A Selection of Wireless Communication Technologies for Small and Medium-sized Enterprises

- A Handbook -

Foreword from DIH SÜD

Dear entrepreneurs,
Dear employees of small and medium-sized enterprises!

Small and medium-sized enterprises (SMEs) often face the challenge of harmonizing necessary innovations with day-to-day business. Many entrepreneurs have forward-looking ideas, but the realization of innovations often requires a considerable investment of time, resources and financial means. As a result, many new approaches are unfortunately not pursued and implemented.

Digital innovation is a decisive factor for the success of companies, especially in the production environment. It enables the creation of new or improved products, services, processes and business models through the targeted use of digital technologies and strategies.

This is precisely where the Digital Innovation Hub Süd (DIH SÜD) comes in with its activities. The competence network supports SMEs with their digitalization measures by providing free information and training.

This guide was also developed as part of the DIH SÜD program with our cooperation partner, Lakeside Labs. It provides an overview of technologies for wireless communication in the industrial environment. The advantages and disadvantages of the various technologies are illustrated using specific use cases. Use this handbook to help you decide which technology is best for your own company. Because only with the right communication can small and medium-sized companies optimally network their production and thus optimize productivity and operate more sustainably.

We would like to thank the research institute for the very successful realization of this guide and wish you, dear innovators, much joy in the application and implementation in your company.

You are also welcome to attend our free DIH SÜD training courses to gain further ideas and inspiration for your digitalization projects.

Martina Eckerstorfer & Stefan Schafranek

DIHSÜD Digital Innovation Hub

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Der DIH SÜD wird unterstützt von:

FFG Forschung wirkt. Das Land Steiermark LAND KÄRNTEN

Foreword from the CEO – Lakeside Labs GmbH

Mag. Claudia Prüggler

As the digital transformation accelerates, the integration of wireless technologies into industrial automation ecosystems reshapes the landscape of manufacturing and production. Organizations that embrace these advancements will likely lead the charge in innovation, setting new benchmarks for performance, productivity, and sustainability.

Internet of Things (IoT) and Cyber-Physical Systems (CPS) become dominant players in the manufacturing industries, supporting the digitalization of supply chains as well as enhancing flexibility of production, logistics, and maintenance. The Internet of Things (IoT) with its sensor-based monitoring solutions has the potential to greatly improve energy and resource efficiency in the energy and production industries. This would be a significant contribution to major societal challenges, such as reducing carbon emissions and protecting the climate. A key enabling technology in digitalization of production is wireless communication. The majority of today's monitoring systems work with wired sensors. A large part of such sensors has to be retrofitted in existing systems. Many companies shy away from the high installation costs associated with cabling. As a result, many potentials for saving energy and resources remain unused. We need sensors that are cheap and easy to retrofit. Wireless sensors or sensor networks are comparatively easier to retrofit and, if necessary, rearranged faster, without expensive cabling installation. In doing so, they support the flexibility and versatility of the energy and production systems.

By embracing wireless technologies, SMEs can not only enhance their operational capabilities but also contribute to the evolution of intelligent industrial networks. As these trends continue to unfold, SMEs that leverage these innovations will likely set themselves apart, driving future growth and fostering a more competitive industrial landscape.

Key Drivers for SME Growth in Industrial Wireless Solutions:

- Cost-effectiveness: SMEs are increasingly seeking affordable solutions to enhance their operational efficiency. Wireless technologies provide a cost-effective means to automate processes and reduce reliance on complex wired systems.
- Increased Productivity: By implementing wireless solutions, SMEs can streamline operations, improve workflow, and reduce downtime. This leads to enhanced productivity, allowing businesses to maximize output without significant capital investment.
- Improved Customer Service: Wireless technologies facilitate better communication and data access, which can significantly enhance customer service. SMEs can respond more quickly to customer inquiries and streamline order fulfillment processes.
- User-friendly Solutions: The availability of low-cost, easy-to-use wireless technologies has made it simpler for SMEs to adopt these innovations. Many wireless solutions are designed with small businesses in mind, requiring minimal technical expertise for implementation.

- Scalability: Wireless solutions are often scalable, allowing SMEs to start small and expand their technology infrastructure as needed. This flexibility is crucial for smaller organizations that may have fluctuating demands.

This handbook is a handy guide to wireless technologies for industrial applications.

Special thanks to our researchers: Dr. Samira Hayat who has coordinated and lectured the handbook; Dr. Christian Raffelsberger, Dr. Andreas Kercek, Denis Chernov, and Milan Ilic, who contributed and participated in the drafting and revision of the technology profiles and worked on the use-cases.

I also want to thank DIH Süd and all funding partners for making this handbook possible, and for enabling us to share these insights with the public.

Enjoy reading!

Table of Contents

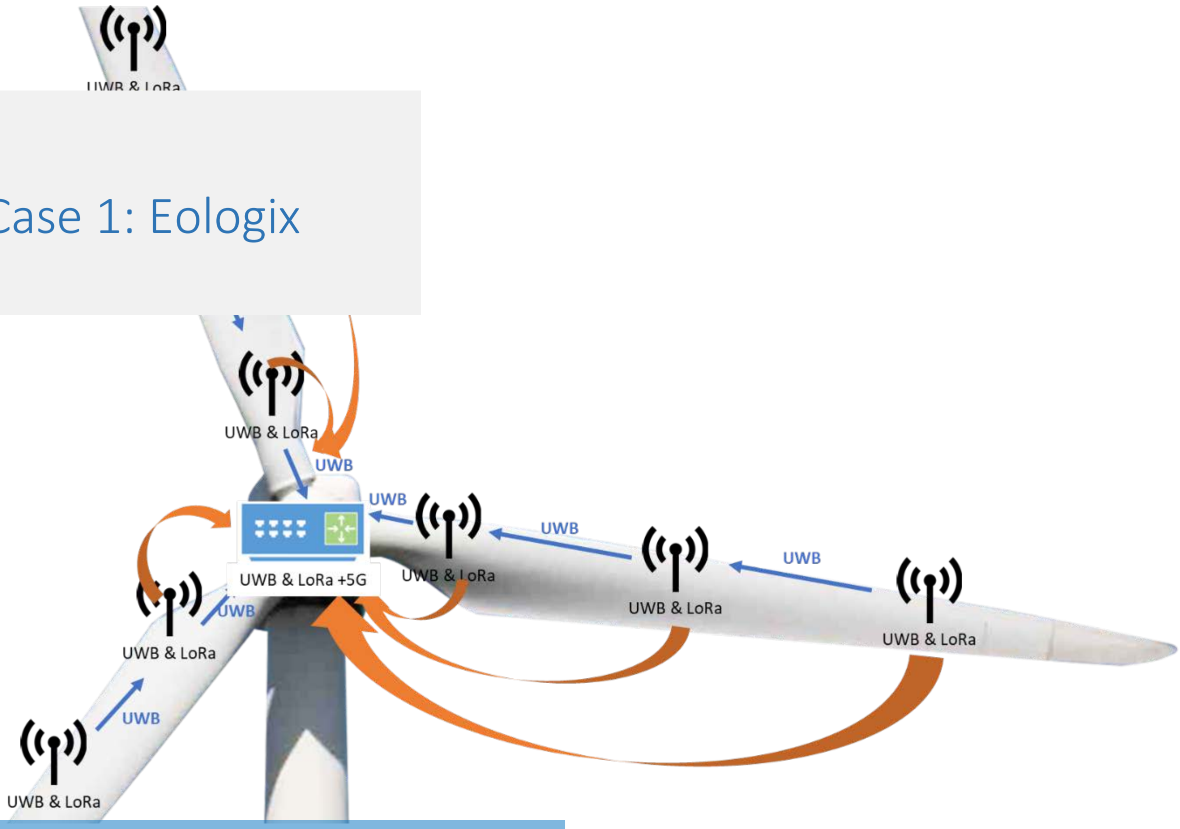
1 Industrial Use Cases

In this chapter, we will describe use cases of our industrial partners, how we collaborated on collecting requirements and designing wireless networks. For the purpose of guiding the reader through the process of use case specification and requirements collection, we select one of the industrial use cases. The guided thought process is based on answering questions that include:

- What is the problem?
- How can we solve it? The problem & solution constituents. This may include parameters to be sensed and the corresponding sensors and their limitations
- What affects the use case? E.g. Environmental conditions
- How to deploy the solution? Deployment requirements (for instance, permanent or temporary deployment, deployment in exposed areas etc.)
- What are the technical requirements? E.g. Sensor requirements such as battery powered, etc.)
- What are the technical requirements specific to the networking technologies

The extracted requirements for the selected use case (provided at the end of this chapter) are listed in a tabular format as **measurement** and **communication** requirements. The aim of requirements extraction exercise was to gather as many requirements as possible, so that a reliable, use case-specific wireless network may be designed. The described use case should help understand how to collect requirements and design networks.

1.1 Use Case 1: Eologix



Measurement and energy harvesting at a wind turbine

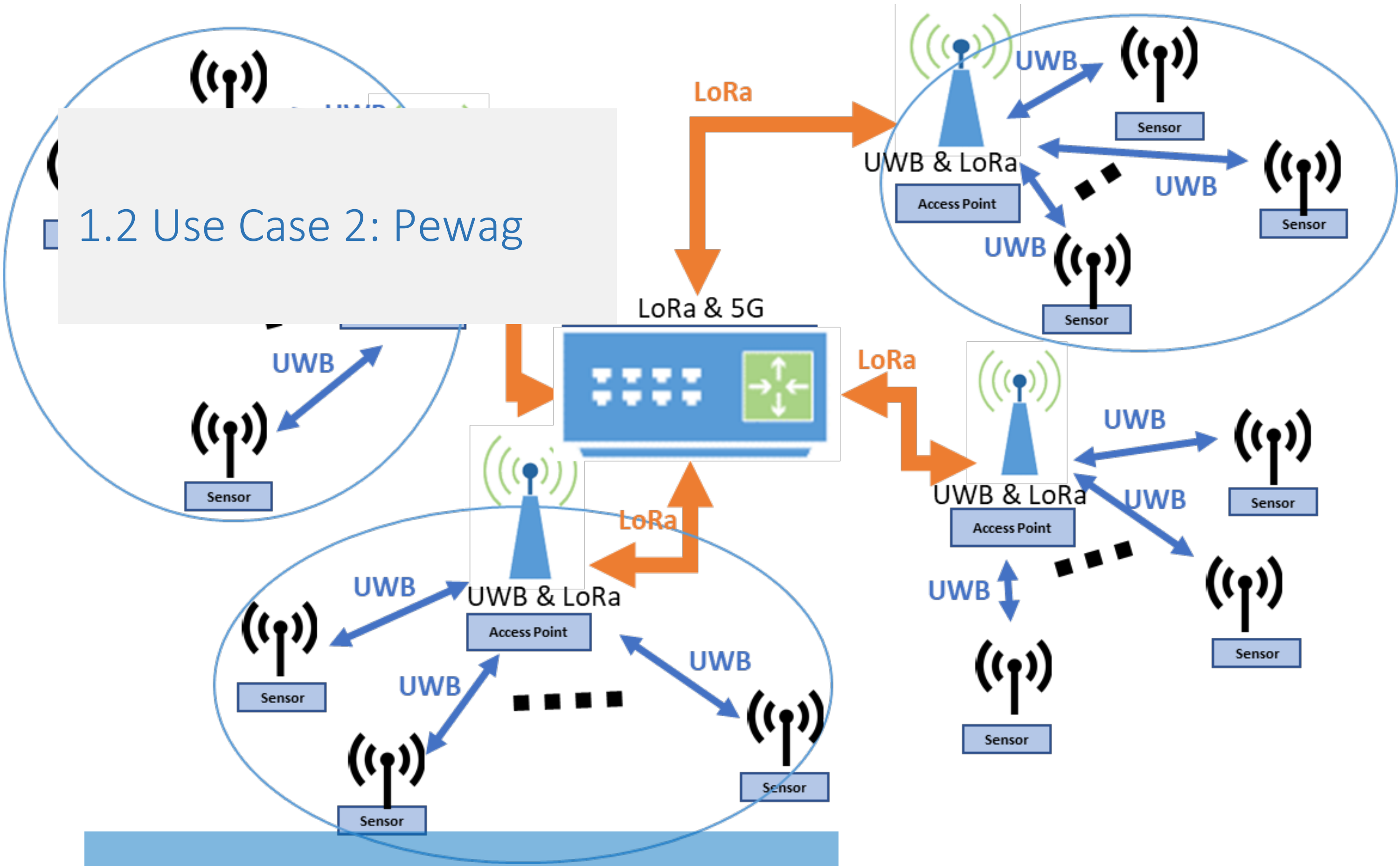
In the realm of renewable energy, wind turbines play a crucial role. These turbines are equipped with sensors that monitor their vibration and structural health. These sensors are powered by a solar energy harvesting system, an accumulator, and a battery pack. However, the powering of these sensor nodes presents a significant challenge due to the harsh weather conditions where these turbines are typically located. In light of these challenges, the potential communication technologies supporting the data communication from the sensor nodes is explored.

The sensors that monitor vibration and structural integrity are located along the turbine blades. The data collected by these sensors is transmitted to a central gateway via a low-rate wireless interface operating at carrier frequencies of 868 MHz and 2.2 GHz (ISM band).

However, powering these sensor nodes is a significant concern due to the harsh weather conditions typically found at turbine locations, which make energy harvesting challenging. Additionally, batteries often struggle to perform at the typical operating temperatures of -20C. In this context, a technological update that can reduce energy consumption at the nodes is highly desirable.

As part of this use case, new methods for wireless monitoring of wind turbines, including energy generation were explored. One of the challenges is that the sensors must be aerodynamic. The sensors are designed to have a lifespan of 20 years. A reference system, eologix's existing system, is already in place.

1.2 Use Case 2: Pewag



Condition and energy monitoring

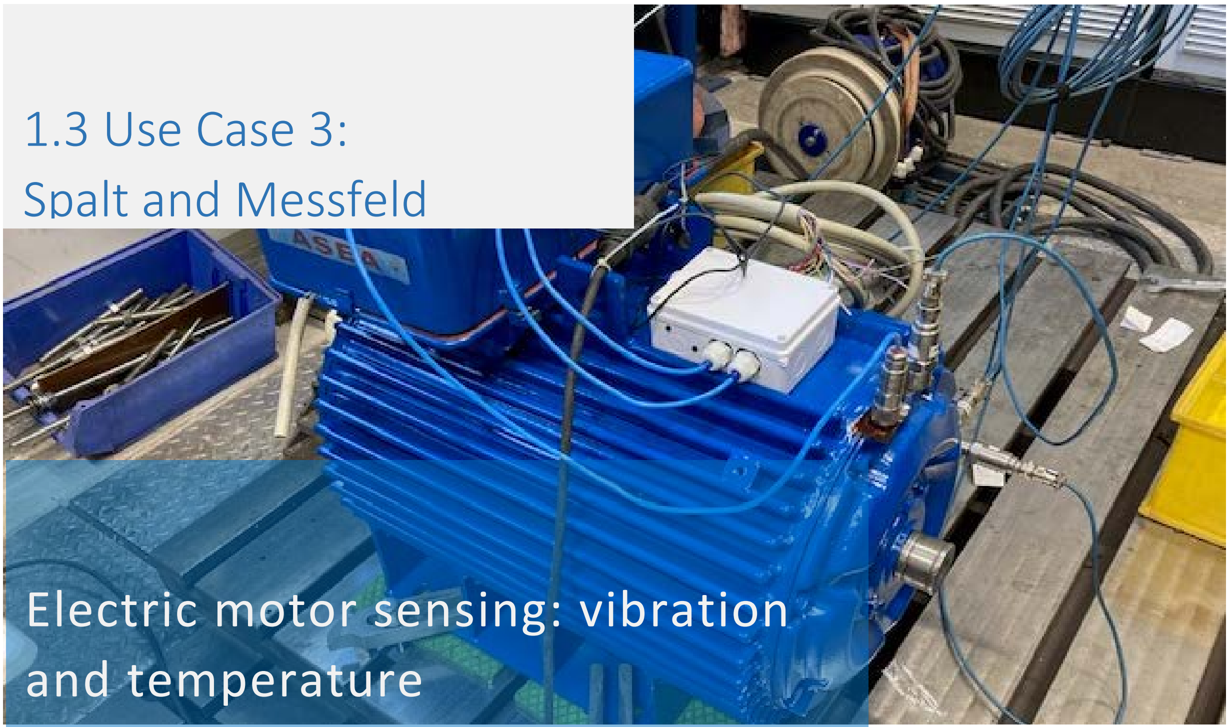
Condition monitoring and energy monitoring are two important aspects of industrial facilities. Condition monitoring is the process of monitoring the condition of machines and equipment to detect any potential issues before they become major problems. This can help to prevent costly downtime and repairs, and ensure that production runs smoothly. Energy monitoring, on the other hand, involves tracking energy usage in a facility to identify areas where energy is being wasted and to find ways to reduce energy consumption. This can help to reduce energy costs and improve the sustainability of the facility.

An example is the power supply quality of a welding machine: The changes in the supply energy of the welding equipment can have an effect on the quality of the weld. Therefore, the power quality is to be measured by means of current and voltage measurements, and conclusions are to be drawn about the quality of the weld seam. The aim is to determine which measurement variables have an influence on the quality of the welds. Another important point to consider is the influence of other welding machines. The challenge is to draw meaningful conclusions for the quality of the weld seam from the measurements and to find improvements for the machines. The measurement is carried out using both a conventional current/voltage measurement and a wireless measurement system.

The production plan comprises a large number of welding machines of different characteristics, connected to a common power supply. Periodic peaks of current consumption that can be assimilated to a rectangular wave characterize the welding process. The wave duty cycle and frequency depends on the features of each machine determining a big spread in terms of frequency and peak current. The temporal overlapping of many machines results in a non-stationary temporal wave of current consumption. The continuous monitoring of this temporal wave might correlate to the quality of the welding process. Therefore, it is of interest to characterize this behavior through a continuous monitoring, as a first step towards the optimization of the working regimes of machines in the production facility. This will also reduce energy consumption in the processes as well as avoiding scrap material and associated energy consumption for recycling.

For condition monitoring of bending machines, vibration measurements are required. At present, vibration measurements can only be carried out with a high effort, wired high-end equipment, and only by specialized personnel. The measurements cannot be carried out over a longer period and are therefore only of limited significance. By means of wireless sensor technology, the sensor nodes can be placed permanently with no additional cabling efforts and measurements can be taken over a longer time, which enables early detection of damage to the bending machine.

1.3 Use Case 3:
Spalt and Messfeld



Electric motor sensing: vibration and temperature

This is yet another use case for condition monitoring: The condition of the motor is monitored at regular intervals or if a failure/damage is suspected. This is done with acceleration sensors. Since it is very time-consuming to mount the sensors on the engine and to lay the signal cables. Also, specialized personnel are needed. For this reason, mounting the sensors instead of shims with wireless data transmission is preferred. The special challenges are the high data rate and a preferred synchronization of the sensor data, as well as the mounting of special piezo sensors instead of shims.

Temperature measurement

In an engine, temperatures are measured by PT 100 for early detection of friction and other abnormalities. The sensor is usually mounted in the bearing shield. The signal cables are routed into the control box. This is very time-consuming and requires trained personnel. The wireless transmission of the data as well as the supply of the sensor with energy should enable a permanent self-sufficient measurement of the temperature. By transmitting the data, it can be transferred to an alarm system and thus damage can be detected at an early stage.

Vibration measurement

Currently, vibration sensors are mostly used in industry to monitor machines such as electric motors. In this case, the signal cables have to be laid around the machine, which is usually labor-intensive. Vibration measurements by means of wireless data transmission are therefore favored. Vibration measurement data from conventional sensors is to be compared with data from a wireless sensor based on an IO-Link data transmission protocol.

Further details on this use case are:

- Sensors: IO- Link Wireless Sensor
- Measured variables: Vibration, temperature

1.4 Use Case 4: Chemical Industry

Monitoring (chemical, wear) and automated control

This is another set of monitoring and automated control use cases provided by a chemical industry partner. They provides an industrial environment, in which chemical products are manufactured. There is a range of specific parameters that cause difficulties when establishing a wireless network. In general, we have to cope with high temperatures, humidity, a lot of dust and dirt, and steel constructions reflecting the wireless signals. The major design goals for wireless networks are guarantees for data delivery, potentially with real time requirements and energy awareness as far as possible. Further, also security aspects have to be considered when designing such network approaches. We selected the set of use cases provided by the partner to do a deep dive into problem specification and requirements collection. These requirements are listed as two separate tables as measurement and communication requirements.

1.4.1 Compressed air leakage monitoring

Leakage is a known problem to all pressurized air supplies. Leakage is typically 10-20% of the supply on an annual average, even in well maintained networks. In Treibacher plants about 6500 MWh are spent annually for the generation of pressurized air. Early detection of air leakage can save between 1000 MWh - 2000 MWh on electrical energy for pressurized air generation. In principle, air leakage is accompanied with acoustic noise that can be heard by naked ear. This is not possible in production plants like the one in this use case, since production noise prevents early detection of leakage in this way. Standard procedures are checks with portable ultra-sound measurement devices that are used to check the air pipes as a matter of routine. Some leakage may have already taken place for a while before noticed. A viable solution is a network of distributed sensors that check the pipes continuously. Sensors may be based on cheap ultra-sound, pressure or even vibration measurements either mounted close to or on the pipes directly. It is not necessary to detect the exact spot of leakage but rather the area where leakage takes place in order to direct maintenance personnel to have a closer look and apply countermeasures.

Requirements for 1.4.1

Measurement requirements

Parameter	Value (Tolerance)
Ambient Temp.	-20 °C – 60 °C
Ambient Humidity	40% – 100%
Housing temp.	n/a
Vibrations	Low
Contamination with dust	High
Sensor principle	Ultra sound or vibration measurement *
Sensor power consumption during sensing	50 mW
Sensing duration	1 s
Sampling rate	0 – 100 kHz
Measurement rate	1 / day

* Remark: Detection of "non-nominal" modes of ultra sound connected to air leakage

Communication requirements

Parameter	Value
Coverage area	In the ha range
Max. distance between sensors	100 m
Max. distance to closest access point	50 m
Number of access points	Min. 2
Number of sensor nodes	50
Communication technology	LoRa

1.4.2 Exhaustion flap monitoring for washer system

At certain locations powders are filled into bags causing high amounts of dust being emitted. In order to avoid the dust contaminating workers and equipment, a washer system is in place that aspirates the dust and transports it away. Typically, the processes that cause dust are not always active and hence there is a possibility that the flaps of the washer system can be closed to save energy needed for heating, as the same amount of air that is sucked into the washer is replaced by outside air that has to be heated up to ambient temperature. Hence, it would be advantageous to have sensors that detect the status of the flaps to enable several applications: First, in combination with a sensor that detects whether or not the process causing dust is active, there could be a suggestion to the worker to open or close the flaps. Second, if the system knows the number of open flaps and hence the amount of air that is sucked in by the washer system, it can regulate/reduce the throughput of the washer system, which again saves energy. Such application could require some sensors for flow or pressure differences in the pipes in order to ensure a minimum airflow that avoids accumulations of dust within pipes.

