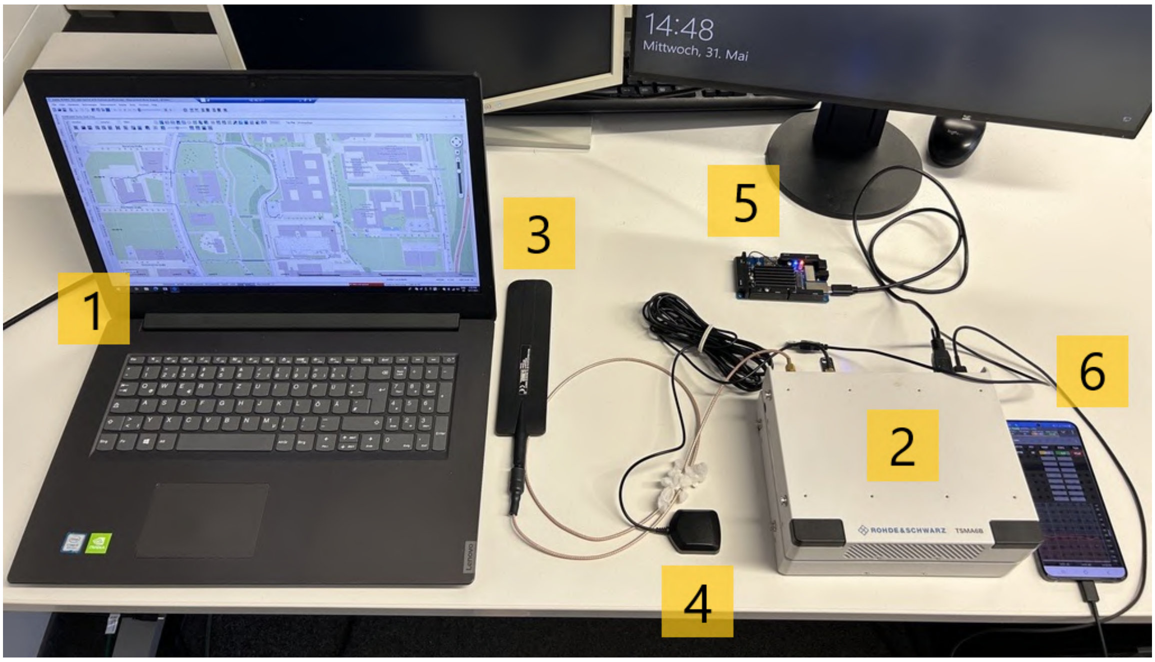
The main objective for this Use Case is to evaluate the benefits of 5G within the scope of a deconstruction process by incorporating emerging technologies such as robotic and computer vision.

4.2.2 Methodology

4.2.2.1 Preparation

For the Construction Site analysis, a different and more sophisticated method of measuring was used. First, since it was an easier area to access and 5G was available for testing, it was possible to connect different devices to the network using Simcards and run the Rohde and Schwartz applications. Figure 26 shows the setup necessary.

Figure 26 – Setup for measurements with the Rohde and Schwartz equipment.



Authorship: Luiza Souza Simões. Creation date: May 31, 2023

Label 1 in Figure 26 indicates the ROMES software running on the laptop. This software provides a unified platform for controlling and automating test equipment and it is designed to improve the efficiency and flexibility of testing processes. Label 2 represents the Scanner, responsible for the licenses, providing access to the ROMES, and enabling the connection between the software and the devices that will facilitate the active and the passive measurements.

Label 3 is the antenna, and it is used for acquiring passive measurements, such as coverage and signal quality. Label 4 is another antenna, but this time for GPS synchronization. It assures an accurate positioning for outdoor measurements, which will be really useful in this case. Labels 5 and 6 stand for the Quectel module and the Samsung smartphone, respectively. Both of them are responsible for active measurements and are capable of performing interactivity tests, which can provide latency and throughput values, for example. They are the devices that are connected to the network via Simcards.

The greatest advantage of using the R&S system is that it can perform a large number of tests simultaneously without the need to stop at each point to do it. This means that, as the user walks along the area to be measured, the system will automatically run the tests and get the desired information along the entire path. Afterwards, the data is made available in a file that can be imported and analyzed by SmartAnalytics - a R&S data analytics software.

To complement these results, the Quectel module was also used separately, in a point-by-point measurement. In that case, similarly to the measuring made in the mine, parameters such as latency and throughput were tested via ping and iperf3 tests. This was the best solution found for avoiding test errors and guaranteeing that the results obtained would be reliable and sufficient for a thorough analysis.

4.2.2.2 Onsite

For the coverage of the construction site, two omni-antennas are planned to be mounted on the crane. They should be connected to IPT's core network in order to extend the 5G outdoor network, enhancing the coverage of the specific area by propagating the signal to the desired spots.

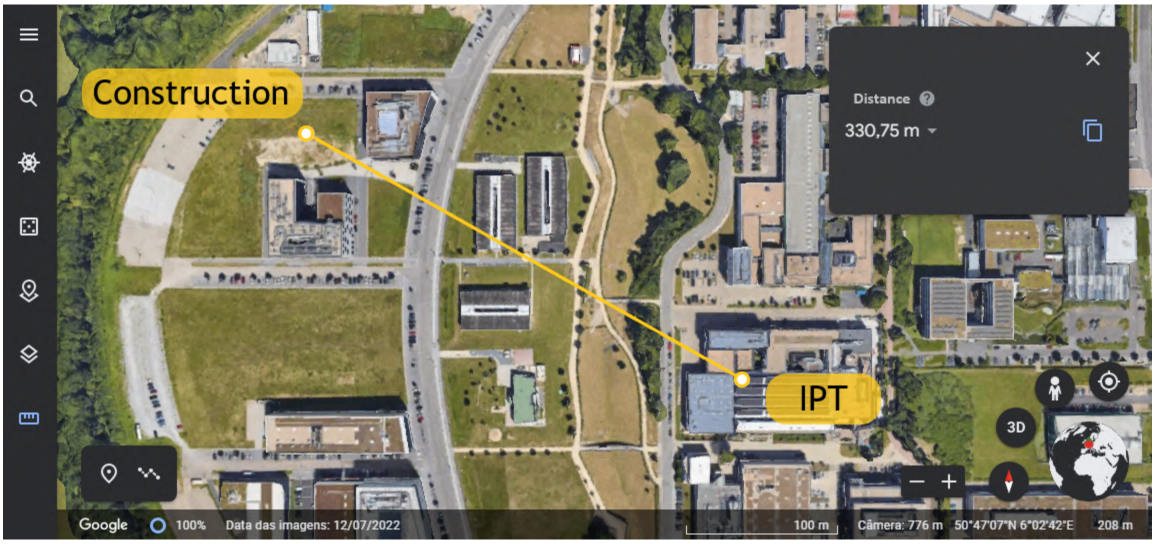
On the visit scheduled for June 2, 2023, however, the installation of the antennas and cables was not finished yet. This setback somewhat compromised the purpose of the tests, but they were anyway performed in the available network with the purpose of making assumptions and predictions for the behavior of the scenario in its finished and ideal state. Under those circumstances, it is expected that the network presents a worst behavior since the signal has to be transmitted from a longer distance.

