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List of Abbreviations

6G	6th Generation
AGV	Automated Guided Vehicle
AMR	Autonomous Mobile Robot
AR	Augmented Reality
AR	Augmented Reality
ARQ	Automatic Repeat Request
AS	Azimuth Spread
B5G	Beyond 5G
CIR	Complex Impulse Response
CNC	Computer Numerical Control
DS	Delay Spread
EMF	Electromagnetic Field
ES	Elevation Spread
FSO	Free-Space Optics
HMI	Human Machine Interface
HMI	Human Machine Interface
HTTP	Hyper-Text Transfer Protocol
IRS	Intelligent Reflecting Surfaces
ISAC	Integrated Sensing and Communications
KPI	Key Performance Indicator
KPI	Key Performance Indicator
LGV	Laser Guided Vehicle
LIDAR	LIght Detection And Ranging
MAC	Medium Access
MIMO	Multiple Input – Multiple Output
MTP	Motion-to-Photon
NLOS	Non-Line-of-Sight
OEE	Overall Equipment Effectiveness
OPC/UA	Open Platform Communications Unified Architecture
PAP	Power Azimuth Profile
PDP	Power Delay Profile
PEP	Power Elevation Profile
PLC	Programmable Logic Controller
POC	Proof-of-Concept
REST API	Representational State Transfer - Application Programming Interface
RMS	Root Mean Square
RTI	Real Time Industrial Bus/Application
RTT	Round Trip Time
SCADA	Supervisory Control And Data Acquisition
SLAM	Simultaneous localization and mapping
SW	Software
TCP	Transport Control Protocol
THz	Terahertz
UDP	User Datagram Protocol
VLC	Visible Light Communications
VR	Virtual Reality
WIET	Wireless Information and Energy Transfer

Executive Summary

The TIMES project is studying the use and potential of THz communications for industrial applications, and as part of the research, the project has described several industrial scenarios and use cases in manufacturing and logistics. In this context, the project has especially looked on how stationary production machines and moving robots need to communicate for an efficient and safe production process.

Industrial scenarios will include low, medium, and high complexity machines with different communication needs. Today, data flow and control are mostly done using industrial, Ethernet based fieldbus technologies. Wireless alternatives often build on Wi-Fi technology. The TIMES industrial scenarios are populated by different types of production machines. Low/medium complexity machines are e.g., wrapping machines, robotic palletizers, pick/place robots and autonomous vehicles. High complexity machines are e.g., paper machines and production lines, robotic production lines, automated warehouses, and beverage production lines. The TIMES project has access to all these types of scenarios via the vertical industry partners Aetna and BI-REX.

The project has further defined use cases for these scenarios in the short, mid, and long term. Short term is in a 3-year perspective, mid-term is between 3 and 5 years, and long term is more than 5 years ahead. The following macro classes of use cases have been defined:

- Macro class A: Mobile Robot Management
- Macro class B: Predictive maintenance, monitoring of machine / Production line with Hi data Flow, substitute Field Bus in non RTI Application
- Macro class C: AR/VR - Digital Twin - Virtual Commissioning - Hi Level Maintenance
- Macro class D: High Dynamic Control, Substitute Field Bus in RTI for Motion and Robotics
- Macro class E: Ensuring Seamless and Secure Field Bus Substitution Process
- Macro class F: Flexible Factory

Industrial scenarios are very complex when it comes to radio wave propagation, and especially at the high frequencies above 100 GHz, there is a need to understand the propagation properties of the wireless channel. This is fundamental to be able to design a robust and efficient wireless 6G system at these frequencies. TIMES will conduct channel sounding measurements at THz frequencies to gain more insight into this challenge. To prepare for this, TIMES has defined initial scenarios for performing measurements.

Measurement scenarios are typically intra- (inside a machine) or inter-machine (between machines), and several scenarios with and without mobility has been defined. The possible inclusion of intelligent reflecting surfaces (IRS) has also been considered. Further, several specific measurement setups to cover most of these scenarios has been defined and will be performed by project partners in the following work of TIMES.

Both the industrial scenarios, use cases, KPI definitions and measurement setups will be further refined through the course of the project.

1 Introduction

Industrial communication is a growing application of wireless technologies, and the interest for using cellular technologies is increasing. 5G has been marketed as an enabler with the power to replace several proprietary technologies used today in manufacturing, logistics, and process industry.

The Sixth Generation (6G) of cellular networks envisions to fully integrate advanced features that are only partially required in 5G technology, including: artificial intelligence, THz communications, optical wireless communications, blockchain, wireless information and energy transfer, and other key enabling technologies. Artificial intelligence can be used to increase efficiency and to reduce delays in communication. THz communications will support increased data rates. Optical wireless communications, which includes visible light communications (VLC) and free-space optical (FSO), can be used to extend the range of applications. Blockchain can be an enabler to improve data management. Wireless information and energy transfer (WIET) will boost battery lifetime of connected devices. Other key enabling technologies are as quantum communications, integrated sensing, and communication (ISAC), and enhanced MIMO techniques.

6G, and especially THz wireless communications, has been launched as a candidate technology for extreme industrial use cases.

This will bring the following benefits to Industry 4.0:

- Using augmented/virtual reality in industrial tasks may benefit from higher resolution and multi-sensory designs.
- Massive deployments of mobile robot swarms and drone performing a vast range of tasks may benefit from increased capacity and link reliability and distributed computing. For example, the interaction between workers and robot or machine can be improved and made safer using 6G/THz capability as integrated sensing and communication.
- Enhanced interaction between workers and robots/machines using ISAC to improve safety.
- Dynamic digital twins may benefit from increased accuracy for synchronous updates from the physical world and higher resolution of real-time mapping and rendering.

1.1 Scope

This deliverable contains definitions and descriptions of the industrial use cases and scenarios to be addressed in the TIMES project. Also, the relevant 5G/6G Key Performance Indicators (KPIs) are identified and defined. Finally, it defines the channel measurement scenarios which is the starting point to understand how THz communications would work in the industrial automation scenarios, and in which cases the replacement of cables with wireless links provides real advantages.

1.2 Audience

The main audience of this deliverable is the technology partners of the TIMES project, which will work on testing, simulations and developing components and devices for THz industrial communications.

1.3 Structure

The rest of the document is structured as follows:

- Chapter 2 contains descriptions of industrial scenarios in which THz based communications could be relevant.
- Chapter 3 contains more specific scenarios which can be addressed in the short, mid, and long term.

- Chapter 4 summarizes B5G and 6G relevant KPIs for industrial communications.
- Chapter 5 contains descriptions of scenarios and setups for radio channel measurements to address the propagation conditions for THz frequencies in industrial scenarios.
- Chapter 6 contains a summary and conclusions.
- Chapter 7 is the reference list.
- Finally, additional information is provided in the Appendix A on common industrial communications protocols, and Appendix B contains specifications and descriptions of the channel sounder equipment from partners TU Braunschweig and Huawei.

2 Industrial scenarios

This chapter presents the industrial scenario to be studied in the TIMES project. First, information on the related industrial machineries and applications are given. Afterwards, typical network/bus architectures of an industrial plant are given.

2.1 Industrial machines and applications

This chapter presents some typical communication in industrial scenarios, with different complexity levels of application.

The industrial scenario is very diverse, with various types of segments of production e.g.: food, beverage, tissue, machine tools, automotive, semiconductors, etc. For each industry segment there are a lot of different machines composing the production line, and for each machine there are many technologies and architectures applicable. Understanding which application and challenge must be addressed is not a simple process but requires an accurate description of the elements that characterize the reference industrial scenario. In this chapter we want to classify the different industrial scenarios based on complexity and identify some main parameters or attributes that characterize this kind of machines and applications.

The attributes and parameters characterizing each machine or line are the following:

- *Number of connected controllers:* Programmable Logic Controller (PLC), Motion Controller, Robot Controller, etc. More controllers mean higher exchange of information over time.
- *Number of connected nodes*: HMI/Servo Drive/Inverter/I-O/Device. The more the nodes are communicating via wired industrial bus, the more challenges need to be solved using wireless communication.
- *Machine Dimension (length x width x height)*: A larger machine creates a longer distance that must be covered by the wireless link.
- *Mechanical Structure of* the *Machine*: The more columns, bars and frames are used to build the machine, the more obstacles can be present on the radio beam path.
- *Bandwidth of fieldbus communications, RTI (Real Time application), NON RTI (non-real time application)*: A typical real-time application have a little sample time (typically < 1ms) and a high number of servo drive and motor to control, this means high data rate for the communication and require high Bandwidth, low latency, high stability, or reliability. Vice versa in the NON RTI application some requirements can be relaxed.
- *Quality of environment, presence of dust, metal dust, moisture, and gases*: The radio beam can be attenuated if some of these contaminating elements are present. For example, the inner part of a machine tool needs to be continuously lubricated to keep the mechanical tools cool, so that all the environment is wet from water and oil. This can affect the quality of the wireless link.

These characteristics reflect their relevance in the current wired fieldbus and are important to set requirements and KPI for the future 6G/THz wireless fieldbus technology.

For the previous reasons, we classify the machines in two categories of complexity and explore the fieldbus type:

- **Low/medium** complexity machines (structure and examples in Table 1)
- **High complexity** machines or production lines with many machines (structure and examples in Table 3).

For each complexity category, we will provide information on the main characteristics of the communication interface and an indication whether Wi-Fi or 5G could be applicable or new 6G based technologies are needed. Even if the industrial scenarios are much more diverse than this collection of examples, they are useful to assume some characteristics and KPIs for the study in the TIMES Project.

Additional information is added in Table 2 and Table 4 and in the sections below. These are related to:

- Connected nodes and their distribution between servo motors, video camera, I/O, PC-HMI, and asynchronous devices.
- Real time or not real time application
- Dimensions of the machine or production line

The aim of this chapter is to create a common terminology about industrial technical applications and stimulate a technical discussion and investigation about the KPIs and requirements of this project.

2.1.1 Low/medium complexity machines

Low/medium complexity machines have a relatively small number of controllers and connected nodes, and a reduced size, where all nodes are connected inside the same electrical cabinet. They can work in a dry/wet and clean/dusty environment. Machines with movable parts or movable machines might take advantage of 6G wireless communication systems. All sensors, controller, nodes etc. are connected in a very small space inside the electrical cabinet, therefore the choice between wireless and wired communication must be carefully evaluated.

Table 1 Examples of low/medium complexity machines

	Wrapping machine (packaging) Machines have a rotating part to apply stretch film around a pallet to stabilize the load for the transport
	Shrink wrapping, wrap around (packaging) Machine to produce bauble of wrapped bottles for drink or can or tetra Brik or food products
	Robotic palletizer cell (product handling) Machine to create a pallet of products like boxes or bundles
	Pick/place robot cluster (packaging) Machine to picking food products and place them in a box
	Autonomous vehicles (high payload – logistics) AGV to move some manufactured products among several production stations. These AGVs have a high load capability (1 Ton)

	Autonomous vehicles (low payload-logistics) AGV to move some manufactured product among several production station, These AGVs have a low load capability (100 Kg)

Table 2 Field Bus and Communication characteristics (Low/Medium Complexity)

	Bus Type	HW Protocol	Data Rate	Nr of Nodes	Application
Real Time Application (Motion Control, Robotics)	• Profinet • Ethernet-IP/Chip • Ethercat • Powerlink • Sercos	Ethernet Based. Isochronous Telegram	100Mbps-1Gbps	1-50: • 30 Servo motors • 20 Asynchronous motors • 20 I/O nodes • 1-2 PLC/HMI	Real Time control of motor Mechatronics Robotics
Non-Real Time Application (I/O, Simple Actuators)	Ethernet	Ethernet Asynchronous Telegram	100Mbps	1-30: • 10 Asynchronous motors • 15 I/O nodes • 5 PLC/ HMI	Intra machine connection among PC/PLC/frequency drive (Inverter)/remote IO/HMI, Scada
Vision Systems	Ethernet	Ethernet	1Gbps	• 1-10 Standard Camera • 1-2 Slow Motion Camera	• Robot Pick/Place • Monitoring • Fast Inspection • Quality Check • Connection PC-Camera

This table represent the actual state of the art of industrial fieldbus. It shows high performance wired fieldbus and type and the maximum number of nodes connected. The faster the communication is and the more nodes are connected at the same controller, the more data are generated for exchange, which require a high data rate. For example, a fast single data rate application, multiplied by a big number of nodes will require exchange of a large amount of data. This is a good example for a future 6G/THz wireless application.

The current wireless protocol standards are not shown here but are explained in appendix A. They are used in industrial application with low data rate, below 100 Mbps and for a small number of nodes, typically in NON RTI application and for not time critical type of communication.

2.1.2 High complexity machines

High complexity machines and lines have a relevant number of controllers and connected nodes: they are bigger size machines, and the lines are extended on the floor. Many nodes are connected inside the same electrical cabinet and other controllers and nodes are connected among several electrical cabinet for distances higher than 50-100 m. These lines can work in a dry/wet and clean/dusty environment. The introduction of 6G wireless communication system can be used to support mobility of machines as well as moving parts inside machines, and cover long distances, where the challenge is to bypass the several obstacles that this kind of plant can originate.

Table 3 Examples of high complexity machines or production line with many machines

	Paper Machine Dimensions: L100m x W10m x H10m (footprint -> one building) Machine produce big rolls of paper
	Converting Paper Production Line Dimensions: L40m x W5m x H5m Line converts the big rolls of paper in small rolls of paper
	Robotic Production Line Dimensions: L20m x W5m x H3m Very flexible and reconfigurable production line to assembly/paint/make assembled parts
	Automated Warehouse Dimensions: L50m x W50m x H20m Organized structure to store goods, parts, components, products

<table>
<tr><td colspan="2">
Beverage Production Line. Dimensions: L20m x W10m x H3m
Production line to make the bottle, fill it, packing and palletize the bundle in a continuous flow of production.</td></tr>
<tr><td></td><td>Converting Paper Production Line
Dimensions: L20m x W20m x H5m
Different Layout of Converting Line.
The Line convert the big rolls of paper in small rolls of paper</td></tr>
</table>

Table 4. Field Bus and Communication characteristics (High Complexity Machines/Production Line)

	Bus Type	HW Protocol	Data rate	Nr of Nodes	Application
Real Time Application (Motion Control, Robotics)	• Profinet • Ethernet-IP/Chip • Ethercat • Powerlink • Sercos	Ethernet Based Isochronous Telegram	100Mbps-1Gbps	50-600: • 300 Servo motors • 200 Asynchronous Motor • 100 I/O node • 10-100 PLC	Inter- and intra machine real time control
Non-Real Time Application (I/O, Simple Actuators)	Ethernet	Ethernet Asynchronous Telegram	100Mbps	10-200: • 50 Asynchronous Motors • 20 I/O Node • 20 HMI • 10-20 PLC	Intra Machine connection among PC/PLC/frequency drive (Inverter)/remote IO/HMI, Scada
Vision Systems	Ethernet	Ethernet	1Gbps	10-100 Standard Camera	• Monitoring • Inspection • Quality check • Connection PC-Camera

Also, this table shows high performance wired fieldbus and type and the maximum number of nodes connected.

2.1.3 Communication architecture based on synchronized fieldbus

In the following figures, typical architectures of Machine Control based on Synchronous Field Buses are shown.

All fieldbus connections shown in the pictures below connect PLC/HMI/Drivers/Inverters for RTI application (real time application) inside the electrical cabinet. The wired connections are short and inside the same cabinets, for these reasons it is not suggested to replace the wired connection inside the electrical cabinet with 6G/THz. In the future PLC and an edge computer may be centralized outside the electrical cabinet and 6G or Wi-Fi connection can be part of this use case.

Figure 1 below shows, in a simplified form, the standard architecture of electronic control in an industrial automated machinery. The three rectangles emphasize the physical distance between the different controllers and the machinery.

The *Motion Control* (red rectangle) is the high demander part for the wired communication because is the most inner part of control where the machine controller is directly connected with Servodrive/Inverter/I-O and with the mechanical groups. All electronic equipment's are assembled very near to each other and inside the same electrical cabinet, wired with short cables. For this reason, in this section could be not more convenient apply 6G/THz technology and its use must be accurately evaluated by cost/benefit analysis.

The *Machine Control* (green rectangle) is always located near the machine and performs the logical control of the machine status. The controller is wired connected via a fieldbus with HMI, process I/O node, vision system, another controller. Some of these connections can be moved from wired to wireless.

The *Plant Control* (blue rectangle) is used to exchange information from single machine to main plant controller and/or from different machines that compose a production line. In this ambit, the wired connection must cover significant distance and the bandwidth is relevant because many machines must exchange data. This function perfectly matches the paradigm to substitute wired fieldbus connection with wireless fieldbus connection.

If we continue to connect machine to other machines, machine to plant and plant to other plant, like shown in Figure 2, is obvious that wireless communication can support much better the increased number of nodes in the network to create new functionality, new digital services, new control, and optimization.

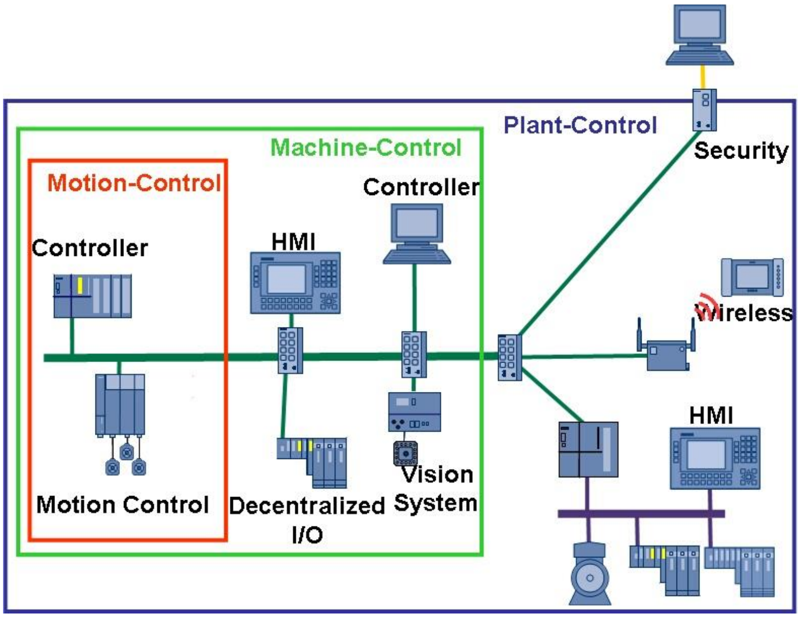


Figure 1 Scalable architecture of controller and communication busses, from Motion Control (Robotics) to Plant Control (Source: AETNA)

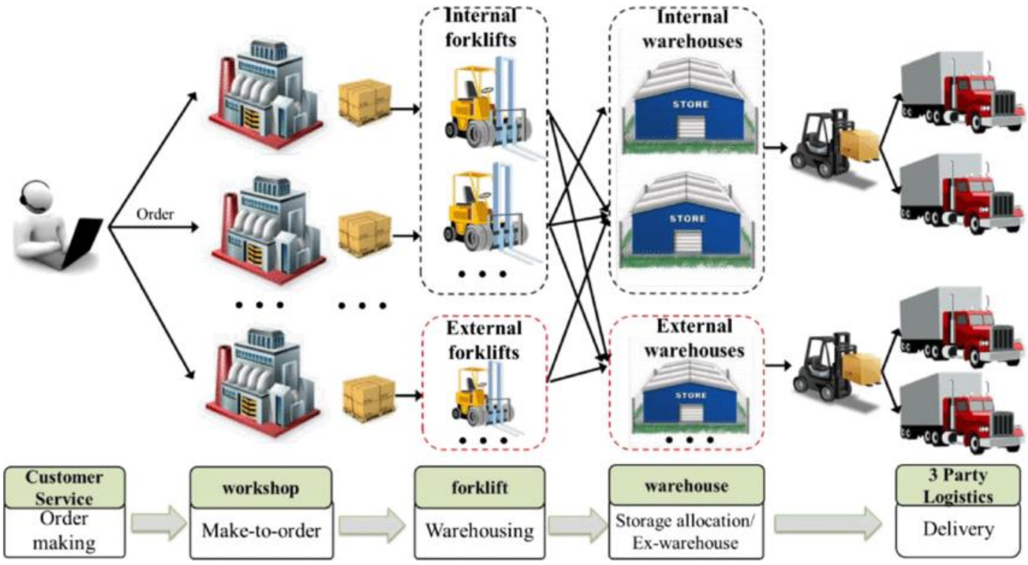


Figure 2 Inter Factory – Inter-Machine Communication for Logistic (Source: AETNA)

3 Use case descriptions in industrial scenarios

In this chapter, it will be presented several use cases and possible applications of 6G in industrial environments in agreement with the type of machine/line in the production plant and with the different network architecture for real time application and for non-real time application. For each use case we indicate the expected realization time, categorized based on 3 timelines: short-, mid- and long-term scenarios. We also indicate the source of the proposal (TIMES partners, 3GPP, 6G BRAINS or others).