Requirements for 1.4.2

Measurement requirements

Parameter	Value (Tolerance)
Ambient Temp.	-20 °C – 60 °C
Ambient Humidity	40% – 100%
Housing temp.	10 °C – 40 °C
Vibrations	Medium
Contamination with dust	Very high
Sensor principle	Capacitive
Sensor power consumption during sensing	10 mW
Sensing duration	100 ms
Sampling rate	1 Hz
Measurement rate	1 / h

Communication requirements

Parameter	Value
Coverage area	50 m
Max. distance between sensors	50 m
Max. distance to closest access point	20 m
Number of access points	Ca. 2
Number of sensor nodes	30
Communication technology	LoRa

1.4.3 Monitoring of wear due to abrasion in pipes and conveyor systems

In the production process there is a need for transporting very hot and abrasive materials either through pipes or by means of chain conveyors. In order to avoid unscheduled downtimes, it is important to monitor wear in a regular fashion, which is currently done manually, e.g., by emptying the conveyor, opening the housing and checking the wear by visual inspection. This procedure can be improved by installing a wear strip and measuring its thickness. If the thickness falls below a given threshold, the maintenance procedure is triggered. The thickness of the wear strip can be estimated by measuring its resistance or by using a capacitive sensor.

Requirements for 1.4.3

Measurement requirements

Parameter	Value (Tolerance)
Ambient Temp.	20 °C – 100 °C
Ambient Humidity	40% – 100%
Housing temp.	300 °C
Vibrations	Very high
Contamination with dust	High
Sensor principle	Resistance strip or capacitive
Sensor power consumption during sensing	50 mW
Sensing duration	100 ms
Sampling rate	10 Hz
Measurement rate	1 / day

Communication requirements

Parameter	**Value**
Coverage area	40 m
Max. distance between sensors	100 m
Max. distance to closest access point	50 m
Number of access points	Min. 2
Number of sensor nodes	30
Communication technology	LoRa

1.4.4 Monitoring of oil/lubricants in gear boxes

The gearbox of geared motors is subject to high mechanical strain, which causes wear in some of its parts. For reliable production, these parts have to be replaced prior to failure to avoid unscheduled production downtimes. Hence, typically scheduled maintenance is adopted to check the status of the parts and replace them at the slightest sign of wear. The effort for checking is quite high as the geared motor has to be switched off and the gearbox has to be opened. This process can be optimized by applying some sensors that are able to measure the wear status of the gearboxes by either detecting swarf in the lubricant using sensors for conductibility or optical sensors, or by detecting vibrations. If something is detected, maintenance procedures should be initiated.

Requirements for 1.4.4

Measurement requirements

Parameter	**Value (Tolerance)**
Ambient Temp.	10 °C – 60 °C
Ambient Humidity	40% – 100%
Housing temp.	10 °C – 60 °C
Vibrations	High
Contamination with dust	Very high
Sensor principle	Conductivity, optical or vibration (combination)
Sensor power consumption during sensing	200 mW
Sensing duration	1 s
Sampling rate	0 – 100 kHz
Measurement rate	1 / day

Communication requirements

Parameter	**Value**
Coverage area	50 m
Max. distance between sensors	2 – 20 m
Max. distance to closest access point	10 m
Number of access points	Min. 2
Number of sensor nodes	30 – 40
Communication technology	LoRa

1.4.5 Automated Control of production plant lighting

Currently, lighting in all production halls are switched on all the time. Although manual switches for the lights are available, they are not used at all and thus high amounts of energy are wasted. The energy consumption could be reduced by installing some sensors that detect people being present in the production halls to automatically switch lights on and off. The key requirement for this use case is that it must be nearly impossible that lights are switched off while any person is present, even in case the person is working in a hardly accessible location that would not be covered by off-the-shelf presence detectors. Hence, a different strategy for detecting the presence of workers has to be applied. Potential solutions could be a high number of very cheap sensors that cover the whole place with high redundancy or some small devices, smart card or similar carried by the workers that is easily detected.

Requirements for 1.4.5

Measurement requirements

Parameter	Value (Tolerance)
Ambient Temp.	-20 °C – 60 °C
Ambient Humidity	40% – 100%
Housing temp.	n/a
Vibrations	Low
Contamination with dust	Medium
Sensor principle	Presence detectors – IR
Sensor power consumption during sensing	100 mW
Sensing duration	1 s
Sampling rate	0 – 100 Hz
Measurement rate	>= 10 / min.

Communication requirements

Parameter	Value
Coverage area	50 m
Max. distance between sensors	5 m
Max. distance to closest access point	25 m
Number of access points	3
Number of sensor nodes	Min. 10
Communication technology	LoRa

Testimonials from Industry Partners

Messfeld

The Wireless Technology application for electric motors helps us to monitor the condition without the need of additional wiring, enabling us to monitor the motors efficiently and cost-effectively. The technologies currently available on the market are very time-consuming and cost-intensive due to the cabling involved.

Ing DI Dr. Jutta Isopp
CEO Messfeld GmbH

Eologix

Thanks to the results of the Project ConSens, we are able to design our next generation of devices with a much better common knowledge on cutting-edge radio interfaces and related optimization potential. The expertise and support from the scientific partners were key to successfully implementing new technologies. We are extremely satisfied with the results and highly value the professional collaboration.

Dr. Michael Moser
CTO Eologix Sensor Technology GmbH

LoRa (Long Range): LoRa is a physical proprietary radio communication technique based on spread spectrum modulation derived from chirp spread spectrum (CSS) technology. It is the wireless platform of choice for the Internet of Things (IoT).

LoRaWAN: LoRaWAN is a low power, wide area networking (LPWAN) standard based on LoRa devices. It is a software layer, which defines how devices use the LoRa hardware, for example when they transmit, and the format of messages. It provides cloud services and enables communication of data and analytics that can be utilized to enhance efficiency and productivity.

LPWAN (Low Power Wide Area Networks): LPWANs are a type of wireless telecommunication wide area network designed to allow long-range communication at a low bit rate between IoT devices, such as sensors operated on a battery. The sensors in such networks require less power, have extended operating ranges, and typically can transmit a limited amount of data per day.

2 LoRa and LoRaWAN

2.1 Introduction

LoRa and LoRaWAN refer to two different layers of the communication protocol stack (see Figure 2.1). LoRa refers to the modulation technique and is the physical layer, while LoRAWAN is a medium access (MAC) layer that is based on the ALOHA protocol.

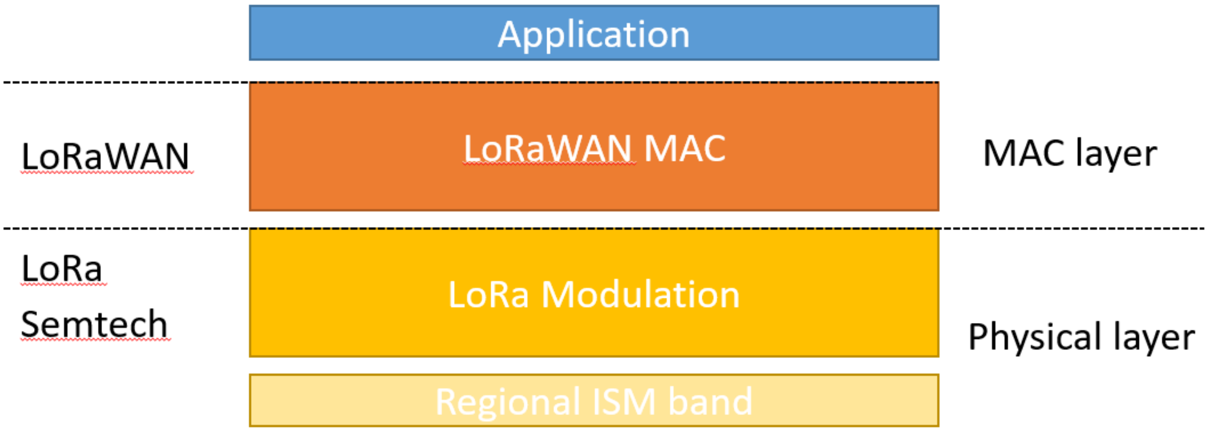


Figure 2.1 Protocol stack (source: https://lora-developers.semtech.com/documentation/tech-papers-and-guides/lora-and-lorawan/)

2.1.1 LoRa Overview

LoRa is a radio frequency modulation technology designed for LPWANs. It can provide long-range data links, with distances up to 4.8 km in urban areas and over 16 km in rural areas. The physical layer supports two different operating frequencies. One operates in a licensed sub-GHz spectrum; the carrier frequency differs from country to country. The second option utilises the unlicensed 2.4 GHz Industrial, scientific, and medical (ISM) band. Adopting the 2.4 GHz band reduces coverage range due to the higher carrier frequency and increased bandwidth (BW), typically around 1 km, compared to the 5-10 km range of the standard LoRa variant. However, this trade-off comes with the advantage of transmitting larger frame sizes and reducing airtime due to the wider BW.

LoRa is a proprietary spread-spectrum modulation technique derived from existing CSS technology. The main idea of the modulation is to multiply the data signal with a spreading code or chip sequence to increase the RF link budget so the signal can travel over a longer range. Increasing the chip rate increases the frequency components of the total signal spectrum. In other words, the energy of the total signal is now spread over a wider range of frequencies, allowing the receiver to discern a signal with a lower (that is, worse) signal-to-noise ratio (SNR). Figure 2.2 shows LoRa modulated signal for different values of spreading factor (SF) and fixed BW of 125 kHz. The symbol duration and frequency span depend on SF and BW. The higher SF means a longer symbol time, and the higher BW means a wider range between lower and higher frequencies.

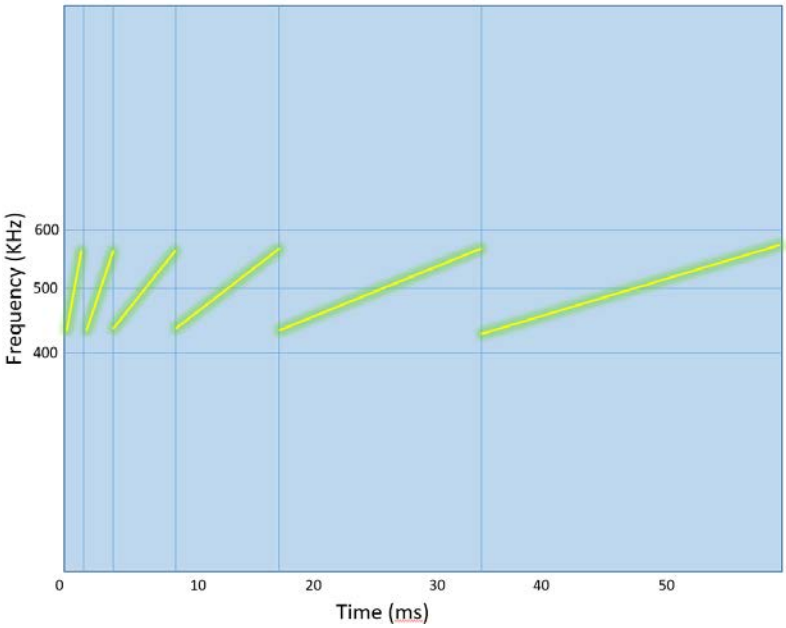


Figure 2.2 Lora modulated signal for SF7 to SF12 (source:https://www.researchgate.net/figure/LoRa-uses-a-chirp-spread-spectrum-modulation-technique-The-figure-also-shows-that-LoRa_fig3_332151302)

2.1.2 LoRa Parameters

In the following, we describe certain technology-specific parameters that influence the data rate and range of communication when using LoRa.

Spreading Factor:
In LoRa terms, the amount of spreading code applied to the original data signal is called the SF. LoRa modulation has seven SFs (SF6 to SF12) for sub-GHz LoRa and eight for 2.4GHz LoRa (SF5 to SF12). The larger the SF, the farther the signal can travel and still be received without errors by the RF receiver. The higher the SF, the slower the transmission and the higher the energy consumption. Notably, the LoRa modulation SFs are inherently orthogonal. This means that signals modulated with different SFs and transmitted on the same frequency channel at the same time do not interfere with each other. Instead, signals at different SFs simply appear to be noise to each other.

Bandwidth:
BW is a critical parameter that refers to the width of the frequency band that the LoRa signal occupies. The choice of BW significantly impacts the system's performance and is a trade-off between communication range, data rate, and power consumption. The larger the BW, the higher the data rate, which means faster data transmission. However, this comes at the cost of reduced communication range and increased power consumption. On the other hand, a smaller BW will lower the data rate, resulting in slower data transmission. The increased communication range and reduced power consumption make it more suitable for applications where long-range communication and power efficiency are more important than data transmission speed.

Duty Cycle:
The duty cycle is another important parameter of LoRa and LoRaWAN in the licensed spectrum. This is different in different regions of the world and is defined by the standards. It informs the user how much they can send during the day. This is because different settings of SF and BW result in different packet time on air (toa), which leads to a reduction in data rates.

Coding Rate:
In LoRa technology, the coding rate (CR) is a parameter that denotes the proportion of bits in a data stream that carry useful information. It is a part of the Forward Error Correction (FEC) process, which involves adding redundant bits to the transmitted data. These redundant bits help restore any received bits that may have been corrupted during transmission. Four coding rates are used: 4/5, 4/6, 5/7, and 4/8. For instance, if the coding rate is 5/7, the coder generates seven bits of data for every five bits of useful information, of which two bits are redundant. The choice of coding rate can influence the data rate and range of the transmission.

The parameters SF, BW, and CR have an influence on toa, energy consumption (En), and data rate (DR) (see Figure 2.3). Energy consumption represents the amount of power consumed over time. It is a multiplication of toa and power for a single packet.

2.4 GHz variation:
While LoRa typically operates in region-specific sub-GHz bands, the development of a 2.4 GHz ISM band version of LoRa has garnered interest due to its potential for worldwide applications. However, this version must coexist with numerous other technologies within the 2.4 GHz band. This version of the technology offers no duty cycle limitations that come with the sub-GHz version. This means that the achievable data rates are much higher, but the transmission distances are significantly reduced due to the operating frequency.

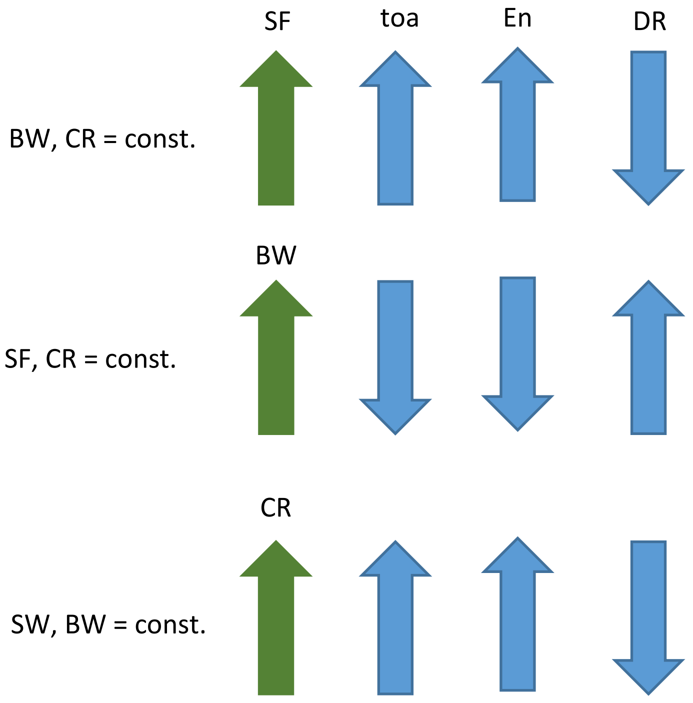


Figure 2.3 Relationship between different parameters. How changes in SF, BW, and CR affect toa, En, and DR

2.1.3 LoRaWAN Overview

Built on top of LoRa modulation, LoRaWAN is a MAC layer protocol that defines the operation of devices using LoRa hardware. It fulfils key IoT requirements such as bi-directional communication, end-to-end security, mobility, and localisation services.

For LoRaWAN to work, it needs an infrastructure. This infrastructure consists of end nodes, gateways, and different servers. Figure 2.4 shows a typical LoRaWAN network infrastructure from the end device to the user application.

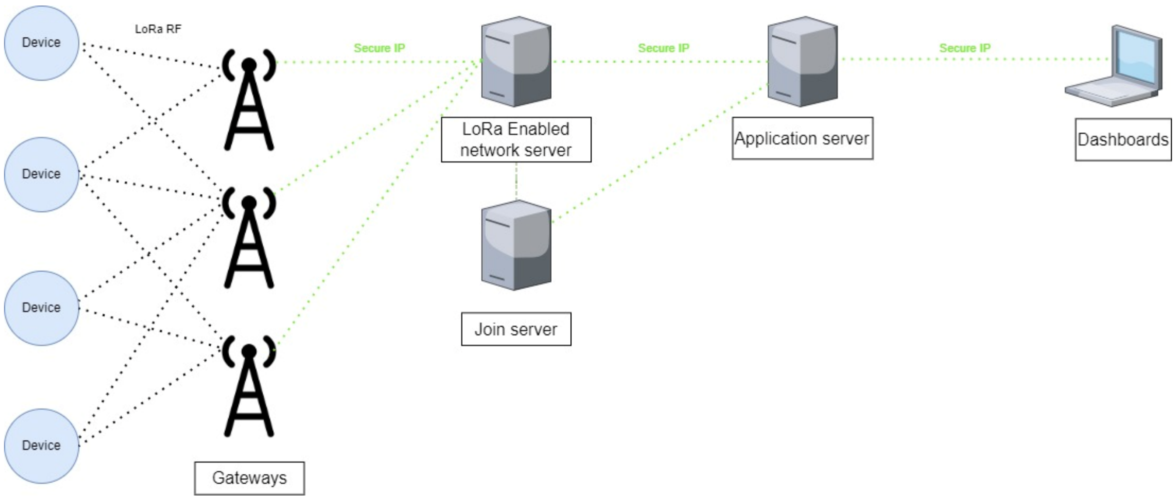


Figure 2.4 Network Infrastructure (source: https://lora-developers.semtech.com/documentation/tech-papers-and-guides/lora-and-lorawan/)

Users have the option to either connect to an existing network (service providers) or construct a custom network with the necessary gateways and servers. It is important to note that only end devices and gateways are enabled with LoRa technology. The servers, on the other hand, operate based on standard internet protocols. There are service providers that offer access to public gateways and servers. However, users are typically required to pay a fee to utilise these services. Users can also install their gateway and connect it to the service provider to utilise the full functionality of the network stack. Another option is to install a personal gateway and servers, which require some networking and software knowledge. Lastly, users can opt to use only a gateway and end devices. This setup allows for data collection at the gateway level. However, the user would need to custom-build all other features.

LoRaWAN end devices send data messages using LoRa modulation to any gateway that is in transmission range. The gateways relay these messages to the LoRaWAN network server (LNS), which is connected to the rest of the network via internet protocol. The end devices do not need to be connected to a single gateway. They can communicate with several gateways in the transmission range. LoRaWAN ensures that all the gateways in range will pick up the same uplink packet from the end device, as shown in Figure 4. This improves the reliability of the data transmission (because it is very likely that at least one gateway will get the message right), lowers the battery consumption for end devices that move around and enables localisation of end devices at a low cost.

The LNS is in charge of the whole network and can adjust the network parameters (SF, BW, transmission power, and channel selection) according to the changing network conditions. It uses secure 128-bit Advanced Encryption Standard connections to send the data from the end device to the end user's application and to manage the traffic between the end device and the LNS. The LNS verifies the identity of every end device on the network and the validity of every message. However, the LNS does not have access to or visibility of the application data.

Application servers are in charge of handling data that is received from end devices and application layer data transmitted back to end devices. The join server is in charge of registering nodes to the network when they join. It is connected to both the LNS and application server and decides which application server is connected to the end device. It further generates encryption keys for these connections between the application server and the end device.

LoRaWAN defines three device types: Class A, Class B, and Class C. All devices must implement Class A, while Class B and Class C are optional extensions. Class A devices are the most energy-efficient, Class B devices extend Class A by adding scheduled receive windows, and Class C devices have nearly continuous receive windows, offering the lowest latency.

2.1.4 Technical Overview

Table 2.1 shows an overview of technical specifications for both sub-GHz and 2.4 GHz LoRa. LoRaWAN parameters depend on the region

Table 2.1 Technical overview of LoRa sub and 2.4 GHz physical layer specifications

Parameters	Values (sub-GHz)	Values (2.4 GHz)
Frequency band, MHz	868, 433, 915, 779, 470	2400
SF	6-12	5-12
BW, kHz	{7.8,10.4,15.6,20.8, 31.2,41.7,62.5,125, 250,500}	{203,406,812,1625}
Effective Data rate	21 bps - 35 kbps (Duty cycle 0.21 bps – 352 bps)	428 bps - 196 kbps
Power Tx/Rx(Sensitivity) mW	100 mW (20 dBm)/-136 dBm	17.8 mW (12.5 dBm)/-132dBm
Maximum distance	15km(Rural) 5km(Urban)	2.7km(Rural) 443m(Urban) 110m(Indoor)
Modulation scheme	LoRa	LoRa
Scalability	LoRaWAN (yes), LoRa (additional implementation needed)	
Security features		
Mobility support		
Restrictions	Yes	No

2.2 LoRa and LoRaWAN Properties

2.2.2 Weaknesses

LoRa and LoRaWAN present an attractive networking solution for most of today's wireless IoT applications. Let us consider how the technology performs in a more demanding industrial IoT environment and whether it is useful for all applications.

Key characteristics

01 Longer transmission range than any other technology

02 Lower equipment cost

03 Low power and energy consumption

Wide Coverage

LoRa's wide coverage range and low power consumption make it ideal for scenarios where measurement points are widely dispersed, such as waste containers distributed across an urban area or containers with raw and auxiliary materials in circulation on a large worksite.

Cost-Efficiency

LoRa modulation has a constant envelope modulation similar to frequency-shift keying (FSK) modulation, allowing the use of low-cost and low-power power amplifier stages with high efficiency. This makes LoRa devices affordable for applications like smart metering, which requires a large number of devices. Smart metering or equipment maintenance monitoring is needed in industry as well. The low cost and easy installation makes it an appealing solution.

Low Power and Energy Consumption

LoRa-based radio sensors are highly energy-efficient with low power consumption, enabling them to operate for several years on a single battery. The lifespan of these nodes is further extended by implementing duty cycle restrictions, which limit the number of packets sent and thus minimize energy consumption. Moreover, LoRaWAN devices, specifically those of Class A and B, have a sleep mode between transmissions. This feature further prolongs their operational lifespan, making them an excellent choice for long-term deployments.

Robustness

LoRaWAN has a well-established infrastructure (see Figure2.4) and its comprehensive protocols for handling data errors make it a powerful tool for IoT applications. It uses Adaptive data rate (ADR) mechanism to ensure the best setting of SF and BW for any scenario.

Flexibility

LoRaWAN's support of three different device classes (Class A, Class B, and Class C), offers flexibility for different application needs. For example, in a smart city application, street lights could use Class C for nearly continuous network connectivity, while battery-operated waste level sensors in trash cans could use Class A to maximize battery life. The level of customization is also necessary for diverse industrial environments.

Regional Restrictions

The sub-gigahertz band used by LoRa varies between regions, which can limit its applicability. For instance, a global logistics company may find it challenging to track its fleet or assets across different countries due to these variations in frequency regulations.