The map displayed in Figure 27 shows the distance between the institute and the location represented as a straight line, totalizing approximately 330 m. In Figure 28, it is also possible to verify how the antennas and the network coverage around Campus Melaten - the area where the Construction Site is located - are positioned. The covered area is represented in light turquoise, while the antennas are highlighted in dark blue.

Initially, a laptop was connected to the network through a WNC Router to work as a server for the iperf3 tests. That is important because for the Quectel to perform throughput tests, it requires a second connection to allow the exchange of data, device-to-device. For the mine, that was not necessary due to the breakout connection to the server, which provided an IP to act and assist during the measurement. Since this breakout was not available at the site, setting this second 5G device was the solution.

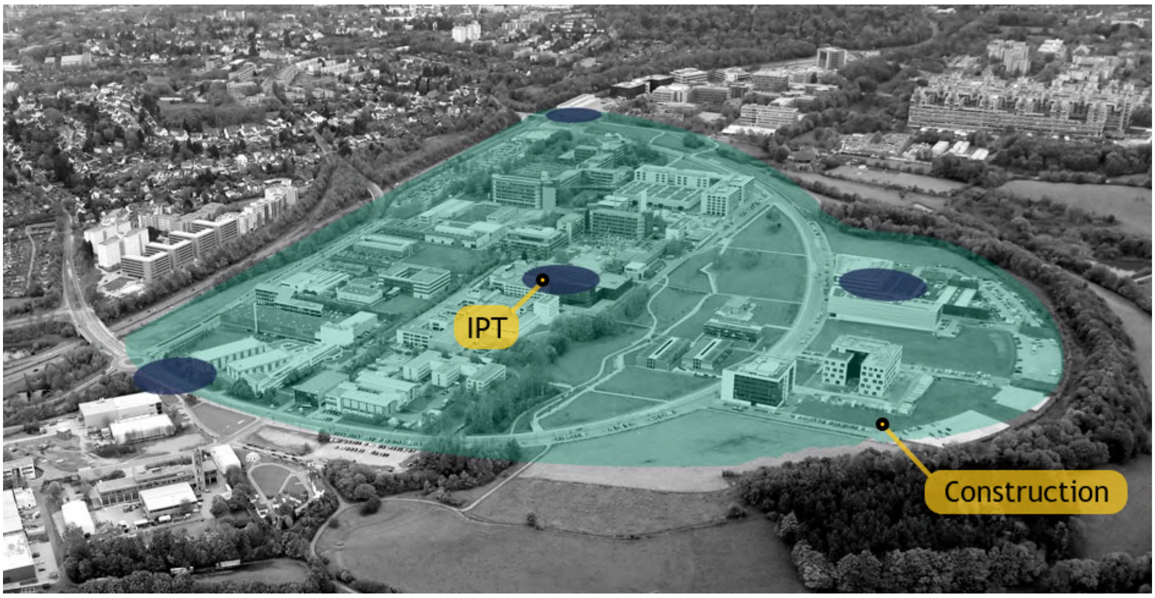
Subsequently, the test points were defined based on the position of the crane and the containers. It was particularly interesting to analyze the surroundings of the crane due to its relevance to the use cases that associate this spot with most of the data transmission

Figure 27 – Google Earth image presenting the location and the distance between Fraunhofer IPT and the Construction Site.



Reference: adapted from (EARTH, 2023).

Figure 28 – Distribution of the antennas around the Construction Site.



Reference: adapted from (EUROPE, 2023).

and reception. Practically thinking, it is around the crane that most of the tasks will be performed, therefore it makes sense that this is a critical spot for communication. With that in mind, a blueprint of the measurement points was drawn which can be seen in Figure 29. The total area is 3400 m^2.

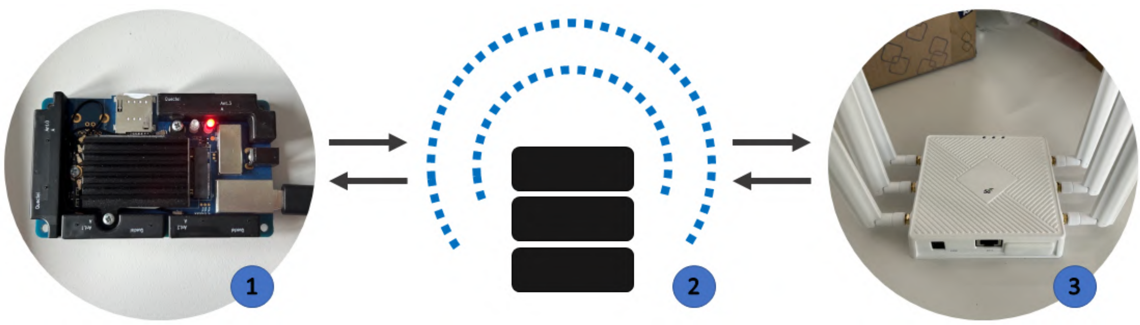
At each point, three tests were held: one iperf3 test and two ping tests. One ping communicated with the device set as the server, and the other with the network controller

Figure 29 – Position of the measurement points based on a Google Earth image.

Reference: adapted from (EARTH, 2023).

(located at IPT). Moreover, at each point, a number of packages between 30 and 50 were sent for the ping and for the iperf3 test. The results for the network controller ping must be lower - hence, better - since the signal goes through a shorter chain of transmission. This chain can be seen in Figure 30. For one scenario it goes from the Quectel (1) to the network controller (2) to the WNC (3) and then back, while for the second, there were fewer steps: it goes from the Quectel (1) to the network controller (2) and back.