- **Short-Term Scenario**: has a duration of **3 years**, from the start to the end of the TIMES project. Coincides with the period of POC's realization.
- **Mid-Term Scenario**: lasts **from 3 to 5 years** from the start of the TIMES project.
- **Long-Term Scenario**: has a duration of **more than 5 years** from the start of the TIMES project.

The aim is to collect some realistic examples to define requirements and specifications to solve the challenges contained in these scenarios. In Table 5, we have identified some **macro use cases classes** and for each we have identified a subgroup of **specific use cases**.

The motivation of using of THz frequencies at mid-term for 6G-links is to demonstrate that wireless links can effectively go beyond the performance of 5G wireless. Specifically, the combination of communication and sensing could leverage on the potential spatial resolution that could be expected at the high end of the millimetre-wave range, i.e., around 300 GHz. Among the challenges, understanding the THz channels to provide high-enough system margins is a critical point as addressing NLOS or reconfigurable THz links is very demanding for the hardware specifications.

Precise pointing with narrow beams would allow the employment of nearby IRS to sweep both vertical and horizontal planes, making possible wireless communications at high altitudes inside the industrial environments, reducing even more interferences or visual line-of-sight obstruction.

Furthermore, the inclusion of mechanical steering of the IRS or antennas would extend even more the network possibilities, at the expense of increased complexity or making the whole system less energy saving.

A subsequent analysis of the IRS will be conducted to determine the feasibility of achieving non-linear polarization communications, thereby increasing the potential communication capabilities.

Table 5 TIMES Industrial use cases' classification and overview.

Macro class	Class description	Subclass	Specific uses case - subclass	Timeline (final)
A	Mobile Robot Management	A.1	Automated and guided vehicles and mobile robots + Offloading of localization and video processing operations for smart transportation vehicles	mid
		A.2	Online cooperative high-resolution 3D map building	mid
B	Predictive maintenance, monitoring of machine / Production line with Hi data Flow, substitute Field Bus in NON RTI Applications	B.1	Predictive Maintenance	mid
		B.2	Monitoring - Video and Mechatronic Data +Remote access and maintenance	short/mid
		B.3	Process Automation + Connectivity for the factory floor	mid

Macro class	Class description	Subclass	Specific uses case - subclass	Timeline (final)
C	AR/VR - Digital Twin - Virtual Commissioning - Hi Level Maintenance	C.1	Virtual Simulation / Commissioning - AR + Maintenance in Factory and Warehouses	mid
		C.2	Ultimate immersive cloud VR/AR + Glass-free 3D and holographic displays	mid
D	High Dynamic Control, Substitute Field Bus in RTI for Motion and Robotics	D.1	Substitution of RTI wired Buses with 6G wireless for Virtual PLC/EDGE + Motion control + Offloading of the PLC control function to the edge	long
		D.2	Control-to-control communication (motion subsystems) + ex of rotating machine	long
		D.3	Motion Control + Seamless integration with Industrial Ethernet	long
E	Ensuring Seamless and Secure Field Bus Substitution Process	E.1	Mobile control panels with safety functions	long
		E.2	Real-time cooperative safety protection	mid
F	Flexible Factory	F.1	Flexible, modular assembly area + Factory of the future	long
		F.2	Collaborative robots in groups + From intelligent robots to cyborgs	long
		F.3	Variable message reliability	mid

The use cases described later came from the current experience of TIMES Partners and from other projects that have explored and investigated 6G implementation in industrial environments. In the following, 6G BRAINS project and 3GPP contributions are provided:

- **6G BRAINS**
  The H2020 6G BRAINS project has presented three use cases related to industrial applications and identified their requirements in terms of communication and localization capabilities [1]
- **3GPP**
  The 3rd Generation Partnership Project (3GPP) is a global organization responsible of defining technical specifications for cellular communication networks, including LTE and 5G technologies. One of the working groups of the organization, System Architecture WG1 – Services (SA1), has the objective of identifying new services and features to be supported by new cellular generations, and to define their technical requirements. To this aim, SA1 carries out detailed analyses of potential use cases covering many different vertical sectors, which result in public reports that are used as an input for the system design. TR 22.804 [2] and TR 22.916 [3] describe multiple use cases related to industrial automation and robotic applications. In the following, we have clustered these use cases and other similar use cases to create a more organic explanation for TIME application scenario.

Each application may have varying standards for real-time, near-real-time, and non-real-time requirements, depending on the specific context. For industrial dynamic robots, stringent values are observed. To categorize industrial applications according to their link latency demands, we have devised a table that assigns them to three distinct categories: real-time, near-real-time, and non-real-time. Table 6 acts as a reference for evaluating the link latency requirements of diverse industrial applications.

Table 6 Real-time requirements terminology and definitions used in this report

Real-Time Requirement	Real Time	Near-Real Time	Non-Real Time
Link Latency	< 0.05 ms	0.05-5 ms	> 5 ms

We have incorporated a comprehensive range of throughput requirements, spanning from small to medium, high, and even ultra-high levels, as shown in Table 7. However, given the complexity of industrial environments, which often involve numerous moving objects, we have assumed of non-line-of-sight (NLOS) conditions, where direct light transmission may be obstructed.

Table 7 Data rate terminology and definitions used in this report

Data Rate	Small	Medium	High	Ultra-High
Mean Throughput	< 50 Mbps	50-200 Mbps	200 Mbps - 1 Gbps	> 1 Gbps

3.1 Macro class A: Mobile robot management

In this macro class some applications related to the management of mobile robots and mobile vehicles in industrial environments are collected. And clustered w.r.t. the data needed for their coordination and self-coordination, and w.r.t. the interaction between robots and the environment. The management of a fleet of vehicles, the interaction with other entities, the management of a 3D map of working space and the reliability of communication due to obstacles and dynamicity represent some of the challenges of this class.

3.1.1 A.1: Automated and guided vehicles and robots

Duration	Mid term
Proposal	AETNA, BI-REX, 6G BRAINS, 3GPP
Real-time requirements	Non real time
Data Rate	Medium

In logistic and in manufacturing industry several types of carriages and robots with autonomous guide capability are used: LGV (Laser Guided Vehicle), AGV (Automated Guided Vehicle), AMR (Autonomous Mobile Robot) are examples of well know vehicles, which can benefit from a fast wireless communication network to optimize the mobility of the whole vehicle fleet.

A 6G/THz Infrastructure could overcome the limit on numbers of LGVs simultaneously connected and handled, and further guarantee a low latency on data transmission for remote control of LGVs.

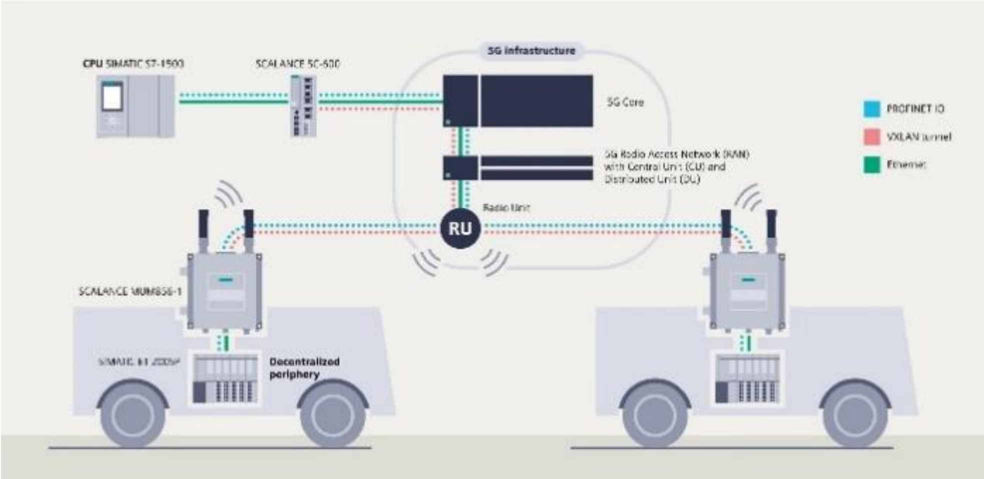


Figure 3 Example of connected LGVs (Source: Siemens[1])

BI-REX uses several mobile robots of the AMR type, each equipped with two LIDAR sensors. These can map the environment and indirectly determine the robot position. This kind of navigation is called SLAM (Simultaneous Localization and Mapping). The robot can exchange data via the REST API protocol, a client-server protocol based on HTTP with user authentication.

Among the variables exchanged there are (reading and writing):

- Registers
- Positions
- Missions

Also, external functions can be called as following:

1. Maps and Mission Creation: Creating and managing maps of the environment where the robots operate and defining specific tasks or goals for the robots to accomplish.
2. Position Monitoring: Real-time tracking and visualization of the robots' positions using LIDAR sensor data.
3. Path Optimization: Generating optimal paths or trajectories for the robots based on maps, positions, and mission requirements to improve navigation efficiency and effectiveness.

Figure 4 BI-REX Mobile Robot (AMR) (Source: CSSI Technologies[2])

[1] https://press.siemens.com/global/en/pressrelease/real-time-communication-5g-profinet
[2] https://cssi.com/product/mir250-amr/

These mobile robots (AMR) or mobile vehicles (AGV) are equipped with multiple sensors to aid their navigation and they can be equipped with robotic arms to manipulate the payload, e.g., to handle dangerous materials without requiring human presence. The information and the data used by AMR/AGV are mainly managed by a central control in the AMR/AGV. This use case aims at the distribution and the localization of the main controller of AMR/AGV, like:

- In a small environment each AMR/AGV can communicate via 6G Radio with a central controller (via cloud or not) to manage AI operation.
- In a bigger environment each AMR/AGV can communicate via 6G Radio with a nearest EDGE and the EDGES can communicate via 6G among them or with a main supervisor (via cloud).

The challenges are the data rate traffic flows to upload sensor data to the edge computing node (data rates, latency, reliability), ultra-high positioning accuracy for the robots, 3D localization capabilities.

3.1.2 A.2: Online cooperative high resolution 3D map building

Duration	Mid term
Proposal	3GPP
Real-time requirements	Near real time
Data Rate	high

Multiple robots and vehicles cooperate to collaboratively build a 3D map of the operating environment. During the mission of each AMR/AGV, it is possible to collect information about the geometry of physical space and send this information via 6G wireless to a central controller that manage and update the digital twin of the geometry 3D of the work environment. The updated 3D information contained in the Digital Twin can be used to optimize the trajectory and the mission of AMR/AGV.

3.2 Macro class B: Predictive maintenance, monitoring of machine/production line with high data flow, substitute fieldbus in non-RT applications

In this macro class, applications related to the substitution of wired connections for non-real time applications are collected. They are used to create a high-level system of monitoring of machines or production lines. The information is generated in the PLC and controller machines and are exchanged with an edge computer or SCADA systems. These computers store the information in a data base for a long time (e.g.: 1 year) and analyse it to give information about the production status of the machine/line with OEE, diagnosis, alarm, predictive maintenance, and condition monitoring. The data exchanged from PLC and EDGE/SCADA Computer are non-real time data (like in the motion controller).

3.2.1 B.1: Predictive maintenance

Duration	Mid term
Proposal	AETNA, 3GPP
Real-time requirements	Near real time
Data Rate	High

Predictive maintenance and condition monitoring are technologies consisting in collecting data and parameters from the machine during its production time related to some physical aspect of the working cycle of machine (e.g.: motor current, motor speed and position, temperature, vibration, acoustic noise etc..) with a very fast rate and store/analyse this information to understand if the machine works in a “physiologic or correct condition” or if it works in a “pathologic condition and is near to a failure”. Predictive Maintenance can predict a future failure before it happens to fix the issue.

The parameters are normally generated by sensors and acquired by a Machine Controller (PLC) to create a numerical image of process. These parameters are delivered by PLC to a supervisor like an EDGE Computer, able to communicate with several machines composing the production line and many PLC cams to exchange information with a supervisor.

Today the communication is wired and done with Field Bus and with protocols explained in chapter 2 mainly based on industrial ethernet. The challenges on this use case are to remove the wired connection and realize the communication with 6G wireless Technology needs ultra-high data rate, sufficient coverage and an increased number of devices connected.

In Figure 5 a typical production floor with several machine and mobile robot/vehicles is illustrated. Each of them can transmit its data set to an EDGE for the Predictive Maintenance.

Figure 5 Plant Floor: Groups of machines and robots communicating (Source: Siemens)

3.2.2 B.2: Fast process monitoring with a mix of mechatronic data and video, high feature remote access and maintenance

Duration	Short/mid term
Proposal	AETNA, 3GPP
Real-time requirements	Real Time
Data Rate	Ultra-High

When an industrial machine has a failure, mechanical or electronic, is important to understand the causes in order not only to replace the damaged component but also to prevent it from happening again. To conduct this analysis if the machine is in another country, we need to connect a “remote room” to the machine controller and gather the last functional parameters. A better comprehension of phenomena can be achieved if a video camera system is installed on the machine. The video systems and machine controller exchange data with a local edge computer that collects all the information when a failure occurs, a dedicated buffer stores the data of the 30 seconds before and after the failure to capture the machine status and video. The data rate (for mechatronic and video data) is very high, and it can be a challenge for 5G/6G to transmit so much data that can be potentially encapsulated. The data collected in the edge buffer can be used to analyse and understand the root causes of the fault. after having locally stored the buffer of information it is important to provide external access to industrial machines to enable control and maintenance of the machine from remote locations. All data is exchanged in non-real time wired network on Field Bus described on Chapter 2 and can be substituted by a 6G wireless network.

3.2.3 B.3: Process automation and connectivity for the factory floor

Period	Short/mid term
Proposal	3GPP
Real-time requirements	Non real time
Data Rate	Medium

This includes use cases for monitoring and controlling industrial processes, as well as managing plant assets. It provides wireless connectivity to sensors, actuators, machines, robots, controllers located within the same factory floor. It is a more general use cases than B.1 Predictive maintenance and B.2 Fast process monitoring with mechatronic data and video.

The challenges for 6G-THz wireless communications are the same as for the other use cases. The aim of this use cases is making the data more accessible to be collected, all information, all signals that can be acquired from PLC, all data exchange with supervisor edge or cloud to have a numerical representation of physical/production/maintenance status of the production machine or line.

3.3 Macro class C: AR/VR - Digital twin, virtual commissioning and high-level maintenance

With 6G THz capabilities, AR/VR experiences become more immersive, realistic, and interactive, merging the virtual and physical worlds. Digital twins powered by 6G can enable real-time monitoring and control of complex systems, optimizing processes across industries. Virtual commissioning can leverage 6G THz bandwidth for accurate testing and simulation, reducing risks and costs. High-level maintenance benefits from ultra-fast speeds and low latency, enabling remote monitoring, predictive maintenance, and cost savings. In summary, 6G THz technology can revolutionize AR/VR, digital twin, virtual commissioning, and hi-level maintenance, enhancing experiences, optimizing processes, reducing risks, and improving efficiency.

3.3.1 C.1: Maintenance in factory and warehouse

Duration	Mid term
Proposal	AETNA, BI-REX, 6G BRAINS, 3GPP
Real-time requirements	Near real time
Data Rate	Medium

With digital twins, simulation processes can be run simultaneously with real physical process. Either information from digital twin and physical twin (the original, physical machine, plant, or device) used as feedback on both thanks to the high data transfer of 6G/THz. Figure 6 is a CNC, and the 3D model is represented on the spatial environment. The virtual reality is used to perform training task for example, building a virtual environment, where the students can join the teacher in virtual rooms.

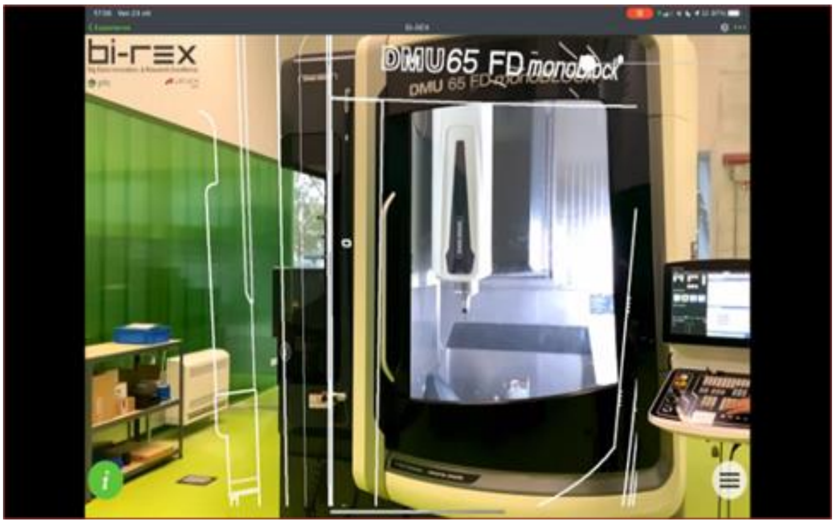


Figure 6 CNC at BI-REX (Source: Bi-rex)

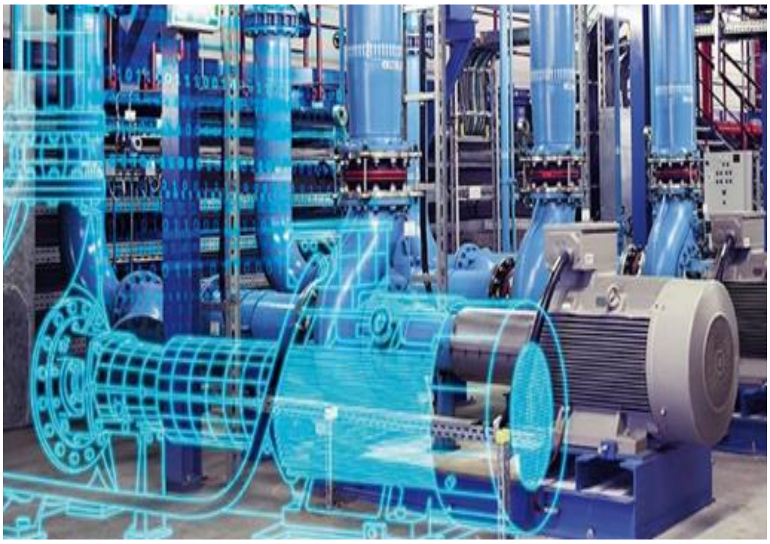


Figure 7 Example of digital twin of hydraulic pump motor (Source: Siemens[3])

3.3.2 C.2: Ultimate immersive cloud VR/AR

Duration	Mid-Term
Proposal	TIMES
Real-time requirements	Non real time
Data Rate	Ultra-high

While wearing VR devices, users always focus on the screen regardless of whether the displayed object is close or far away. Because this affects users' ability to perceive depth correctly, they may experience dizziness or other unwanted effects. Glass-free 3D displays based on visual accommodation are expected to be the next game-changing solution, relying on techniques such as light field and holographic display. Such displays would allow users to see far-away family members up close without the need to wear glasses, delivering an immersive and true-to-life experience. Allowing users to experience this anywhere and anytime requires support from the 6G mobile system. New applications such as mobile 3D navigation will require 3D images to be transmitted over mobile networks, giving rise to extremely high requirements in terms of network bandwidth. The raw data rates, depending on image size, resolution, colour, and so on, will vary from sub-1 Tbit/s to a few hundred Tbit/s [4]. Research on compression techniques that can reduce the bandwidth consumption is ongoing.