Limited Network Size

The size of both LoRa and LoRaWAN networks is limited by a parameter known as the duty cycle, which is defined as the percentage of time during which the channel can be occupied. This can be a limitation for dense networks with many devices, such as in a smart city deployment.

Not Ideal for High-Frequency Data Transmission

LoRa and LoRaWAN can only be used for applications requiring low data rate, i.e., up to about 100 bps for sub GHz LoRa and 196 Kbps for 2.4 GHz LoRa. If you want to measure multiple parameters at high frequencies, LoRa and LoRaWAN may not be fast enough. For example, it may not be suitable for a manufacturing facility that requires real-time monitoring of hundreds of parameters from its machinery.

Figure 2.5 Illustration of strengths and weaknesses of LoRa and LoRaWAN

2.3 LoRa and LoRaWAN in Industrial Applications

LoRa is made for long range, low power and low data rate applications. It is robust to different propagation conditions which makes it suitable for condition monitoring in industrial networks. LoRaWAN provides infrastructure that has security and scalability for easier network deployment and maintenance.

Use cases

01 Eologix: Vibration monitoring on wind turbines

02 Pewag: Condition and energy monitoring of welding machines

03 Spalt: Temperature and vibration monitoring for machine maintenance

04 Chemical Industry: Reduce production downtime and increase efficiency through machine monitoring and automation

2.3.1 Use case requirements

General:

- Packet loss rate (PLR) measurements across different locations
- Small data rate
- Long battery life
- Star network topology

Specific:

- Use case 1:
    - Communication range up to 150m
    - Outdoor LOS environment
- Use case 2:
    - Communication range up to 70m
    - Indoor NLOS environment
- Use case 3:
    - Communication range up to 20m
    - Indoor NLOS environment
- Use case 4:
    - Communication range up to 180m
    - Combination of Indoor and Outdoor environments with NLOS conditions

2.4 Technology Evaluation

We study the industrial LoRa sensor network with a primary focus on coverage and monitoring applications in industrial environments. Specifically, we focus on NLoS scenarios both outdoors and indoors with diverse and non-optimal node locations.

Goal	Description
Design of a custom MAC Layer	We have developed a custom MAC layer to reduce packet collisions and increase network capacity. The difference between LoRWAN MAC and our custom MAC is that ours is time division multiple access (TDMA) based while LoRaWAN is based on ALOHA.
Parameter Analysis	The obstacles characterize the environment, which is different from factory to factory. It is of interest to test how communication performs for different values of SF and BW for different distances from the AP and in different locations that are not perfect LOS.

In industrial sensor networks, different configurations deliver different performances. The main focus was on analyzing how different configurations that include different SF, BW, frequency, and MAC layers impact the reception quality at different locations.

For example, the machines and equipment are scattered throughout the factory floor, where not all conditions are ideal for communication. Most of these locations are NLOS; what configuration can provide sufficient coverage for different node locations is a critical question.

Different parameters available in LoRa allow the user to configure the network to suit the requirements, whether the focus is on a higher data rate and smaller coverage or vice versa.

Analyzing how different configurations impact the transmission quality gives a better insight into the best set of parameters for monitoring applications.

Monitoring Modes

Small data rate, high range: In scenarios where data needs to be transmitted over large distances, setting a high SF and low BW ensures the packet is reliably delivered. To achieve a higher range, sub-GHz LoRa provides a longer transmission range.

High data rate, small range: For different scenarios where the data rate is more important, low SF and higher BW is a better option. 2.4 GHz LoRa has a much higher BW, outperforming sub-GHz LoRa by the factor of 6 when it comes to data rates.

High robustness: For high robustness, the best option is to opt for LoRaWAN, which is a well-established protocol with a well-working infrastructure. The user can either choose to use already existing network services like “The Things Network” (https://www.thethingsnetwork.org/) or build a private network, which requires some knowledge about networks and systems.

2.5 Testbed Implementation

To measure behavior in different envionments, we have designed and implemented a small-scale network using LoRa. For LoRaWAN we used a dedicated gateway.

2.5.1 Experimental Setup

Environment:

- Indoor and outdoor setups.
- NLOS environment filled with foreign objects of different materials that obstruct the signal propagation.

Parameters:

- PLR:
  - Using different configurations of SF and BW.
  - Using different transmission range and node placement.

Network setup shown in Figure 2.6:

- LoRa using custom TDMA MAC layer.
- LoRaWAN using dedicated MAC.
- The access point (AP) is connected to a laptop for power and data logging; nodes are scattered around the measurement area.
- In LoRaWAN case gateway refers to an AP. It is used without a laptop since it is a standalone system with its own operating system which is capable of logging data.
- Star network topology.

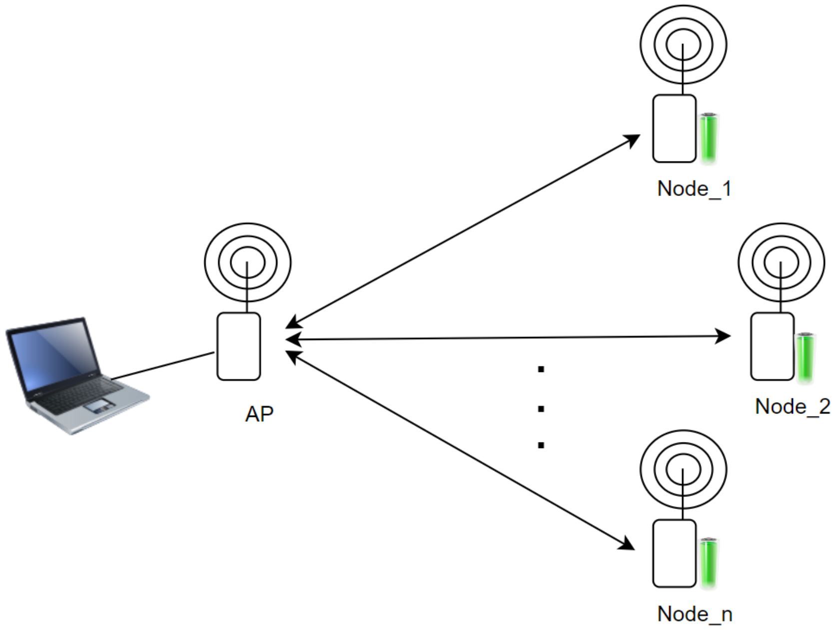


Figure 2.6 Network architecture with star topology

2.5.2 Custom MAC

The custom MAC layer setup is shown in Figure 2.7:

- Medium divided into time slots grouped into sub-frames.
- Sub-frame begins with a downlink message from the AP, followed by uplink messages from the nodes in their designated time slots.
- Time slots separated with guard intervals $t_g = 50\ ms$.
- Nodes enter sleep state after transmission and wake up to receive the beacon.

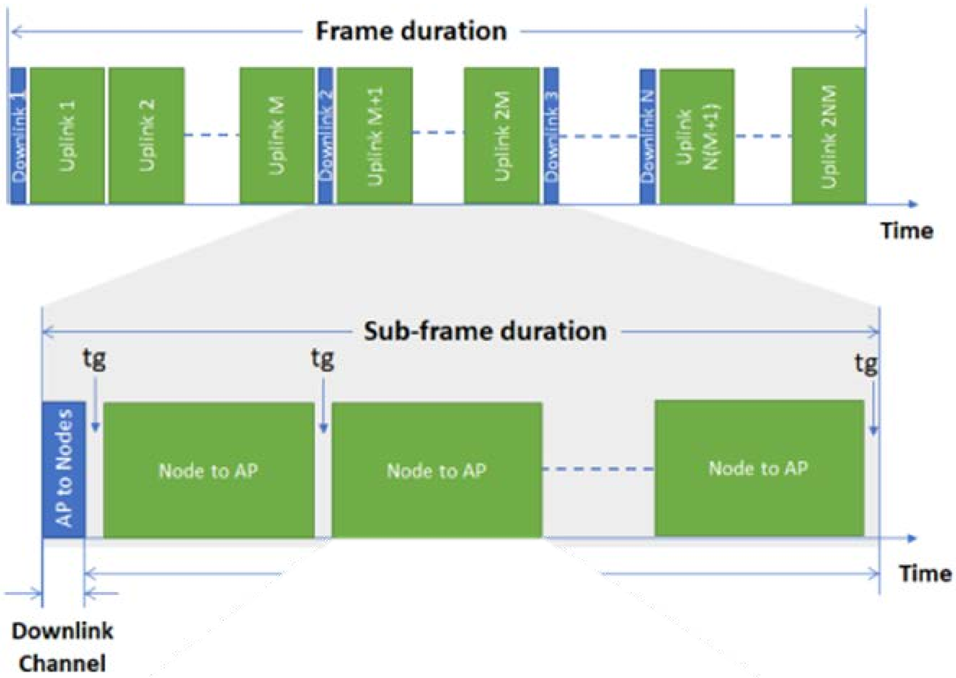


Figure 2.7 TMDA protocol for custom MAC layer

2.5.3 Findings

We now report the measurement results for the LoRa physical layer with the custom TDMA MAC layer and LoRaWAN. The measurements are separated by the operating frequency (2.4 and sub-GHz) and location. The measurements for 2.4 GHz LoRa were performed in real industrial environments inside factory halls (use cases 2, 3, and 4). Since time in a real factory setting was limited, additional experiments were done, referred to as baseline experiments. These additional tests were done outdoors and indoors to gain insight into different LoRa configurations. Measurement locations are in both LOS and NLOS conditions. Sub-GHz LoRa tests were only performed outdoors for two different AP positions. There was no option to test sub-GHz LoRa custom MAC in the industrial setting. LoRaWAN was tested in the production hall for both frequencies, where, in the case of 2.4GHz, the AP was modified not to use server infrastructure but only to receive data from the node. Table 2.2 shows the road map of all locations and use cases for specific physical and MAC layers.

Table 2.2 Findings road map

Frequency	**2.4 GHz**			**Sub-GHz**	
Mac layer	Custom MAC		LoRaWAN	No MAC	LoraWAN
Location	Indoor	Outdoor	Indoor+Outdoor (mix)	Outdoor	Indoor, Indoor+Outdoor (mix)
Use case	2 and 3		4		4

For each specific distance, some setups have multiple locations per distance, and some have only one. There was only one measurement round per location due to time constraints. The measurement results are presented in two distinct ways: the mean PLR and the PLR deviations between locations for each distance. When measurements were taken across different locations for the same distance, we calculated the mean PLR and displayed the deviations. However, in cases where only a single location was available for a particular distance, no mean or deviation could be calculated. Instead, we reported the single PLR value for that location. There are a few exceptions, such as when a configuration yielded only one result per distance while other distances in the same measurement campaign had multiple. Those exceptions are marked in Figures.

In the following: First, results for 2.4 GHz LoRa are shown starting with the baseline outdoor, then covering baseline indoor, followed by use cases 2 and 3 and finishing with LoRaWAN in use case 4. The second part shows the results for sub-GHz LoRa in an outdoor scenario and results for LoRaWAN in use case 4.

2.4 GHz LoRa

We explore various scenarios tested for this specific frequency. We begin with the outdoor baseline scenario, showing the setup layout and the results. Following this, we transition to the indoor baseline scenario, providing insights into the performance of an office indoor environment. Finally, we delve into the findings from use cases 2, 3 and 4. These cases are grouped due to their similar environmental conditions. We performed the following experiments:

- **Baseline outdoor:** The findings are reported with detailed plots as we could test both LOS and NLOS conditions.
- **Baseline indoor:** NLOS and LOS experiments could not be separated, as is the case in a real-life factory scenario.
- **Real factory setups (Use cases 2, 3, and 4):** The nodes were placed in non-ideal conditions (NLOS) to test the limits of different configurations.
  The main studied configurations for 2.4 GHz LoRa are the combinations of the following parameters: SF= {5, 10} and BW= {400 kHz, 1600 kHz}. For LoRaWAN, SF= {5, 6, 9, 12} and BW={200 kHz, 1600 kHz}.

In all experiments except use case 4, we opted for SF10 as the higher SF option instead of SF12 and BW of 400 kHz as the lowest instead of 200 kHz because SF12 and BW of 200 kHz do not support ranging functionality. Ranging refers to the process of transmitting a signal and measuring the time it takes for the signal to reach the receiver. This allows the receiver to calculate the distance to the transmitter. Ranging measurements were not relevant to this analysis but were mentioned to clarify why SF12 was not used as a higher SF option.

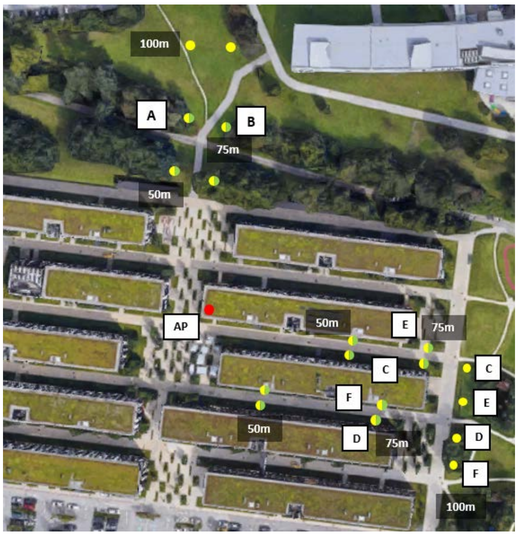
Baseline Outdoor

The test setup comprises two different measurement campaigns. In the first campaign, nodes were placed in front of and to the side of the AP. In the second campaign, they were placed only in front. The second campaign also provides more measurement locations per distance. The AP was placed at a height of around 0.5 m from the ground, while the nodes were mostly placed on the ground with a few exceptions, which were elevated on poles or in the trees.

We collect approximately between one and two thousand packets from each node for a single parameter configuration. There were exceptions that sent less due to compromised communication to the AP. Here, each node represents a unique location.

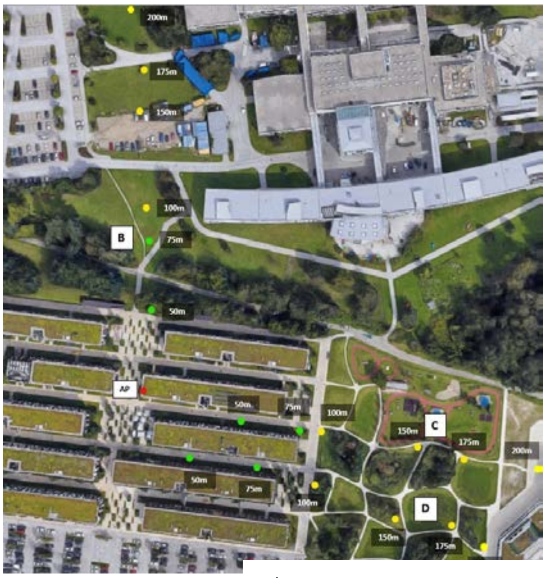
Figure 2.8 shows two different campaigns for two different SFs. Since different SFs have different range capabilities and not all distances are reachable for lower SF, there are some differences in distances between two SFs. Figure 2.8 a) and b) shows locations for SF5 and c) and d) for SF10. Locations are marked with letters in relation to the node's id value for easier analysis. Dots are also marked with different colours, which, in the first campaign, show what location belongs to the specific value of BW (yellow BW400 and green BW1600). In the second campaign, colours were used to show locations that are approximately at the same distance from the AP.

The first measurement campaign covered three different distances {50 m, 75 m and 100 m} for SF5, and for SF10, a few additional locations are added {150 m, 175 m and 200 m}. The second measurement campaign covered similar distances. The nodes were placed around the following distance values {40 m, 60 m, 70 m, 100 m, 110 m, 150 m} for SF5, with a few additions for SF10 {175 m, 200 m, 220 m}. Measurements were not conducted simultaneously across all distances. Instead, we measured one distance at a time with different locations for that distance.



a)

b)

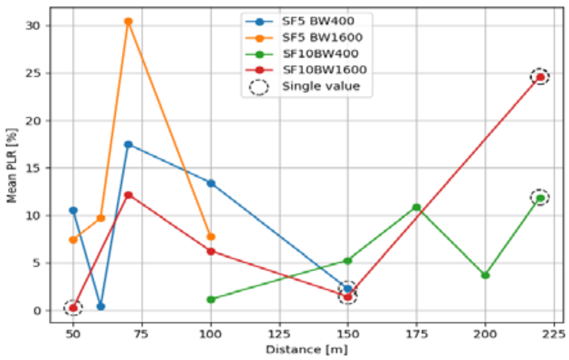


c)

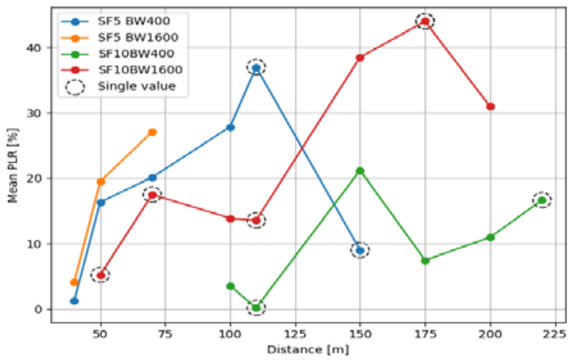
d)

Figure 2.8 Setup layouts of outdoor measurements a) SF5 campaign one, b) SF5 campaign two, c) SF10 campaign one, d) SF10 campaign two

The values of PLR were grouped from both measurement campaigns. Furthermore, results are grouped into two categories: LOS and close to LOS locations, as well as NLOS locations. Figure 2.9 shows mean PLR results for four different configurations of SF and BW and two different LOS groups. Due to the positioning of the nodes and different distance values, some distances had a single measurement (one location), so no mean could be calculated. These exceptions are encircled in the figure.



a)



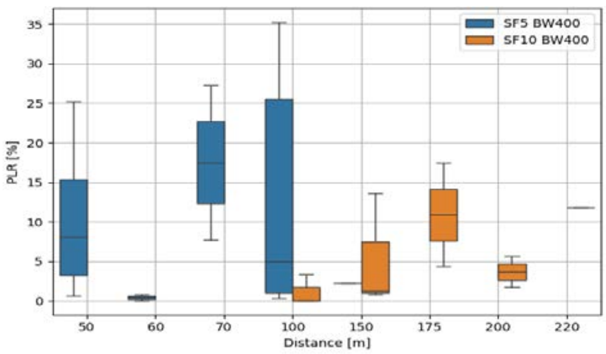
b)

Figure 2.9 Mean PLR values for SF={5, 10} and BW={400, 1600} kHz with different measurement locations a) LOS and close to LOS, and b) NLOS; Locations with single measurement are encircled.

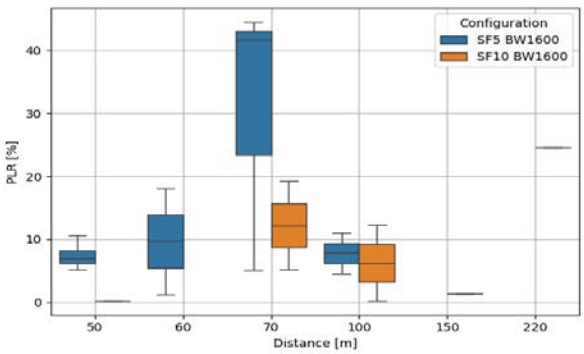
The main findings:

- **Higher SF with lower BW is optimal**: The configurations with a higher SF and lower BW have the best PLR.
- **Node placement matters**: The position of the nodes, some of which were placed on the ground while others were elevated, significantly impacts the results. This will be explored further below.
- **NLOS conditions have higher PLR**: Under NLOS conditions, the PLR is higher than in LOS conditions.
- **Outlier at 150m for SF5BW400 configuration**: An outlier observed at a distance of 150 m for the SF5BW400 configuration is due to node placement. Some nodes placed closer to the ground did not receive anything, thereby lowering the mean PLR. The mean PLR for the SF10BW400 configuration is higher because more locations per distance provided results. This means that those measurement locations that recorded nothing for SF5 reported high values of PLR for SF10, thereby increasing the mean of this configuration.

The next set of plots shows how the placement of the nodes influences the PLR. The values on the plots are grouped by LOS conditions and BW. Figure 2.10 shows the distribution of numerical data with median (50% of data is higher, and 50% is lower than this median), maximal, minimal values and lower and upper quartiles, which show data lower than 25% of the values, and lower than 75% of the time respectively. To avoid overlap, both values for a give reading are plotted side-by-side (e.g., Figure 2.10a, at 100 m, left = SF5, right = SF10).



a)



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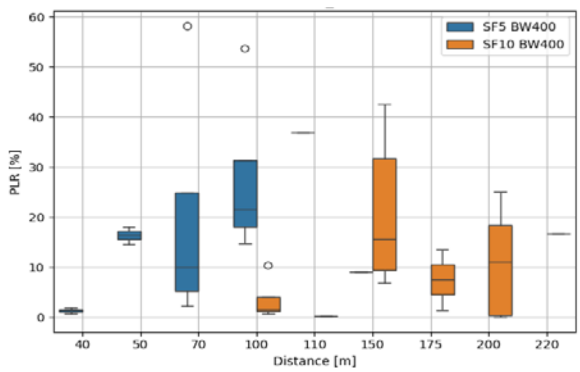

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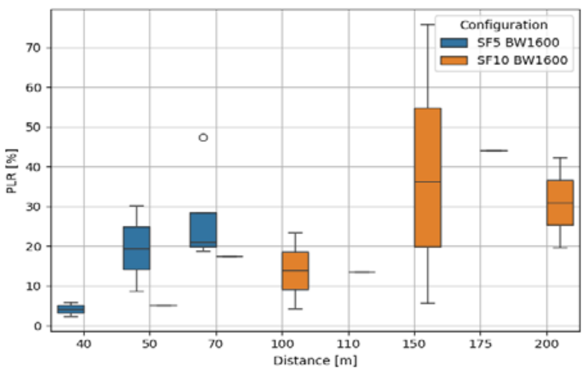


d)

Figure 2.10 Bar plot representation of PLR for a) LOS and close to LOS SF={5, 10}, BW=400kHz, b) LOS and close to LOS SF={5, 10}, BW=1600kHz, c) NLOS SF={5, 10}, BW=400kHz, d) NLOS SF={5, 10}, BW=1600kHz; Locations with single measurement are shown as a horizontal line.

The main findings:

- **LOS with SF5BW1600**: There is a lower deviation for a distance of 100 m, but this is due to fewer measurements than SF5BW400. SF5BW1600 did not receive a signal at locations where SF5BW400 did, so SF5BW1600 may not necessarily be better. If values from the same distance are considered, SF5BW400 has a lower PLR. Lower SF shows higher deviations between locations per distance, which is expected as it is less robust to propagation losses.
- **NLOS case**: Lower SF shows outliers (empty circles in the plot), which result in high PLR values. For SF10, the deviations are higher than in the LOS case.
- **Best results**: The best results are observed when the nodes are:
    - in front of the AP,
    - elevated above the ground, and
    - don’t have a large surface underneath them.
- **Effect of increasing BW**: Increasing the BW increases the PLR since the signal is more susceptible to interference. This is mainly due to the presence of multipath propagation in the studied scenarios.

Baseline Indoor

The indoor tests were performed for three scenarios: baseline indoor and use cases 2 and 3. The baseline indoor scenario results are shown separately, while use cases 2 and 3 are combined due to similar environments.