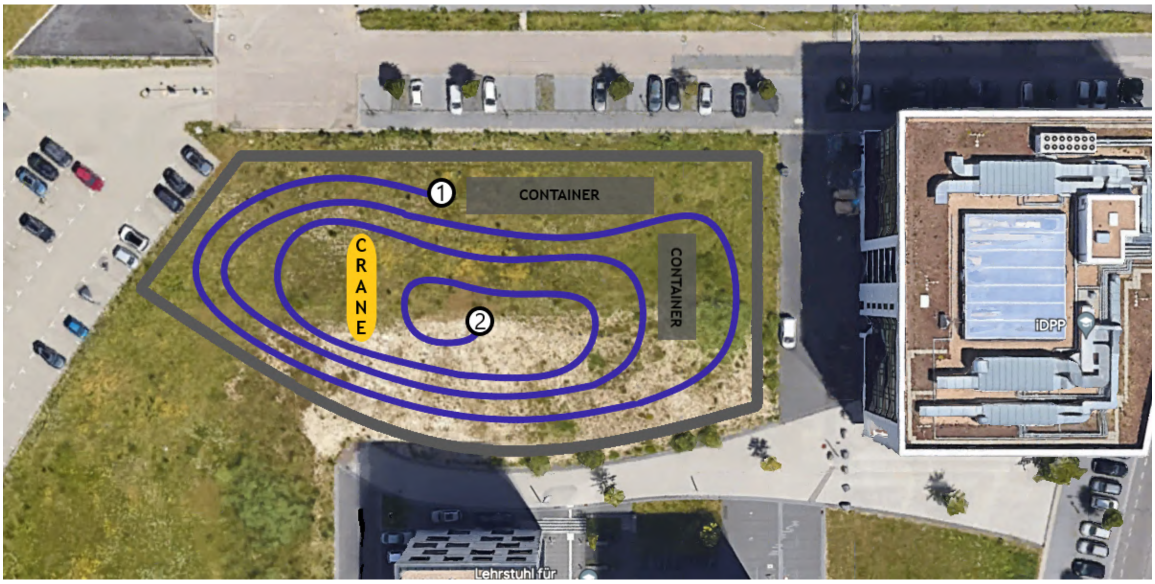
Figure 30 – How the ping behaves when executed through devices.



Authorship: Luiza Souza Simões. Creation date: May 31, 2023

As a further test scenario, the R&S equipment was used. For this one, a snail shape walking test was executed, following the path highlighted in Figure 31 in dark purple-blue, starting at point 1 and ending at point 2, getting closer to the crane.

Figure 31 – Path for the R&S measurements based on a Google Earth image.



Reference: adapted from (EARTH, 2023).

4.2.3 Obtained results

After analyzing the extracted data, the tables, maps, and graphs were generated. Figures 32 and 33 present the results for the first latency tests (to the Network Controller and to the WNC Router), distributed by the measuring points.

Figure 32 – Ping results from the Quectel to the WNC Router.

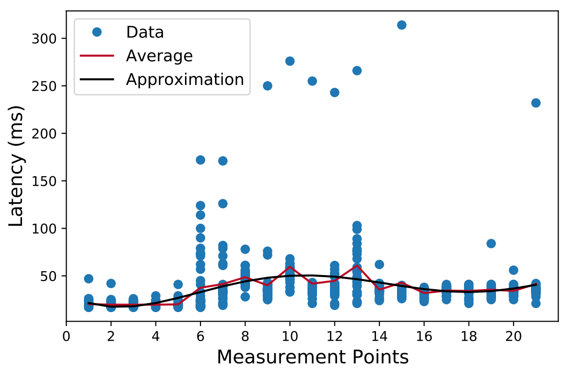
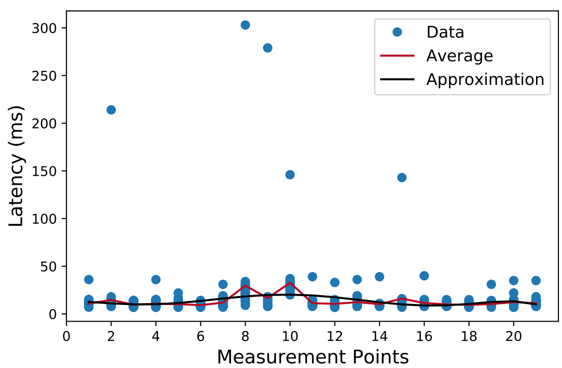


Figure 33 – Ping results from the Quectel to the Network Controller.

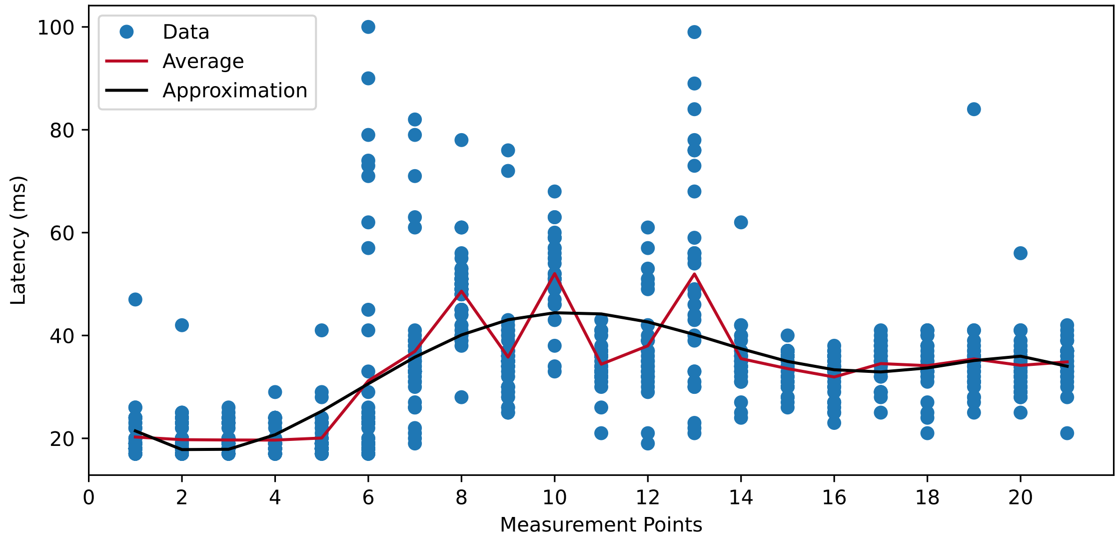


Authorship: Luiza Souza Simões. Creation date: June 3, 2023

According to the number of tests performed at the measurement points, the blue dots represent the latency of each ping test in the Figures. In the measurement points where more dots appear, it is actually because the spot was less stable, causing the measurements to fluctuate. The red line stands for the average values between the latency values, whereas the black line is a polynomial approximation of the data, calculated with the *polyfit* method from Python's library, Numpy, as described in Section A.3.2 of the Appendix. This type of calculation is relevant to show the general behavior of the parameter, considering the number of points and their convergence towards a certain result.