360° extreme, immersive XR is an evolution of current XR services, offering an even higher resolution and video frame rate close to the limit of human perception. It provides an extremely low interactive latency, delivering the optimal immersive visual experience. For example, it will enable an engineer or technician to visualize the 3D details of smart factory and machineries in VR remotely. When the engineer or the technician is onsite, the immersive cloud AR can help to visualize the hidden details of the machineries so that problems can be quickly located and solved without unnecessary uncovering and disassembling operations. The digital twin can be combined to enable such kind of applications.

[3] https://resources.sw.siemens.com/en-US/white-paper-digital-twin

To enable extended periods of use without making users experience dizziness, motion sickness is an important consideration in cloud VR. The target motion-to-photon (MTP) latency, close to the limit of human perception, is approximately 10 ms, which is half that of current VR requirements. In addition to requiring extreme video resolution and colour depth, ultimate VR is expected to require more than a 100-fold increase in the raw data rate. Furthermore, an architecture that enables pure remote rendering is more suitable for devices that have limited computing capabilities — user devices often have strict constraints in terms of power and weight. In this case, a stringent transmission latency (a round trip time (RTT) of less than 2 ms) and higher data rate will be required.

3.4 Macro class D: High dynamic control, substitute fieldbus in RTI for motion and robotics

3.4.1 D.1: Motion controller – virtual PLC

Duration	Long term
Proposal	AETNA, BI-REX, TIMES, 6G BRAINS
Real-time requirements	Real time
Data Rate	Ultra-high

Motion control is the core logic in the automation field [5]. It is responsible for controlling every aspect of a machine's movements in a well-defined manner. This type of operation already exists in modern manufacturing, but it is implemented via wired technologies such as industrial Ethernet and is normally located inside an electrical cabinet near the machine. We can imagine two scenarios of application of 6G to motion controller:

- Substitute the wired ethernet communication between drives and PLC (motion controller) inside electrical cabinet.
- Think to a future scenario in which the PLC is not more a physical device inside electrical cabinet but is a virtual PLC located in a server far from the machine and the communication between virtual PLC and drives is done by 6G wireless.

The first scenario is possible but less attractive and convenient compared to the second.

The second one look for a future scenario of machine controllers (PLC/Motion/Robotic PC/Edge Computer) in which is possible carry out these devices from electrical cabinet and centralized and virtualized in a server. This architecture can have benefit in performing maintenance of machine software, with controller firmware that can be updated like a simple application. A second benefit is that the machine software (SW) is less dependent by the hardware and all controllers will be "virtual". In this scenario we can remove the wired connection from driver and devices inside electrical cabinet and the new virtual version of PLC into the server with a 6G Connection. The adoption of this solution involves challenging requirements in terms of guaranteed latency and reliability to support the cycle times required by the industrial application with precise synchronicity. The channel can allow a communication from many drivers with virtual PLC and virtualized controllers. The communication channel must deliver on these RTI requirements:

- Real time with time stamp ≤ 200µs

- Reliable and redundant communications (guarantee of no communication loss) greater than 99.9999%).

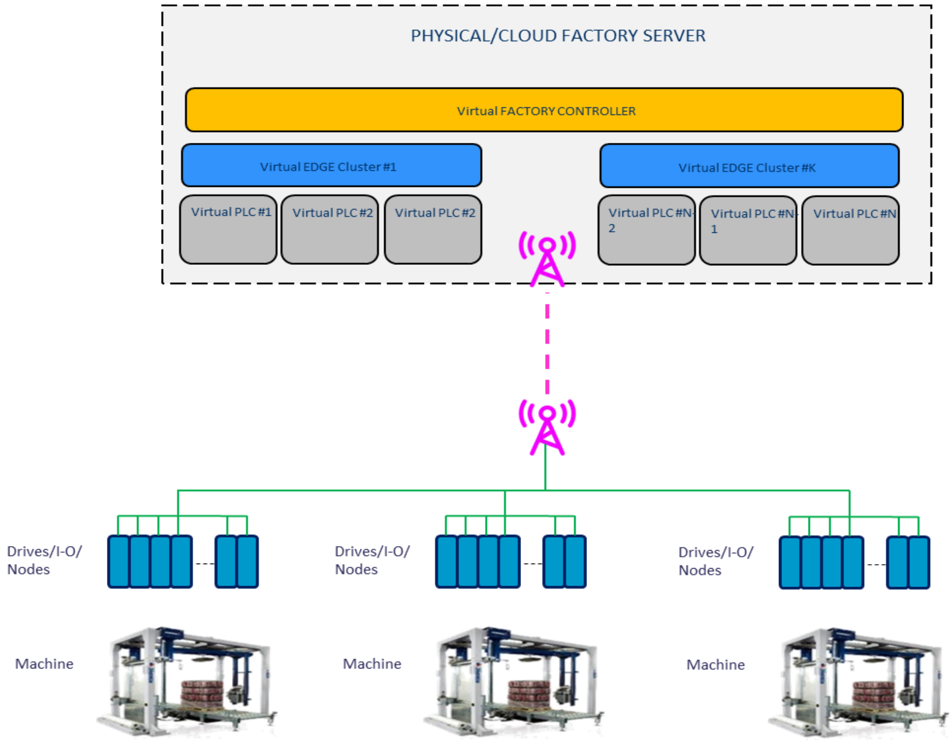


Figure 8 Virtual PLC Example (Source: AETNA)

3.4.2 D.2: Control-to-control communication (motion subsystems)

Duration	Long term
Proposal	AETNA, 3GPP
Real-time requirements	Near real time
Data Rate	High

This use case considers communication between different industrial controllers, e.g., to synchronize the operations from different part of a machine or to synchronize the operation of machines in a production line. This use case can describe two typical situations:

- Complex machine: the functional groups can have an independent motion controller or PLC, and some can be in movement with respect to the other one. In this case, it can be profitable to connect the Group's PLC via 6G wireless with respect to wired communication. This is an example of *intra* machine communications.
- In a production line in which many machines are present and each machine has one motion controller (PLC), it can be useful to connect the PLC via 6G wireless with respect to wired communication. This is an example of *inter* machine communications.

Also, this solution involves challenging requirements in terms of guaranteed latency and reliability to support the cycle timing required by the industrial application with precise synchronization. The channel allows a communication from many drivers with virtual PLC and virtualized controllers. The communication channel must deliver on these RTI requirements:

- Real time with time stamp ≤ 200µs.
- Reliable and redundant communications (guarantee of no communication loss) greater than 99.9999%).

Example of first case:

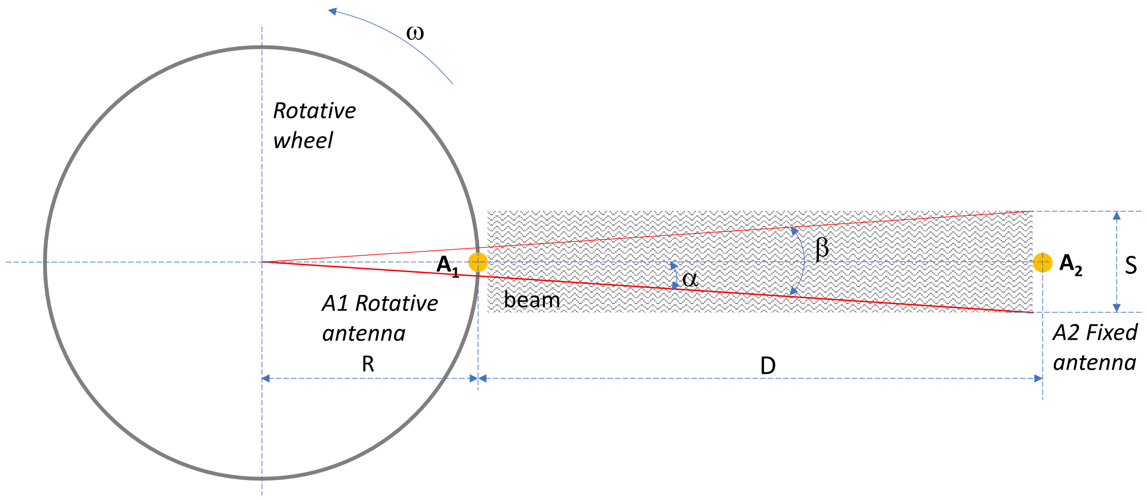
Several machines have an important mechanical group that is in a rotating movement, with sensors and actuators that cannot be reached by a classic wired connection. So, it is necessary to develop innovative applications to carry in the electrical and fluidic power to move the actuator and to carry in/out the control information to/from sensor and controller. The actual technology to carry in/out the control information are from electro mechanic slipring (the slipring is a metallic ring with metallic brushes, the brushes have a rotational movement around the ring and guarantee an electrical connection between the ring and the brushes. The ring is connected to a fixed part of machine, the brushes are connected to a rotating part of machine, in this way is possible transmit signal between a fixed part and a rotating part of a machine) or Wi-Fi connection via industrial Ethernet Wi-Fi 100 Mbps and industrial Bluetooth. These solutions have a tight limit in the available throughput, especially the slipring solution, which is very sensitive to the dust and the capacitive effect.

Another industrial case is the mobile robot, which requires exchange of information during the movement. In this scenario a very fast 6G wireless connection can be used, but the challenge is to handle the non-line of sight (NLOS) situations that may arise.

One possible idea is based on following process:

- The two wireless nodes are continuously searching to establish a link towards each other.
- When one node recognizes the signal, a trigger starts the communication.
- Both antennas are in movement but if the antenna beams remain aligned for the time necessary to complete the information transmission, the communication can be effective. The maximum spatial displacement of two antenna will depend on:
    - Transmission frequency
    - Amount of data to transmit
    - Relative speed between the two antennas
    - Beamwidth
    - Distance between two antennas
    - Etc.

Examples: with 20-GHz Bandwidth and beamwidth 6 mm, by considering the available bandwidth and referring to the parameters outlined in the table below, it is evident that approximately 0.54 MB of data can be transmitted between the two antennas in a line-of-sight (LOS) scenario, see Figure 9.



Parameter	[um]	Formula	Value	Description
R	mm		1200	Rotative Wheel Radius
Ω	rpm		50	Angular Speed Wheel in rpm
D	mm		2000	Antennas Distance
S	mm		6	Beam Width
Bw	GHz		**20**	Bandwidth
ω	rad/s	Ω*2π/60	5,24	Angular Speed Weel in rad/s
α	rad	atan(S/2/(R+D))	9,37E-04	semi angle of antennas light up
β	rad	2*α	1,87E-03	angle of antennas light up
Tβ	s	β/ω	3,58E-04	Time of antenna light up
Tc	s	60%*Tβ	2,15E-04	Time available for communication
Tbit	s	1/(Bw*1e9)	5,00E-11	Time for each bit TX/RX
Nbit	nr	Tc/Tbit	4,30E+06	Nr of bit potentially Transmittable for each shoot
NMbyte	nr	Nbit/8/1e6	**0,54**	Nr of Mbyte potentially Transmittable for each shoot

Figure 9 Concept of rotating machine with antenna

3.4.3 D.3: Motion control - seamless integration with Industrial Ethernet

Duration	Long
Proposal	3GPP
Real-time requirements	Real time/ near-real time
Data Rate	high

Many industrial controllers use an industrial Ethernet connection among between the nodes of the systems. The PLC is connected to an I/O node, sensor, actuator with fieldbus. The system is normally composed by a small group of nodes connected with an RT fieldbus and a high number of nodes connected using a non-RT fieldbus.

Even if the system is less complex than a full RTI control system and much of the communication over the fieldbus is asynchronous, a huge number of nodes to connect may be challenging (ex: in oil/gas industry, paper industry, water treatment etc..). The wired communication for RT node can work together with 6G THz communication for non-RT application.

3.5 Macro class E: Seamless and secure fieldbus substitution

6G THz technology enables a seamless and secure fieldbus substitution process, ensuring continuous operations and enhanced security during the transition. With ultra-fast speed, low latency, and high bandwidth, 6G facilitates real-time monitoring, control, and data exchange, minimizing downtime and optimizing system performance. Advanced security features provide robust protection against cyber threats, making 6G an ideal solution for industries seeking a smooth and secure migration of fieldbus systems.

3.5.1 E.1: Mobile control panels with safety functions

Duration	Long term
Proposal	3GPP
Real-time requirements	Non real time
Data Rate	Medium

6G THz technology could offer a transformative solution for a key use case that focuses on eliminating wired connections between the control panel and industrial controller. By leveraging the capabilities of 6G THz, this use case aims at enhancing accessibility to safety functions for human operators. The ultra-fast speeds, low latency, and high bandwidth of 6G facilitate seamless wireless communication, enabling operators to access safety features conveniently and securely. With the removal of wired connections, operators can experience greater flexibility and freedom of movement, while maintaining reliable and responsive control over industrial processes. 6G THz technology empowers this use case by revolutionizing the access to safety functions, improving operational efficiency, and ensuring a safer working environment for human operators.

3.5.2 E.2: Real-time cooperative safety protection

Duration	Mid
Proposal	3GPP
Real-time requirements	Non real time
Data Rate	Medium

6G THz technology could enable real-time cooperative safety protection by facilitating seamless collaboration between human operators and robots. This use case focuses on securing specific geographical areas through tasks such as intrusion detection, fall detection, smoke and flame identification, and helmet identification. With ultra-fast speeds, low latency, and high bandwidth, operators and robots can exchange real-time data, ensuring swift and accurate identification of potential hazards. The collaborative efforts empowered by 6G THz technology enhance overall safety measures, creating a secure environment for individuals within the designated area.

3.6 Macro class F: Flexible factory

A flexible factory is a cutting-edge manufacturing facility that can swiftly adapt and cater to evolving production demands, accommodating rapid changes in processes, product variations, and customization requirements. It harnesses state-of-the-art technologies like automation, robotics, artificial intelligence, and data analytics to drive efficiency, boost productivity, and enhance agility within the manufacturing ecosystem. By leveraging these advanced tools, a flexible factory optimizes operations, enables seamless adjustments, and empowers manufacturers to meet the ever-changing demands of the market.

3.6.1 F.1: Factory of the future

Duration	Long term
Proposal	TIMES, 3GPP
Real-time requirements	Near real time
Data Rate	Medium

Unlike traditional assembly lines, which are suited to mass production, factory of the future aims at implementing full automation and flexibility, meeting the demands of mass customization. To enable this revolution, the 6G network will play a key role. The precondition for modules to freely move around to instantly form a customized assembly line is the use of ultra-high performance radio links, which untether machines from interconnection cables. Furthermore, with AI and digital twins, it will be possible to accumulate and share manufacturing experience and knowledge among machines and robots, helping optimize the evolving manufacturing process. 6G could also bring many other benefits to the factory of the future. For example, a ubiquitous RF sensing system would enable proactive maintenance of the entire production environment and processes. And, as the factory of the future requires no human onsite, lights-out manufacturing would significantly lower the OPEX and carbon footprint. If there are no applications within the factory that rely on light as a critical component or dependency.

3.6.2 F.2: Collaborative robots in groups

Duration	Long
Proposal	TIMES
Real-time requirements	Near real time
Data Rate	Medium

In the future factory, robots will take on most of the major tasks, supported by technologies like automation, robotics, and AI. Various types of robots, such as automated guided vehicles (AGVs) and drones, will handle material transportation within the production line, with collaboration among multiple robots for moving large or heavy parts [5]. To ensure safe and efficient cooperation, a cyber-physical control application will coordinate their movements, leveraging the synchronization, latency, and localization accuracy capabilities of the 6G network. Additionally, collaborative robots (cobots) [6]are emerging, capable of working alongside humans and requiring integration of AI, ICT, and OT. 6G's high-performance sensing and communication technologies are vital for supporting the mobility and interaction of co-bots with humans. Looking ahead, the concept of cyborgs, where humans are enhanced with machines, could be realized with advancements in neuroscience, making 6G pivotal for cyborg interconnection.

3.6.3 F.3: Variable message reliability

Duration	Mid
Proposal	3GPP
Real-time requirements	Non real time
Data Rate	Low

6G THz technology may present a valuable opportunity to assign data traffic flows different priorities based on the system state or message "urgency." By leveraging the ultra-fast speeds, low latency, and high bandwidth of 6G THz, data traffic management can be enhanced to optimize the transmission and reception of critical information.

4 KPIs for industrial communications

An industrial scenario can be characterized by several system parameters and Key Performance Indicators (KPIs). Table 8 and Table 9 below list the relevant system parameters and network KPIs for the THz industrial communications scenarios defined in TIMES. The 5G mm-wave performance is included as the starting point. Further, the performance goals for the project proof-of-concept (PoC) are given, and finally the target values for the system concept and technology, which will be developed before the end of the project.

Table 8 System parameters and targets for the TIMES THz system

Parameters	Current 5G performance in mm-wave bands	Estimated KPIs of TIMES HW PoC	Estimated KPIs of scaled up TIMES networks
Frequency	<100 GHz	300 GHz	>300 GHz
Bandwidth	<1 GHz	2.16 GHz	>20 GHz
Service area	N/A	5x5 m^2	30x30 m^2
Max number of IRS hops	N/A	2	2

Table 9 Network KPIs and target values for the TIMES THz system

KPI	Current 5G performance in mm-wave bands	Estimated KPIs of TIMES HW PoC	Estimated KPIs of scaled up TIMES networks
Typical wireless user mean data rate (at half-max distance LoS connection, MAC layer)	LoS: < 10 Gbps NLoS: 1 Gbps	LoS: < 10 Gbps NLoS[1]: 5 Gbps	LoS: up to 1 Tbps NLoS: > 100 Gbps
Reliability	LoS: 10^{-5} NLoS: 10^{-2}	LoS: 10^{-5} - 10^{-9} NLoS: 10^{-3}	LoS: 10^{-9} NLoS: 10^{-4}
L2 latency	> 0.5 ms	128 µs	RTI :50 µs NON RTI 200 µs
L2 jitter	> 0.25 ms	2 µs	RTI :1 µs NON RTI 2 µs
Localization accuracy	LoS: 0.5 m NLoS: N/A	LoS: 1 cm NLoS: <0.5 m	LoS: 1 mm NLoS: < 10 cm
Localization latency	>10 ms	N/A	<1 ms
Area Traffic Capacity	10 Mbps/m^2	up to 10 Gbps/m^2	>10 Gbps/ m^2
THz-related KPIs: Sensing Resolution	N/A	N/A	1cm @ 1m

In the following, some of the system parameters related to a THz reference scenario are described and then each KPI in the table is defined. Some considerations are presented on the current performance of 5G mm-wave bands and on the desired performance from and end-user point of view [7].

4.1 Channel bandwidth

The two different frequency ranges in 5G, FR1 and FR2, shown in Table 10 standardizes up to 100 MHz and 400 MHz maximum carrier bandwidths, respectively.

Table 10 5G Frequency ranges and bandwidths

Frequency range		Supported channel bandwidth [MHz]
FR1	450 MHz – 7125 MHz	5, 10, 15, 20, 25, 30, 40, 50, 60, 80, 90, 100
FR2	24250 MHz – 52600 MHz	50, 100, 200, 400

Carrier aggregation is a technique that groups together various channel (*component carriers, CC*) to increase the channel bandwidth available for a single transmission. Maximum number of configured component carriers for a UE is 16 for DL and 16 for UL. CC having different bandwidths (in both FR1 and FR2 frequency bands) and different duplex schemes, can be aggregated allowing for overall transmission bandwidths of up to 6.4 GHz (16 x 400 MHz) in 3GPP Release 15.

Even though, the provided bandwidth is not sufficient for the applications we foresee for 6G/THz. Target data rates and channel bandwidths for 6G is still not decided, but the 5G-PPP Test, Measurement and KPIs Validation Working Group has provided proposals in their white paper "Beyond 5G/6G KPIs and Target Values" [8]. Supported channel bandwidths for higher frequency bands (above 6 GHz) should be up to 1 GHz.

4.2 Wireless user mean data rate

It is a measure of how fast on average a user can send data through the network. Another metric can be considered, that is the throughput. The latter refers to the average number of information bit correctly received in the unit of time, and this means that it is lower or at most equal to the data rate. It is therefore influenced by the type of application that is considered, as well as the underlying protocol stack (e.g., whether TCP or UDP is used at the transport layer, whether random or scheduled access is adopted at the MAC layer, whether retransmissions – ARQ – are allowed, etc.).