In this environment, only a few points were in LOS with the AP. Both LOS and NLOS results are grouped since there was only one location per measured distance in the LOS of the AP. The AP was placed about 0.5 m above the ground, while the nodes were positioned directly on the ground. There are in total eight measurement distances {5 m, 9 m, 15 m, 19 m, 27 m, 30 m, 34 m, 38 m} where each distance had six different locations marked with letters that also correspond to the node's id (see Figure 2.11). Locations belonging to the same distance share the same color. Measurements were not conducted simultaneously across all locations. Instead, we measured different locations that lay on the same distance in a single instance.

We collect approximately two thousand packets from each node per configuration. Here, each node represents a unique location. The collection of data is done only once.

The main studied configurations are the combinations of the following parameters: SF= {5, 10} and BW=1600 kHz. Testing configurations with wider bandwidth was of greater interest since they provide a higher data rate.

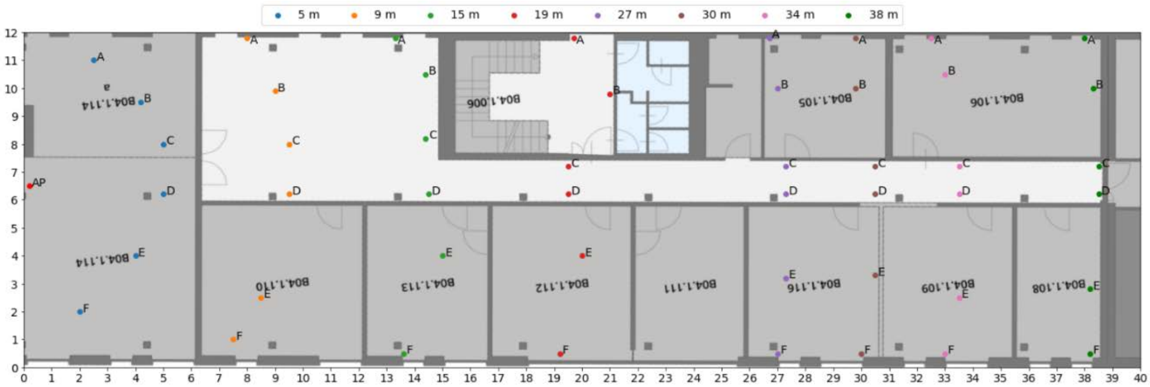
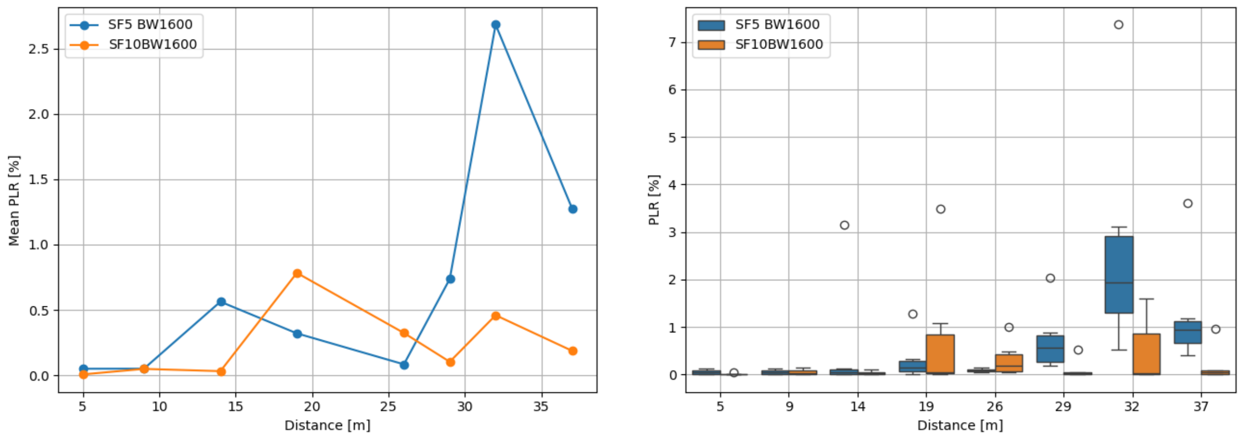


Figure 2.11 Setup layouts of indoor measurements for eight different locations {5 m, 9 m, 15 m, 19 m, 27 m, 30 m, 34 m, 38 m}

Figure 2.12 shows the mean PLR over the increase in distance. Each distance has six different locations, all positioned in a cone in front of the AP.



a) b)

Figure 2.12 Results for SF = {5, 10}, BW = 1600 kHz with location changes a) mean PLR, b) deviations per location.

The main findings:

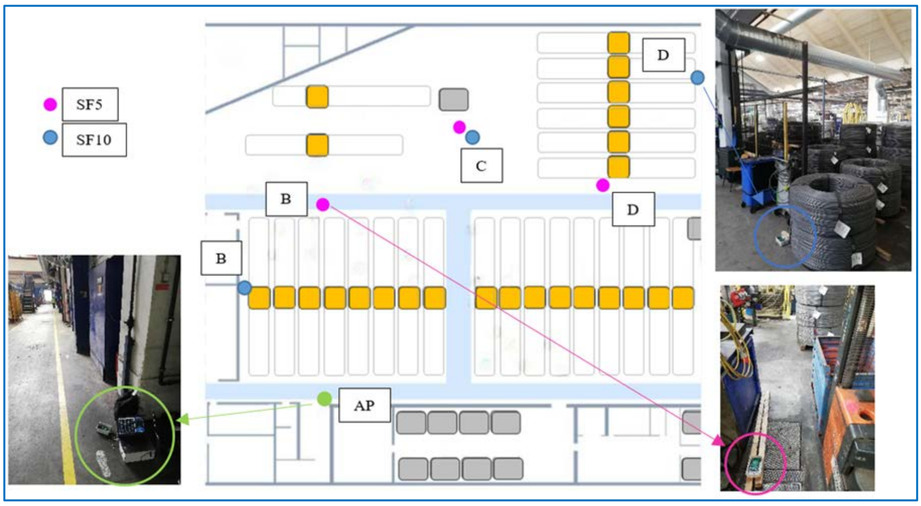
- **Similar PLR for two configurations**: The plot shows little difference in PLR between the two configurations.
- **SF5 PLR increases with distance**: For higher distances, the PLR of SF5 increases, while SF10 does not show any problems. SF10 seems to handle longer distances better than SF5, as it does not show any problems even at higher distances due to higher robustness to interference and lower receiver sensitivity.
- **Lower SF with high BW is favourable up to 40m indoors**: Up to 40m indoors, a lower SF with a high BW offers slightly worse PLR, but it provides high data rates, which can be beneficial for some applications.
- **PLR increase with increased distance**: With further distance increase, the PLR might increase drastically, but the limit needs further testing.
- **Increasing deviation with distance:** The plot shows that as the distance increases, the deviation becomes higher due to the increasing number of reflected signals and signal strength degradation. The evident positioning of LOS and NLOS highlights the significant impact of distance on the performance of these configurations. This further emphasises the need for careful consideration of node placement and distance in real-world applications.

Use Cases 2 Pewag and 3 Spalt

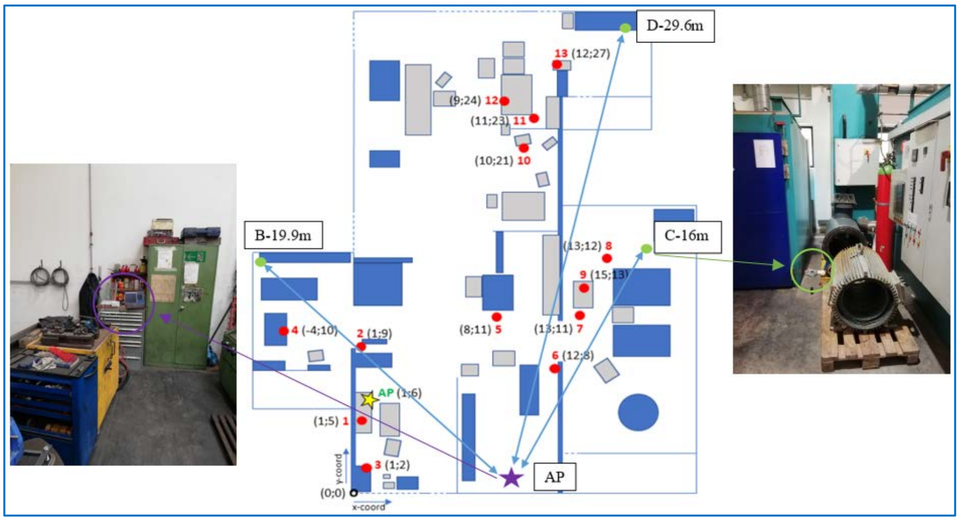
Two use cases (Pewag and Spalt) are combined since the test environments were similar. Both production hall environments were filled with equipment and metallic objects (see Figure 2.13). The nodes were placed in NLOS locations, mainly on the floor, with few exceptions. The AP was placed on the floor for use case 2 and on a table for use case 3. Three locations were tested simultaneously for a single SF and BW configuration.

We collect approximately four to five thousand packets from each node and configuration. Here, each node represents a unique location, and each location has a single round of measurements.

The main studied configurations are the combinations of the following parameters: SF= {5, 10} and BW=1600 kHz. Testing a configuration that provides a higher data rate was of greater interest.



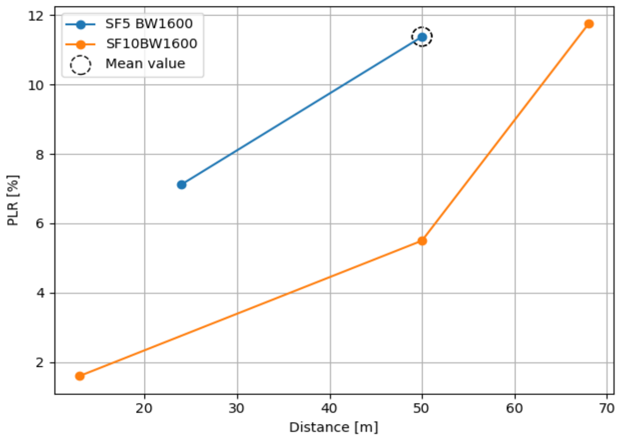
a)



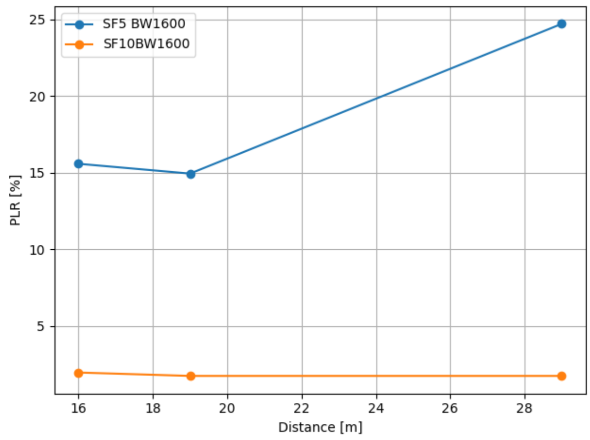
b)

Figure 2.13 Layout of industrial indoor measurements a) use case 2, b) use case 3

Figure 2.14 shows PLR for use cases 2 and 3. Only one node was placed per location, so the deviations are not presented. Only one location has two measurements for which mean value is calculated (encircled in Figure 2.14 a)).



a)



b)

Figure 2.14 PLR for SF={5, 10} and BW=1600 kHz in a) use case 2, b) use case 3; Location with two measurements and a mean value is encircled.

The main findings:

- **Different behaviour in different indoor scenarios**: The behavior in this indoor scenario is different compared to the office indoor scenario. Both scenarios present obstacles, but the materials from which these obstacles are constructed differ. The office environment is less harsh as it contains mostly hollow, non-concrete walls. On the other hand, use cases 2 and 3 feature metal machinery and concrete walls, which increase reflections.
- **Better performance of SF10 and more robust across different environments**: SF10 shows much better performance and a slower increase in PLR with distance compared to the lower SF. It shows consistent performance across different scenarios, including the office and indoor environments.
- **Comparable performance of SF10**: The performance of SF10 in the use case 3 scenario is comparable to that in the office scenario.
- **Poor performance of SF5**: SF5 does not perform as well as it does in the office scenario.
- **Lower SF is more sensitive to the environment**: The environment, particularly in scenarios with many equipment and metallic objects, significantly affects the performance of lower SF, such as SF5.
- **Use case 2 had fewer walls:** By having a more open space, signals are less obstructed, providing better results for SF5.
- **Environment plays a crucial role in signal propagation**: The presence of equipment and metallic objects in the environment can significantly impact signal propagation, highlighting the importance of considering the environment in network planning and optimisation.

Indoor and Outdoor Mix

This scenario covers LoRaWAN tests for use case 4. The chapter shows the locations of the nodes as well as the results that were obtained.

Use Case 4 Chemical Industry

The LoRaWAN MAC layer was used for this use case without the full network backbone. This means it did not use servers but used the MAC layer functionality. Only one device at a time sent packets to the AP (see Figure 2.15). The sending device was moved from location to location, where multiple configurations were tested at each location. The numbers in the figure represent different measurement locations. The lowest and highest BW options are tested with various SF values. In this scenario, the focus was put on testing different combinations of SF= {5, 6, 9, 12} with the lowest and highest BW={200 kHz, 1600 kHz}. For this scenario, only around 100 packets were collected per location due to time constraints.

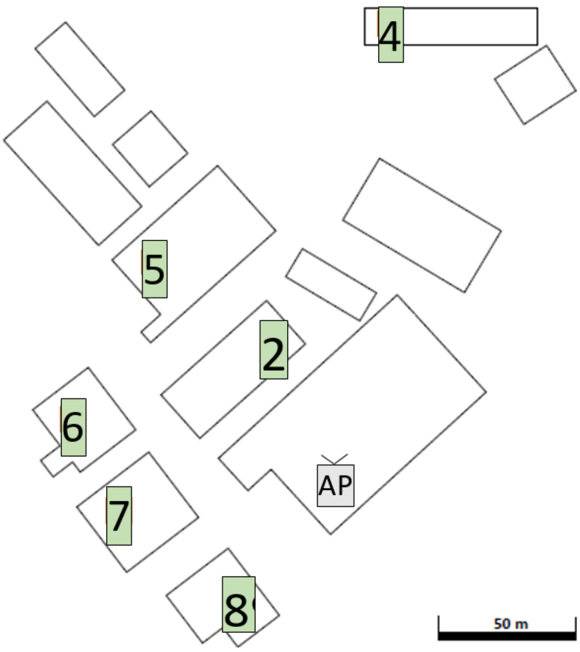


Figure 2.15 Layout of the measurements with different measurement locations

Table 2.3 shows PLR for different locations. Multiple locations were tested, and only the ones that provided results are shown. The locations are a mixture of indoor and outdoor scenarios. The AP was placed in one building on the first floor close to the window while nodes were taken to different buildings where some locations were deep inside the building and even in the cellar, making the signal propagation even harder.

Table 2.3 Inter-building measurements Mixture of indoor and outdoor NLOS scenario.

Configuration	Location	Distance [m]	PLR [%]
SF6 BW200	8	34.22	2.83
SF12 BW200	2	47	63.57
	4	172	80.22
	5	96.39	32.89
	6	86.61	46.24
SF5 BW1600	8	34.22	7.14
SF9 BW1600	6	86.61	98.69
	8	34.22	1.85

Location number 8 shows the lowest PLR for the highest SF. SF12 was not tested for this location since the PLR was low enough when SF9 was used. Location 6 with SF9 had a high PLR, so the lower SF were not tested since a worse PLR was expected.

Results show that communication between buildings with multiple walls in the communication path affects the PLR significantly. Only the location near the AP showed low levels of PLR, while others performed poorly. The positioning of the nodes was versatile between the locations, which affected the PLR more than the distance.

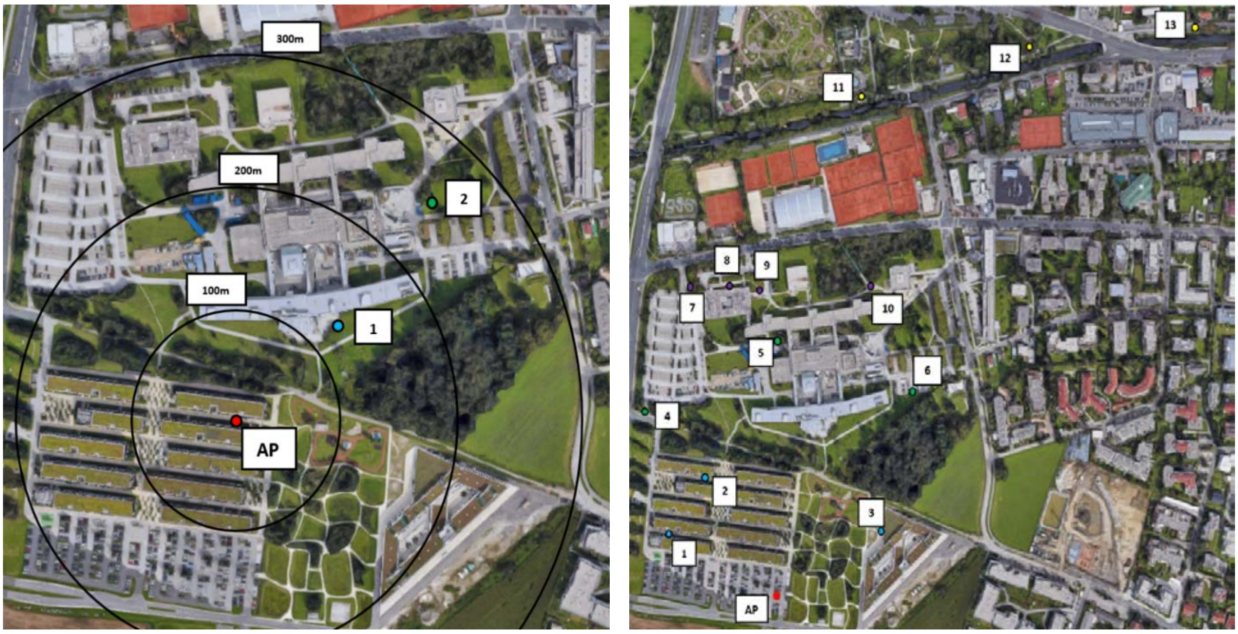
Sub-GHz LoRa

We conducted our tests in two scenarios, each with a single sending node moved to various locations. This eliminated the need for any MAC protocol. In the first scenario, we placed the AP inside the office, 1 m above the ground in the centre of the room (see

Figure 2.16 a). We tested several locations at three different distances from the AP. However, most of these locations had weak or no signal, and only two produced some data. We marked these locations as one and two in the figure. Since we could not find enough locations with good signal, we relocated the AP.

In the second scenario, we put the AP on a garage roof and tested different locations around it (see Figure 2.16 b). We had three measurement locations for each distance, where the same color was used to mark the locations with the same distance in the figure. Three distances had only one measurement location each: locations 11, 12 and 13. When the AP was in the office, around two thousand packets were collected per location and configuration. In the second case, when AP was moved to the garage, around five hundred packets per location and configuration were collected. It is worth mentioning that duty cycle regulations were not taken into account to decrease the time needed to collect data.

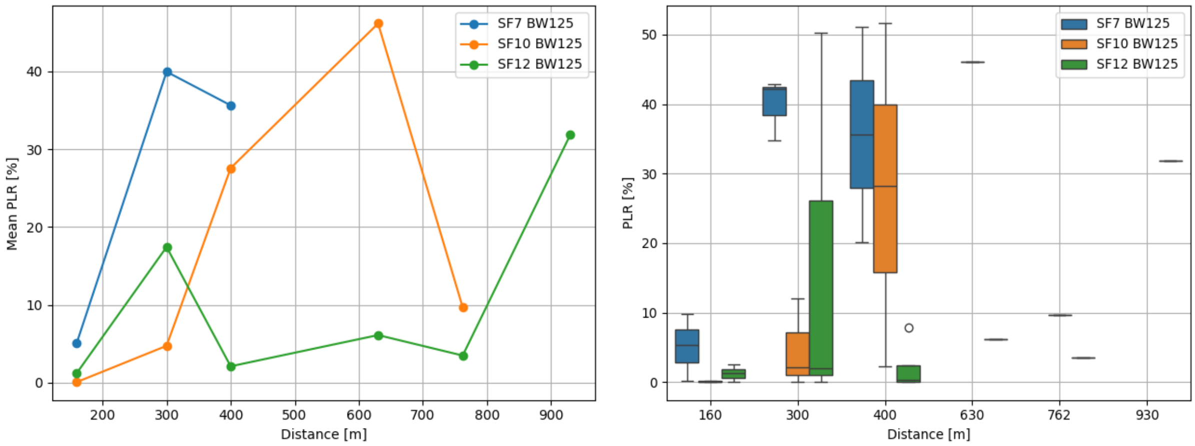
Regarding parameter configuration for this scenario, bandwidth was fixed to BW=125 kHz since only SF7 can use BW=250 kHz, and we wanted to compare the differences in PLR between different SFs for the same BW. Regarding SF, the lowest, mid and highest values are chosen SF= {7, 10, 12}.



a) *b)*

Figure 2.16 Layout of the measurements: a) AP in the office, b) AP on the roof of the garage

Figure 2.17 shows both mean PLR and deviation results in an outdoor setting. The scenario when AP was inside the building did not provide enough measurement locations to compare to the case when AP was placed on the roof.



a) *b)*

Figure 2.17 Results for AP on the roof of the garage a) mean PLR, b) PLR deviation per location.

The main findings:

- **Significant Impact of AP position**: The position of the AP significantly impacts the performance of different SFs, particularly SF7. This suggests that careful consideration should be given to AP placement in network planning and optimisation.
- **Performance of Higher SF**: Higher SFs show smaller differences when the AP is inside. In the case of SF12, it even achieves better results when the AP is inside, but as the distance increased, the connection got worse to the point of being unable to measure anything. The robust performance of SF12 is due to longer signal toa and better sensitivity.
- **Deviation with Distance**: As the distance increases, the deviation gets higher, apart from SF12 in the case of 300 m, where the deviation is higher than the following measurement distance. The variation in PLR with distance and SF underscores the complex interplay between these factors and highlights the need to carefully consider network planning and optimisation.
- **Comparison with Standard**: These results show much smaller ranges than what is provided in the standard for urban areas, which is 4.8 km.

LoRaWAN with sub-GHz LoRa

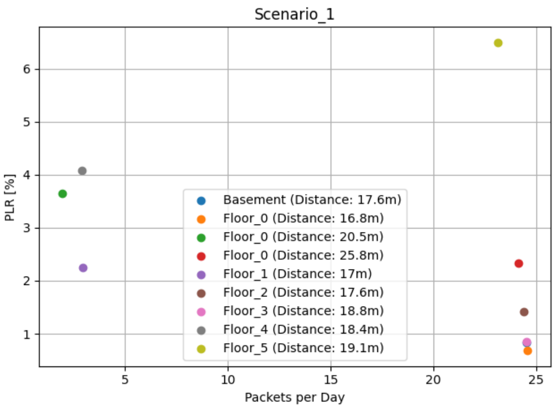
Use case 4 Chemical Industry

This use case covers three different scenarios. The AP was placed in the server room in the first scenario (shown in Figure 2.18a). In the second scenario, the AP was moved to another room while the nodes were left at the same locations, creating around 60 m of distance between the AP and the nodes. In the third scenario, the AP and nodes were placed in different buildings except location 4, where the node is in the same building as the AP (Figure 2.18 b).