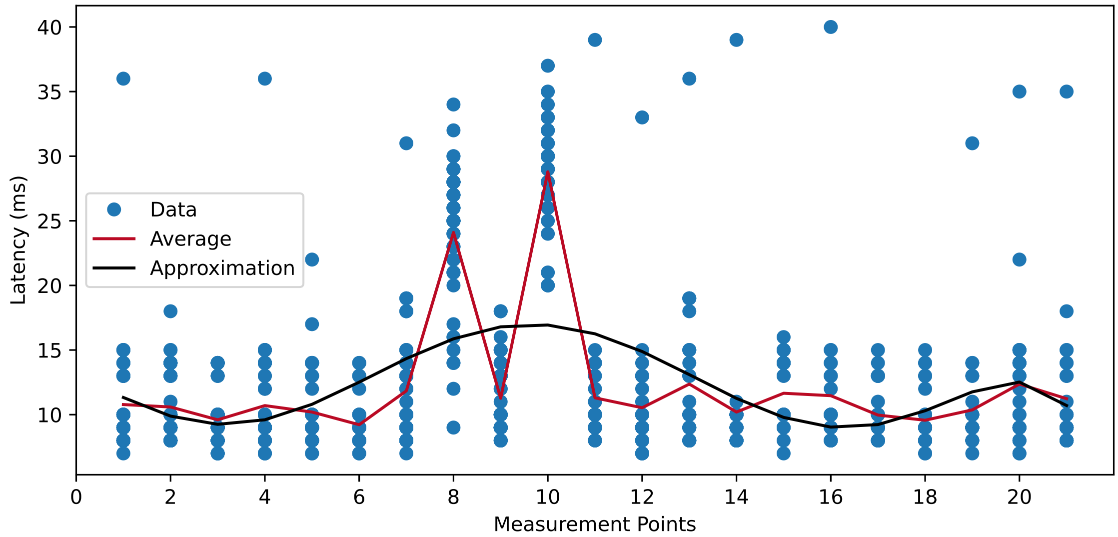
Some points are outside of the normal range, so a filter can be applied aiming to observe the lines more closely. Figures 34 and 35 exhibit those charts.

Figure 34 – Filtered ping results from the Quectel to the WNC Router.



Authorship: Luiza Souza Simões. Creation date: June 3, 2023

Figure 35 – Filtered ping results from the Quectel to the Network Controller.

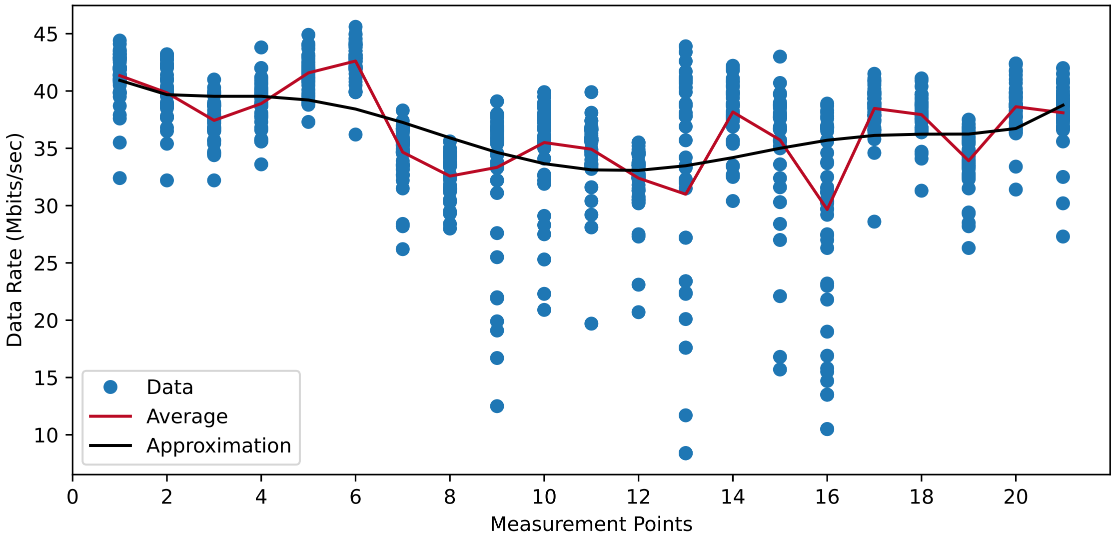


Authorship: Luiza Souza Simões. Creation date: June 3, 2023

By noticing the range of the values obtained in the results for each test, it is possible to confirm the hypothesis raised in the previous section. The Device-to-Device (D2D) communication takes almost three times the time the communication to the Network Controller takes, an average of 36,38 ms against 13,40 ms. This is a coherent pattern considering that, as shown before, the signal from the D2D test has to travel a longer distance. Removing the steps in between, it could be possible to obtain better outcomes, as confirmed by the test with the network controller.

In the following, Figure 36 reveals the throughput results. Although it shows a slightly less meaningful change, in the chart it is also possible to perceive a drop within the mentioned points. The general average is 36,61 MBits/sec.

Figure 36 – Throughput results obtained with the iperf3 test.



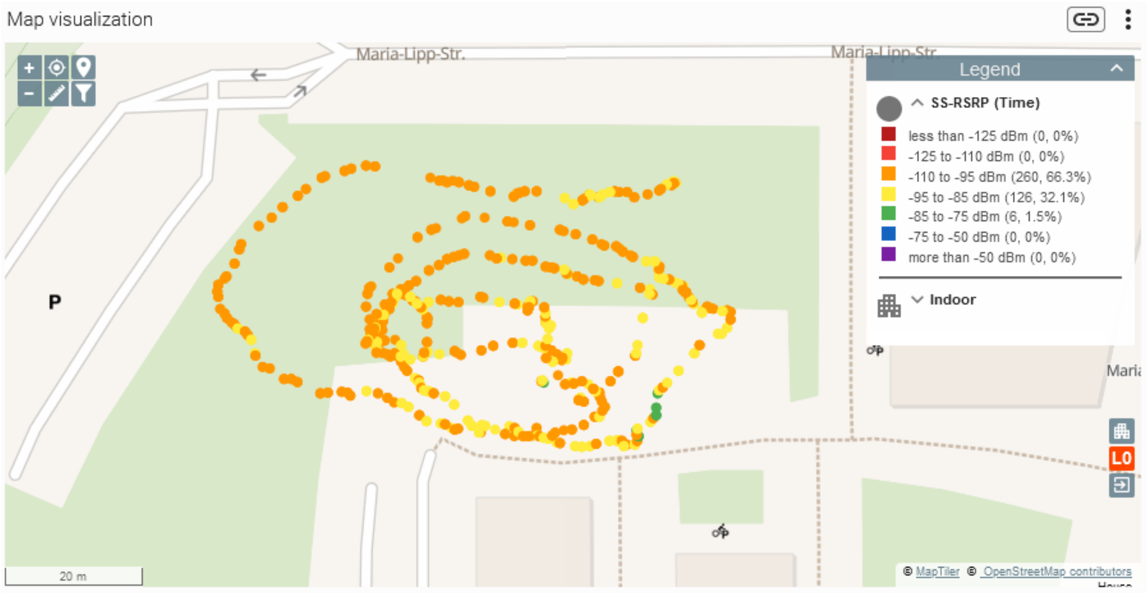
Authorship: Luiza Souza Simões. Creation date: June 3, 2023

Especially when observing the red line with the average values in the latency and throughput charts, it is notable that the communication was particularly worsened at points 8 to 10. There is a spike in the latency results and a drop in throughput, and this might be because of the large amount of metal around these positions. Looking back at Figure 29, these spots appear to be the most surrounded ones, standing near the containers, the crane, and directly behind the building. This kind of positioning can result in signal reflection, penetration or even shielding, which would lead to the attenuation of the parameters.