The current type of data streamed are of different characteristics:

- Robot mission commands (very light, frequency of seconds),
- Images (a bit heavier, but low frequency (less than 1 Hz),
- Video streaming for AR/VR (heavier with higher frequency).

4.3 Reliability

Reliability (to be compared with actual standard), is defined as the ability to perform as required for a given time interval, under given conditions [9], or, otherwise stated, the capacity of providing continuity of correct operation; the 5G specifications for the use cases identified in this document shall support service availability better than 99.999%.

4.4 Latency (End-to-End)

E2E lantency is the time it takes to transfer a given data burst from a source device to a destination device, measured at the application service access point, from the moment it is transmitted by the source to the moment it is successfully received at the destination. A data burst is defined as the Service Data Unit at the Application Layer [10].

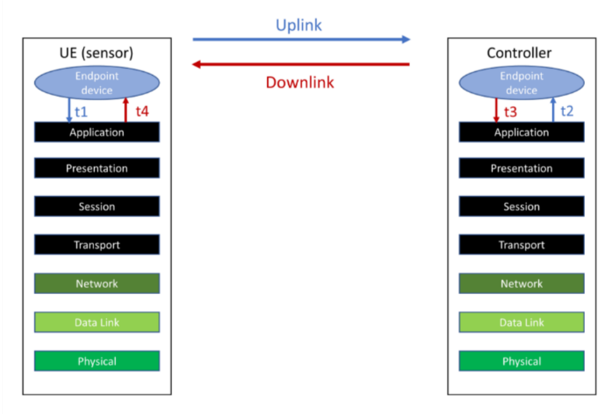


Figure 10 Protocol stack illustrating the end-to-end latency measurement points

According to Figure 10 above, where the communication is made between a UE and a controller, the end-to-end latency in uplink is defined as t2-t1, while the end-to-end latency in downlink is t4-t3. The end-to-end latency accounts also for the time needed to add the headers across the protocol stack, I.e., to create the data block ready to be transmitted over the channel, starting from the data burst.

4.5 Delay and jitter

L2 jitter: It is measured as the mean deviation in the actual arrival times, versus the theoretical/predicted arrival times. Jitter may be an issue if different data packets encounter different delays, and the application using the data (audio and video data) at the receiver is time sensitive.

In terms of periodicity, industrial wireless communications can be divided into two classes: *periodic traffic* with very stringent delay requirements and *aperiodic traffic,* which is non-cyclic but can still be time critical. In general, to enable a deterministic wireless network that replaces wired fieldbus it is necessary to keep the latency as small as possible.

Table 11 Industrial Automation Use Cases and Requirements [11]

Communication Requirements		**Link requirements**					
		Time-critical or cyclic			**Non-critical**		
Use case		**Cycle time**	**Payload**	**Jitter**	**E2E Latency**	**Data rate**	**Jitter**
Motion control	Printing machine	< 2 ms	20 B	< 1 µs	-	> 1 Mb/s	-
	Machine tool	< 0.5 ms	50 B	< 1 µs	-	> 1 Mb/s	-
	Packaging machine	< 1 ms	40 B	< 1 µs	-	> 1 Mb/s	-
Control-to-control communication	Communication between different industrial controllers	4-10 ms	< 1 kB	< 1 µs	< 10 ms	5-10 Mb/s	-
Process Automation	Closed-loop control	10-100 ms	Few Bytes	<1-10 ms	-	-	-
	Process Monitoring	50 ms	-	-	-	-	-
	Plant Asset Management	50 ms	-	-	-	-	-
Mobile Robots	Precise cooperative robotic machine control	1 ms	40-250 B	< 50% of cycle time	-	> 10 Mb/s	-
	Machine control	1-10 ms	40-250 B		-		-
	Cooperative Driving	10-50 ms	40-250 B		-		-

Communication Requirements		Link requirements					
		Time-critical or cyclic			Non-critical		
Use case		Cycle time	Payload	Jitter	E2E Latency	Data rate	Jitter
	Video-operated remote control	10-100 ms	15-150 kB		-		-
	Standard robot operation & Traffic management	40-500 ms	40-250 kB		-		-
Human-centred Monitoring	Safety Control Panels	4-8 ms	40-250 kB	<2.4 ms	< 30 ms	> 5 Mb/s	< 15 ms
	Augmented reality	< 10 ms	20-50 Mbit	-	-	-	-

4.5.1 Periodic traffic

Periodic traffic is transmitted with a given time repetition period. Reasons for a periodic transmission can be the periodic update of a position or the repeated monitoring of a characteristic parameter. Note that a transmission of a temperature every 15 minutes is a periodic transmission. However, most periodic intervals in communication for automation are rather short. The transmission is started once and continuous unless a stop command is provided.

An example of a periodic transmission is the *motion control case* from [2]. Motion control presents one of the most formidable and exacting challenges in the realm of closed-loop control applications. Its primary function involves regulating the movement and rotation of machine components in a well-defined manner, as observed in machines such as printing, machine tools, and packaging devices. A motion controller periodically sends desired set points to one or several actuators, which thereupon perform a corresponding action on one or several processes (in this case usually a movement or rotation of a certain component). At the same time, sensors determine the current state of the process(es) (in this case for example the current position and/or rotation of one or multiple components) and send the actual values back to the motion controller. This is done in a strictly cyclic and deterministic manner, such that during one communication cycle time T_{cycle} the motion controller sends updated set points to all actuators, and all sensors send their actual values back to the motion controller. Nowadays, typically Industrial Ethernet technologies are used for motion control systems. Examples for such technologies are Sercos®, PROFINET® IRT or EtherCAT®, which support cycle times below 50 µs. In general, lower cycle times allow for faster and more accurate movements/rotations.

The requirement for such use cases is that a THz system shall support cyclic traffic with cycle times in the order of 0.5 ms for a communication group of about 20 UEs and payload sizes of about 50 Bytes. The maximum jitter time is set to 50% of the cycle time.

4.6 Localization accuracy and location latency

Location accuracy: it defines the accuracy from the positioning point of view which is derived through trilateration or triangulation. It is crucial in indoor applications to perform basic tasks.

Location Latency: it is the time interval in between a positioning request and the corresponding reply by the positioning service.

For this purpose, different scenarios were considered:

- Scenario safety: under ideal conditions, the ISAC solutions provide imaging capabilities with a theoretical image resolution of 1 cm at 1 m from the closest sensor within an area of 5 m x 5 m.
- Scenario sensing-assisted communication: under ideal conditions, the ISAC solutions will ensure a minimum localization accuracy of 1 mm in LoS and less than 10 cm in NLoS, along with a location latency less than 1 ms. These performance goals are targeted for an area of 30 m x 30 m and leverage cooperation among ISAC devices.

However, in the presence of hardware impairments and unfavourable propagation scenarios, the solutions will guarantee a minimum localization accuracy of less than 1 cm in LoS and less than 0.5 m in NLoS, within an area of 5 m x 5 m.

4.7 Area traffic capacity

Area Traffic Capacity (important for number of wireless sensor), defined as the network traffic throughput served per geographic area (in bits/s/m^2) [12], and it constitutes a measure of how much traffic a network can carry per unit area It depends on network density, bandwidth, and spectrum efficiency.

4.8 Sensing resolution

Sensing resolution for detection of 'passive' objects are the *lateral resolution* as given in Table 9, the *depth resolution* and determination of the object's *radar cross section (RCS)*. A high angular resolution maps directly to the lateral resolution, while a large bandwidth provides the required depth resolution. In addition, a sufficient received reflected SNR is needed to determine the RCS. The parameters are shown in Figure 11.

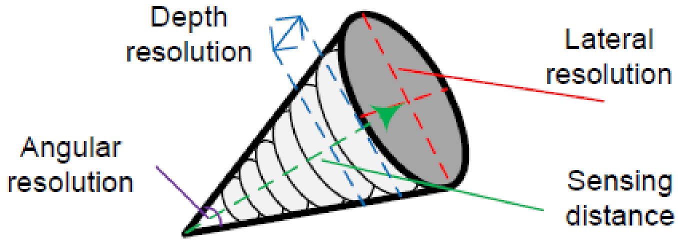


Figure 11 Sensing resolution: Key parameters for the detection of 'passive' objects.

4.9 Final considerations

The KPI requirements of the THz based solutions will be determined by the end-to-end application that is to use the THz bands. Two different sets of KPIs exist: the localization and communication ones. In case of integrated sensing and communication (ISAC), they might be fixed/related to the same hardware.

The data-rate requirement is dependent of the hardware/link configuration. In TIMES the KPI on the data-are is defined at the MAC layer, that means that this KPI requirement will be primary determined by the modem performances. Typical targeted performances leveraging on modem 2.16 GHz bandwidth is up to 10 Gbit/s.

5 Channel measurement scenarios

This chapter contains definitions and descriptions of the scenarios for performing the channel measurements in the TIMES project, along with the specifications of the measurement equipment used.

5.1 Approach for measurement scenario definitions

This section explains the approach taken for selecting and defining the channel measurement scenarios listed in the next section.

The purpose of channel measurements as defined in the TIMES project plan is to collect knowledge about the propagation behaviour of THz radio waves in industrial scenarios. The project has defined five target classes of scenarios to support the environmental diversity, the introduction of novel technologies, and non-communication aspects.

The environmental diversity is addressed by doing measurements both intra device and inter device. The focus will be on medium to large machines, covering both intra- and inter-device communication needs. Mobility will be covered, both by introducing a moving object, like e.g., an industrial robot, in the environment as a scattering or diffracting and obstructing object. A moving Tx or Rx will also be included.

In the context of TIMES, devices are not the usual terminals, like smartphones and CPEs, but denote the industrial machines used. We focus on medium to large machines which dimensions ranging from 1 to 100 m. The communication nodes, consisting of RF front ends and antennas are then placed inside or outside these machines to fulfil specific communication needs.

The project aims to develop and test intelligent reflecting surfaces (IRS) and how they can be utilized in both intra- and inter-device environments. Non-communication aspects include investigating integrated sensing and communications (ISAC) and assessment of EMF exposure limits. ISAC could e.g., include the sensing of stationary and mobile objects.

EMF exposure assessment investigation is targeting safety of workers. This can address very large machines in which people can work 'inside' machines for maintenance or repair. EMF 'hot zones' can e.g., be estimated and provide guidelines for the operation of the communication components.

Table 12 shows the logic used to define scenarios and meeting the project goal.

Table 12 Channel measurement scenario matrix

Type	Intra-device scenarios	Inter-device scenarios
Device type	Medium and Large	Medium and Large
Static	Yes	Yes
Mobile scenario, moving Tx or Rx	No	Yes
Mobile scenario, moving object	Yes	Yes
Includes IRS	Yes	Yes
ISAC relevant	Yes	Yes
EMF relevant	Yes	Yes
Environment, e.g., air quality	Clean/Dusty/Humid...	Clean/Dusty/Humid...

Channel measurements will be undertaken by project partners TUBS and HWDU, and will mostly be done in their respective premises, and not in the premises of the industrial partners. The BI-REX and AETNA set-ups will be used to define scenarios for simulations. The BI-REX layouts are explained in section 5.3.3. To verify the channel models, it is sufficient to measure in very similar scenarios avoiding transporting the expensive measurement equipment around. This means that we are considering replicating main properties of the industrial scenarios into the lab environment (dimensions, materials etc.). Specifications of their channel sounding equipment is found in Appendix B.

5.2 Channel metrics

The complex impulse response (CIR) measured by the channel sounder can be post-processed to obtain different metrics to describe different channel characteristics, as described in the following.

Total received power

The total received power for a certain polarization can be calculated as the summation of all the energy in the different dimensions. The power is averaged over the Tx angular scans and polarizations to make the results comparable to a single antenna system.

Marginal power profiles from directive scans

The 2-dimensional marginal power profiles can be calculated for certain dimensions by summing the power of the measured CIR in the remaining ones. Examples of the most relevant power profiles are the power delay profile (PDP), power azimuth profile (PAP), and power elevation profile (PEP). If no polarization is discriminated, the contributions in the different polarizations are averaged.

Delay and angular spreads

The root mean square (RMS) spread values are calculated from the single dimension power profiles, including the delay spread (DS), azimuth spreads (ASs), and elevation spreads (ESs).

5.3 Initial scenario list

This section contains a list with initial descriptions of possible measurement scenarios. As indicated in the table above, we foresee that there are basically two types of communication situations, intra- or inter-device, that covers the need, and will contain scenarios supporting static, mobility, IRS, ISAC, and EMF relevant measurements. Detailed measurement setups to address the propagation properties of the scenarios are further defined in section 5.4.

5.3.1 Intra-device scenarios

5.3.1.1 Scenario 1: Large machine; static conditions

Description:	Investigating the communication link between two nodes inside a large machine with few or no moving parts, to replace a cabled connection.
Links to use case:	E.g., predictive maintenance; substitution of wired RTI
Physical conditions:	LOS and NLOS
Tx-Rx distance:	1-10m
Mobility:	None (static)
Type of measurement	Limitations of wireless connections inside complex mechanical structures.
Measurement setup	Setup A

5.3.1.2 Scenario 2: Large machine; moving object

Description:	Investigating the communication link between two nodes inside a large machine with moving parts, to replace a cabled connection.
Links to use case:	E.g., predictive maintenance; substitution of wired RTI
Physical conditions:	LOS and NLOS
Tx-Rx distance:	1-10m
Mobility:	Yes, moving parts
Type of measurement	Limitations of wireless connections inside complex mechanical structures and how much moving parts in the propagation path affects the channel.
Measurement setup	TBD

5.3.1.3 Scenario 3: Large machine; IRS inside

Description:	Investigating the communication link between two nodes inside a large machine with few or no moving parts, to replace a cabled connection.
Links to use case:	E.g., predictive maintenance; substitution of wired RTI
Physical conditions:	NLOS
Tx-Rx distance:	1-10m
Mobility:	None (static)
Type of measurement	Investigate gain of installing IRS inside the machine to mitigate NLOS conditions and to improve the link performance in a complex mechanical structure.
Measurement setup	TBD

5.3.1.4 Scenario 4: Medium machine; static conditions

Description:	Similar to scenario 1; but smaller dimensions
Links to use case:	E.g., predictive maintenance; substitution of wired RTI
Physical conditions:	LOS and NLOS
Tx-Rx distance:	10 cm-100 cm
Mobility:	None (static)
Type of measurement	Limitations of wireless connections inside complex mechanical structures.
Measurement setup	Setup A

5.3.1.5 Scenario 5: Medium machine; moving object

Description:	Similar to scenario 2, but smaller dimensions
Links to use case:	E.g., predictive maintenance; substitution of wired RTI
Physical conditions:	LOS and NLOS
Tx-Rx distance:	10 cm-100 cm
Mobility:	Yes, moving parts (stationary Tx and Rx)
Type of measurement	Limitations of wireless connections inside complex mechanical structures and how much moving parts in the propagation path affects the channel.
Measurement setup	Setup A

5.3.2 Inter-device scenarios

5.3.2.1 Scenario 6: Medium machines; static conditions

Description:	Investigating the link can be between an access point/base station and a sensor device. Communicating with a sensor or actuator outside or inside a machine.
Links to use case:	E.g., Wireless sensors and connection
Physical conditions:	LOS and NLOS
Tx-Rx distance:	10 m – 100 m
Mobility:	None (static)
Type of measurement	Propagation properties of the link outside the machine. Loss properties to reach inside a machine.
Measurement setup	Setups B, C, D, E, F, and J

5.3.2.2 Scenario 7: Medium machines; moving object

Description:	Same as scenario 6, but with a moving object in the propagation path. This can be a moving robot in a factory hall or moving humans.
Links to use case:	E.g., wireless sensors and connections, safety for operators,
Physical conditions:	LOS and NLOS
Tx-Rx distance:	10 m – 100 m
Mobility:	Yes, moving object (stationary Tx and Rx)
Type of measurement	Propagation properties of the link outside the machine. Dynamic behaviour of the channel due to environmental dynamics.
Measurement setup	Setups B, D, G, H, K, and I

5.3.2.3 Scenario 8: Medium machines; moving Tx or Rx

Description:	Investigating the communicating between an access point and a robot or other moving object in a factory /production environment. This can be a moving robot, a moving part on a stationary machine, or even a human operator.
Links to use case:	E.g., Mobile robots; safety for operators
Physical conditions:	LOS
Tx-Rx distance:	10 m – 100 m
Mobility:	Yes, moving Tx or Rx
Type of measurement	Propagation properties of the link outside machines. Dynamic behaviour of the channel due to mobility.
Measurement setup	Setup E

5.3.2.4 Scenario 9: Medium machines; IRS to mitigate propagation loss

Description:	Similar to scenarios 6 and 8. Investigating the communicating with a sensor or actuator outside a machine, or with a moving robot and the benefits of using IRS in the environment.
Links to use case:	E.g., Mobile robot; wireless sensors and connections
Physical conditions:	NLOS
Tx-Rx distance:	10 m – 100 m
Mobility:	Both static and mobile measurements
Type of measurement	Investigate how an IRS installed in the factory environment can improve the propagation channel and path loss in NLOS situations
Measurement setup	TBD

5.3.3 BI-REX Layout for channel modelling

The following section describes the BI-REX layout where several industrial machines and a TIM base station are located. That area is the **BI-REX Pilot Line**, and it represents the most suitable scenario for channel measurements. The Pilot Line represents an advanced manufacturing system that blends the latest Industry 4.0 technologies with conventional ones, all in a digitally interconnected setting.

The pilot space is organized as in Figure 12, where different **thematic areas** can be identified:

1. **Big Data and Internet of Things**: IoT platform development, 5G connectivity, data acquisition and data processing on local data centres and remote clouds, Big-Data Analytics and Artificial Intelligence (AI) techniques, Digital Twin.
2. **Additive Manufacturing**: Additive manufacturing of metals with powder bed laser and direct deposition, supplemented with secondary processing (e.g., heat treatment, laser hardening, EDM), polymer printing.
3. **Robotics**: Implementation of advanced robotics, mobile robotics, and collaborative robotics, aimed at production collaborative assembly and logistics.
4. **Finishing and metrology**: Finishing with mechanical processing on numerical control centres, dimensional control systems (with and without contact), laser light scanning, and reverse engineering.

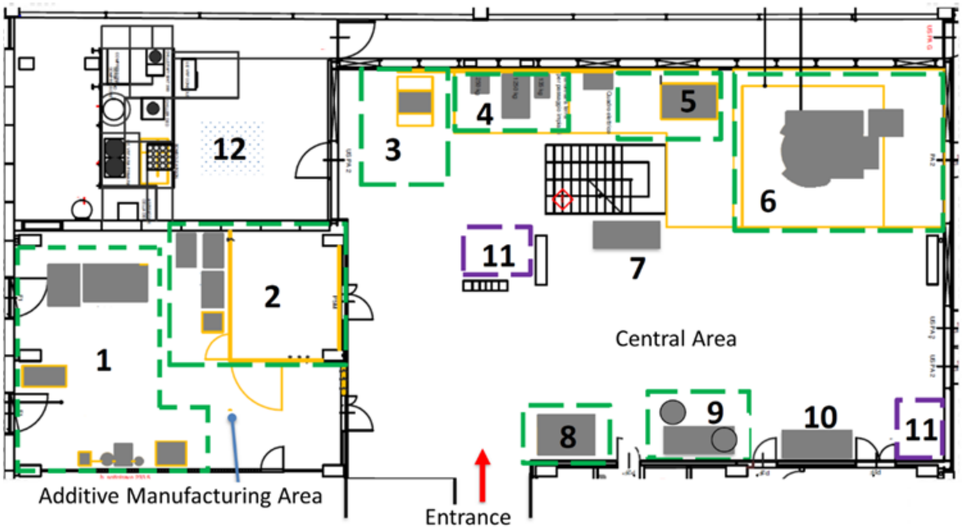


Figure 12 Layout of BI-REX Pilot Space

The BI-REX pilot space is an open area of dimensions 22.04 × 14.24 m^2 which mimics an industrial plant. It is composed of a central area and an additive manufacturing area.

The following contains the machines that are more interesting for channel measurements.

<u>Work Centre CNC – DMG Mori DMU 65 Monoblock</u>

Figure 13 Model of DMG Mori DMU 65 Monoblock

Description: Numerical control work centre. Versatile machine equipped with 5 axes for turning and milling for subtractive manufacturing operations. Processing for surface trim and gears manufacturing.