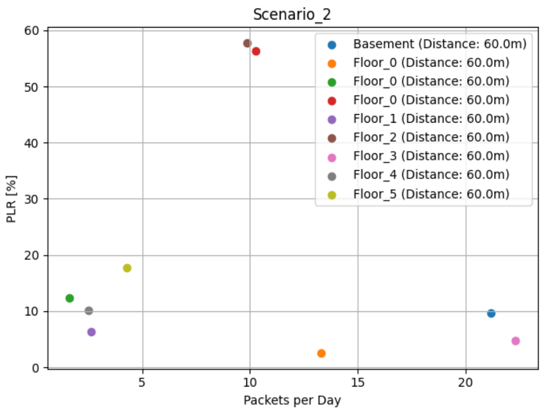
In this campaign, data was collected over different time periods. Over 23 weeks for the first scenario, 16 weeks for the second scenario and 17 weeks for the third scenario.

Figure 2.18 Layout of the measurements: a) scenarios 1 and 2, b) scenario 3

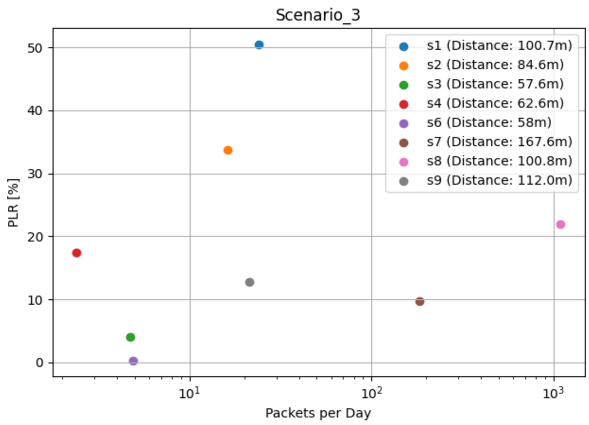
Figure 2.19 shows PLR on the y-axis and the number of packets sent on the x-axis. Since the adaptive data rate (ADR) setting was used, there is no direct information on the SF and BW configuration. ADR chooses which combination of SF and BW to use based on the current channel conditions. Class A nodes were used for the measurements.



a)



b)



c)

Figure 2.19 PLR for nodes located on different floors a) AP in the same building as nodes, b) AP in different building, c) AP and nodes in different buildings

The main findings:

- **Scenario 1 - ADR and PLR**: Scenario 1 shows that ADR works by keeping the PLR low. An increase in distance does not necessarily correlate to a worse PLR or smaller data rate.
- **ADR's Effectiveness**: The effectiveness of ADR in keeping PLR low, even with an increase in distance, highlights the potential of this technology in maintaining good performance in various scenarios.
- **Impact of Obstacles and Node Placement**: The node on floor 5 (in scenario 1) shows the worst result, suggesting that obstacles and node placement significantly decrease performance. The significant impact of node placement and the environment on PLR underscores the importance of these factors in network planning and optimisation. This is particularly important when dealing with obstacles and harsh environments.
- **Scenario 2 - Impact of AP Position**: By moving the AP to a different room in scenario 2, it is confirmed that for the same distance, PLR is different, suggesting again that the positioning of the nodes is a significant factor.
- **Scenario 3 - Harsh Environment and Node Placement**: When the nodes are moved further away to a different building, making the environment significantly harsher, PLR

increases dramatically, indicating again the impact of the environment and node placement on PLR.

PLR to range relationship

We conducted some tests to understand the relationship between PLR and range. The question investigated is: With a PLR=10%, what **range** can be achieved in indoor and outdoor scenarios? The results are summarized in the following tables.

Table 2.4 Range for 2.4 GHz case.

2.4GHz	Indoor	Outdoor	Data rate
SF 5BW1600	50m	100m	196 Kbps
SF 10BW1600	60m	175m	
SF5 BW400	-	150m	48 Kbps
SF10 BW400	-	210m	

Table 2.5 Range for sub-GHz case.

Sub-GHz	Outdoor	Data rate
SF7 BW125	170m	50 bps
SF10 BW125	780m	6.28 bps
SF12 BW125	810m	1.8 bps

Chapter Afterword

LoRa has become a widely used technology in IoT applications due to its long-range, low-power communication capabilities, making it a cornerstone technology in fields like smart cities, agriculture, and environmental monitoring. However, from a research perspective, it offers considerable potential for innovation, particularly in enhancing reliability and scalability in complex environments. We explored this potential by testing LoRa in an industrial IoT setting within a chemical plant, where the challenges of interference, structural obstructions, and dynamic conditions provided a rigorous environment for evaluation. This blend of practical utility and research potential makes LoRa an exciting area for continued exploration.

Dr. Christian Raffelsberger
Senior Researcher

Impulse-Radio Ultra-Wideband (UWB) is a short-range wireless communication protocol described by standard IEEE 802.15.4z-2020, similar to Wi-Fi or Bluetooth. It uses radio waves of short pulses over a spectrum of frequencies ranging from 3.1 to 10.5 GHz in unlicensed applications. The term UWB is used for a bandwidth (BW) that is larger or equal to 500 MHz or a fractional bandwidth (FBW) greater than 20%.

3 Ultra-Wide Band (UWB)

3.1 Introduction

The history of UWB technology dates back to the time of the first man-made radio when Marconi used spark-gap (short electrical pulses) transmitters for wireless communication. In 1920, UWB signals were banned from commercial use and were restricted to defense applications under highly classified programs for secure communication. It was not until 1992 that UWB started receiving noticeable attention in the scientific community.

Developments in high-speed microprocessors and fast-switching techniques have made UWB commercially viable for short-range, low-cost communication. Early applications include radar systems, communication, consumer electronics, wireless personal area networks, localization, and medical electronics. In 2002, the US Federal Communication Commission (FCC) was the first organization worldwide to release UWB regulations allowing the unlicensed use of the allocated spectrum.

UWB technology transmits data stably and quickly within a short range. Due to its unprecedented accuracy, speed, and reliability, it is an ideal technology for the indoor location of moving targets in space-sensitive and complex environments. Many industry observers claim UWB could prove more successful than Bluetooth because it has superior speed, is cheaper, uses less power, is more secure, and provides superior location discovery and device ranging.

3.1.1 Technical overview

Table 2.1 shows the technical parameters of the UWB technology.

Table 3.1 Technical overview of UWB

Parameters	Values
Frequency band, GHz	3.5-8
Bandwidth, MHz	500, 1000
Effective Data rate	Up to 4Mbps
Power Rx/Tx, mW	350/155
Maximum distance*(we (me and Jorge)are using this with PLR below 5%, real maximum always higher), m	25
Latency	320 µs
Modulation scheme	BPSK
Scalability	Yes
Security features	Yes
Mobility support	Yes
Channel Utilization	Not necessary but can be added

3.2 UWB Properties

3.2.1 Strengths

UWB presents an attractive solution to the problems for most of today's wireless industry research and applications. Let us consider them in more detail.

Key characteristics

01 High data rates and low latency

02 Robustness in multipath environments

03 Low power consumption

No RF spectrum limitations

The limitations of high frequency (HF) spectrum availability hinder the evolution and sprawl of wireless technologies. UWB technology does not use HF carriers, bringing many new advantages and opportunities. Today we see a pattern of hardware technology development where the degree of integration of single-chip solutions is much higher than it was in the recent past and is constantly growing. Therefore, UWB hardware solutions are expected to be more than just PHY devices or even PHY+MAC devices. Such hardware solutions should include a complete UWB transceiver together with a flexibly configurable Input/Output (I/O) controller in a single device, enabling easy integration of UWB electronic components into a wide range of applications.

Speed and latency

The same UWB device can be scaled in terms of speed over a huge range, which is simply essential for very low speed applications (driven by the need to keep power consumption low), such as handheld measuring devices.

One more advantage of the technology is low latency. The extremely low latency makes UWB an ideal candidate for automatic real-time positioning systems for fast-moving objects, such as cars, UAVs etc. The latency value depends on the configuration of the packet. It is the sum of the preamble duration and the payload duration. A commonly used configuration with a preamble length of 64 symbols, a pulse repetition frequency of 64 MHz, and a payload of 125 bytes will result in a latency of 250 µs.

Multiple channels

UWB can support hundreds of channels simultaneously (as opposed to three in 802.11b and ten in 802.11a). It is like driving: it is much more comfortable and better to drive on a multi-lane motorway than on a single-track road.

Integration to the different types of networks

UWB technology can function as a Personal Area Network (PAN), Local Area Network (LAN) and Wide Area Network (WAN) simultaneously. The ability of UWB to serve as PAN, LAN, and WAN simultaneously means it can effectively unify the functionalities of Bluetooth (for PAN), Wi-Fi (for LAN), and cellular technologies like 3G (for WAN) into a single network. This convergence enables a single UWB-equipped device to seamlessly transition between these networks.

Lower cost and complexity

Devices using the HF spectrum require a real radio receiving system and therefore they have more complex designs and components, their price is higher and they consume much more power. They are also less reliable than UWB devices, which operate at levels below the noise floor of conventional radio systems. UWB devices are low-power, undemanding in terms of equipment parameters and need only a few external components.

Global compatibility

Variations in the assignment of radio spectrum in different countries prevent global compatibility for devices using the radio spectrum. Without such limitations, UWB technology provides the prerequisites for future global interoperability.

Greater Security

In addition to the specific nature of the UWB signal and equipment, UWB devices utilize signal power at almost noise level, which protects the information being transmitted - UWB signals are virtually impossible to receive by a non-target system, especially at some distance from a functioning device. This fact makes UWB communication perhaps the most secure of all wireless communication systems in terms of protection against unauthorized access to information. The high degree of data protection is a consequence of low power spectral density and very short time of pulses. As a result, UWB is difficult to detect and intercept. The latest revision of IEEE 802.15.04z-2020 increased data security by introducing a new physical layer of line-frequency modulation, and added encryption methods such as scrambled timestamp and substitution cipher. Cheap and accurate location detection

One of the main advantages of UWB is its resistance to multipath effects due to its high temporal resolution and short wavelength. This is why the technology is a low-cost solution for distance measurement and tracking: UWB is 100 times more accurate than Wi-Fi or Bluetooth Low Energy in such tasks and is accurate to within a few centimetres. This offers great potential for many location applications as well as short-range human-machine interfaces.

Coexistence

Because UWB signals do not interfere with each other or with traditional radio frequency carriers, the technology offers tremendous communication opportunities by creating a new, self-contained communications environment that can peacefully coexist with other functioning wireless technologies. The use of ultra-wide bandwidth in turn gives high immunity to frequency selective hiccups when compared to Bluetooth and Wi-Fi. This makes it possible to deploy multiple UWB-based systems in the same environment without causing conflicts with other standards.

The ECC definition of an UWB system is any radio transmission technology with a spectrum occupancy of more than 20 per cent of the center frequency or a minimum of 500 MHz. Realizing the benefits of this new technology that could be seen in consumer electronics applications, in 2002 the ECC licensed spectrum from 3.1 GHz to 10.6 GHz specifically for this purpose. Additional spectrum is available for use in medical, scientific organizations and for fire and emergency services. The UWB radio interface for information transmission requires the use of the full 7.5 GHz wideband or an available portion of it. The FCC has defined a specific minimum frequency bandwidth of 500 MHz at -10 dB. This minimum bandwidth, in conjunction with other FCC requirements, is intended to protect equipment operating above this frequency range. The flexibility provided by the FCC rules greatly expands the possibilities for UWB communication systems. Designers are free to use combinations of 500 MHz wide sub-bands within the frequency spectrum, to optimize system quality, power dissipation and design complexity. UWB systems can maintain the same low transmit power as if they were using full bandwidth. This is achieved by interleaving symbols in these sub-bands.

For multi-band systems, information can be transmitted using traditional single-carrier pulse methods or more complex multi-carrier methods. Single-carrier pulse systems transmit the signal by modulating the phase with very narrow pulses. While this improved technique allows for a very simple transmitter design, it has several disadvantages. These include the following: it is difficult to collect sufficient signal energy in typical environments (where there are many reflective surfaces) using only one Radio Frequency (RF) circuit; switching time requirements can be very stringent for both receiver and transmitter; the received signal processing circuits are very sensitive to group delay fluctuations introduced by components of the analogue external stages; and the width of the frequency spectrum may be narrowed somewhat on purpose to reduce narrowband interference.

Spectrum Flexibility

Since the frequency spectrum for UWB devices is unlicensed, all UWB wireless devices sharing this spectrum should be able to co-exist with each other without problems. Regardless of the current state or future state of frequency allocation and radiation restrictions in different regions of the world, MB-OFDM is able to enforce local (geographically) frequency restrictions by dynamically muting certain tones or channels in a software-defined manner. This flexibility is not offered by competing solutions, providing huge potential for the adoption of UWB systems worldwide.

Complexity and power dissipation

MB-OFDM systems are specifically designed to reduce the complexity of their implementation. A single analogue receiver circuit simplifies the overall architecture of the whole system and therefore the DAC/ADC resolution and internal accuracy of the digital baseband controller can be significantly reduced. Relatively large carrier spacing also relaxes phase noise requirements in frequency synthesis circuits and improves robustness to synchronization errors. Mobile device uptime is a very important factor. The MB-OFDM can provide a minimum of two hours of continuous operation from a single battery (350mAh) under typical conditions.

3.2 UWB Properties

3.2.2 Weaknesses

Distance dependence of transmission data

Due to the short pulse length and ultra-wide spectrum, the BW of UWB drops much more strongly (compared to narrowband transmission) with distance. Much faster than narrowband wireless standards, such as 802.11a/g, which provides throughput of up to 54 Mbit/s at a distance of up to 100 m - UWB at a distance of up to 10 m is 27 Mbit/s, at a distance of 50 m - already 5-6 Mbit/s. This is because the dispersion of electromagnetic radiation in the air leads to significant distortion of the ultra-wideband signal compared to the narrowband signal. The distortion accumulates with distance and finally leads to the fact that the signal at the receiver input undergoes significant distortion.

Limited usage in some areas of the world

The availability of spectrum in a number of countries is limited by government agencies and security services.

Pricey IC implementation

Transceivers for the physical layer of UWB have higher prices compared to narrow band implementations.

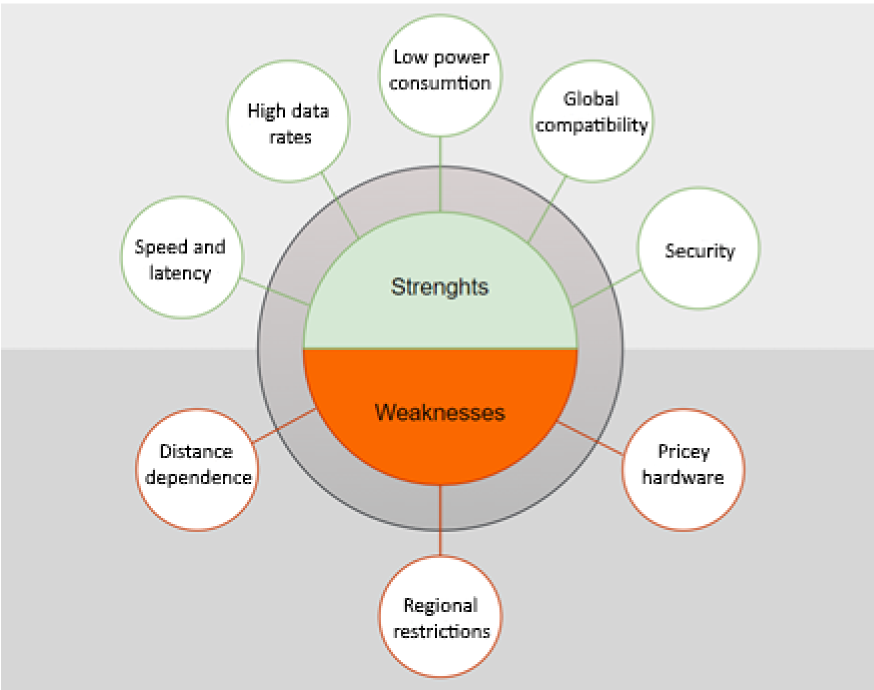


Figure 3.1 Illustration of strengths and weaknesses of UWB

3.3 UWB in Industrial Applications

UWB technology provides fast short range wireless communication in industrial environments. It’s secure, low-power communication supports real-time data transmission for enhancing efficiency and safety.

Use cases

01 Experimental setup in the office environment

02 Pewag: Condition and energy monitoring of welding machines

03 Spalt: Temperature and vibration monitoring for machine maintenance

3.3.1 Use case requirements

UWB technology was tested as a wireless technology for transmission of condition monitoring data. All use cases involve **vibration condition sensor data** as a payload for UWB packets.

Use case 1:

- Transmission range of up to 20 m
- Multiple device support
- Star network topology
- Different types of environments: office to industry

Use case 2:

General:

- Industrial environment

Specific:

- **2.1 requirements** (Optimization of the welding process for reducing power consumption)
  - High frequency analog measurements for current and voltage Distributed system/mesh
- **2.2 requirements** (Controlling quality of a single welding machine)
  - High frequency analog measurements for current and voltage
- **2.3 requirements** (Vibration monitoring on bending machines to prevent damage during the working process)
  - Control of «no human zone»

Use case 3:

- Analog and digital sensing of the condition of the motor
- Industrial environment
- Star network topology
- Coexistance with other technologies

Network condition measurements, including packet lass rate (PLR) and received signal strength indicator (RSSI) metrics were performed in all use case scenarios.

Initial test:

- Office space
- Industrial environments test on factory side

3.4 Technology Evaluation

We study the intricacies of designing, implementing, and evaluating an industrial Ultra-Wideband (UWB) sensor network with a primary focus on high-rate applications, specifically machine vibration monitoring. The following aspects are explored.

Goal	Description
Design of a Flexible Medium Access Control (MAC) Layer	We have developed a robust MAC layer tailored to the unique requirements of industrial settings. This MAC layer operates seamlessly atop the UWB physical (PHY) layer and is designed to offer flexibility and adaptability.
Parameter Analysis	To cater to different use cases, we conducted an in-depth analysis of how various parameters can be adjusted. These adjustments are crucial in achieving the desired levels of latency and reliability for specific industrial applications.
Proof-of-Concept Implementation	Our team successfully implemented a proof-of-concept utilizing a commercial UWB platform and custom design boards. This implementation not only validates the potential of UWB technology but also showcases the effectiveness of our custom-designed MAC layer in the context of machine vibration monitoring.
Experimental Comparison	To further assess the performance of our UWB testbed, we conducted experimental comparisons with existing industrial solutions. This comparative analysis provides valuable insights into the advantages and capabilities of our approach.

In the context of our industrial UWB sensor network designed for machine vibration monitoring, different operation modes are essential to cater to various throughput requirements. The choice of operation mode is contingent upon the specific vibration patterns that need to be detected and analyzed.

For instance, consider a sensor that samples vibration data at a rate of 40,000 samples per second (40 KS/s). In this configuration, the sensor generates a substantial 2.88 Mbps of data. However, the required throughput may vary based on the application's needs and the vibration patterns under scrutiny.

The ability to switch between these operation modes allows our UWB sensor network to adapt to the specific requirements of different industrial applications. Whether the focus is on high-frequency vibration analysis or conserving bandwidth for simpler scenarios like energy monitoring, temperature monitoring, our system's flexibility ensures optimal performance and resource utilization.

Throughput Modes

High Throughput Mode: In scenarios where high-frequency vibration patterns are crucial for analysis, the sensor operates in a high-throughput mode, sampling at 40 KS/s, and generating a data rate of 2.88 Mbps. This mode allows for the capture of the entire range of vibration frequencies relevant to assessing the machine's state.

Medium Throughput Mode: In situations where a slightly lower sampling rate suffices, the sensor can be configured to operate at 10 KS/s. This mode yields a data rate of 0.72 Mbps, still providing ample information to monitor and analyze vibration patterns effectively.

Low Throughput Mode: For applications where only essential vibration data is required, the sensor can be set to a reduced sampling rate of 1 KS/s. In this mode, the data rate is a modest 0.07 Mbps. This configuration may be suitable for scenarios where the vibration patterns to be detected are relatively simple or infrequent.

3.5 UWB Features

Designing a wireless vibration monitoring system for industrial applications necessitates careful consideration of two paramount features. These features are fundamental to ensuring the system's effectiveness and reliability in the demanding environment of industrial machinery.

Flexibility in operation modes and resource allocation	**System reliability**
One of the primary challenges in designing a wireless vibration monitoring system is accommodating nodes with different operation modes. Vibration sensors may need to operate at various sampling rates based on the specific application and the vibration patterns to be analyzed. Therefore, a resource allocation design must efficiently multiplex sensors with vastly different bandwidth demands. To achieve this flexibility, the network should enable vibration sensors from several machines to communicate with a single access point (AP). This approach not only optimizes the network implementation cost but also streamlines management and maintenance. Engineers and operators should have the capability to seamlessly switch between operation modes to tailor the system's performance to the exact requirements of their application.	The second critical aspect of wireless vibration monitoring design is system reliability, particularly in terms of packet losses. In an industrial setting, the reliability of the wireless system should be on par with that of a wired implementation. However, defining a precise reliability goal can be challenging as it varies depending on the specific environment and application. An essential consideration in ensuring reliability is the propagation environment. The coverage area that can be reliably served by a single AP is inherently limited by the propagation characteristics of the wireless signals. Environmental factors such as interference, signal attenuation, and obstacles within the factory floor influence the network density required for reliable operation.

Balancing flexibility and reliability is a complex undertaking in wireless vibration monitoring design. Engineers must devise resource allocation strategies that efficiently accommodate diverse sensor requirements while also accounting for the propagation environment's constraints. By addressing these two key features, a wireless vibration monitoring system can deliver the necessary adaptability and robustness to thrive in industrial settings.

Ultimately, the successful design of such a system requires a deep understanding of both the unique demands of vibration monitoring applications and the intricacies of wireless communication technology.

The UWB standard offers data rates of up to 27 Mbps, providing ample capacity to support all sensor configurations as well as the concurrent operation of several nodes per access point (AP). Although the IEEE 802.15.4z-2020 standard is designed for general-purpose applications, its adaptability allows for the creation of a customized medium access control (MAC) tailored to the unique demands of industrial applications, with a specific focus on vibration monitoring.

3.6 Testbed Implementation

To showcase the practical implementation of our concepts, we have designed and implemented a small-scale network using EVK1000 UWB boards. These off-the-shelf devices effectively demonstrate the feasibility of our test case. The transceiver integrated into our boards is a complete single-chip CMOS UWB IC, fully compliant with the IEEE 802.15.4-2011 specification. It supports data rates of 110 kbps, 850 kbps, and 6.8 Mbps over link distances of up to 290 meters.

For small payload sizes (as shown in Figure 3.2), we observed that locations over 40 meters away, even in non-line-of-sight (NLOS) conditions, could be reached. However, as the payload size increases, the connectivity over NLOS areas deteriorates rapidly. With the maximum supported payload of 1024 bytes, even reaching the corners of the office near the border wall becomes challenging. Thus, different combinations of effective load have been tested, which are widely used in wireless sensor networks. Figure 3.4 shows schematically the coverage we obtained for different combinations in an office environment. The expected maximum connection distance ranges from 15 to 25 meters. The smaller payload provides wider coverage but results in a higher overhead factor. The measurement procedure is as follows: The sending node is positioned at a fixed location and the AP is carried within office while monitoring the packet reception at a PC. The positions where the link between node and AP is lost are marked in a floor plan of the office to compute coverage.