For a better scenario, it would be necessary to optimize the placement of the antenna, amplify the signal, utilize devices to redirect it, and perhaps wireless repeaters. This performance should improve with the planned setup of the omni-antennas.

Observing the results from the R&S equipment, it is possible to obtain a GPS-oriented map, indicating the signal quality around the covered area. Nevertheless, since the ground is relatively small when compared to the precision of the antenna, the map shows some path flaws. This is seen in Figure 37.

Figure 37 – Map resulted from the passive measurements obtained with ROMES.



Authorship: Luiza Souza Simões. Creation date: June 1, 2023

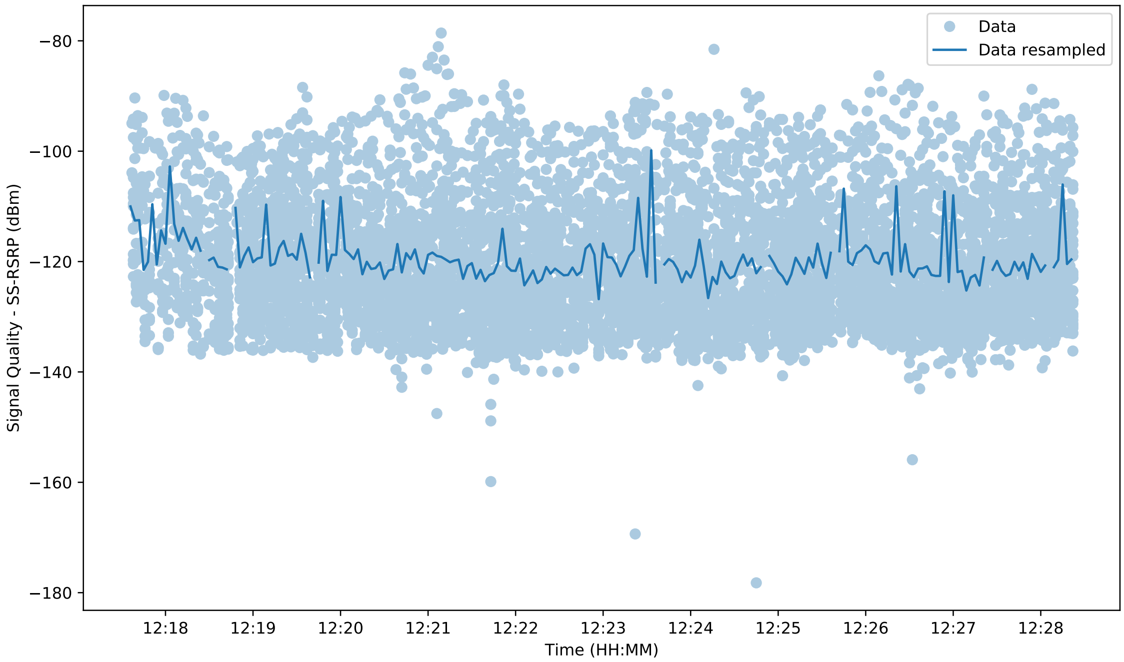
Although these GPS inconsistencies were presented in the image, it was still possible to get an idea of the system as a whole, considering that it was mostly stable along the path. All 7600 measurements acquired during the test were plotted in a graph, and it shows the peaks and valleys reflected in the signal quality of the area. The graphic can be seen in Figure 38.

Since there were so many measurements (light blue points), to better perceive the information, it was necessary to readjust the provided sample. For that, the *resample* function from the Python library, Pandas, was used. It allows changing the frequency or granularity of the data by aggregating the existing values.

In this example, the function calculated the mean of all the points contained in an interval of 3 seconds. This '3S' value was chosen after an iterative analysis of which sampling would provide the most reliable and precise result. The '3S' resample showed the best preservation of the peaks while still removing most of the noise. In Figure 38, the light blue color represents the original data, while the resampled data is displayed in darker blue.

Figure 38 also shows that signal quality is constantly around the -120 dBm zone, with an average of -120,51 dBm. Although this means poor coverage, that was an expected result due to the conditions explained before. Comparing to the requirements from Table 2, the parameters would not be fulfilled, but this is not a surprise, since improvements are

Figure 38 – Signal quality R&S results through time.



Authorship: Luiza Souza Simões. Creation date: June 4, 2023

still planned for the area.

For the next stages, after the omni-antennas are correctly installed along with fiber cables, the results from the test are expected to show improvements and will probably present values that are similar to the ones displayed in Table 2. This enhancement will enable the correct performance of the use cases, making them viable for the application and thus meeting the desired objectives.

5 Conclusion

This thesis addresses the 5G NAMICO project, delving into the validation of parameters and network comparison. As explained in the bibliographic review, the implementation of 5G in the industry is challenging but crucial for encouraging real progress in the field. Automation, process speed, efficiency, productivity, and safety improvements are only some of the benefits that can be generated by providing a connected work environment.

In the research here conducted, a thorough explanation of the main 5G features was brought into the contextualization section, aiming to clarify what makes 5G ideal for the use cases required in the applications, such as latency lower than 10 seconds for example. From that, it was easier to understand how those characteristics would provide the ideal conditions to meet the requirements of the involved scenarios and visualize the objective of the purposed challenges in Table 1.

As the next step, a detailed description of the Underground Mine and the Construction Site was held in order to provide a deep comprehension of the conditions explored in each application. Furthermore, it was possible to see how improving wireless communication will largely impact those hazardous environments, and understand the possibilities to secure operations by having autonomous robots instead of people working directly in dangerous situations.

In the preparation sections, the desired parameters were defined, and the strategy was drawn. Different devices were used for providing data, such as routers and modules (Milesight, WNC, Quectel) and equipment (Rohde & Schwartz), performing tests like ping and iperf3. On top of that, various resources assisted with the analysis of the data, including Python, and software like SmartAnalytics and Excel. For both scenarios, the main study variables consisted of signal quality, latency, throughput, and coverage, and the differences between these two scenarios were evident. It was not coherent to directly compare them since they have particularities, but it was reasonable to associate some results.

In the mine, the tests conducted using Wi-Fi technology did not yield the necessary architecture to meet the network requirements. However, the analysis of the results revealed a positive projection, where the allocated resources and programmed installation could really benefit the environment and improve the parameters to the expected level.

Moreover, due to installation delays, the tests at the Construction Site could not be conducted with the proper setup. The results obtained using the Institute's antenna indicated a pattern that strongly implies signal attenuation caused by the presence of buildings and metal surfaces in the vicinity. Nevertheless, once the installations are completed, it is anticipated that the results will demonstrate 5G as a reliable and high-quality wireless communication technology, ultimately fulfilling the expectation and achieving the set goals.