Features:

- 5-axis milling/turning module with rotary table.
- Equipped with rectification module.
- Equipped with gear Skiving module.

- Siemens Sinumeric CNC with CELOS.
- Marposs Touchprobe and Hybrid plus measurement systems.
- IoT parameters opening and integrated for automatic side loading with robot.

Table 13 DMU 65 specifications

Technical Information	DMU65
Working area	735x650x560 mm
Spindle Power	35 kW (S3 40%) 25 kW (S1)
Spindle Speed	Until 20.000 rpm
Turning Speed (C axis)	1000 rpm (1200 rpm per <10 min)
Pallet for lateral automatic loading	500 x 500 mm
Warehouse	30 tools
Linear axes Precision	<0,006 mm
Gears Module	Until 10
Rotation speed for gears	90% of the table (C axis)
Cut off speed for grinding tools	50 m/s with 2.4 g/cm3 density

Scenarios: inter-machine and intra-machine communications

- Wireless sensor and connection
- Augmented Reality

Large machine: moving Tx or Rx (the sensor that takes the measurements is mounted on the spindle, which in turn is rotating).

Measuring/Scanning system: FARO – QUANTUM S with Geomagic Design X

Figure 14 Model of FARO – QUANTUM S with Geomagic Design X

Description: Tool capable of performing 3D scanning in manual mode of arbitrarily placed components. Comparison of the error with existing CAD models or reconstruction by reverse engineering.

Features:

- 7 degrees of freedom scanning arm.
- Blue light laser for scanning and probes for contact measurements.
- Equipped with Geomagic Design X: scanning software and reconstruction of CAD models for reverse engineering.
- Reference indicative error 0.02 mm (with probe).

Table 14 FARO – QUANTUM S specifications

Technical Information	QUANTUM S V2
Measure ranges	2,5 m
Accuracy with contact	0.020 mm (Single Point)
Accuracy without contact	0.043 mm (ISO 10360-8 D)
Laser Probe	FAROBlu HD
Points acquisition rate	Until 1,2 million/sec
Points per line	Until 4000
Scanning frequency	Until 600 Hz
Minimum distance between points	20 µm
Scanning amplitude	80 mm -160 mm

Scenario: Inter-machine communication

Medium machine: moving Tx/Rx

Robotics and logistics - Collaborative robotics and assembly –

FANUC CR-14iA, FANUC CRx-10iA

Figure 14 Models of FANUC CR-14iA, FANUC CRx-10iA.

Description: Two collaborative robots employed in an assembly station with human/robot collaboration. Usable in a variety of operations: servo raw materials, handling of semi-finished products, interaction with passive warehouses.

Features: Compact and light in weight, they can be applied in transversal applications across the entire line, individually and/or in pairs. Scheduled to stop in case of contact to ensure safety.

CR-14*i*A/L

Max. load capacity at wrist: **14 kg**

Max. reach: **911mm** *1

Controlled axes	Repeatability (mm)	Mechanical weight (kg)	Motion range (°)						Maximum speed (mm/s)	J4 Moment/ Inertia (Nm/kgm²)	J5 Moment/ Inertia (Nm/kgm²)	J6 Moment/ Inertia (Nm/kgm²)
			J1	J2	J3	J4	J5	J6				
6	± 0.01*	55	340	166	383	380	240	720	500*2	31.0/0.66	31.0/0.66	13.4/0.30

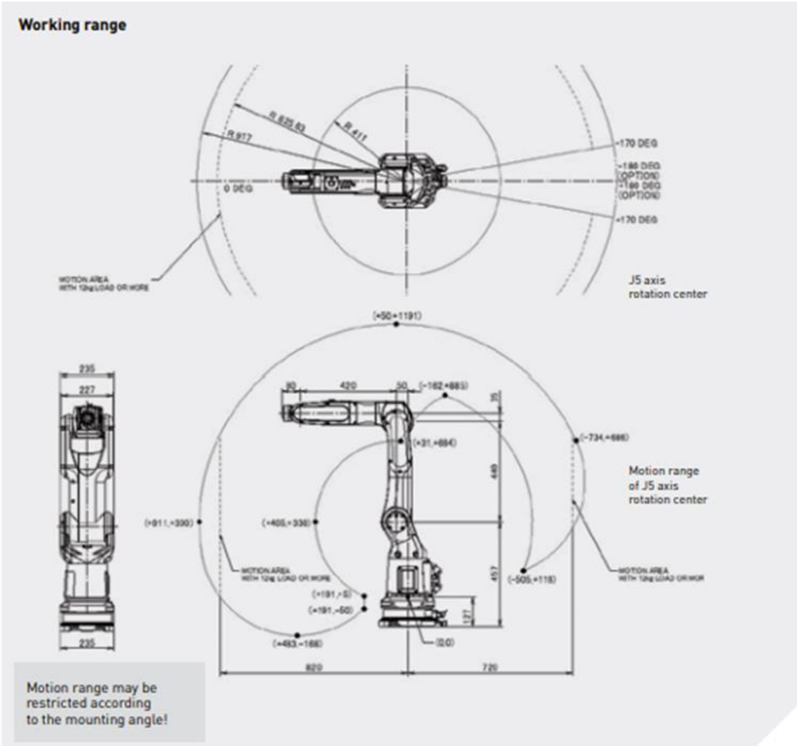


Figure 15 FANUC CR-14iA Dept Description

CRX-10*i*A/L

Max. load capacity at wrist: **10 kg**

Max. reach: **1418 mm**

Controlled axes	Repeatability (mm)	Mechanical weight (kg)	Motion range (°)						Maximum speed (°/s) *2						Maximum linear speed (mm/s)	J4 Moment/Inertia (Nm/kgm²)	J5 Moment/Inertia (Nm/kgm²)	J6 Moment/Inertia (Nm/kgm²)
			J1	J2	J3	J4	J5	J6	J1	J2	J3	J4	J5	J6				
6	± 0.04*	40	360	360	540	380	360	450	120	120	180	180	180	180	1000*1	34.8/1.28	26.0/0.90	11.0/0.30

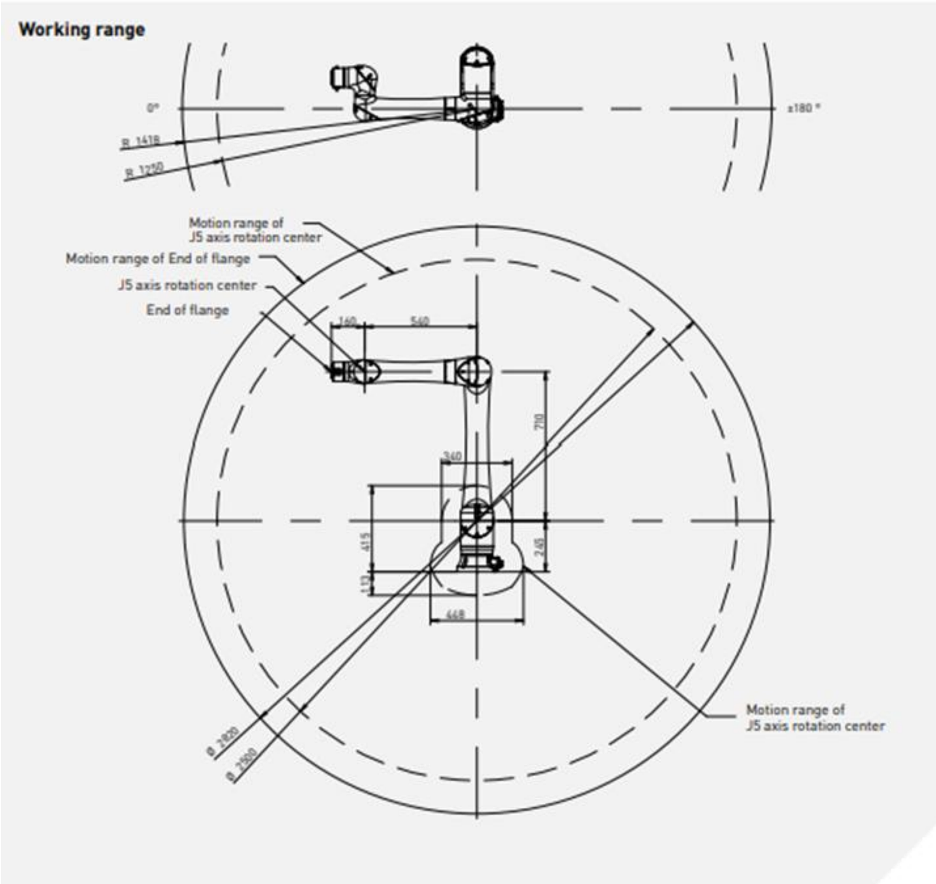


Figure 16 FANUC CRx-10iA Dept. Description

Table 15 FANUC CR-14i and FANUC CRx-10iA specifications

Technical Information	FANUC CR-14i	FANUC CRx-10iA
Axes	6	6
Maximum payload	10 kg	14 kg
Outreach	1249 mm	911 mm (<12kg) - 820 mm (>12kg)
Maximum speed	1000 mm/s	500 mm/s
Controller	R-30iB Mini Plus	R-30iB Plus
Repeatability	±0.04	±0.001
Weight	40 kg	55 kg
Map	/	296.5 x 235 mm

Scenario: Inter-machine communications between the two robots

Inter-machine communications can be realized either using direct (peer-to-peer) wireless links, or by communicating via an access point or base station.

- Assembling
- Security of human operators

Medium machine: moving TX/RX

Mobile robotics (AMR) – MIR 250

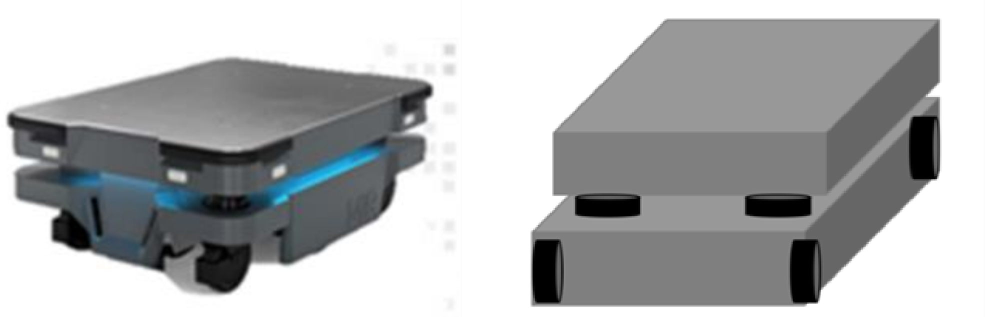


Figure 17 Model of MIR 250

Description: Autonomous mobile robot (AMR) capable of moving within the line pilot and integrate with the machinery within it. Employable for logistics operations, transport of semi-finished products, raw materials. Compact and suitable for complex and dynamic environments.

Features: Autonomous mobile robot (AMR), by means of laser scanner and 3D camera. 8 proximity sensors for obstacle detection.

Table 16 MIR 250 specifications

Technical Information	MIR250
Ground map (loading area)	800 x 580 mm
Height	300 mm (30 mm from ground)
Weight	83 kg
Maximum payload	250 kg
Max speed- max acceleration	2 m/s - 1 m/s^2
Precision	±0.005 mm
Operating time	10 h
Load 10% to 90%	1 h
Wheel diameter	200 mm (pull) - 125 mm (idle)

Scenario: AGV that communicates with a controller. Inter-machine communications.

Medium machine: moving Tx/Rx.

5G Connectivity- Indoor 5G Cell

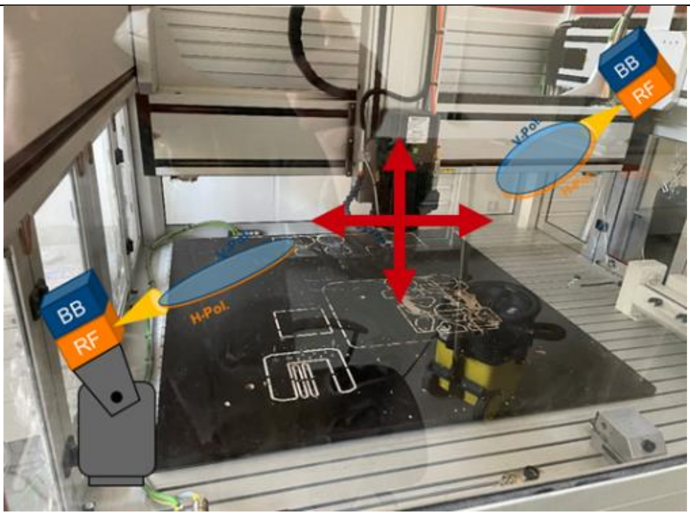
Manufacturer and model: TIM – 5G antenna

Description: 5G cell dedicated to the pilot line, for 360° integrations with the orientation, innovation, training, and research activities. Connection of plant devices and machinery through dedicated gateways, in anticipation of a gradual replacement of wired communications. From a future point of view to be integrated with 5G with direct access to the public network.

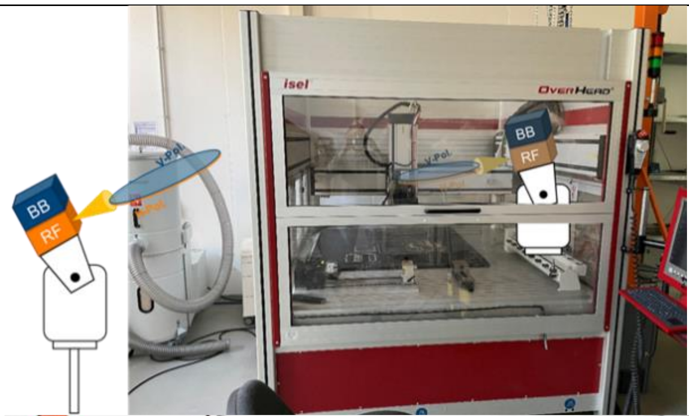
5.4 Measurement setups

This section contains descriptions of measurement setups defined to address the scenarios in section 5.3. At this stage of the work, not all scenarios are covered. Further definitions will emerge when the work with software and hardware components for THz communications have progressed, especially with respect to the use of IRS and addressing ISAC applications.

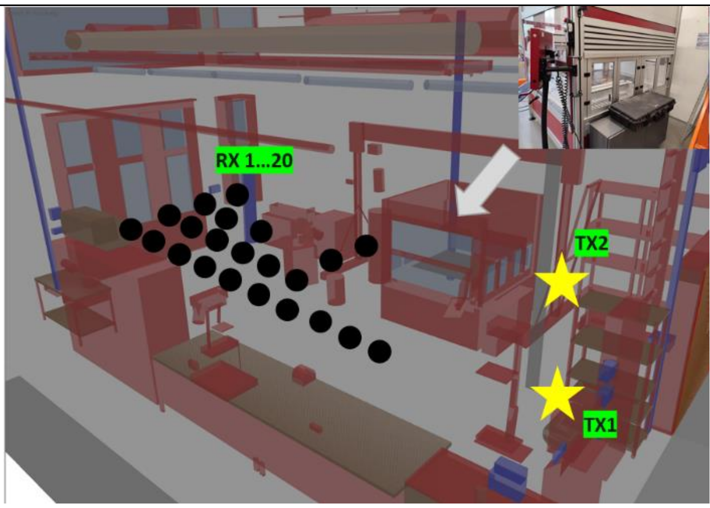
5.4.1 Setup A: Milling machine - intra-device

Type	Intra-device communication
Use case	The application can be THz transmission between two sensors in a machine.
Environment description	Inner part of a milling machine, mainly composed of metallic surfaces. The milling head can move to different locations and block the LOS.
Setup description	The Rx and Tx are located inside a milling machine. Multiple measurement with the milling head in different positions can be performed.
Measurement frequency	300 GHz
Path type	LOS/OLOS
Number of TXs	1
Number of RXs	1
Distance TX-RX	between 10 cm and 100 cm
Height TX	10 to 100 cm with respect to the base of the milling machine
Height RX	10 to 100 cm with respect to the base of the milling machine
Time invariant/variant	Time invariant, quasi-dynamic
Expected results	PDP, PAEP
Schematic view	

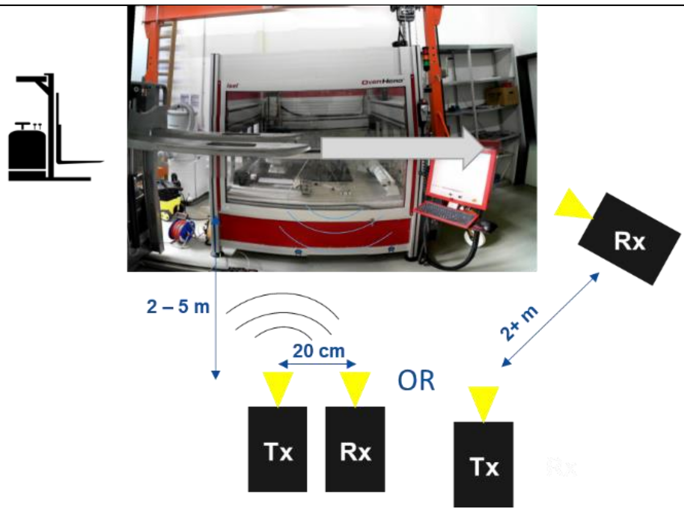
5.4.2 Setup B: Milling machine - inter-device

Type	**Inter-device communication**
Use case	This can cover the application of a THz indoor base station communicating with a sensor/controller in a machine.
Environment description	Industrial workspace with a milling machine and other equipment.
Setup description	The Rx is located inside the milling machine, Tx outside of the machine. The opening or closing of the machine gate can cause LOS blockage.
Measurement frequency	300 GHz
Path type	LOS/OLOS
Number of TXs	1
Number of RXs	1
Distance TX-RX	Between 100 cm and 200 cm
Height TX	0.5 to 2 m
Height RX	0.5 to 2 m
Time invariant/variant	Time invariant
Expected results	PDP, PAEP
Schematic view	 

5.4.3 Setup C: Small industrial workshop

Type	Inter-device communication
Use case	Communication between industrial devices, or between device and access point.
Environment description	Industrial workspace with milling machine, bridge crane, workbench, lathe machine, shelves, and other equipment.
Setup description	2 different Tx and 20 different Rx positions are considered. Static measurement between a single Tx position and a single Rx position is performed.
Measurement frequency	300 GHz
Path type	LOS/NLOS
Number of TXs	1 TX, 2 different positions
Number of RXs	1 RX, 20 different positions
Distance TX-RX	Between 3 m and 10 m
Height TX	0.5 to 2 m
Height RX	0.5 to 2 m
Time invariant/variant	Time invariant
Expected results	Pathloss, PDP, PAEP
Schematic view	

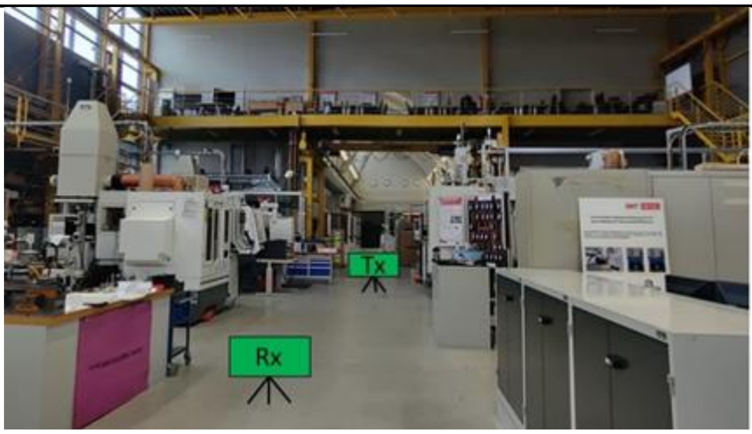
5.4.4 Setup D: Milling machine – mono/bi-static sensing

Type	Integrated sensing and communication
Use case	Object recognition
Environment description	Industrial workspace with a milling machine and other equipment.
Setup description	Characterization of a quasi-dynamic scenario with either mono-static or bi-static setup. A blocking object (e.g., pallet truck) is placed between Tx and Rx and is moved in a stepwise manner with steps of ~10 cm.
Measurement frequency	300 GHz
Path type	Monostatic or bi-static
Number of TXs	1 TX, 2 different positions
Number of RXs	1 RX, 20 different positions
Distance TX-RX	20 cm with the monostatic setup, >2 m with the bi-static setup
Height TX	0.5 to 2 m
Height RX	0.5 to 2 m
Time invariant/variant	Quasi-dynamic
Expected results	Analysis of footprints for object recognition
Schematic view	