An additional advantage of Ultra-Wideband (UWB) technology is its capability for precise positioning. This precision is attributable to its high BW, typically around 500 MHz, with an option up to 1 GHz. Such a wide BW facilitates various positioning techniques that leverage precise time-of-flight measurements, with resolutions reaching up to picoseconds. In our research, we have extensively tested the stability and resolution, achieving microsecond accuracy for our node devices. Moreover, we explored the application of Time Division Multiple Access (TDMA) in this context, which further underscores the potential of UWB technology in high-precision positioning systems.

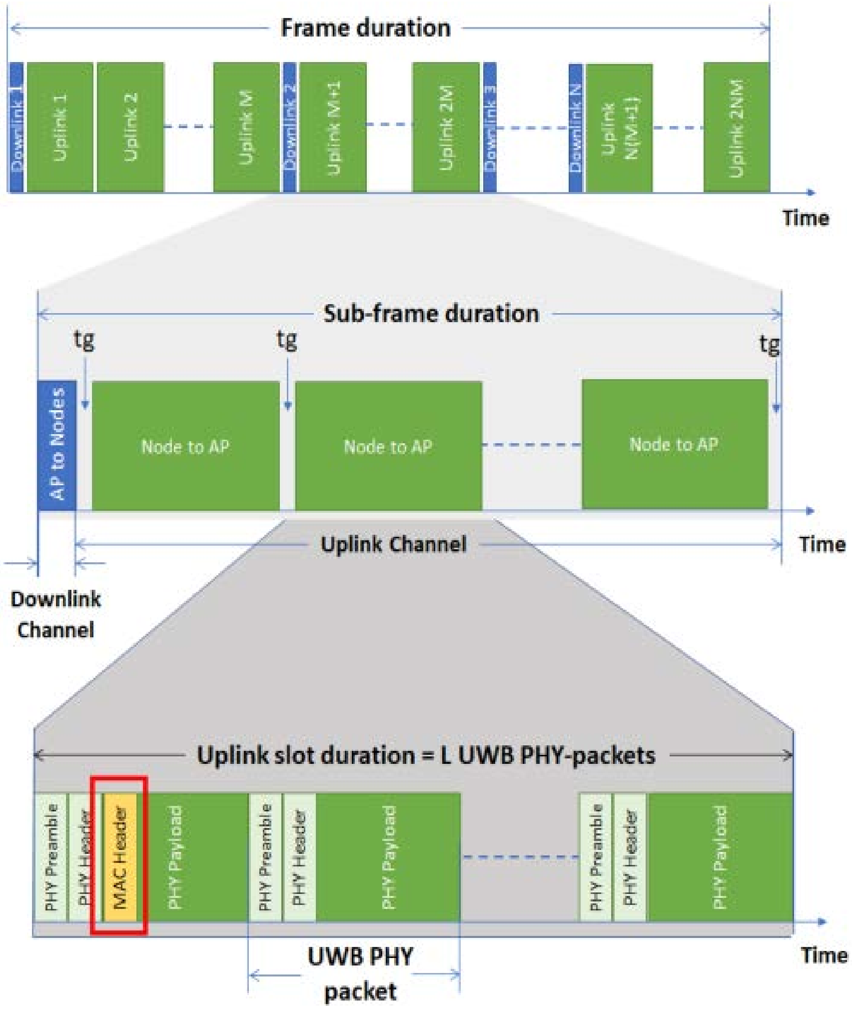


Figure 3.2 – Design of the custom TDMA based protocol

The network architecture is composed of centrally coordinated wireless sensor clusters. These clusters adhere to a star topology, where resources and channel access are efficiently coordinated by a central AP within each cluster. This architecture is widely adopted in industrial wireless networks because it offers deterministic latency, ensuring that data transmission occurs predictably and reliably. Additionally, it optimizes the utilization of air resources, which is critical for achieving efficient and responsive communication. Example of such implementation is shown by Figure 3.3.

Access opportunities are arranged within frames, with their length determined by the maximum number of transmission channels allocated by the AP for the uplink, as depicted in the upper portion of Figure 3.2. Downlink slots are periodically interspersed among the uplink slots to ensure timely synchronization and control signaling. All uplink slots maintain uniformity, while the value of M, signifying their frequency and duration, depends on mobility expectations.

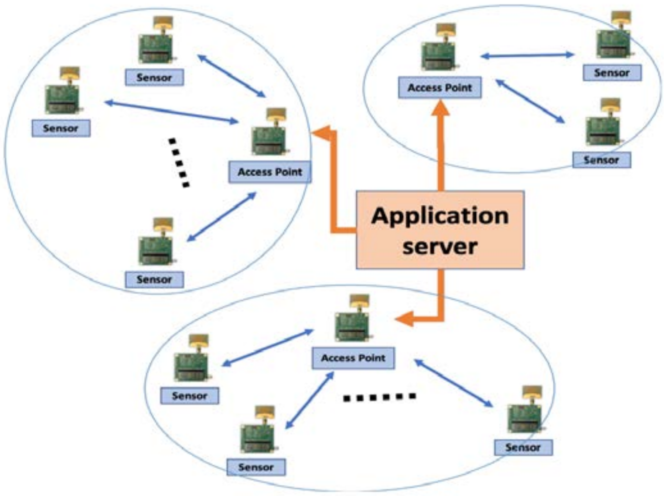


Figure 3.3 – UWB star network topology

This distinction justifies the creation of a custom MAC scheme, which prioritizes uplink resources over downlink.

Uplink slots are equitably distributed among the nodes, with some reserved for the retransmission of lost packets. The number of reserved slots is contingent on the PLR under normal operating conditions. To accommodate the timing tolerances inherent in our commercial platform, each slot includes a guard interval.

From a practical perspective, both the downlink and guard intervals introduce inefficiencies that diminish the AP's capacity. Therefore, there is an imperative to minimize them. Fewer but lengthier uplink slots decrease the need for guard intervals but heighten latency for a fixed number of nodes connected to the AP. Conversely, shorter slots reduce latency but demand a greater share of airtime allocated to guard intervals. In light of these considerations, we adopt a balanced solution that prioritizes network capacity over latency, as the latter is not a critical concern in our specific test case.

To expedite network registration, the Access Point (AP) periodically disseminates a comprehensive list containing information about both occupied and available uplink slots. This proactive approach eliminates the necessity to set aside specific time intervals for network registration, ensuring a seamless experience for nodes that are already connected to the network.

Nodes seeking to join the network initiate the registration process by requesting resources on one of the available slots, which are selected randomly. Upon receiving a registration message, the AP promptly allocates the requested slot to the node and promptly removes it from the broadcast list. In cases where the requested slot remains listed, the node initiates the registration process again to ensure successful registration.

This streamlined registration mechanism optimizes network efficiency, minimizes delays, and simplifies the onboarding process for nodes, ensuring a robust and agile wireless sensor network.

In the context of industrial networking, a key performance metric is the quantity of retransmission slots required to achieve a specified PLR. This metric is influenced by the initial throughput and PLR prior to retransmissions. Through our research, it has been determined that a single retransmission slot is sufficient for a group of 12 nodes, assuming an effective throughput of 3Mbps, to compensate for a 5% packet loss. Furthermore, it has been observed that in our network configuration, the typical connections include both LOS and NLOS links. These links are established to nodes positioned at distances ranging from 18 to 25 meters from the AP, all within the same room as the AP. This finding is crucial for designing and optimizing industrial networks to ensure reliable and efficient communication.

3.6.1 Findings

Use Case 1 Eologix - Experimental setup

- One AP and three sensor nodes were implemented using EVK1000 boards. AP collects data and relays it to a USB-connected PC for in-depth analysis.
- To maximize network capacity, 6.8 Mbps transmission mode is used, with 850kbps showing only marginal advantage. The 110 kbps transmission mode is not suitable for the considered use cases.
- One critical finding from our experiments was the need for a guard interval of 0.1 ms between transmissions from different boards to prevent packet collisions during synchronous transmission. This precaution proved essential in maintaining the reliability of data exchange within our network.
- To analyze the link range, the length of the preamble sequence preceding each PHY packet was adjusted, with marginal gains. We opted for the minimum preamble length of 64 symbols.

Consequently, we conclude that a payload size between 256 and 512 bytes represents a practical compromise for industrial applications, with an expected maximum link distance ranging from 15 to 25 meters. Lower payloads provide broader coverage but result in a higher overhead ratio. The payload size is selected to yield a PLR of 20% over a 25-meter line-of-sight (LOS) link, ensuring a balance between range and overhead for practical industrial applications (Figure 3.4).

This meticulous analysis and optimization of payload size, preamble length, and guard intervals demonstrate our commitment to tailoring the network for real-world industrial scenarios, where reliability and coverage are paramount.

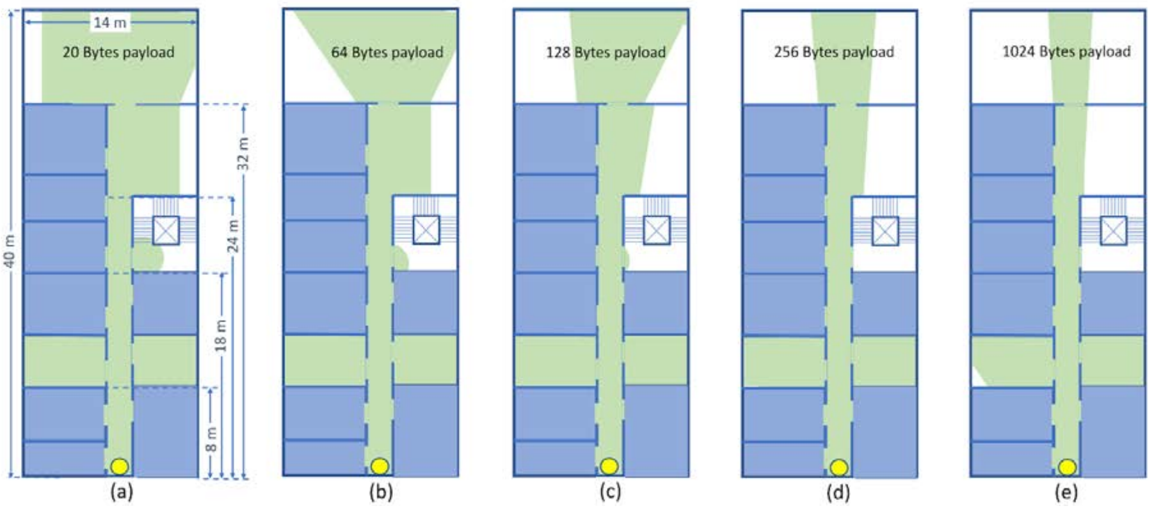


Figure 3.4 – Illustration how payload size influences coverage area of the UWB transmissions

The main findings:

- **Higher payload size deteriorates connectivity rapidly**: For small payload sizes (as shown in Figure 3.4 (a)), we observed that locations over 40 meters away, even in NLOS conditions, could be reached.
- **Distance to PLR compromise**: We conclude that a payload size between 256 and 512 bytes represents a practical compromise for industrial applications, with an expected maximum link distance ranging from 15 to 25 meters (Figure 3.4 c-d). Lower payloads provide broader coverage but result in a higher overhead ratio
- **Antenna orientation matters**: Connectivity depends on antenna pattern and orientation.
- **NLOS conditions have higher PLR**: the presence of obstacles in the signal propagation path reduces the chances of successful data transmission at the same distance.

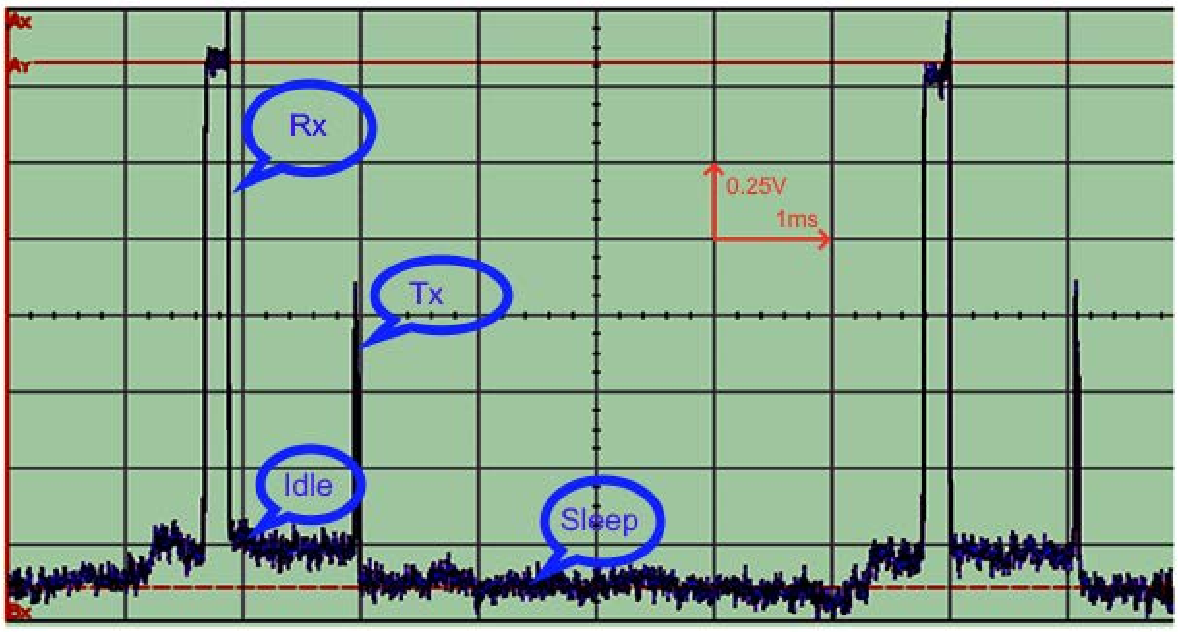


Figure 3.5 -Current consumption of the UWB transceiver at our sensor nodes. An AP communicating with a side node over two frames is visualized. The longer (shorter) periods correspond to receive (transmit) mode. Current is measured by means of the voltage drop on a 0.7 Ω resistor. (axis X –time in 1ms, axis Y-0.25V per cell)

As part of the experiment, we also measured the power consumption of the transceiver in different states. The current consumption for Transmit (Tx), Receive (Rx), Idle, and Sleep is presented in Figure 3.5.

The main findings:

- **Transmission power:** Receive power 353.56 mW and transmit power 155.1 mW (Figure 3.5).
- **Consistency:** power for transmission and receiving consistent over the time.
- **Sleep current:** low level of the idle state of the transceiver, 1mA.

We also performed a theoretical analysis of the node lifetime under different data transfer configurations using a 2000mA battery pack. The results are shown in Figure 3.6.

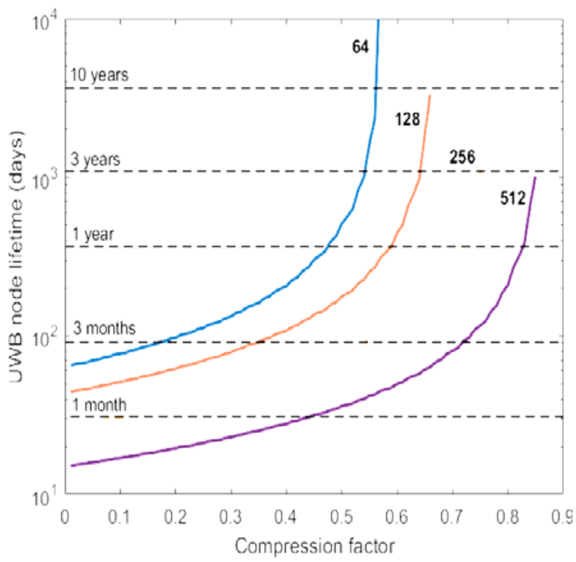


Figure 3.6 – Influence of the preamble length to a life time of the node with 2000mA battery

The main findings:

- **Increasing preamble length reduces lifespan:** Figure 3.6 shows that longer preamble lengths drastically reduce node lifetime.
- **Way to increase lifetime:** One way to prolong lifetime is using compression.

Use Case 2 Pewag - Experimental setup:

- One AP and nine sensor nodes were implemented using DWM1001C boards. AP collects data and relays it to a USB-connected PC for in-depth analysis.
- To maximize network capacity, 6.8 Mbps transmission mode is used, fixed preamble length, custom TDMA protocol with approx. 2.8Mbps effective data rate and retransmission option
- Industrial hall with a huge variety of machines for metal chain production including bending, welding, storing, and automated lines with minimum people involved in the production process.
- Different types of data from the sensors, both analogue and digital, with low and high measurement frequencies

The second use case of the UWB wireless transmission is about connection in a high dense EMI environment. This was done in a welding manufacture during regular work of the hall with 10000A welding machines.
In environments with high-current welding machines, electromagnetic interference (EMI) poses significant challenges to wireless transmissions due to several factors. Firstly, welding machines generate a broad spectrum of electromagnetic noise that overlaps with frequencies used in wireless communication, leading to signal distortion or loss. Additionally, the high intensity of emissions from these machines can overwhelm wireless receivers. The metallic structures in these environments can reflect and scatter wireless signals, causing multipath propagation and potential signal degradation. The EMI produced by welding is often intermittent and unpredictable, making it difficult for wireless systems to adapt or filter out the interference. To mitigate these challenges, careful planning of the wireless network is required, including the selection of robust communication protocols, frequency bands less susceptible to interference, and the strategic placement of antennas and shielding

The measurement procedure is as follows: The sending node is positioned at a fixed location and the AP is carried within the test area while monitoring the packet reception at a PC. Industrial environment and schematic placement of the UWB nodes from AP showed by Figure 3.7. Distances circa 20, circa 27m and circa 34(based on SS distance measurements) represented by light blue, blue and violent dots accordingly.

The setup includes 12 welding stations, each with varying power levels and operating at distinct welding frequencies. This arrangement results in a complicated electromagnetic interference landscape, which negatively affects the reception of UWB transmissions. The surroundings remain largely unchanged. We conducted experiments involving 10,000 packet transmissions per node. Positioning multiple nodes at similar distances to the AP, but under different propagation conditions, helped us gauge an average performance level.

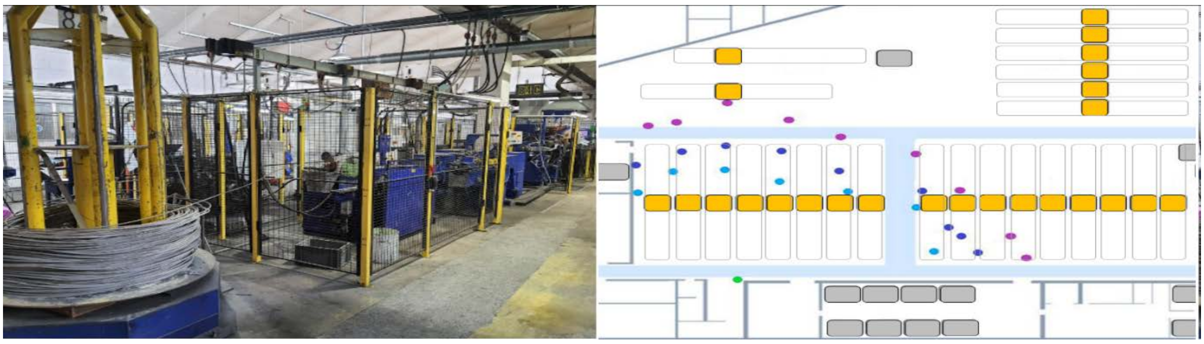


Figure 3.7 – Use case 2 scenario in a production hall with different types of machines.

The main findings:

- **Industrial environment influence:** We found out that working in an industrial environment with high EMI doesn't influence connectivity
- **Connectivity threshold:** We revealed a significant drop in the packet delivery rate for nodes positioned more than 24 meters away from the AP.
- **Channel recovery and retransmissions of lost packets:** Our data on different propagation conditions showed that while some longer links maintained high performance, the level of performance degradation in others was substantial enough to hinder packet recovery. However, for some nodes approximately 21 meters from the AP, the observed minor PLR could potentially be offset through effective retransmission strategies.

The welding process under consideration operates cyclically every 1 second (Figure 3.8). This regular interval is important for ensuring consistent welds and allows for synchronous data collection by the voltage sensing system. The average voltage recorded by the DWM1001 current sensor is **1.63 Volts**. The DWM1001 sensor is likely part of a wireless device setup that captures voltage readings at a set frequency. In comparison, the average voltage recorded using the Messfeld GmbH setup is slightly lower at **1.56 Volts**.

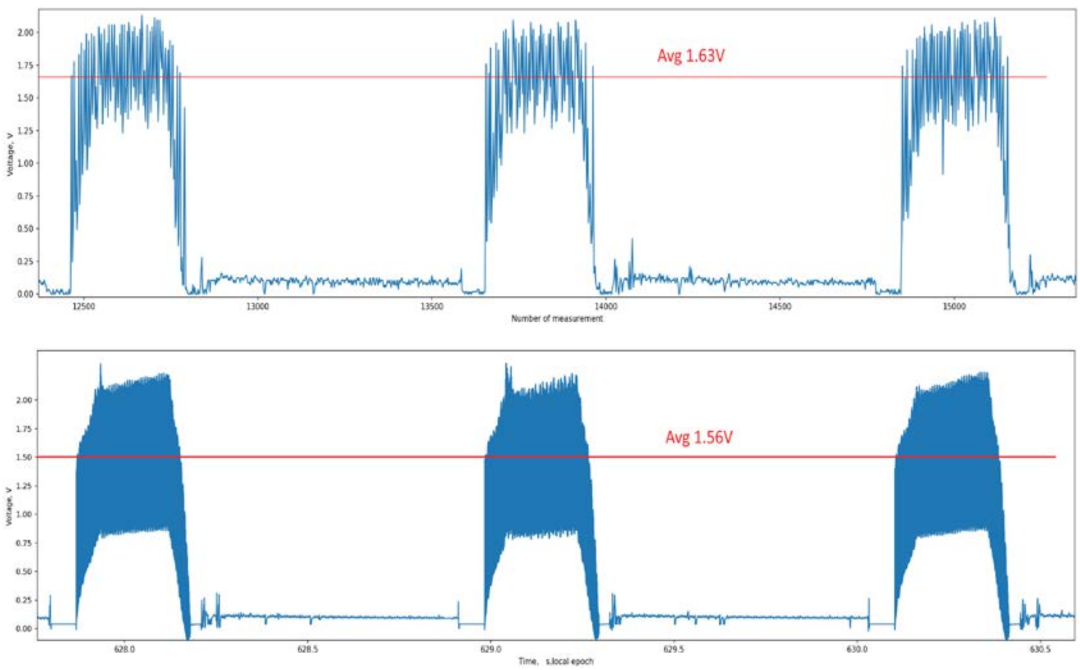


Figure 3.8 – Analog data of the welding process transmitted over UWB compared with reference system.

The main findings:

- **Channel capabilities:** Designed (custom protocol + chosen combination of physical characteristics of the UWB channel, payload+transmission rate+PHR length) channel of the UWB supports high frequency real-time analog measurements to transmit.
- **Multipurpose channel:** Our experiment showed that integration of a new type of sensor into the system is simple. We integrated an analog current measurement sensor to work together with distance measurements using the same communication channel. This channel allows monitoring the welding process in real time.