In essence, with the imminent introduction of 5G to the Underground Mine and the final adjustments at the Construction Site, it is expected that the use cases will be able to operate seamlessly. To ensure a comprehensive understanding of the system's performance, it would be beneficial to conduct measurements at each stage of the installation process for both the Underground Mine and the Construction Site scenarios. This approach will enable a thorough assessment of the impact and influence of each component involved. Such meticulous analysis can provide valuable insights into the effectiveness of the system, improvement points, and how the network interacts with each individual element.

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APPENDIX A – Codes

This Appendix contains the codes used for the analysis of the results necessary in this document. Each section will be referenced to a certain chapter, and named accordingly.

A.1 Ping and Iperf3 tests - Shell Scripts

- Ping

For the ping test, it was necessary to specify the IP and amount of pings necessary. The 'ts' attach a date and time label, and the '>' sends all the data to a text file.

```
ping <IP> -c <Number of PINGS> | ts > ping.txt
```

- Iperf3

Iperf3 requires two connections, one to run the server and another for the client. The server is specified by the first line of the code, 'iperf3 -s'. The client demands a little more information so it can communicate to the client. First, there should be the designated IP, then the port, and finally, the amount of time it should be performed, '-t 300' in that case.

```
iperf3 -s
iperf3 -c <Server's IP> -p <PORT> -t 300 > iperf3.txt
```

- Ping and Iperf3 tests at the Underground Mine

At the mine, all tests were conducted in the same shell script so it would save time. It performs TCP and UDP measurements, as well as a ping test.

```
echo 5G.NAMICO iperf Measurement Program
::cd C:\5G.NAMICO_Messung\iperf-3.1.3-win64\

set "num=%1"

echo Measurement Nr.: %num%
::call script.bat %num%
```

```
iperf3.exe -c 192.168.113.77 -t 10 -V -T Messpunkt%num%
                        --logfile result_final.txt

echo TCP-Measurement completed.

iperf3.exe -c 192.168.113.77 -t 10 -V -u -T Measuring_point%num%
                        --logfile result_final.txt

echo UDP-Measurement completed.

ping 192.168.113.77 -n 20>> result_final.txt

pause
```

A.2 Latency and throughput analysis - Python

The Python code used to develop the Quick 5G Analyser is available online and can be found in the GitHub repository indicated in reference Simões (2023b).

A.3 Data Analysis - Python

In the following, there are the Python codes used to generate the charts associated with this appendix. Each section - Underground Mine and Construction Site - has only one long code. The codes were only broken down into pieces to clarify how and in which part of the code each Figure was generated.

It is important to highlight that all of the following scripts are also comprised in a GitHub repository (SIMÕES, 2023a).

A.3.1 Underground Mine

A.3.1.1 Milesight device graphics

- Figure 18.

```
import matplotlib.pyplot as plt
import pandas as pd

data = pd.read_excel(r'Downloads\202305-NAMICO-UM-Milesight.xlsx')
```

```
data = data.replace({'-':float('nan')})

colors = ['#1F77B4', '#BA0A24', '#000000', '#22B14C', '#FFC90E',
                    '#FF7F27', '#FF80A9', '#A349A4', '#B97A57']

distance = data['Distance (m)']
latency = data[' AvgLat']

fig, ax1 = plt.subplots(figsize=(8, 4))

ax1.plot(distance, latency, marker='o', color=colors[0],
                            linestyle='None', label="Latency")
ax1.set_xlabel('Distance (m)')
ax1.set_ylabel('Latency (ms)')

df_mean = data.groupby('Distance (m)').mean()

distance_m = df_mean.index
latency_m = df_mean[' AvgLat']

ax1.plot(distance_m, latency_m, color=colors[1],
                        linestyle='-', label="Average Latency")

ax1.legend()
ax1.legend(loc='upper left', bbox_to_anchor=(1.0, 1.0))

plt.show()
```

A.3.1.2 BrosTrend device graphics

- Figure 19.

```
import matplotlib.pyplot as plt
import pandas as pd

data = pd.read_excel(r'Downloads\202305-NAMICO-UM.xlsx')

data = data.replace({'-':float('nan')})
data_complete = data.dropna(subset=['TWAMP AvgLat']).copy()
```

```
data_complete.reset_index(drop=True, inplace=True)

colors = ['#1F77B4', '#BA0A24', '#000000', '#22B14C', '#FFC90E',
                    '#FF7F27', '#FF80A9', '#A349A4', '#B97A57']

distance = data['Testtag']
signal_quality = data['Signalstärke']

fig, ax1 = plt.subplots(figsize=(8, 4))

ax1.plot(distance, signal_quality, marker='o', color=colors[0],
                        linestyle='None', label="Signal Quality")
ax1.set_xlabel('Distance (m)')
ax1.set_ylabel('Signal Quality (dBm)')

df_mean = data.groupby('Testtag').mean()
distance_m = df_mean.index
signal_quality_m = df_mean['Signalstärke']

ax1.plot(distance_m, signal_quality_m, color=colors[1],
                    linestyle='-', label="Average Signal Quality")

ax1.legend()
ax1.legend(loc='upper left', bbox_to_anchor=(1.0, 1.0))

plt.show()
```

- Figure 20.

```
latency = data['TWAMP AvgLat']
latency_m = df_mean['TWAMP AvgLat']

fig, ax1 = plt.subplots(figsize=(8, 4))

ax1.plot(distance, signal_quality, marker='o', color=colors[0],
                            linestyle='None', label='Signal Quality')
ax1.set_xlabel('Distance (m)')
ax1.set_ylabel('Signal Quality (dBm)')
```

```
ax1.plot(distance_m, signal_quality_m, color=colors[0],
                            linestyle='-', label='Average Signal Quality')

ax2 = ax1.twinx()

ax2.plot(distance, latency, color=colors[1], marker='o',
                            linestyle='None', label='Latency')
ax2.plot(distance_m, latency_m, color=colors[1],
                            linestyle='-', label='Average Latency')
ax2.set_ylabel('Latency (ms)')

ax1.legend()
ax1.legend(loc='upper left', bbox_to_anchor=(0, 1.2))
ax2.legend()
ax2.legend(loc='upper right', bbox_to_anchor=(1.0, 1.2))

plt.show()
```

- Figure 21.

```
throughput_up_m = df_mean['TCP Up']

fig, ax1 = plt.subplots(figsize=(8, 4))

ax1.plot(distance, signal_quality, marker='o', color=colors[0],
                            linestyle='None', label='Signal Quality')
ax1.set_xlabel('Distance (m)')
ax1.set_ylabel('Signal Quality (dBm)')

ax1.plot(distance_m, signal_quality_m, color=colors[0],
                            linestyle='-', label='Average Signal Quality')

ax2 = ax1.twinx()

ax2.plot(distance, throughput_up, color=colors[1], marker='o',
                            linestyle='None', label='Throughput')
ax2.plot(distance_m, throughput_up_m, color=colors[1],
                            linestyle='-', label='Average Throughput')
ax2.set_ylabel('Latency (ms)')
```

```
ax1.legend()
ax1.legend(loc='upper left', bbox_to_anchor=(0, 1.2))
ax2.legend()
ax2.legend(loc='upper right', bbox_to_anchor=(1.0, 1.2))

fig.tight_layout()
fig.savefig('ol-mean-all-sig-qual-x-thgpt--distance.pdf', format='pdf')

plt.show()
```