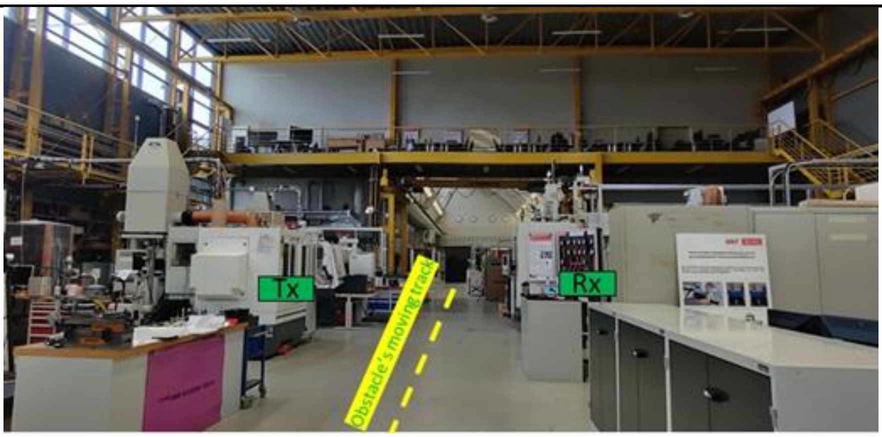
5.4.5 Setup E: Access point

Type	Inter-device communication
Use case	THz transmission between sensor (Rx) on the stationary/moving machines with different heights and the access point (Tx)
Environmental description	Industrial workspace with a lot of different machine types, complicated ceiling
Setup description	Tx is in the upper level of industrial space two Rxs in the low level
Measurement frequency, GHz	304.2
Path type	LOS/OLOS
Number of Txs	1
Number of Rxs	2
Distance Tx-Rx, m	~10 m
Height Tx, m	~5 m
Height Rx, m	0, 0.5, 1
Time invariant/variant	time invariant
Expected results	Path Loss, PDP (DS)
Schematic view	

5.4.6 Setup F: Full-omni 360° rotation measurements

Type	Inter device communication
Use case	Spatial characterization of industrial space. 2 or 3 different measuring positions are planned.
Environmental description	Industrial workspace with a lot of different machine types, complicated ceiling
Setup description	Tx and Rx located at the top of rotation units and the horizontal plane is sampled in steps of 8°
Measurement frequency, GHz	304.2
Path type	LOS/NLOS
Number of Tx	1
Number of Rx	1
Distance Tx-Rx, m	~10
Height Tx, m	1.5
Height Rx, m	1.5
Time invariant/variant	time invariant
Expected results	Path Loss, PDP (DS), AOD and AOA
	

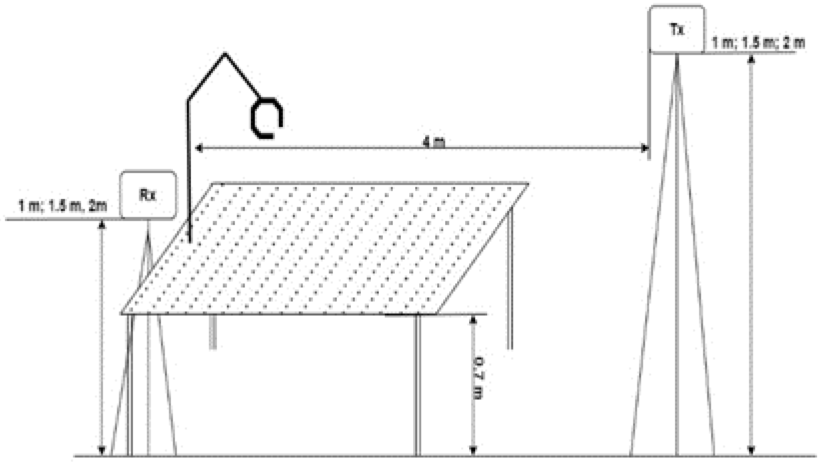
5.4.7 Setup G: Moving obstacle: blocking

Type	Inter device communication
Use case	THz transmission between sensors on two machines in case of moving another machine between them.
Environmental description	Industrial workspace with a lot of different machine types, complicated ceiling
Setup description	Tx and Rx located near two machines, moving metal plate between them.
Measurement frequency, GHz	304.2
Path type	NLOS
Number of Tx	1
Number of Rx	1
Distance Tx-Rx, m	~3
Height Tx, m	1.5
Height Rx, m	1.5
Time invariant/variant	time variant
Expected results	Path Loss, PDP (DS)
Schematic view	

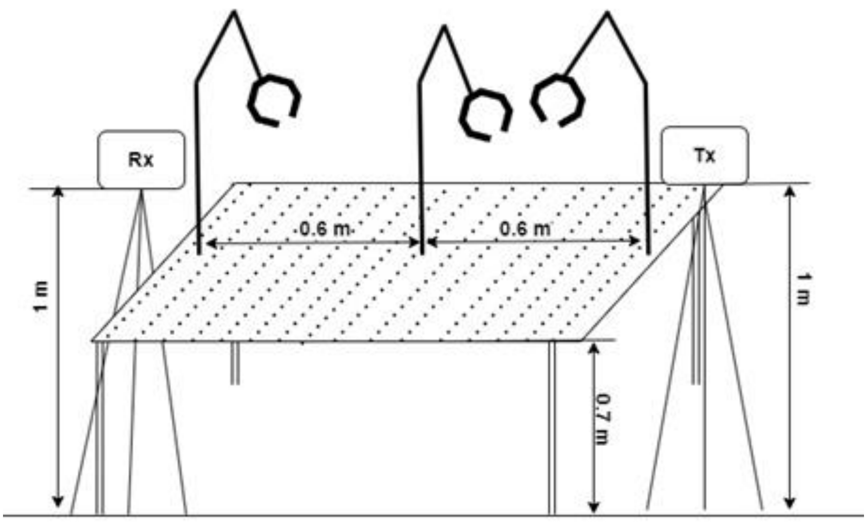
5.4.8 Setup H: Moving obstacle: reflection

Type	Inter device communication
Use case	THz transmission between sensors on two machines in case of moving another machine near them.
Environmental description	Industrial workspace with a lot of different machine types, complicated ceiling
Setup description	Tx and Rx located near two machines, moving metal plate near them.
Measurement frequency, GHz	304.2
Path type	LOS
Number of Tx	1
Number of Rx	1
Distance Tx-Rx, m	~2
Height Tx, m	1.5
Height Rx, m	1.5
Time invariant/variant	time variant
Expected results	Path Loss, PDP (DS)
Schematic view	

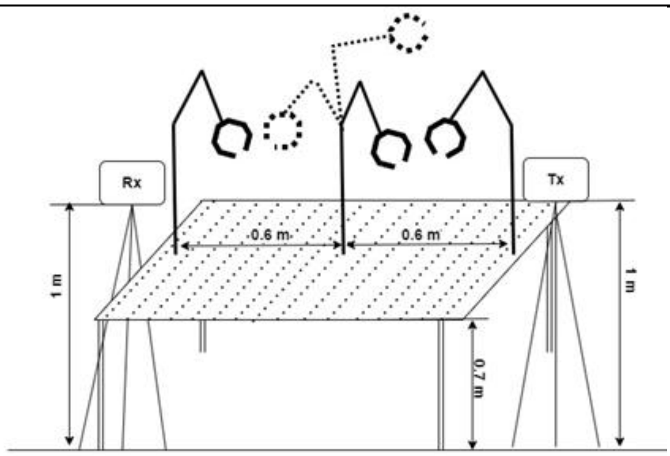
5.4.9 Setup I: Robotic arms characterization: Access point

Type	Inter device communication
Use case	THz transmission between sensor on the base of the robotic arm and access point (control unit) on the wall.
Environmental description	Robotic laboratory with several different types of robotic manipulators. It is not a “complicated” industrial space.
Setup description	Rx located near the robotic arm, Tx is far from arm, near the wall.
Measurement frequency, GHz	304.2
Path type	LOS
Number of Tx	1
Number of Rx	1
Distance Tx-Rx, m	~4
Height Tx, m	1, 1.5, 2
Height Rx, m	1, 1.5, 2
Time invariant/variant	time invariant
Expected results	Path Loss, PDP (DS)
Schematic view	

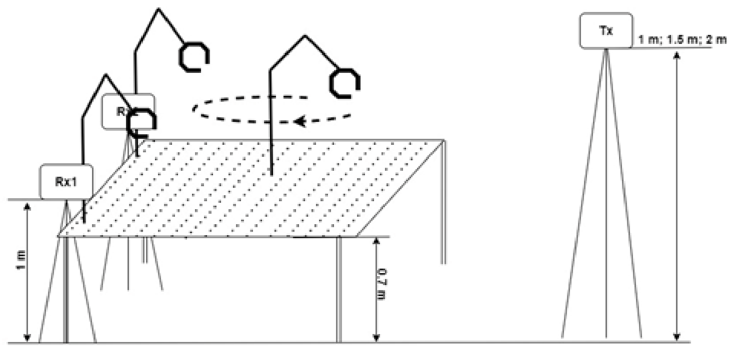
5.4.10 Setup J: Robotic arms characterization: Stationary obstacle

Type	Inter-device communication
Use case	THz transmission between sensor on the robotic arm and main control unit on the wall, in case of manipulator between them.
Environmental description	Robotic laboratory with several different types of robotic manipulators. It is not a “complicated” industrial space.
Setup description	Tx and Rx fixed near the robotic arms. Static robotic arm between them. Several different obstacle arm configurations are planned.
Measurement frequency, GHz	304.2
Path type	OLOS/NLOS
Number of Tx	1
Number of Rx	1
Distance Tx-Rx, m	~1.2
Height Tx, m	1
Height Rx, m	1
Time invariant/variant	time invariant
Expected results	Path Loss, PDP (DS)
Schematic view	

5.4.11 Setup K: Robotic arms characterization: Moving obstacle

Type	Inter device communication
Use case	THz transmission between sensor on the robotic arm and main control unit on the wall, in case of moving manipulator between them.
Environmental description	Robotic laboratory with several different types of robotic manipulators. It is not a “complicated” industrial space.
Setup description	Tx and Rx fixed near the robotic arms. Moving robotic arm between them. Different directions and speeds of obstacle arm are planned.
Measurement frequency, GHz	304.2
Path type	LOS/OLOS/NLOS
Number of Txs	1
Number of Rxs	1
Distance Tx-Rx, m	~1.2
Height Tx, m	1, 1.5, 2
Height Rx, m	1
Time invariant/variant	time variant
Expected results	Path Loss, PDP (DS), AOD and AOA
Schematic view	

5.4.12 Setup L: Robotic arms characterization: SIMO with moving obstacle

Type	**Inter device communication**
Use case	THz transmission between sensors on the two robotic arms, standing in one line and main control unit on the wall, in case of moving robotic manipulator among them.
Environmental description	Robotic laboratory with several different types of robotic manipulators. It is not a “complicated” industrial space.
Setup description	Rxs located near the two robotic arms, Tx near the wall. Moving robotic arm between them.
Measurement frequency, GHz	304.2
Path type	OLOS/NLOS
Number of Txs	1
Number of Rxs	1
Distance Tx-Rx, m	~4
Height Tx, m	1
Height Rx, m	1
Time invariant/variant	time variant
Expected results	Path Loss, PDP (DS), AOD and AOA
Schematic view	

6 Conclusions

Industrial communication is a growing application of wireless technologies, and the interest for using cellular technologies is increasing. 5G has been marketed as an enabler with the power to replace several proprietary technologies used today in manufacturing, logistics and process industry. Still, applications will emerge that event 5G cannot serve with sufficient performance. Therefore, 6G, and especially THz wireless communications has been launched as a candidate technology for extreme industrial use cases.

The TIMES project is studying this domain, and in this report, the project has described several industrial scenarios and use cases in manufacturing and logistics. In this context, the project has especially looked on how stationary production machines and moving robot need to communicate for an efficient and safe production process.

The report describes some typical industrial scenarios with low, medium, and high complexity machines as operated by the vertical industry partners of the project. Further, several use cases for communication in these scenarios have been defined. The relevant KPIs have also been identified.

The other main part of this report contains the definitions of generic scenarios for performing channel sounding measurements. An industrial scenario is very complex when it comes to radio wave propagation, and especially at the high frequencies above 100 GHz, there is a need to understand the propagation properties of the wireless channel. This is fundamental to be able to design a robust and efficient wireless 6G system at these frequencies.

Measurement scenarios are typically intra- (inside a machine) or inter-machine (between machines), and several scenarios with and without mobility has been defined. The possible inclusion of intelligent reflecting surfaces (IRS) has also been considered. Further, several specific measurement setups to cover most of these scenarios has been defined and will be performed by project partners in the following work of TIMES.

Both the industrial scenarios, use cases, KPI definitions and measurement setups will be further refined through the course of the project.

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Appendix A – Industrial communications protocols

The concept of Cyber-Physical Production Systems (CPPS) is the incorporation of digital operations with physical operations executed within an intelligent manufacturing setting. To do so the physical processes are continuously monitored and regulated within the digital realm through a computational process that has a direct impact on the actual manufacturing process. The input received from the physical processes also affects computational procedures in a feedback loop for optimization. Intelligent production facilities may comprise various CPPS, which not only automate machine communication but also minimize production irregularities, thereby maximizing production efficiency.

The concept of CPPS has started to gain momentum with the emergence of Industry 4.0, where machines are assuming many of the roles previously assigned to the human workforce. Among the challenges posed by these novel productions systems achieving seamless, synchronised, and reliable data communications is probably one of the most critical aspects. The requirements for several different CPPS scenarios are shown in Table 17.

Table 17 Various CPPS scenarios with corresponding link and system requirements [2]

Requirements / Use Cases	Link Requirements					System Requirements		
	Time Critical			Non Critical				
	Cycle Time	Payload	Jitter	Latency	Datarate	Service Area	No. of Nodes	Mobility
Collaborative Machines	4-10 *ms*	<1 *KB*	<1 μ s	<10 *ms*	<5-10 *Mbps*	1 *km* X 1 *km* X 0.3 *km*	5-10	-
Human-Machine Interaction	<10 *ms*	20-50 *Mbit*	-	<30 *ms*	-	Typical factory floor size	<= no. of workers	Low
Digital Twins	50 *ms*	20-100 *KB*	-	-	5-10*Mbps*	<1 km^2	100	Fairly high
Video Surveillance	10-100 *ms*	15-150 *KB*	<50% of cycle time	-	<10 *Mbps*	<1 km^2	100	Fairly high
Remote Operation	50 *ms*	Few *Bytes*	<1-10 *ms*	-	-	Several km^2	<10 *k*	Low
Predictive Maintenance	50 *ms*	-	-	-	-	Several km^2	<10 *k*	Low

At their inception, data communications for industrial communications have been based on wired links and, currently, most wired communication technologies rely on either Industrial Ethernet technologies or fieldbuses technologies such as PROFIBUS®, CC-Link®, and CAN®. However, thanks to the recent advances in mobile communication systems, particularly higher data throughputs, lower latencies and flexible spectrum and deployment models with the emergence of 5G, wireless connectivity could fundamentally change the way goods are produced, shipped, and serviced throughout their entire lifecycle, providing flexibility, mobility, versatility, and ergonomics.

Appendix A.1 - Industrial wired communications

Traditionally, most existing wireless technologies did not meet the stringent requirements of industrial applications such as end-to-end latency, communication service availability and jitter, and most communications systems are implemented with wired technologies, which are commonly used to link sensors, actuators, and controllers.

Ethernet is a widely used protocol for computer networks and has been adapted for use in industrial applications. It offers high-speed data transfer rates, typically up to 10 Gbps, which makes it well suited for applications that require large amounts of data transfer, such as video streaming, remote monitoring, and control systems. Ethernet also offers longer communication distances, up to 100 meters, and can support multiple nodes on a network. Ethernet is a standardized protocol, which means that devices from different vendors can communicate with each other.

Early attempts to use Ethernet for real-time communications in factories have often failed because of its shortcomings on the intrinsic non-determinism. The competitive CSMA/CD media access mechanism of

Ethernet makes time determinacy impossible: if two stations are waiting to transmit a message while the medium is used by another station, it is not possible to know in advance which station would transmit next because the choice is random. Therefore, it is not possible to give an upper bound for the time required to transmit a message from one station to another. This randomness is critical because real-time constraints in terms of maximum transfer delay, jitter and available bandwidth are key factors in an industrial setting. Thus, for many years, Ethernet and the TCP/IP have been used in industrial environments, but not for the controlling communications inside the actual machines and equipment. The machine controller itself and the communications to the actuators invariably demand the use of ad hoc protocols, which may be categorized as

- Fieldbus technologies, or
- Industrial Ethernet technologies.

These two different technologies differ in several ways, including their speed, distance, and applications.

Fieldbus Technologies

Fieldbus is a generic term used to describe a range of industrial communication protocols that are typically used in control systems. Fieldbus protocols typically offer slower data transfer rates than Ethernet, usually at most 12 Mbps, but they can support longer distances than Ethernet, up to several kilometres. Fieldbus protocols are often used in applications that require real-time communication, such as process control, where speed and reliability are critical. Starting from the 1970s, several proprietary networks were in use to connect programmable logic controllers (PLCs) and once Ethernet was shown not to be up to the task of providing the desired connectivity for industrial communications, many companies realized the strategic importance of the fieldbus in the industrial automation systems and developed their own products, pushing to have them standardized. In the beginning of the 1980s, several projects started in Europe and the US. Among these there was the Process Field Bus (PROFIBUS) fieldbus project in Germany in 1984 and in 1983 the Bosch Company developed the specifications of the Controller Area Network (CAN) for cars manufactured in Germany. Different fieldbus technologies have been developed for different applications such as manufacturing automation, process automation or embedded systems. Because of the heterogeneity and the competition among different products, it has taken a long time to arrive to a common standard. A partial result has been obtained by the International Electrotechnical Commission (IEC) with the IEC 61158 Industrial communication networks - Fieldbus specifications, which collects eight completely heterogeneous and incompatible fieldbus families. Among them the most important is PROFIBUS, which is the world's most successful fieldbus with 65.9 million devices installed by the end of 2021.

Currently, PROFIBUS DP (Decentralised Peripherals) is the most used variation of this fieldbus and is used to operate sensors and actuators via a centralised controller in production (factory) automation applications. PROFIBUS uses a bus topology. In this topology, a central line, or bus, is wired throughout the system. Up to 32 devices are attached to this central bus, eliminating the need for a full-length line going from the central controller to each individual device. Bit rates range from 9.6 kbit/s to 12 Mbps, the cable length between two repeaters is limited from 100 (rate max 12 Mbps) to 1200 m (rate max 93.75 kbps), depending on the bit rate used.

CAN, originally developed for vehicles, is widely used in the automotive industry and for computer diagnostics of the vehicles. After the extension of the communication profile, it was introduced in industrial automation, as CANopen. It is mainly used in Europe, and overseas, thanks to Rockwell Automation, has taken the form of the DeviceNet standard.