Use Case 3 Spalt - Experimental setup

- One AP and ten sensor nodes were implemented using DWM1001C boards. AP collects data and relays it to USB-connected PC for in-depth analysis.
- To maximize network capacity, 6.8 Mbps transmission mode is used, fixed preamble length, custom TDMA protocol with approx. 2.8Mbps effective data rate and re-transmission option
- Industrial hall with a huge variety of machines for electric motor including winding wires, bending, welding, storing, and automated lines with minimum people involved in the production process.
- Different types of data from the sensors, both analog and digital, with low and high measurement frequencies

Our initial experiment in the industrial environment took place at the manufactory, where we strategically deployed a network of nine nodes spanning a distance of approximately 20 meters. The test area is a 30x10 m hall with two lateral rooms separated by concrete walls. Within this area there are many obstacles like heavy machinery, cranes, walls and panels. The environment mobility can be considered to be moderate, with over 15 people and several cranes permanently moving. Pictures of the involved obstacles and the node deployment positions describe the propagation environment. The primary objective was to provide coverage to the main workshop, with an AP strategically positioned within the main hall as shown on Figure 3.9. Additionally, nodes 6, 7, and 8 were strategically placed within enclosed rooms.

The schematic representation of the node placement within the hall can be observed in the accompanying figure. Notably, the distance measurements obtained via Symmetric Double-Sided Two-Way Ranging (SS TWR) are graphically depicted. The recorded distance is indicated by the final number of transmissions, which is 10141 (approximated for all transmissions).

Table 3.2 Packet loss for first scenario of the experiment

Node number	Distance, m	Packets transmitted #	Packets Received #	Packets received with retransmission #	PL Ratio, %	Rx level,dBm
1	20.94	10141	10099	10139	99.98	-86.22
2	18.87	10141	10138	10141	100	-86
3	18.59	10141	10125	10141	100	-83.81
4	24.35	10141	10129	10141	100	-86.1
5	17.32	10141	10119	10131	99.90	-87.8
6	19.27	10141	10115	10034	98.94	-91.84
7	19.85	10141	4988	6300	62.12	-94.85
8	18.37	10141	8506	9885	97.47	-90.56
9	22.81	10141	10141	10141	100	-82
10	16.98	10141	10140	10141	100	-83.88

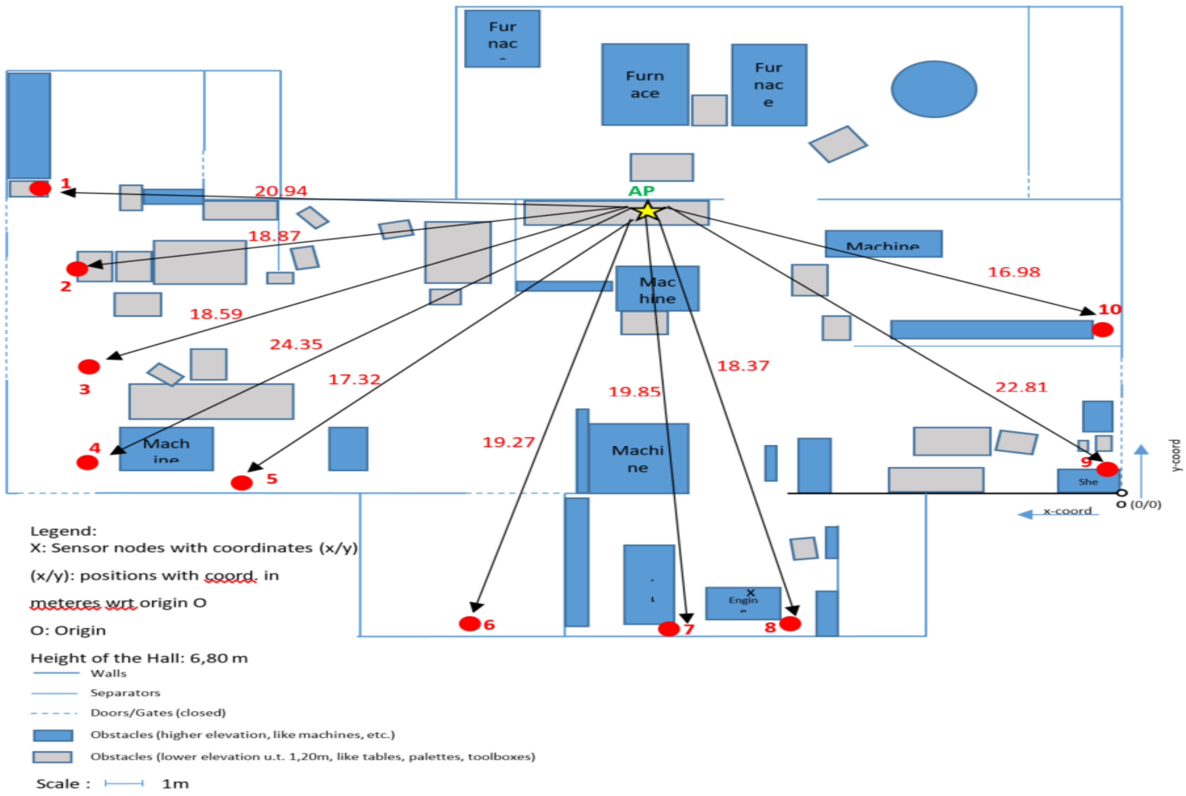


Figure 3.9 – Industrial scenario to cover hall of the motor production .

The main findings:

- Our data on different propagation conditions showed that while some longer links maintained high performance, the level of performance degradation in others was substantial enough to hinder packet recovery.
- **Positioning of the AP:** Our observations reveal that the most challenging scenario occurs when Node 7 (N7) is positioned in a NLOS configuration, separated by machinery (Table 3.2). Despite the reception level being notably lower in this scenario, the occurrence of packet losses is relatively limited.

Our second experiment focused on establishing communication over the longest possible link within the workshop environment. The AP was strategically positioned directly opposite Node 7, resulting in an average distance of approximately 32 meters between them (Figure 3.10). Notably, Nodes 1 and 2 were placed at the corner of the hall, whereas Node 2 was uniquely located within a storage box of the storage rack. Meanwhile, Node 9 was situated at the opposite corner of the hall.

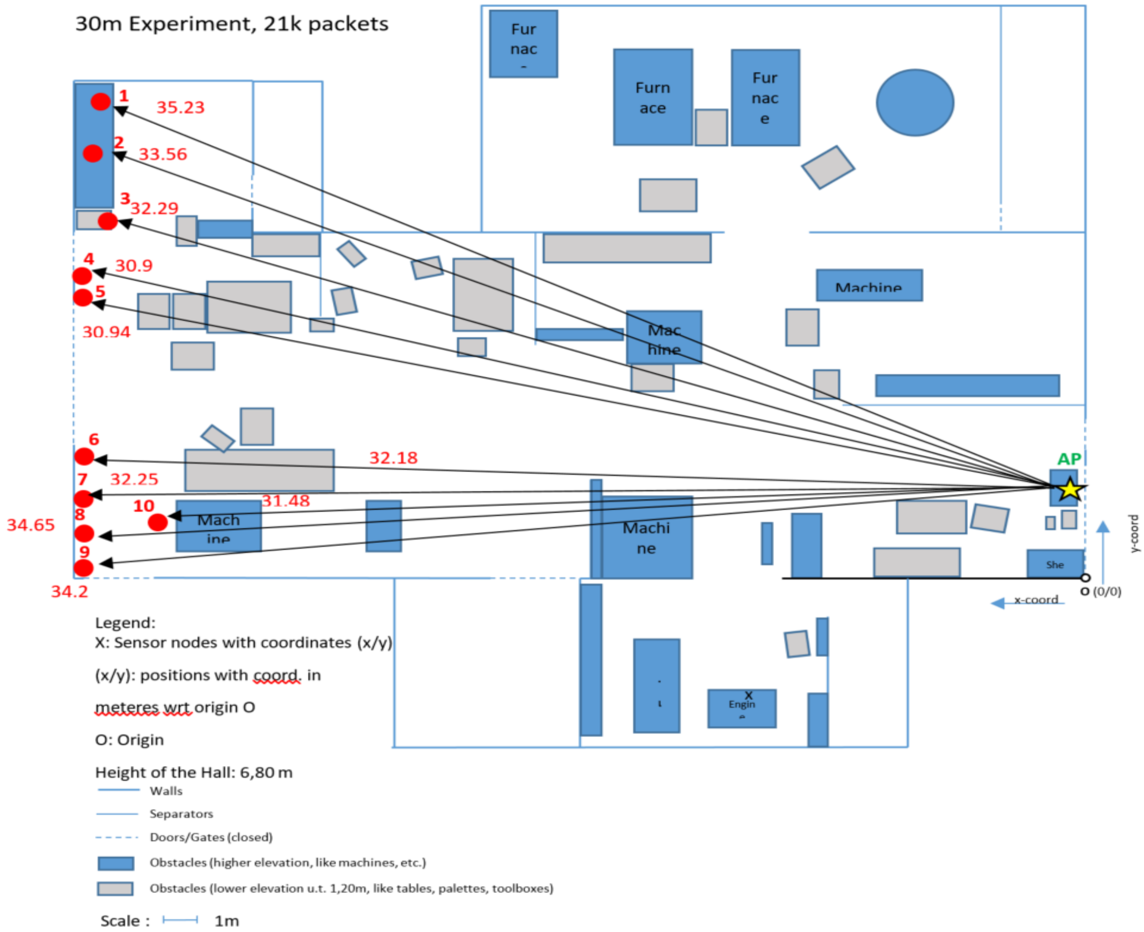


Figure 3.10 – Challenging setup for UWB in the motor production factory .

The main findings:

- **RSSI level threshold:** In this setup, Nodes 1, 2, and 9 exhibited a discernibly lower level of received signal strength. If the level drops below -96 dBm we experience high packet loss (Table 3.3).
- **Concrete obstacles limit connectivity:** This observation highlights the significant impact of concrete obstacles on the network's performance and capabilities.
- **LOS and NLOS granted condition:** results indicate that the target range of up to 20 m links in LOS & NLOS conditions can be reliably reached in most cases. Nodes behind concrete walls are an exemption since concrete seems to severely degrade NLOS signal reception. Other obstacles do not show an impact on PLR. Also, mobility does not appear to play a major role. Finally, the dimensioning of the redundancy channel seems adequate.

Table 3.3 Packet loss for second scenario of the experiment

Node number	Distance, m	Packets transmitted #	Packets Received #	Packets received with retransmission #	PL Ratio, %	Rx level, dBm
1	35.23	21628	15602	17767	82.15	-92.23
2	33.56	21628	9896	13618	62.67	-98.8
3	32.29	21628	21489	21586	99.81	-88.26
4	30.9	21628	21559	21627	99.995	-83.02
5	30.94	21628	21626	21626	99.99	-86.87
6	32.18	21628	21621	21621	99.97	-86.1
7	32.25	21628	21619	21628	100	-86.13
8	34.65	21628	21289	21376	98.83	-89.3
9	34.2	21628	20463	20896	96.62	-91.47
10	31.48	21628	21628	21628	100	-85.48

In our sensing experiment, we made measurements on the test electric engine (Figure 3.11). On the engine, 2 vibration sensors and 5 temperature sensors were installed. Electric engines come with pre-installed vibration and temperature sensors. Two monitoring systems were connected to these sensors: one commercial, another of our design. The design includes a custom sensor board with 5 temperature inputs based on PT100 sensors, 2 inputs for 1-axis vibration sensors, operating at a 10kHz rate. In picture 8, it's shown as a big gray box. The sensor board was transmitting data via the UWB channel to the AP, which is a small white box connected via USB to the Raspberry Pi with a running database for storing data and creating a simple GUI, which was remotely accessible via a 4G network.

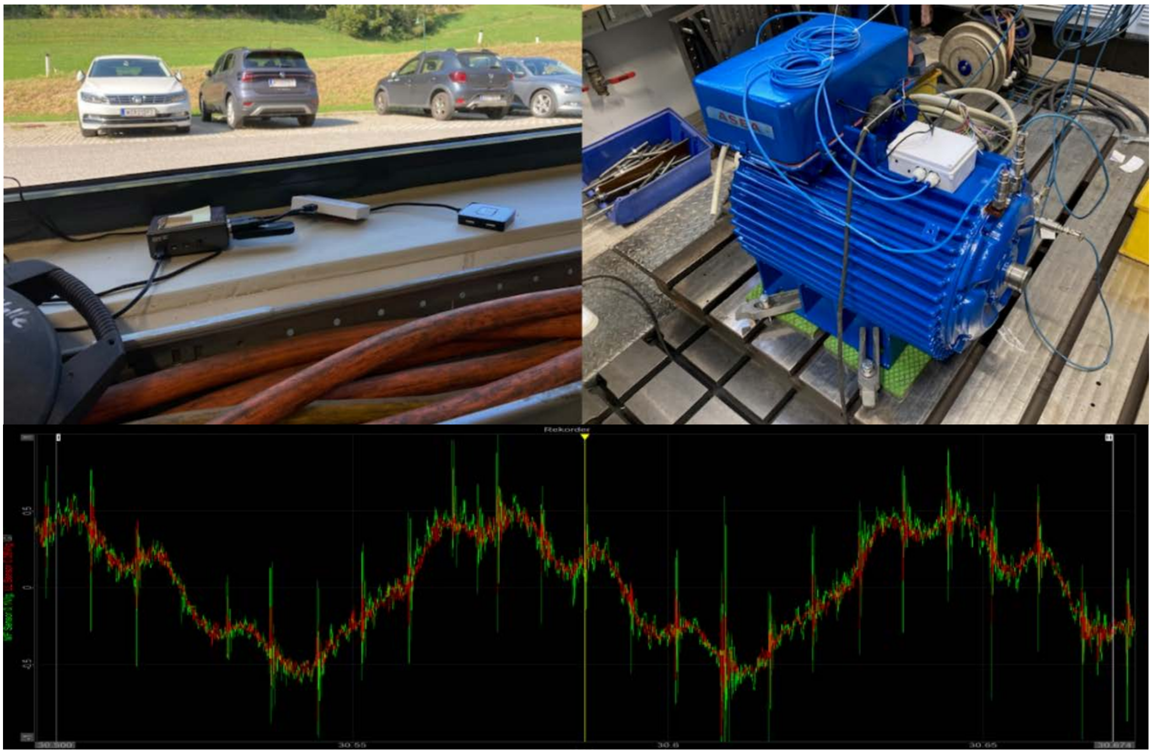


Figure 3.11 - Sensing setup of the electric motor with the comparison of the vibration sensor data measurements

The main findings:

- **Coexistence:** Condition data from the tested electric motor was going via UWB and 4G network to the server with database.
- **Vibration condition monitoring:** We proved that UWB technology can be used to transmit 20 kHz vibration sensor data in real-time applications.
- **Temperature condition monitoring:** We proved that UWB technology can be used to transmit 1 kHz temperature sensor data in real-time applications.
- **Scalability:** We proved that the UWB channel can be scalable to collect different type of data of the different sensors.

Chapter Afterword

Being very well established for location applications in industry, UWB is also an interesting option for wireless communication in industrial environments. As the experiments and examples show, it is very flexible in terms of configuration and is very energy efficient. Due to its physical properties it can account for high reliability and is hard to disturb (jamming attacks, etc.) and hard to identify. It can coexist with other wireless technologies as it does not interfere with esp. narrow band technologies like Wifi, Bluetooth, WirelessHART, etc. The real strengths of UWB are high data rate and low latency communication in short ranges up to 20m. Very often UWB can be combined with other technologies (like e.g. LoRa) to use the "best of many worlds". For industrial applications it is an interesting complementary technology in all situations where a lot of data has to be transferred reliably.

Dr. Andreas Kercek
Senior Research Manager

5th generation cellular networks (5G) represent the latest advancement in mobile technology, offering faster speeds and more reliable connections than previous generations. This technology is characterized by the "triangle of 5G", which includes enhanced Mobile Broadband (eMBB) for higher data rates, Ultra-Reliable Low Latency Communications (URLLC) for extremely reliable and low-latency connections, and massive Machine Type Communications (mMTC) to support a vast number of connected devices. It enables quicker data downloads and uploads, smoother streaming, and enhanced connectivity for various devices. These capabilities are essential for the growth of smart cities, autonomous vehicles, and the Internet of Things (IoT).

This chapter includes a special use case, “establishing a network of drones”.

4 5th Generation Cellular Networks (5G)

4.1 Introduction

5th generation cellular networks, or 5G, have their roots in the evolution of mobile technology that began in the 1980s with 1G, which introduced analog voice communication. The transition to 2G brought digital voice and text messaging, while 3G enabled mobile internet access. The advent of 4G in the late 2000s revolutionized mobile broadband, facilitating high-speed data and video streaming. Research and development for 5G started around 2010, focusing on overcoming the limitations of 4G in terms of speed, latency, and connectivity, leading to the first standardization efforts in 2015, with the first 5G specification (Release 15) being released in 2017. In 2020 Release 16 was published, focusing on the needs of verticals such as Automotive or Industrial IoT.

Key developments in 5G technology include the introduction of millimeter-wave (mmWave) frequencies, which offer high bandwidth but shorter range, and the use of massive Multiple Input Multiple Output (MIMO) antennas that enhance capacity and coverage. Additionally, advancements in network slicing allow operators to create virtual networks tailored to specific applications and services. 5G also incorporates edge computing to bring data processing closer to the source, reducing latency and improving performance for real-time applications. These technological advancements have enabled 5G to meet diverse requirements across various industries.

Currently, 5G is being deployed globally, with many countries rolling out networks and expanding coverage. Major telecom operators are offering 5G services in urban areas, providing significantly faster speeds and more reliable connections compared to 4G. The current state of 5G includes ongoing enhancements in network infrastructure, broader availability of 5G-enabled devices, and the development of new applications leveraging 5G’s capabilities, such as smart cities or autonomous vehicles.

In this report, we explore the performance of 5G technology for autonomous vehicles. Drone network implementation is selected as a special use case to evaluate the technology’s performance. We did not perform evaluations in an industrial setting, as 5G implementation is a costly solution for industries due to infrastructure and licensing costs.

4.1.1 Technical Overview

Table 4.1 shows the technical parameters of the 5G technology.

Table 4.1 Technical overview of 5G

Parameters	**Values**
Frequency band, GHz	low-band (<1), mid-band (1-6), high-band/mmWave (24-40)
Bandwidth, MHz	≤20 (low), ≤100 (mid), ≤400 (high)
Effective Data rate, Gbit/s	up to 0.1 (low), 1 (mid), 10 (high)
Power Tx/Rx, dbm	23 dBm (typical)/≥80 (excellent) to ≤100 (weak)
Maximum distance (with PLR below 5%), km	10 (low), 1-3 (mid), 0.5 (line-of-sight, high)
Latency, ms	1-10, <1 (URLLC)
Modulation scheme	OFDM, QAM
Scalability	Yes
Security features	Yes
Mobility support	yes, up to 500 km/h

4.2 5G Properties

4.2.1 Strengths

5G is designed for ultra-fast data speeds, low latency, and high device density. Its adaptability to diverse conditions makes it ideal for critical applications. 5G infrastructure offers enhanced security and scalability for easy network deployment and maintenance.

Key characteristics

01 High data rates and low latency

02 Enhanced coverage and reliable connectivity

03 Network slicing, allowing customization to meet specific application requirements

High Data Rates and Low Latency

5G technology offers significant advantages for industrial applications with its high data rates and low latency. The high data rates enable new applications such as control of complex environments via virtual presence (teleoperations). Additionally, the low latency of 5G networks supports critical applications such as remote machinery control, autonomous robots, and augmented reality for maintenance and training. This combination of high data rates and low latency enhances productivity, reduces downtime, and improves safety in industrial environments, making 5G a pivotal technology for the advancement of Industry 4.0.

Enhanced coverage and connectivity

5G technology's enhanced coverage and reliable connectivity provide substantial benefits for industrial applications. With its ability to maintain strong and consistent connections across vast areas, 5G ensures that all parts of an industrial facility, including remote and hard-to-reach locations, are connected. This robust connectivity is crucial for the seamless operation of automated systems, IoT devices, and sensor networks, enabling real-time data collection and analysis. The enhanced coverage and reliability of 5G networks minimize downtime and disruptions, leading to increased operational efficiency, better resource management, and improved overall productivity in industrial environments.

Network slicing

5G technology's network slicing capability offers significant advantages for industrial applications. By creating multiple virtual networks within a single physical 5G network, each tailored to specific needs, network slicing ensures that critical industrial operations receive the dedicated resources and performance they require. This enables the simultaneous support of diverse applications, such as real-time control of machinery, high-bandwidth data analytics, and low-latency communication for autonomous systems, all within the same infrastructure. Network slicing enhances operational efficiency, provides greater flexibility, and ensures that different industrial processes can run smoothly without interference, leading to more reliable and optimized industrial operations.

4.2 5G Properties

4.2.2 Weaknesses

Infrastructure Costs and Spectrum Licensing

While 5G offers numerous benefits for industrial applications, it comes with higher infrastructure costs. Deploying 5G infrastructure requires significant investment in new base stations, small cells, and advanced hardware, making it more expensive than other wireless technologies. Additionally, 5G often necessitates access to licensed spectrum, which can incur substantial costs and is subject to regulatory constraints. These financial and regulatory challenges can pose significant barriers for smaller industrial operations and increase the overall complexity and cost of implementing 5G networks.

Power Consumption

5G technology, while offering advanced features such as high data rates and low latency, tends to have higher power consumption compared to other wireless technologies. The increased power usage stems from several factors, including the need to support more complex modulation schemes, higher data throughput, and the operation of multiple antennas for techniques like Massive MIMO. In industrial applications, where devices may need to operate continuously and reliably, this higher power consumption can lead to increased operational costs and more frequent battery replacements or recharging, which is less ideal for remote or hard-to-access locations. Additionally, the infrastructure components of 5G, such as base stations and small cells, also consume more power to maintain the enhanced performance levels, further adding to the energy demands and operational expenses. This can be a disadvantage in scenarios where energy efficiency and long battery life are critical.

Complex Deployment

Deploying a 5G network is more complex than other wireless technologies due to the need for a dense network of base stations and small cells, particularly for high-frequency mmWave bands, which requires extensive planning and installation. Advanced technologies like beamforming, Massive MIMO, and network slicing demand sophisticated management tools and specialized expertise, increasing the complexity. Integrating 5G with existing infrastructure and ensuring interoperability with legacy systems adds further challenges. Additionally, securing necessary spectrum licenses and regulatory compliance can be resource-intensive. Deployment options include partnering with mobile operators for broader coverage or establishing private campus networks tailored to specific industrial needs.

4.3 5G Special Use Case

Drone communication

Due to the complexities and costs associated with 5G network deployment, we have not tested the technology with industry partners. Here, we present a special use case where it is easier to explore the characteristics of 5G, providing insights for other industrial use cases.

4.3.1 Comparison of WiFi/LTE and 5G for UAV communication

In industrial applications, uncrewed aerial vehicles (UAVs), also referred to as drones, have emerged as crucial tools for tasks such as infrastructure monitoring, asset inspection, and logistics operations. These UAVs rely on robust and efficient wireless communication to coordinate among themselves and with ground stations. As industries increasingly integrate drones for complex operations, understanding the performance of various wireless technologies becomes essential to ensure reliability, particularly in environments where real-time data exchange is critical for safety and mission success.