- Figure 22.

```
fig, axes = plt.subplots(nrows=3, ncols=3, figsize=(12, 10))

for i in range(1, 10):
    for j in range(1, 10):

        measurement = f"M{j}{i}"

        filtered_data = filtered_data.append
                        (data[data['Name'].str.contains(measurement)])

        if j == 9:

            row = (i - 1) // 3
            col = (i - 1) % 3

            ax = axes[row, col]

            df_mean = filtered_data.groupby('Testtag').mean()
            distance_m = df_mean.index
            sq_m = df_mean['Signalstärke']

            ax.plot(distance_m, sq_m, color=colors[i-1],
                                linestyle='-', label='M' + str(i))
            ax.set_ylim(-82, -50)

            ax.set_xlabel('')
            ax.set_ylabel('')
```

```
            ax.set_xlim(0, 650)

            ax.legend()

            filtered_data = filtered_data.append
                        (data[data['Name'].str.contains(measurement)])

            distance_f = filtered_data['Testtag']
            sq_f = filtered_data['Signalstärke']

            ax.spines['bottom'].set_color('white')
            ax.spines['left'].set_color('white')
            ax.spines['top'].set_color('white')
            ax.spines['right'].set_color('white')

            ax.tick_params(axis='x', colors='white')
            ax.tick_params(axis='y', colors='white')

            ax.plot(distance_f, sq_f, marker='o', color=colors[i-1],
                                                    linestyle='None')

            filtered_data = pd.DataFrame()


plt.show()
```

A.3.2 Construction Site

- Figure 32.

```
import matplotlib.pyplot as plt
import matplotlib.dates as mdates
import pandas as pd
import numpy as np

colors = ['#1F77B4', '#BA0A24', '#000000', '#22B14C',
'#FFC90E', '#FF7F27', '#FF80A9', '#A349A4', '#B97A57']
```

```
for i in range(1, 21 + 1):
    filename1 = r"C:\Users\Temp\Documents\UFBA\2023\TCC\CS\\"
    + f"cs-m{i}.txt"
    filename2 = r"C:\Users\Temp\Documents\UFBA\2023\TCC\CS\\"
    + f"cs-ping-m{i}.txt"
    filename3 = r"C:\Users\Temp\Documents\UFBA\2023\TCC\CS\\"
    + f"cs-ping-m{i}-192.txt"

    with open(filename1, 'rb') as file:
        data_tm = file.read().decode('latin-1')
        exec(f"data_tm{i} = {data_tm!r}")

    with open(filename2, 'rb') as file:
        data_pm = file.read().decode('latin-1')
        exec(f"data_pm{i} = {data_pm!r}")

    with open(filename3, 'rb') as file:
        data_pm_192 = file.read().decode('latin-1')
        exec(f"data_pm{i}_192 = {data_pm_192!r}")

data1 = []

for i in range(1, 21 + 1):
    data_tm_aux = locals()[f"data_tm{i}"]

    for line in data_tm_aux.split('\n'):
        if 'MBytes' in line:
            line_data = line.strip().split()
            transfer = float(line_data[4])
            bitrate = float(line_data[6])
            data1.append((i, transfer, bitrate))

df1 = pd.DataFrame(data1, columns=["Measurement", "Transfer", "Bitrate"])

data2 = []

for i in range(1, 21 + 1):
    data_pm_aux = locals()[f"data_pm{i}"]
    for line in data_pm_aux.split('\n'):
```

```
        if "Zeit=" in line:
            value = line.split("Zeit=")[1].split("ms")[0].strip()
            data2.append((i, int(value)))

df2 = pd.DataFrame(data2, columns=["Measurement", "Value"])

data3 = []

for i in range(1, 21 + 1):
    data_pm_192_aux = locals()[f"data_pm{i}_192"]
    for line in data_pm_192_aux.split('\n'):
        if "Zeit=" in line:
            value = line.split("Zeit=")[1].split("ms")[0].strip()
            data3.append((i, int(value)))

df3 = pd.DataFrame(data3, columns=["Measurement", "Value"])

df2_mean = df2.groupby('Measurement').mean()
df2_point = df2_mean.index
df2_pm = df2_mean['Value']

# Perform polynomial approximation for all measurements
degree = 6
x_values = np.arange(1, 22)
coeffs = np.polyfit(df2['Measurement'], df2['Value'], degree)
approximation = np.polyval(coeffs, x_values)

# Plot the approximation
fig, ax = plt.subplots()
ax.plot(df2['Measurement'], df2['Value'], 'o',
label='Data', color=colors[0])

ax.plot(df2_point, df2_pm, '-',
label='Average', color=colors[1])

ax.plot(x_values, approximation, '-', label='Approximation', color=colors[2])
ax.set_xticks(range(0, 22, 2))

ax.set_xlabel('Measurement Points')
```

```
ax.set_ylabel('Latency (ms)')
ax.legend()

fig.tight_layout()
fig.savefig('cs-ping-172.pdf', format='pdf')

plt.show()
```

- Figure 33.

```
df3_mean = df3.groupby('Measurement').mean()
df3_point = df3_mean.index
df3_pm = df3_mean['Value']

# Perform polynomial approximation for all measurements

degree = 6  # Choose the degree of the polynomial (e.g., linear: degree=1)
x_values = np.arange(1, 22)  # Define x-axis values as [0, 1, 2, ..., 21]
coeffs = np.polyfit(df3['Measurement'], df3['Value'], degree)
approximation = np.polyval(coeffs, x_values)

# Plot the approximation
fig, ax = plt.subplots()
ax.plot(df3['Measurement'], df3['Value'], 'o', label='Data',
color=colors[0])

ax.plot(df3_point, df3_pm, '-', label='Average',
color=colors[1])

ax.plot(x_values, approximation, '-', label='Approximation', color=colors[2])
ax.set_xticks(range(0, 22, 2))

# Set labels and show the plot
ax.set_xlabel('Measurement Points')
ax.set_ylabel('Latency (ms)')
ax.legend()

fig.tight_layout()
fig.savefig('cs-ping-192.pdf', format='pdf')
```

```
plt.show()
```