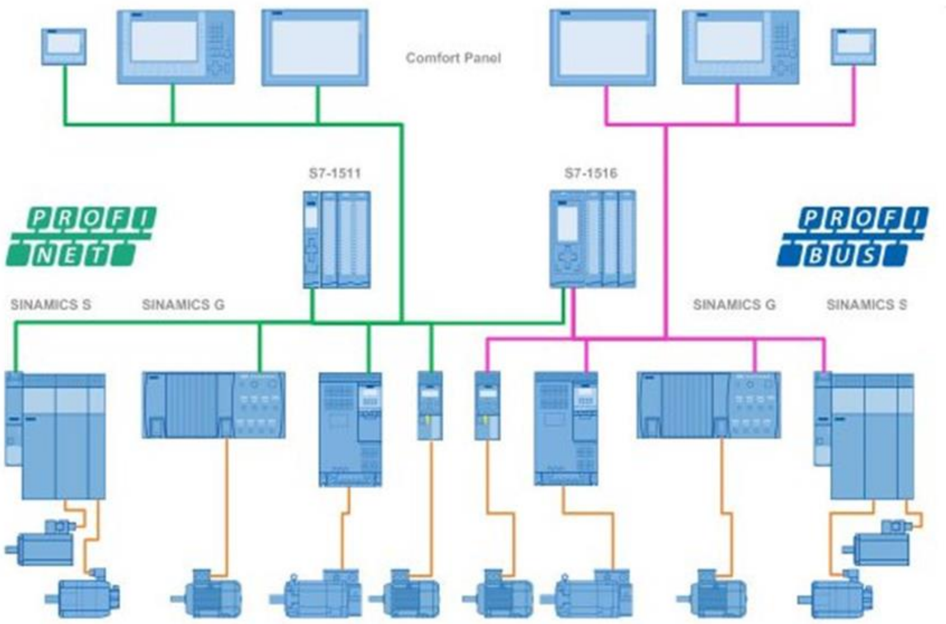

Figure 18 Example of Control Field Bus Architecture – Profibus and PROFINET (Source: Siemens[4])

The CC-Link standard is designed primarily for machine users from Japan and Asia. It features a simple structure and ensures easy integration of components from different manufacturers, which is why it is also becoming popular with users from Europe.

Industrial Ethernet technologies

Over the years several modifications of the Ethernet standard have been proposed with various degree of changes for industrial communications and by the 1990s, Ethernet has spread into industry. Beyond conventional Ethernet, which is anyway employed in several scenarios, the most common Ethernet-based protocols are:

[4] https://support.industry.siemens.com/cs/document/73257075/how-can-you-integrate-a-drive-into-tia-portal-via-the-device-master-file-(gsd)-?dti=0&dl=en&lc=it-IT

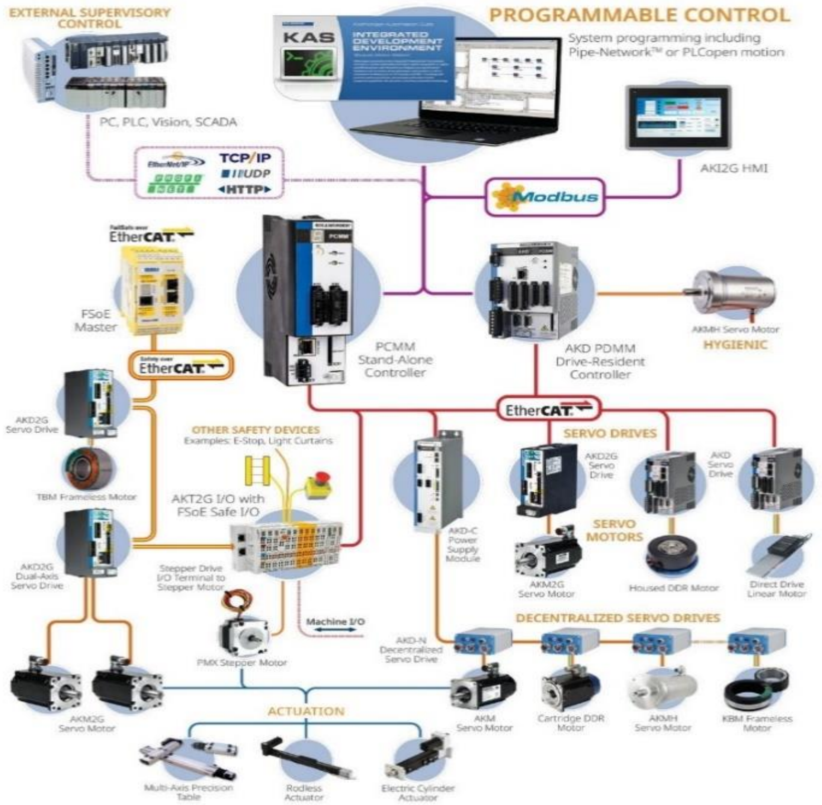

Figure 19 Example of Control Field Bus Architecture – ETHERCAT (Source: Kollmorgen[5])

The EtherCAT protocol was initially developed by Beckhoff, and the standard has now been handed off to the EtherCAT Technology Group (ETG). Real-time results have shown that EtherCAT delivers the most deterministic response of any industrial real-time Ethernet system available. Being able to process 1,000 I/Os in 32.5 µs or 100 axes in 125 µs, EtherCAT offers machine builders the opportunity to deliver breakthrough in machine performance at a lower price. With EtherCAT, all devices are networked with the bus master in a ring formation. During each cycle, relevant output data is extracted by the devices from the Ethernet data packets sent by the bus master. EtherCAT uses the telegram structure of Ethernet, but with an entirely different basic mode of operation. Within a communication cycle, a telegram is not sent to each station separately as in other Ethernet approaches, but rather a single Ethernet telegram runs through all stations/slaves. The slaves do not treat incoming Ethernet telegrams in the usual manner, interpreting the contents and then copying the process data for forwarding transmission. Instead, the EtherCAT slaves read and write their process data from and to the predetermined location in the telegram while the telegram is passing through the slave. By this mechanism, the EtherCAT mechanisms permit extremely short cycle times to be implemented. The efficacy of the protocol is demonstrated by the fact that that more than 500 I/O and drive vendors have now adopted EtherCAT for their slave device configurations.

PROFINET ("Process Field Network") is differentiated into different performance classes to address various timing requirements: PROFINET RT for soft real-time, or no real-time requirements at all, and PROFINET IRT for hard real-time performance. The technology was developed by Siemens and the member companies of the PROFIBUS user organization, PNO. The Ethernet-based successor to PROFIBUS DP, PROFINET I/O specifies

[5] https://www.kollmorgen.com/en-us/blogs/what-are-basic-elements-servo-system

all data transfer between I/O controllers as well as the parameterization, diagnostics, and layout of a network.

Ethernet/IP (Industrial Protocol) is an industrial network protocol that adapts the Common Industrial Protocol (CIP) to standard Ethernet. It combines the requirements of deterministic, real-time, closed loop motion control with standard, unmodified Ethernet, offering full compliance with Ethernet standards, including IEEE 802.3 and TCP/IP. EtherNet/IP uses standard Ethernet physical, data link, network, and transport layers, while using Common Industrial Protocol (CIP) over TCP/IP. CIP provides a common set of messages and services for industrial automation control systems, and it can be used in multiple physical media. For example, CIP over CAN bus is called DeviceNet, CIP over dedicated network is called ControlNet, and CIP over Ethernet is called EtherNet/IP. Because of its architecture, EtherNet/ IP is compatible with many standard internet and Ethernet protocols but has limited real-time and deterministic capabilities.

A freely available real-time communication standard for digital drive interfaces, SERCOS III not only specifies the hardware architecture of the physical connections, but also a protocol structure and an extensive range of profile definitions. For SERCOS III, Standard Ethernet according to IEEE 802.3 serves as the data transfer protocol. This communication system is predominantly used in motion control-based automation systems. SERCOS-III uses the Ethernet physics (100Mbps) and the Ethernet telegram while retaining the existing SERCOS mechanisms. SERCOS-III is likewise based on a time slot mechanism in which bandwidth is reserved for the isochronous (real-time channel) and asynchronous (IP channel) data traffic. SERCOS- III works without hubs or switches. Each station has a special integrated ASIC or FPGA with two communication ports, enabling it to be connected via line or ring topology. Eliminating the switches means shorter cycle times can be implemented, though at the cost of flexibility in the network topology. While specific hardware is categorically needed for the slave, a software solution is also feasible for the master.

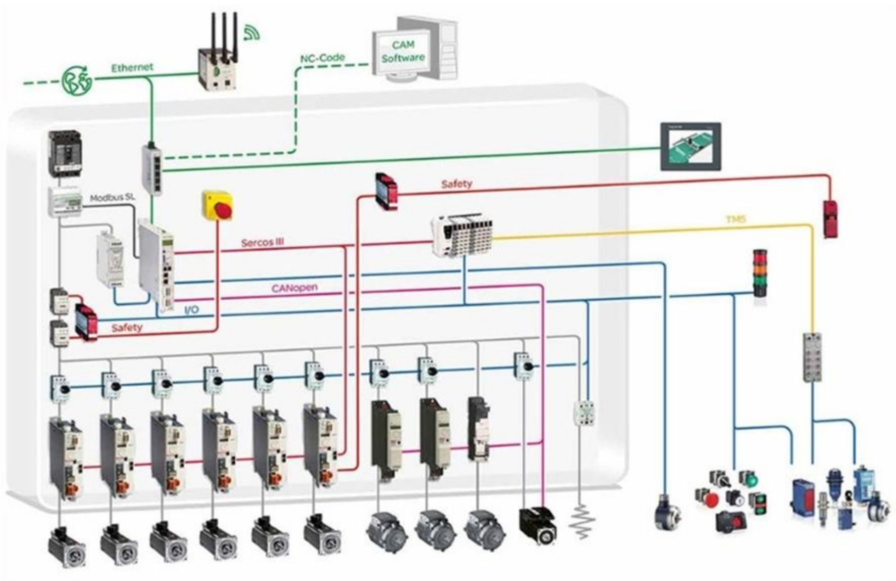

Figure 20 Example of Control Field Bus Architecture – SERCOS (Source: Schneider Electric[6])

ETHERNET Powerlink was introduced by B&R in 2001. Its goal was to provide standard Ethernet with real-time properties and allow universal solutions all the way down to demanding motion applications. Since that

[6] https://www.se.com/us/en/work/solutions/machine-control/compact-sercos-motion-controller-lmc078.jsp

time, the EPSG (ETHERNET Powerlink Standardization Group) has promoted ETHERNET Powerlink and taken responsibility for its openness, continuous improvement, and independence. Powerlink is a strictly cyclical protocol that organizes the access to a network as well as the synchronization of the devices. Because ETHERNET Powerlink is a cycle-based real-time system, it superimposes a time slot mechanism over the CSMA/CD mechanism. The master (controller) successively polls the slaves (drives) within an allocated communication cycle period. The remaining cycle time is left over for asynchronous data traffic, such as for configuration of the devices. Data transport occurs via a standard Ethernet telegram, with the Ethertype set to 'Powerlink' for the real-time data and to 'IP' for the general data.

In summary, the main differences between Ethernet and fieldbus technologies are their speed, distance, and applications. Fieldbus have been introduced earlier and are now progressively replaced by industrial Ethernet for most industrial applications. Fieldbus protocols offer slower data transfer rates but can usually support longer distances and are often used in real-time. Industrial Ethernet protocols offer faster data transfer rates making it suitable for high-level applications that require large amounts of data transfer, and they exhibit various degrees of compatibility with Ethernet.

Full compliance with IEEE 802.3 and TCP/IP gives many advantages as shown in Table 18.

Table 18 Field bus properties

Field Bus Name	Protocol Based	Bandwidth	Applicator	Scope	Normative	Real Time Application	Jitter
PROFINET	Industrial communications over Ethernet, backward compatible with PROFIBUS	100BASE-TX, 100BASE-FX (100Mps)	Profibus and Profinet International (Siemens)	**Data exchange, Industrial Control**	IEC 61784-2, IEC 61158 IEEE 802.3	**Yes. Cycle-times 250 µs -10 ms**	**10-100 µs**
ETHERNET/IP – CIP	Ethernet integrated with CIP	100BASE-TX	ODVA (Rockwell)	**Data exchange, Industrial Control**	IEEE 802.3 IEEE 1588	**Yes. Cycle time 1ms-10ms**	
ETHERCAT	Industrial communications over Ethernet	100BASE-TX, 100BASE-FX (100Mps) (Exist also 1Gbps an 10Gbps)	Back-off EtherCAT Technology Group (ETG)	**real-time computing in automation technology**	IEEE 802.3 IEEE 1588	**Yes: Cycle Time 1ms-10ms**	**< 1us**
POWERLINK	Ethernet based fieldbus, mixed polling and time slicing mechanism	100BASE-TX (Exist also 1Gbps)	B&R	**Data exchange, Industrial Control**		**Yes 0.2ms-10ms**	**< 1us**
SERCOS							
Ethernet	Industrial Data Communication	100Mbps	All	**Industrial Data Exchange, No Real Time**		**5ms-100ms**	**Not Significant**

Appendix A.2 - Industrial wireless communications

Communication for factory automation is characterized by periodicity, determinism, and isochronism: for these reasons, system and communication requirements are very different from the specifications typically assumed in traditional broadband wireless communications. In addition, the picture is further made more elaborated, by the fact that manufacturing systems with soft real-time constraints may coexist, which allow some deadline misses, and thus require latencies in the order of tens of milliseconds, and that manufacturing systems exist with hard real-time constraints, in which all operations must be completed within a deadline, with typically sub-millisecond latencies.

This is the reason why wired technologies, such as the field-bus-based and the Ethernet-based solutions detailed in A.1, represent the lion's share when dealing with factory automation. However, in industrial networks this solution does not provide the required scalability and flexibility, because the wiring cost increases as manufacturing equipment is added or relocated frequently.

To construct scalable networks and offer mobility of manufacturing equipment, the current trend is to resort to wireless technologies. Currently, a wide range of technologies exists that have applicability in smart manufacturing. To understand if a wireless technology is suitable for a particular use case application, features and capabilities of each technology need to be compared, for instance based on communication range, data rates, and infrastructure needs. To this aim, Table 19 provides an overview of the most relevant existing wireless technologies and solutions which can be used for various smart manufacturing applications. In the remainder of this section, we will review both existing and emerging wireless solutions, further subdivided in typical ranges and technologies they are based upon.

Table 19. Overview of wireless technologies [1].

Type	Cove- rage	Underlying technology	Name	Range [m]	Data rate [Mbps]	Typical infrastructure
Incumbent	Short-to-medium range	IEEE 802.15.1	Bluetooth	100	< 3	Point-to-point communications
			WISA	5-15	1	Infrastructure network
			WSAN-FA			
			IO-Link			
		IEEE 802.15.4	WirelessHART	15	0.25	Mesh network, gateway to the fieldbus
			ISA100.11a			
			6TiSCH			
			WIA-PA	10-100		
		IEEE 802.11	WLAN	100	600	Infrastructure network
			Industrial WLAN	100	450	Infrastructure network, gateway to fieldbus
			WIA-FA	5-30	<54	
	Long range	Proprietary	LoRA / LoRaWAN	<10,000	<0.03	Infrastructure network
		Proprietary	SigFox	10,000-40,000	<0.0006	Infrastructure network from provider
		3GPP 4G	NB-IoT	1,000-10,000	<0.1	
			LTE/M	500-5,000	<1	
Emerging	Short range	IEEE 802.11	WIFI 6	10	<11,000	Infrastructure network
			WIFI 7		<40,000	
	Long range	3GPP 5G	5G	10,000	<20,000	Infrastructure network, typically from provider

Existing wireless technologies

Below in Table 20 is a comprehensive list of renowned brands that offer Industrial Wi-Fi Communication solutions widely utilized in various industries worldwide.

Table 20 Brand list of industrial Wi-Fi communications suppliers and manufacturers (non-exhaustive)

Vendor Name	Devices Type
• Siemens • Schneider • Rockwell • Omron	Router, Gateway, Switch, Server, LAN device, HMI, Radio
• Phoenix • Wago's • Moxa • Hirshmann • Cisco	Router, Gateway, Switch, LAN device, Radio

Moreover, Table 21 shows industrial access point for Wi-Fi and 5G communication, by manufacturer BI-REX.

Table 21 Industrial access points for Wi-Fi and 5G by BI-REX

Model	Description
SCALANCE W1788-2IA M12	IWLAN Access Point, SCALANCE W1788-2IA M12, 2 interface radio, 8 internal antennas, iFeature via CLP, IEEE 802.11a/b/g/h/n/ac, 2,4/5 GHz, 1733 Mbit/s gross per radio interface, 2x M12 max. 1 Gbit/s, PoE, DC 24 V redundant, A-coded M12 IP65, -20 ... +70 °C, slot per CLP, WPA2/802.11i/e, ID-Cert: RAPAC-W2-M12-I4
SCALANCE MUM856-3AA1	SCALANCE MUM856-1 5G router (RoW), IP65, for wireless IP communication of Ethernet-based applications via public 3/4/5G mobile radio networks and private 5G networks, , VPN, firewall, NAT, IPv6, connection to SINEMA RC via CLP, 4 N- connect connections, 1x micro SIM slot, 1x10/100/1000 Mbit/s M12 socket, redundant DC 24 V, M12 L-coded, PoE, -30… +60 °C, CLP slot, 1x DI and 1x DO, A-coded, observe national approvals

However, based on the feasible communication distance, we can broadly classify existing wireless solutions in two categories: short-to-medium range (up to 100 meters), and long range (beyond 100 meters).

Short-to-medium range

<u>Bluetooth-based technologies.</u> Bluetooth-based technologies are currently used in industrial plants such as chemical, oil-gas, water, and power plants, as a part of monitoring and maintenance solutions. Ease of deployment, wide availability, low-power and low cost makes these technologies a viable choice for sensing and device monitoring.

Bluetooth. Bluetooth is a short-range wireless technology which operates in the 2.4 GHz ISM frequency band. The initial versions (1-3) are not widely adopted in industrial automation due to high power consumption, short communication range, and lack of support for an increased number of nodes in a network. Improved battery lifetime management is supported by version 4, known as Bluetooth Low Energy (BLE). Improved coverage and network management is introduced in Bluetooth Mesh Networking [13], a low power personal area network (PAN) technology capable of supporting up to 32,000 nodes in a many-to-many connection.

WISA, WSAN-FA, IO-Link Wireless. Wireless Interface for Sensors and Actuators (WISA) [14], initially developed by ABB and released in 2004, is based on the Bluetooth physical layer. In 2010, ABB made the WISA technology specification available to the PROFIBUS and PROFINET user organization (PNO) to develop it into an open standard, called Wireless Sensor Actuator Network for Factory Automation

(WSAN-FA) [15]. However, WSAN-FA was never adopted by industry due to significant gaps in the specifications. To address these gaps, PNO and the IO-Link consortium developed the IO-Link Wireless Systems Extensions (IOLW) [16], published in 2019. The IO-Link standard specifies a half-duplex, fieldbus-neutral, point to point communication mechanism between the sensor/actuator and the controlling device.

IEEE Std 802.15.4-based technologies**.** IEEE Std 802.15.4-based wireless networks are another class of short-range, low-cost, low-power communication technology targeting wireless sensor networks. The basic IEEE Std 802.15.4 MAC schemes were deficient in supporting identified industrial application requirements such as reliability and real-time capability. The addressed improvements resulted in the evolution of various industrial wireless standards described in this section, which are widely meant for process automation industries.

WirelessHART. WirelessHART [17] was specifically designed for process automation applications, based on an industrial automation protocol, Highway Addressable Remote Transducer (HART), adopting IEEE Std 802.15.4 PHY. A WirelessHART network consists of a set of field devices, adaptor(s), access point(s), gateway(s), a network manager, and a security manager. Typically, 80-100 field devices are connected to one gateway in a star or mesh topology with the help of access points. Adaptors enable wireless functionalities to legacy HART field devices.

ISA100.11a. ISA100.11a [18] is another industrial standard that runs on top of the IEEE Std 802.15.4 PHY and exhibits many similarities with the WirelessHART (although they are not interoperable). A typical ISA100.11a network consists of a set of field devices (I/O devices and routing devices) and infrastructure devices (backbone routers, gateways, and system and security manager). ISA100.11a operates in either tree or mesh topology while the second is preferable because it offers increased robustness and enhanced reliability. Like WirelessHART, ISA100.11a supports graph routing, source routing, and security.

WIA-PA. WIA-PA, like WirelessHART and ISA100.11a, was built upon the IEEE Std 802.15.4 standard, and was designed to target process automation applications in industry setups. However, unlike the other two technologies, WIA-PA avoided any modification to the IEEE 802.15.4's MAC layer [19]. WIA-PA supports a hierarchical network topology that is basically mesh-of-stars, in which the first level of the network is a mesh topology of routers and gateways, while the second level is a star network that connects redundant routers and field devices to routers from the first network level.