This use case presents an empirical evaluation of three wireless technologies—Wi-Fi, Long-Term Evolution (LTE), and 5G—used for both drone-to-drone and drone-to-base station communication. The study examines how these technologies perform in rural and urban environments, focusing on key metrics such as signal strength (RSSI), latency, and throughput.

By analyzing the strengths and weaknesses of each communication technology, the study provides insights into how industries can leverage Wi-Fi, LTE, and 5G networks for reliable drone-based operations. Understanding these wireless technologies' performance will help industries make informed decisions about deploying drones in challenging environments, such as densely built urban areas or remote industrial sites.

4.3.2 Measurement Setup

To evaluate the performance of drone-to-drone communication, the study outlines a series of field tests that focus on the cellular-enabled UAV setup. The experiment involved using commercial drones equipped with LTE/5G and WiFi modules where drones need to maintain reliable and efficient communication. Key metrics in the study include signal strength (RSSI), latency, and throughput, which were measured at various distances and altitudes to simulate different operational conditions.

Figure 4.1: UAV with LTE/5G (left) and WiFi (right) communication modules.

The drones used in the experiments are twinFOLD SCIENCE quadcopters, custom-manufactured by Twins GmbH (Figure 4.1). Each drone is equipped with a Raspberry Pi 4 B2 single-board computer for onboard processing and communication, and controlled by a Pixhawk 4 flight controller. The Pixhawk 4 FC integrates several sensors for positioning and control, including GPS, magnetometer, gyroscope, and barometer. The drones have a maximum payload of 800 g, a maximum horizontal velocity of 10 m/s and 3 m/s vertically, with a flight time of approximately 15 minutes, depending on the payload weight.

For communication the following equipment was used:

- A Samsung S20 5G smartphone running Android 11, equipped with a Snapdragon 865 chipset and X55 5G modem, supporting dual-band Wi-Fi including 802.11ac.
- A Samsung Galaxy A42 5G smartphone, also running Android 11, equipped with a Snapdragon 750G chipset and X52 5G modem.
- For Wi-Fi measurements, a UniFi UAP-AC-M dual-band access point, supporting 2x2 MIMO and 802.11ac with a maximum link data rate of 867 Mbit/s, was used. It was connected to the Raspberry Pi 4 via Gigabit Ethernet, which hosted the server application for measurement software.

All devices, including smartphones and the Wi-Fi access point, were mounted onto the quadcopters for the experiments.

All experiments utilized the Cellular Drone Measurement Tool (CDMT)[1]. CDMT was responsible for reporting critical LTE and 5G NR parameters, such as:

- RSRP (Reference Signals Received Power)
- RSRQ (Reference Signal Received Quality)
- PCI (Physical Cell Identity)
- Channel number (EARFCN) for both serving and neighboring cells.

Additionally, the tool logged GPS location, time, and measured throughput and two-way latency. For throughput and latency measurements, a client-server model was employed, with the server running either as a standalone Java application or as an Android app. Throughput was assessed by sending a random stream of data from the client to the server.

Latency was measured by sending 10 UDP packets per second with sequence numbers and timestamps from the client to the server. These timestamps were used to calculate two-way latency by recording the send and receive times at both the client and server.

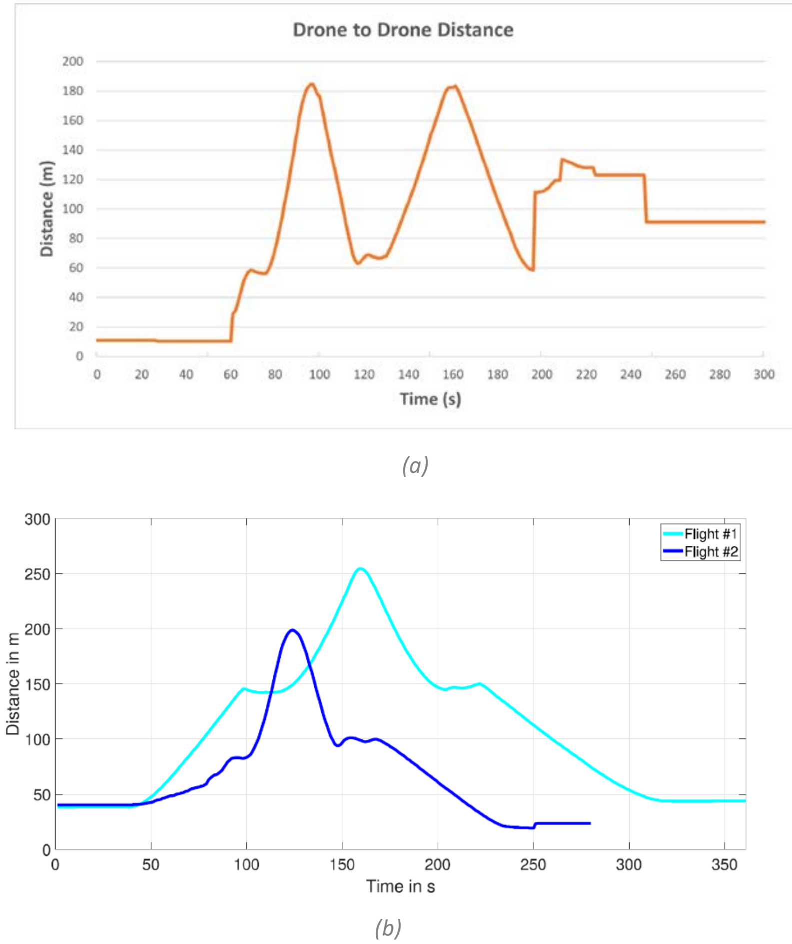


Figure 4.2: Distance between the drones (a) and between the drones and the Wi-Fi ground station (b)

[1] CDMT is available here: www.lakeside-labs.com/cdmt

4.3.3 Experimental Results

For the results, it is important to understand the difference between drone-to-drone communication in Wi-Fi and cellular technologies such as LTE-A and 5G. In Wi-Fi, the ability to form an adhoc network between devices allows drones to communicate directly to one another. Till date, the commercial cellular networks don't support adhoc connectivity, which mean that drone-to-drone communication in reality translates to drone-to-base station (ground)-to-drone.

Table 4.2: Drone to Drone results summary

	Drone	Wi-Fi	5G	LTE-A
Throughput (Mbit/s)	both	54	43	51
Latency (ms)	both	7,44	96	141

In the drone-to-drone scenario, the performance of Wi-Fi, LTE-A, and 5G technologies was measured in terms of throughput and latency as the drones flew at varying distances from each other (Figure 4.2 a, Table 4.2). The drone-to-ground tests focused on how the drones communicated with a ground server using Wi-Fi, LTE-A, and 5G technologies (Figure 4.2 b, Table 4.3). The results are split between downlink (ground-drone, represented as DL in the Table) and uplink (drone-ground, represented as UL in the Table) throughput, providing a detailed comparison of the three wireless technologies.

Table 4.3: Drone to Ground results summary

	Drone	**Wi-Fi**	**5G UL**	**5G DL**	**LTE UL**	**LTE DL**
Throughput (Mbit/s)	#1	39	50	68	43	33
	#2	71	40	83	57	41
Latency (ms)	#1	11,2	47	47	61	61
	#2	11,1	51		58	

Throughput Results for drone-to-drone scenario:

Wi-Fi provided the highest throughput during the initial phase of the experiment when the drones were in close proximity and moving at low velocities. This favourable scenario allowed Wi-Fi to outperform both LTE-A and 5G (Figure 4.3). However, Wi-Fi's performance was inconsistent, as throughput fluctuated throughout the experiment due to varying link quality between the drones. LTE-A and 5G, in contrast, maintained more stable throughput levels, as these technologies rely on air-to-ground links, which are less affected by the drones' proximity to one another. LTE-A slightly outperformed 5G in this scenario, which is later explained by uplink limitations in the 5G technology in the air-to-ground tests.

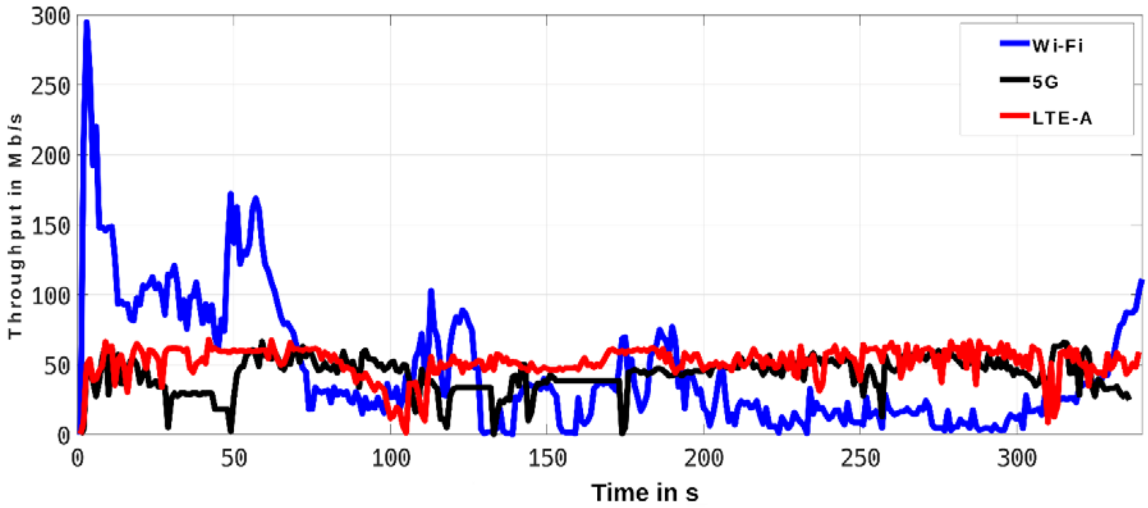


Figure 4.3: Drone-to-drone throughput

Latency Results for the drone-to-drone scenario:

Wi-Fi exhibited the lowest average latency (7 ms) due to its direct drone-to-drone communication without routing through a base station. However, Wi-Fi also had occasional outliers of up to 350 ms, likely caused by retransmissions when the connection quality dropped (Figure 4.4).

For cellular networks, 5G provided better performance than LTE-A, with an average latency of 96 ms, which is significantly lower than LTE-A's 141 ms. The better performance of 5G reflects its design for low-latency communications, although further improvements could be made with the deployment of standalone 5G networks (as these tests used a non-standalone 5G (LTE+5G) system).

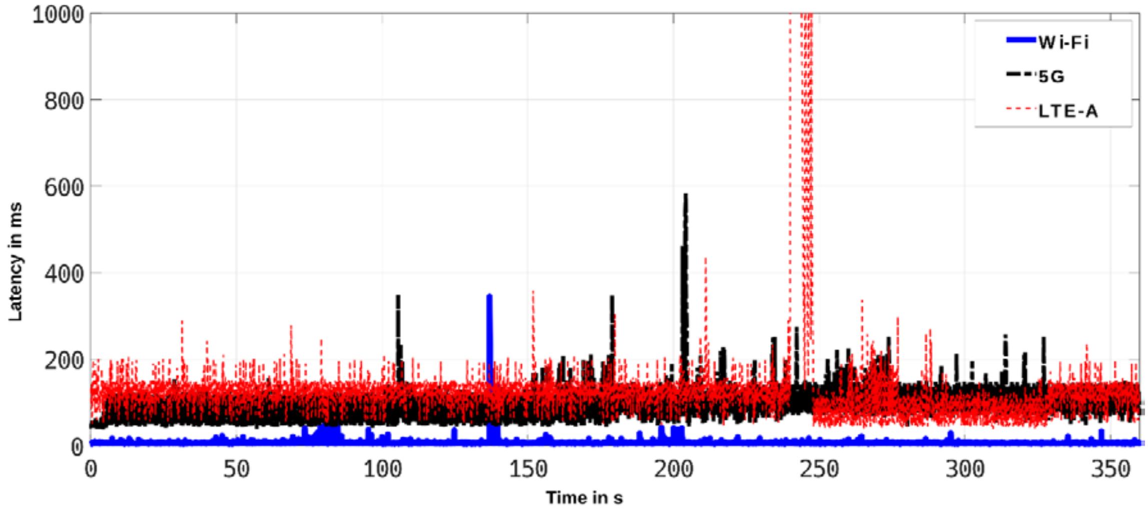


Figure 4.4: Drone-to-drone latency (round trip time)

Throughput results for the drone-to-ground scenario:

In the drone-to-ground (U2G) communication tests, the performance of Wi-Fi, LTE-A, and 5G was again evaluated, but this time focusing on the communication between the drones and a ground server (Figure 4.5). The results revealed that Wi-Fi throughput was highly dependent on the drone's distance from the access point. When the drone was close to the ground station, Wi-Fi achieved high throughput, especially during take-off. However, as the drone moved farther away, throughput dropped significantly, illustrating the limitations of Wi-Fi over longer distances in an air-to-ground context. At peak performance, Wi-Fi reached 50 Mbit/s, but it struggled to maintain these rates when the drone was far from the access point.

For cellular technologies, 5G outperformed LTE-A in terms of downlink throughput. During both flight trajectories, 5G demonstrated higher downlink rates, with average values of 68 Mbit/s and 83 Mbit/s for the two flights, compared to LTE-A's 33 Mbit/s and 40 Mbit/s, respectively. This superior performance highlights 5G's ability to handle higher data transfer rates when downloading information from the ground server to the drone.

However, in the uplink, LTE-A performed better than 5G. The uplink throughput was enhanced by uplink carrier aggregation in LTE-A, which provided additional capacity for transmitting data from the drone back to the ground server. LTE-A's average uplink throughput reached 50 Mbit/s and 57 Mbit/s during the two flights, surpassing 5G's 43 Mbit/s and 41 Mbit/s. This performance difference explains why LTE-A had slightly higher throughput in drone-to-drone communication, as the uplink capacity limits the overall drone-to-drone data exchange.

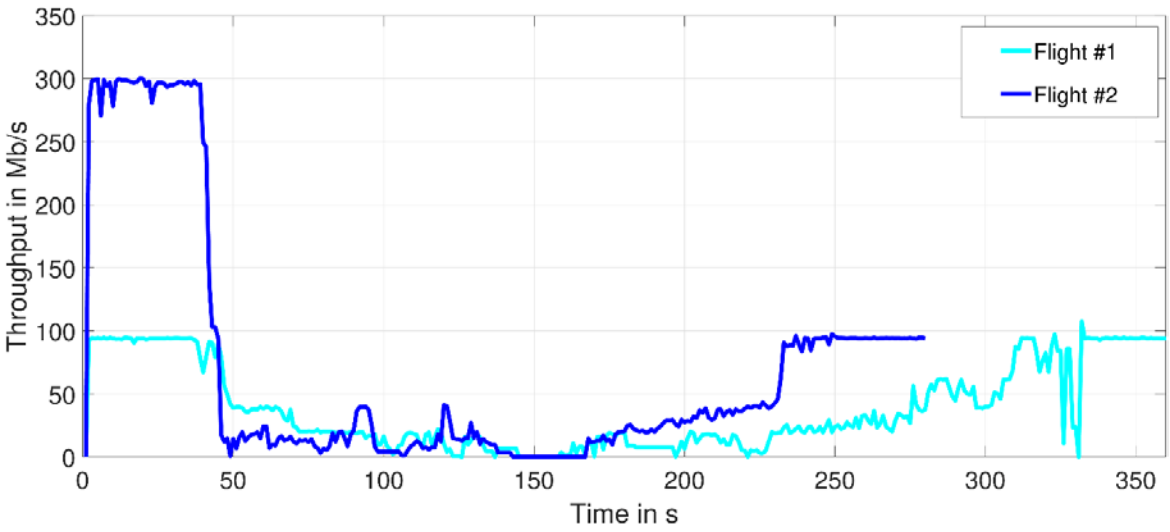


Figure 4.5: Drone-to-ground throughput for Wi-Fi

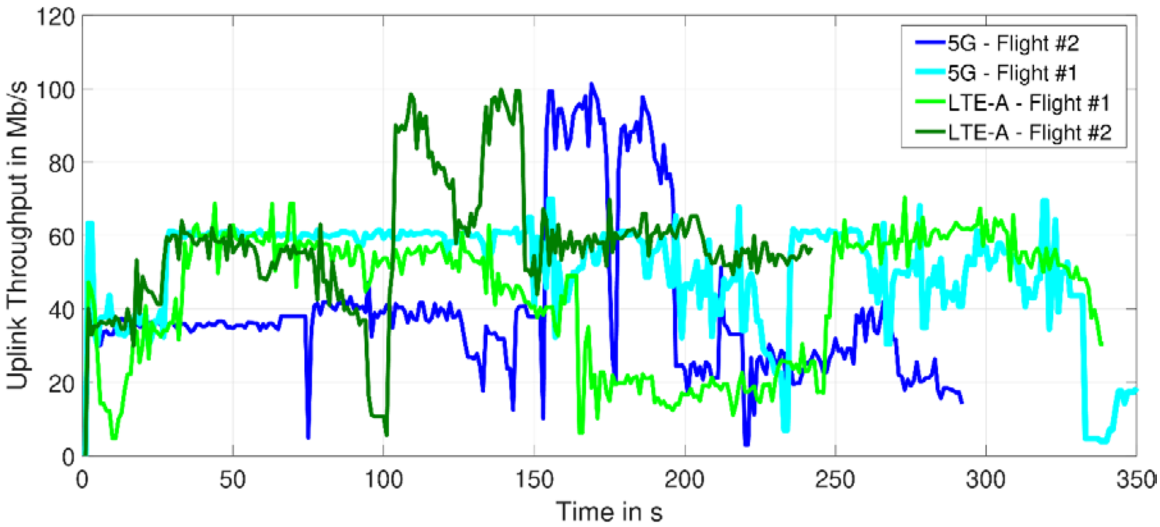


Figure 4.6: Drone-to-ground throughput for LTE and 5G

Latency results for the drone-to-ground scenario:

Regarding latency, Wi-Fi once again offered the lowest delays, with an average of 11 ms in both flight trajectories (Figure 4.6). This result is consistent with the drone-to-drone scenario, where Wi-Fi's direct communication path provides minimal latency. Cellular technologies performed slightly worse in the drone-to-ground scenario compared to drone-to-drone due to the increased number of retransmissions required in air-to-ground links. Nonetheless, 5G continued to outperform LTE-A, with latency values of 47 ms and 51 ms across the flights, compared to LTE-A's 61 ms and 58 ms.

These results indicate that 5G is more suitable for high-throughput, low-latency applications in industrial drone operations where reliable downlink performance is critical. On the other hand, LTE-A may still be preferable in scenarios where uplink capacity is prioritized, such as when drones need to send large amounts of data (e.g., sensor readings or video footage) back to the ground server.

The main findings of the experimental campaigns are:

- Wi-Fi offers the best performance in terms of throughput and latency when drones are in close proximity or near a ground access point. However, Wi-Fi's performance is highly dependent on the quality of the air-to-air link, and its throughput fluctuates significantly when the distance between drones increases or when operating at higher speeds. These fluctuations limit Wi-Fi's reliability for more extensive industrial applications that require consistent, high-performance communication.

- 5G shows significant promise in providing stable throughput and low latency, especially in downlink communications where it outperforms LTE-A. The latency results for 5G are considerably lower than those for LTE-A, demonstrating its suitability for real-time drone operations. However, 5G's current limitations in uplink throughput suggest that further improvements, especially with the deployment of standalone 5G networks, could enhance its viability for uplink-heavy industrial tasks, such as data transmission from drones to ground stations.
- LTE-A, while offering lower downlink throughput and higher latency than 5G, proves advantageous in the uplink, thanks to its use of uplink carrier aggregation. This feature makes LTE-A a more favorable option for applications where drones need to upload large amounts of data to the ground.

In summary, the choice of communication technology depends heavily on the specific industrial application. Wi-Fi is suitable for short-range, low-latency tasks where drones operate in close proximity. 5G shows great potential for real-time operations with high downlink demands, while LTE-A remains a strong contender for uplink-intensive applications. Future improvements in 5G networks, especially with the rollout of standalone 5G, are expected to further enhance its performance, making it a key technology for future drone-based industrial operations.

Chapter Afterword

Experimental work on 5G, like that undertaken at Lakeside Labs GmbH, is invaluable for those exploring cutting-edge tech for industry-specific needs. By actively testing and validating 5G network capabilities, Lakeside Labs offers a practical understanding of what the technology can deliver in real-world scenarios, reducing uncertainties for SMEs looking to innovate. Emerging use cases in areas like drone-based precision agriculture, real-time asset tracking, and intelligent manufacturing are ideal candidates for these advanced networks. 5G’s low latency and massive IoT capacity enable seamless automation, predictive maintenance, and new levels of efficiency in distributed operations. For any organization aiming to stay competitive, this research may provide insights as to how 5G can unlock customized, scalable solutions, positioning their business to lead in an increasingly connected world.

Dr. Samira Hayat, Senior Researcher

List of Abbreviations

Abbreviation	Definition
1G	1st Generation Mobile Communication (standard)
2G	2nd Generation
3G	3rd Generation
4G	4th Generation
5G	5th Generation
5G NR	5G New Radio
ADC	Analog-to-Digital Converter
ADR	Adaptive Datarate
ALOHA	Advocates of Linux Open-source Hawaii Association - data transmission protocol
AP	Access Point
BPSK	Binary Phase Shift Keying
BW	Bandwidth
CDMT	Cellular Drone Measurement Tool
CR	Coding Rate
CSS	Chirp Spread Spectrum
DAC	Digital-to-Analog Converter
DL	Downlink
DR	Datarate
EARFCN	E-UTRA Absolute Radio Frequency Channel Number
ECC	Electronic Communications Committee
EMI	Electromagnetic Interference
FCC	Federal Communications Commission
FSK	Frequency Shift Keying
GHz	Gigahertz
GPS	Global Positioning System
GUI	Graphic User Interface
HART	Highway Addressable Remote Transducer
HF	High Frequency
IEEE	Institute of Electrical and Electronics Engineers, Inc.
ISM	Industrial, scientific and medical - frequency band
kHz	Kilohertz
LAN	Local Area Network
LNS	LoRaWAN Network Server
LoRa	Long Range
LOS	Line-of-sight
LPWAN	Low Power Wide Area Network
LTE	Long Term Evolution
MAC	Medium Access Control
MB	MegaByte
MIMO	Multiple Input Multiple Output
NLOS	Non-line-of-sight
OFDM	Orthogonal Frequency Division Multiplexing

PAN	Personal Area Network
PC	Personal Computer
PCI	Physical Cell Identity
PHR	Packet Header
PHY	Physical layer
PLR	Packet Loss Rate
QAM	Quadrature Amplitude Modulation
RF	Radio Frequency
RSRP	Reference Signal Received Power
RSRQ	Reference Signal Received Quality
RSSI	Received Signal Strength Indicator
Rx	Receiver
SF	Spreading Factor
SME	Small and Medium Enterprise
SNR	Signal-to-Noise Ratio
TDMA	Time Division Multiple Access
Tx	Transmitter
U2G	User-to-ground
U2U	User-to-user
UAV	Uncrewed Aerial Vehicle
UDP	User Datagram Protocol
UL	Uplink
URLLC	Ultra Reliable Low Latency Communications
USB	Universal Serial Bus
UWB	Ultra Wide Band
WAN	Wide Area Network

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