- Figure 32.

```
df2_mean = df2.groupby('Measurement').mean()
df2_point = df2_mean.index
df2_pm = df2_mean['Value']

# Perform polynomial approximation for all measurements
degree = 6
x_values = np.arange(1, 22)
coeffs = np.polyfit(df2['Measurement'], df2['Value'], degree)
approximation = np.polyval(coeffs, x_values)

# Plot the approximation
fig, ax = plt.subplots()
ax.plot(df2['Measurement'], df2['Value'], 'o', label='Data',
color=colors[0])

ax.plot(df2_point, df2_pm, '-', label='Average', color=colors[1])

ax.plot(x_values, approximation, '-', label='Approximation',
color=colors[2])
ax.set_xticks(range(0, 22, 2))

ax.set_xlabel('Measurement Points', fontsize=14)
ax.set_ylabel('Latency (ms)', fontsize=14)
ax.legend(fontsize=12)

fig.tight_layout()
fig.savefig('cs-ping-172.pdf', format='pdf')

plt.show()
```

- Figure 33.

```
df3_mean = df3.groupby('Measurement').mean()
df3_point = df3_mean.index
df3_pm = df3_mean['Value']

# Perform polynomial approximation for all measurements
degree = 6  # Choose the degree of the polynomial (e.g., linear: degree=1)
x_values = np.arange(1, 22)  # Define x-axis values as [0, 1, 2, ..., 21]
coeffs = np.polyfit(df3['Measurement'], df3['Value'], degree)
approximation = np.polyval(coeffs, x_values)

# Plot the approximation
fig, ax = plt.subplots()
ax.plot(df3['Measurement'], df3['Value'], 'o', label='Data', color=colors[0])

ax.plot(df3_point, df3_pm, '-', label='Average', color=colors[1])

ax.plot(x_values, approximation, '-', label='Approximation', color=colors[2])
ax.set_xticks(range(0, 22, 2))

# Set labels and show the plot
ax.set_xlabel('Measurement Points', fontsize=14)
ax.set_ylabel('Latency (ms)', fontsize=14)
ax.legend(fontsize=12)

fig.tight_layout()
fig.savefig('cs-ping-192.pdf', format='pdf')

plt.show()
```

- Figures 34 and 35.

```
filtered_df2 = df2[df2['Value'] <= 100]
df2_mean_filtered = filtered_df2.groupby('Measurement').mean()
df2_point_filtered = df2_mean_filtered.index
df2_pm_filtered = df2_mean_filtered['Value']

filtered_df3 = df3[df3['Value'] <= 100]
df3_mean_filtered = filtered_df3.groupby('Measurement').mean()
df3_point_filtered = df3_mean_filtered.index
```

```
df3_pm_filtered = df3_mean_filtered['Value']

# Perform polynomial approximation for all measurements
degree = 6  # Choose the degree of the polynomial (e.g., linear: degree=1)
x_values = np.arange(1, 22)  # Define x-axis values as [0, 1, 2, ..., 21]
coeffs = np.polyfit(filtered_df2['Measurement'], filtered_df2['Value'],
degree)
approximation = np.polyval(coeffs, x_values)

# Plot the approximation
fig1, ax1 = plt.subplots(figsize=(8, 4))
ax1.plot(filtered_df2['Measurement'], filtered_df2['Value'], 'o',
label='Data', color=colors[0])

ax1.plot(df2_point_filtered, df2_pm_filtered, '-',
label='Average', color=colors[1])

ax1.plot(x_values, approximation, '-', label='Approximation',
color=colors[2])
ax1.set_xticks(range(0, 22, 2))

# Set labels and show the plot
ax1.set_xlabel('Measurement Points')
ax1.set_ylabel('Latency (ms)')
ax1.legend()
plt.show()


# Perform polynomial approximation for all measurements
degree = 6
x_values = np.arange(1, 22)  # Define x-axis values as [0, 1, 2, ..., 21]
coeffs = np.polyfit(filtered_df3['Measurement'], filtered_df3['Value'],
degree)
approximation = np.polyval(coeffs, x_values)

# Plot the approximation
fig2, ax2 = plt.subplots(figsize=(8, 4))
ax2.plot(filtered_df3['Measurement'], filtered_df3['Value'], 'o',
label='Data', color=colors[0])
```

```
ax2.plot(df3_point_filtered, df3_pm_filtered, '-',
label='Average', color=colors[1])

ax2.plot(x_values, approximation, '-', label='Approximation',
color=colors[2])
ax2.set_xticks(range(0, 22, 2))

# Set labels and show the plot
ax2.set_xlabel('Measurement Points')
ax2.set_ylabel('Latency (ms)')
ax2.legend()

fig1.tight_layout()
fig1.savefig('cs-ping-172-filtered.pdf', format='pdf')

fig2.tight_layout()
fig2.savefig('cs-ping-192-filtered.pdf', format='pdf')

plt.show()
```

- Figure 36.

```
df1_mean = df1.groupby('Measurement').mean()
df1_point = df1_mean.index
df1_tm = df1_mean['Bitrate']

# Perform polynomial approximation for all measurements
degree = 6  # Choose the degree of the polynomial (e.g., linear: degree=1)
x_values = np.arange(1, 22)  # Define x-axis values as [0, 1, 2, ..., 21]
coeffs = np.polyfit(df1['Measurement'], df1['Bitrate'], degree)
approximation = np.polyval(coeffs, x_values)

# Plot the approximation
fig, ax = plt.subplots(figsize=(8, 4))
ax.plot(df1['Measurement'], df1['Bitrate'], 'o', label='Data', color=colors[0])

ax.plot(df1_point, df1_tm, '-', label='Average', color=colors[1])
```

```
ax.plot(x_values, approximation, '-', label='Approximation', color=colors[2])
ax.set_xticks(range(0, 22, 2))

# Set labels and show the plot
ax.set_xlabel('Measurement Points')
ax.set_ylabel('Data Rate (Mbits/sec)')
ax.legend()

fig.tight_layout()
fig.savefig('cs-datarate.pdf', format='pdf')

plt.show()
```

- Figure 38.

```
df = pd.read_csv(r"C:\Users\TCC\CS\Codes\cs-rsrp.csv", delimiter=';')

# Convert 'Time' column to datetime format
df['Time'] = pd.to_datetime(df['Time'])
df['Time'] = df['Time'].dt.time

# Set the 'Time' column as the index
df.set_index('Time', inplace=True)

# Convert time values to datetime format
df.index = pd.to_datetime(df.index, format='%H:%M:%S')

# Resample the data to reduce the number of points
df_resampled = df.resample('3S').mean()

# Plot the data
plt.figure(figsize=(10, 6))
plt.plot(df.index, df['SS-RSRP'], 'o', label='Data', color='#abcae0')

# Plot the resampled data
plt.plot(df_resampled.index, df_resampled['SS-RSRP'], linestyle='-',
label='Data resampled', color=colors[0])
```

```
# Format x-axis as time
plt.gca().xaxis.set_major_formatter(mdates.DateFormatter('%H:%M'))
plt.gca().xaxis.set_major_locator(mdates.MinuteLocator(interval=1))

plt.xlabel('Time (HH:MM)')
plt.ylabel('Signal Quality - SS-RSRP (dBm)')
plt.legend()

plt.tight_layout()
plt.savefig('cs-ssrsrp.pdf', format='pdf')

plt.show()
```