6TiSCH. 6TiSCH (IPv6 over the TSCH mode of IEEE Std 802.15.4e) is a wireless standard meant to provide IPV6 connectivity for low power wireless networks consisting of IEEE Std 802.15.4 devices. The basic architecture of a 6TiSCH network consists of a device called a "Border Router", which acts as the intermediate gateway between the wireless network composed of low power devices and the external world (internet). The communication between each pair of nodes in an IEEE Std 802.15.4 TSCH network follows a synchronous schedule consisting of "dedicated cells". This cell allotment scheme helps to avoid collisions and hence improve reliability and battery life.

IEEE Std 802.11-based technologies. IEEE Std 802.11-based wireless technology is well known by the common name "Wi-Fi" (Wireless Fidelity) and provides wireless connectivity to most today's digital devices such as mobile phones, laptops, and smart TVs. Wi-Fi is the most used wireless technologies in smart manufacturing, especially discrete manufacturing industries. In this section we provide a brief overview of IEEE Std 802.11 and its applicability in industrial automation and smart manufacturing domains.

Wi-Fi variants. Wi-Fi is based on IEEE Std 802.11 (a/b/g/i/e/n/ac/ax) standards for wireless local area networks (WLAN). The main purpose is to provide wireless connectivity for devices within a local area, through an Access Point (AP). Wi-Fi can be more advantageous with respect to traditional wireless sensor networks (WSNs) due to higher data rate (up to 300 Mbps), non-line-of-sight transmission, large coverage area (100 m indoor, 300 m outdoor), and high reliability to treat the network handling and fault recovery. Although Wi-Fi consumes more power than other standards (e.g., IEEE Std 802.15.1 and IEEE Std 802.15.4), it is suitable for real time and high data rate implementations.

The WLAN standard IEEE Std 802.11ax, marketed as Wi-Fi 6 by Wi-Fi Alliance [20], improves the performance of previous versions, thanks to introducing OFDMA, the adoption of spatial reuse, to mitigate co-channel interference across nearby access points, the introduction of target wake time (TWT), to improve battery life of IoT sensors and other devices, and to maximize the population of connected devices and the support for multiuser MIMO and higher modulation schemes, to increase the nominal data rate. Thanks to these enhancements, Wi-Fi 6 can enable use cases such as massive sensor network deployments and Human-Machine Interaction with Augmented/Virtual Reality (or Mixed Reality) applications.

WIA-FA. Wireless Networks for Industrial Automation – Factory Automation (WIA-FA) [21] is based on the physical layer of Wi-Fi (IEEE std 802.11 WLAN). The typical network architecture encompasses sensors and actuators connecting to an access device. Multiple access devices may communicate with the field devices in parallel and form multiple, optionally redundant, star topologies. WIA-FA supports a number of application data types that are transferred between the gateway device and field devices: non-periodic urgent commands such as start and stop commands; periodical input data (e.g., sensor measurement values, actuator feedback values), and periodical output data (e.g., actuator setpoints, switch set values); non-periodical requests and responses for attribute read/write accesses, as well as alarm acknowledgements; non-periodical alarm reports; and periodic management data.

Long range

<u>LoRa and LoRaWAN.</u> LoRa (Long Range) is a proprietary radio technology with long range capabilities as well as high resistance to interference, based on spread spectrum code-division multiple access (SS-CDMA). LoRa can be used in both license-free sub-GHz and 2.4GHz radio frequency bands. The current LoRa-based standard for sub-GHz transmissions is called LoRaWAN. This protocol has been developed and is maintained by a non-profit association called the LoRa Alliance. LoRaWAN provides several services for LoRa-enabled devices such as device registration, acknowledgements, and end-to-end security. Unlike some short/medium range technologies such as those based on the IEEE Std 802.15.4 radios, which use multi-hop deployments, LoRaWAN uses 1-hop deployments in a star topology where the nodes communicate with one or more gateways and the gateways forward their packets to a network server via a backhaul network. However, LoRaWAN cannot guarantee packet delivery and low latency, two requirements of many industrial applications. Nevertheless, it is suitable for applications that generate small amounts of data (e.g., predictive maintenance) and for applications that require high levels of mobility (e.g., asset tracking).

<u>SigFox.</u> Sigfox is an inexpensive, reliable, low-power wireless protocol solution that connects sensors and devices, which is a part of the Low-Power Wide Area Networks (LPWAN) suite of technologies, deployed mainly for the development of the IoT networks. The modulation technique used by Sigfox is ultra-narrow band, which makes it robust against jamming. Sigfox is designed for the transmission of small payloads over long distances (up to 40 km), with ultra-low-power consumption and inexpensive antenna design. All these

benefits come at an expense of a maximum throughput of only 100 bps. The achieved data rate clearly falls at the lower end of the throughput offered by most other LPWAN technologies limiting application opportunities for Sigfox. The successful deployment of Sigfox within a manufacturing environment is very dependent on the specific use cases.

NB-IoT and LTE-M. Narrowband IoT (NB-IoT) is a 3GPP open standard for low-power and low data rate devices such as sensors and actuators. In contrast with the other two major players in LPWAN (i.e., LoRa and Sigfox), NB-IoT is designed to operate over cellular licensed radio frequencies. NB-IoT uses the existing 2G-4G network infrastructure, and its transmissions (packets) are accommodated within a subset of the existing frame layout provided by LTE (4G). Consequently, NB-IoT uses Single-Carrier Frequency Division Multiple Access (SC-FDMA) policy to access the medium for uplinks, and Orthogonal FDMA (OFDMA) for downlinks. Strengths of NB-IoT are the high levels of coverage possible while maintaining a data rate of at least 160 bps, the connectivity of a massive number of devices, low implementation complexity for IoT applications, and low latency (<10 seconds for 99% of the devices). Negative aspects are increased overhead due to the synchronization mechanism, which significantly reduces the battery lifetime, and need for an existing infrastructure, which does not give the flexibility to the users to deploy their own private network.

Emerging wireless technologies

The evolution of Industry 4.0 envisions use cases that have communication link and system requirements that may not be fulfilled by existing technologies. The increasing demand for higher throughput, lower latency and higher user capacity in smart manufacturing applications led the demand for more capable technologies. In this section, we provide an overview of the emerging wireless technologies that are being considered, their new features, and how they support the new use cases associated with smart manufacturing.

5G and evolved 5G

The 5G cellular network aims at highly adaptable, converged, and pervasive wireless information exchanges, and is expected to be a game changer, unlocking novel opportunities, services, applications, and a wide range of use cases. In terms of wireless networking, 5G is intended to allow three distinct types of services namely, enhanced mobile broadband (eMBB), massive machine-type communications (mMTC) and ultra-reliable low-latency communications (URLLC). The eMBB aims to have uplink and downlink data speeds up to 10 Gbps and 20 Gbps, respectively. The mMTC will enable autonomous environments in industry by allowing interaction between a large number (e.g., up to 1 million devices per square km) of smart sensors and gateways. For single transmission, URLLC aims at a 1 ms over-the-air round-trip time (RTT) and 99.999% reliability, which is important for time-critical control applications. The correlation between the above services and smart manufacturing use cases can be identified as follows:

- predictive maintenance and collaborative machines are intermediate use cases between eMBB and mMTC.
- human-machine interface and remote operation are intermediate use cases between eMBB and URLLC.
- critical control is an intermediate use case between URLLC and mMTC.

To support such types of services, the following major features are introduced:

- new radio (NR) interface, to enable extremely high data rates everywhere, extremely low latency, ultra-high reliability and availability, extremely low computing cost and energy usage, and energy-efficient networks.

- flexible spectrum formation, to operate in unlicensed spectrum (such as 2.4 GHz, 5 GHz, and 66 GHz) while co-existing with technologies such as Wi-Fi, and to flexible subcarrier spacing, particularly important to support a wide range of data services with distinct QoS requirements in terms of reliability, latency, and data rate.
- millimetre-wave spectrum, to exploit new frequency bands, and to support augmented reality (AR) /virtual reality (VR) like advanced use cases of industrial environments, where very high data throughput is required.
- massive multiple-input multiple-output (M-MIMO) systems and smart beamforming, to increase the capacity of the system to support many sensor nodes simultaneously in a smart factory.
- advanced signal processing, to derive reduced complexity non-linear methods for multiuser detection, to boost communication quality.
- software defined networking (SDN), in which the data plane is separated from the control plane, to improve network performance and monitoring.
- network function virtualization (NFV), to meet, together with SDN, the needs of demanding applications while optimizing physical network infrastructure utilization; and
- network slicing (NS), to support several logical networks customized to various types of data services and business operators, and thus to enable individual design, deployment, customization, and optimization of different network slices on a common infrastructure, for instance to interconnect different industrial sites and to provide the required end-to-end connectivity and processing features for smart manufacturing.

Wi-Fi 7 (IEEE P802.11be)

Wi-Fi 7 (IEEE P802.11be), also named Extremely High Throughput (EHT) Wi-Fi, is a new amendment to the Wi-Fi standard that promises to scale up the nominal throughput to as high as 40 Gbps. This is achieved mainly by further enhancing the PHY layer. Wi-Fi 7 enables clients to seamless roam between access points in dense deployments by introducing a multi-access-point cooperation feature. This technology allows for fast association and re-connection with an access point as users move around. Because of the mobility support, some use cases will be more benefited by Wi-Fi 7 than Wi-Fi 6, particularly in cases where there are dense access point deployment and robotic tools, and autonomous intelligent vehicles are moving. Once moving robots can seamlessly roam, productivity can be boosted by allowing robots to perform complex and dangerous tasks. These tasks may demand high data rate, ultra-low latency, and mobility to support the manufacturing process's synchronization and management by offloading their potentially heavy computational workload to edge servers.

Appendix B – Channel measurement methods and equipment

This appendix describes the channel measurement systems to be used in the project. Channel measurements will be performed by the Technische Universität Braunschweig (TUBS) and Huawei (HWDU).

Appendix B.1 - TU Braunschweig channel sounder

The TUBS is using a correlative channel sounder (CS). **With the CS we can measure the Channel Impulse Response (CIR) of a radio channel.** For more detailed information about the measurement system see [22]. A schematic view of the measurement System is Figure 21 and the detailed CS parameter are listed in Table 22.

In TIMES measurements are done at a frequency of 300 GHz.

We can measure in different measurement setups.

- Static channel measurements, where the TX and RX are fixed in a chosen constellation.
- Rotational measurements, where every combination of the Angle of Departure (AoD) and Angle of Arrival (AoA) between the Antennas can be measured. This gives us information about the spatial properties of the environment.
- Multiple Antenna setup, where a MISO (2x1), SIMO(1x2) or MIMO (2x2) setup can be measured.
- Real-Time (RT) measurements are used for dynamic scenarios and MIMO/MISO measurement setups. The measurements must be planed carefully, because of the big amount of data produced by this kind of measurements (approximately 576 Mbyte per second)
- Averaged measurements, where multiple CIR are averaged. These are used in static scenarios. (Improves the dynamic range due to the average)
- To do dynamic scenarios we use a rail system, were either one or two Tx/Rx or an object can be mount, Figure 22.

Measurement limitations and constraints

- Due to the Measurement system the maximum distance between Tx and Rx are 15m.
- For Real-Time Measurements max. scenarios up to 10 seconds should be measured to insure an appropriate post processing time.
- For dynamic scenarios where the Rx are moving vibrations must be reduced by a minimum.

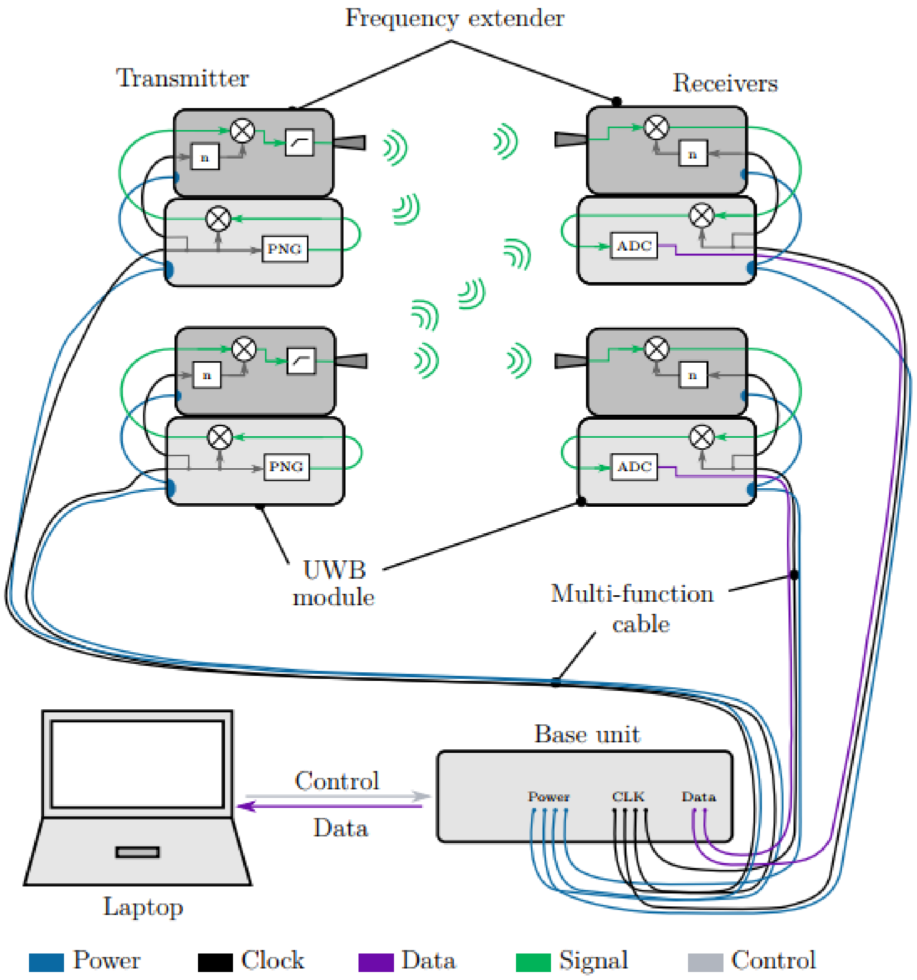

Figure 21 Schematic view of the TUBS Channel Sounding System

Table 22 TUBS Channel Sounder parameters

Parameter	Value
Clock Frequency	9.22 GHz
Bandwidth	approx. 8 GHz
Chip duration	108.5 ps
M-sequence order	12
Sequence length	4095
Sequence duration	444.14 ns
Subsampling factor	128
Acquisition time for one CIR	56.9 µs
Measurement Rate	17,590 CIR/s
Centre Frequencies	9.2/64.3/304.2 GHz
SISO/MIMO	Up to 2x2

Figure 22 Rail system used for dynamic measurement scenarios

Appendix B.2 - Huawei channel sounder

HWDU will perform channel measurements using a dual-polarized ultra-wideband channel sounder composed of a Tx unit, Rx unit, and a control unit. Tx and Rx units are mounted over positioners that can scan the angular domain in azimuth and elevation. The block diagram of the measurement system is depicted in Figure 23.

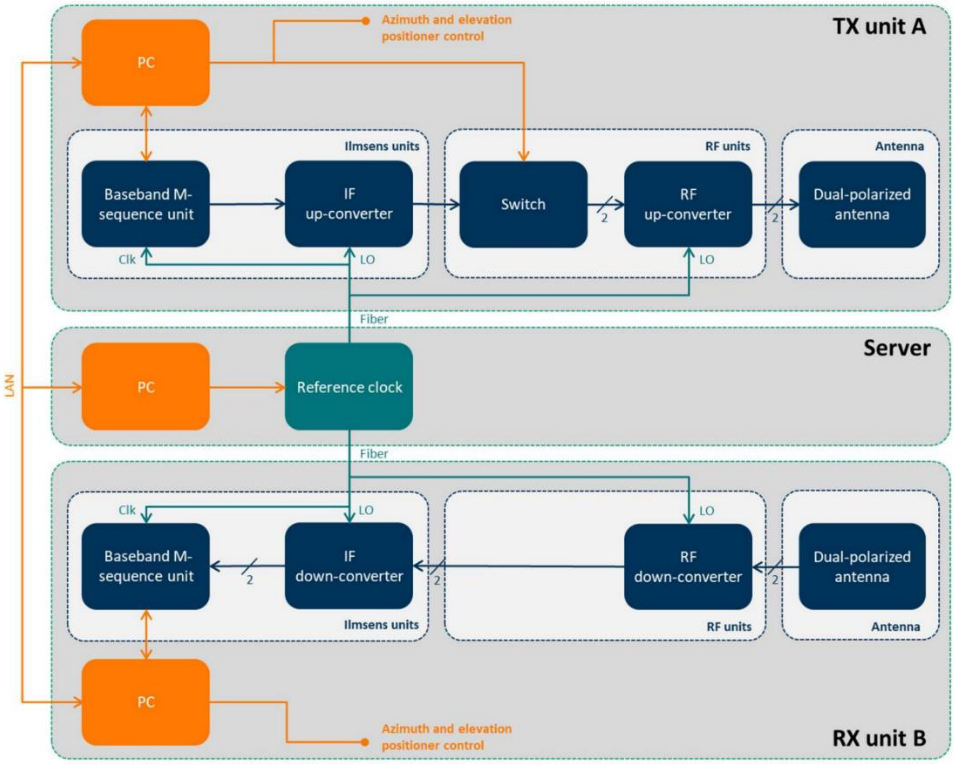

Figure 23 Overall structure of the HWDU channel sounder

Tx and Rx units are composed of three main components, namely Ilmsens modules[7], RF modules, and antennas. At the transmitter side, the Ilmsens module generates an excitation signal is a 12-bit maximum-length binary sequence (MLBS), also known as M-sequence with length 4095 samples. The baseband signal is then up converted using an integrated IF stage and used as input to the RF module. Finally, the RF module up-converts the IF signal to 300 GHz using internal multipliers (x48). At the receiving side, the RF signal is down converted to IF and used as input to the Ilmsens unit to obtain the baseband signal. The system supports different types of antennas, including high-directive horn and open-ended waveguide antennas.

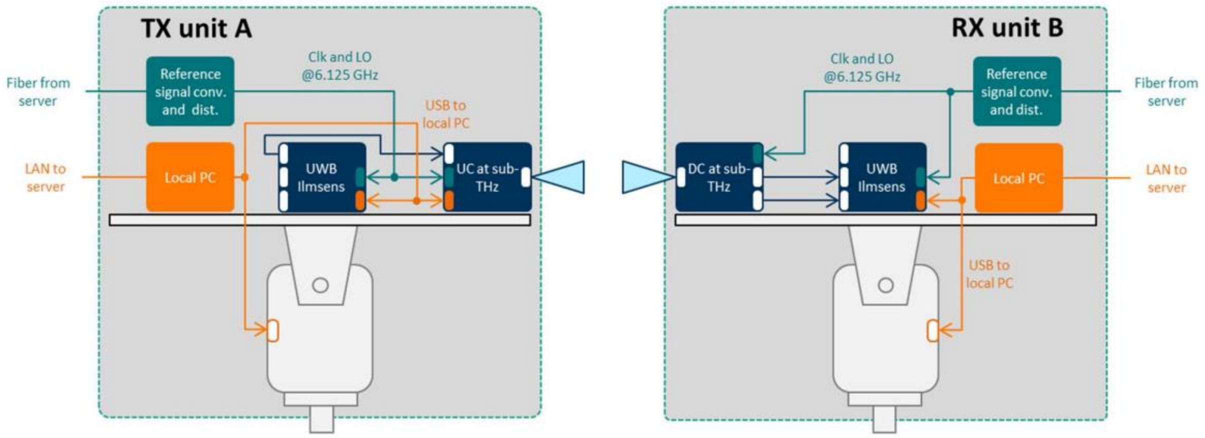

Figure 24 Schematic of the channel sounder and the positioners

The CIR is obtained by cross correlating the received signal with a copy of the transmitter signal in the frequency domain. To characterize the omni-directional properties of the channel, angular domain is sampled by rotating directive antennas at the Tx and Rx in azimuth and elevation.

The details of the channel sounder are reported in Table 23 below.

Table 23 HWDU Channel Sounder parameters

Parameter	Value
TX power	-8 dBm
TX antenna gain	25 dBi
RX Antenna Gain	25 dBi
Received Power	-49.54 dBm
M-sequence order	12
Sequence length	4095
IF Frequency	6.2 GHz
Measurement bandwidth	6.2 GHz
Bandwidth (after calibration)	5 GHz

[7] See: https://www.ilmsens.com/products/