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List of Abbreviations

BE	Back end
BPSK	Binary Phase Shift Keying
CINR	Carrier-to-interferer plus noise ratio
DIN	Deutsches Institut für Normung
ETH	Ethernet
FDD	Frequency Domain Duplex
FE	Front-end (RF or THz)
FREF	Frequency Reference
HW	Hardware
IF	Intermediate Frequency
IRS	Intelligent Reflective Surface
KPI	Key Performance Indicator
LNA	Low Noise Amplifier
LO	Local oscillator
LoS	Line of sight
MEMS	Micro Electro Mechanical System
MMIC	Microwave Monolithic Integrated Circuit
MODEM	Modulator/Demodulator
MPA	Medium Power Amplifier
NLoS	Non-line of sight
PLC	Power line communications
PLL	Phase Locked Loop
PHY	Physical Layer
PoC	Proof of Concept
PoE	Power over Ethernet
PSK	Phase Shift Keying
x-QAM	Quadrature Amplitude Modulation with x states
QPSK	Quadrature Phase Shift Keying
RF	Radio Frequency
RH	Relative humidity
RSSI	Received signal strength indicator
SoTA	State of the art
SNMP	Simple Network Management Protocol
TDD	Time-domain Duplex
THz	Terahertz
WG	Waveguide
WR	Rectangular waveguide
XN	Multiplication factor by N

Executive Summary

This document offers a description of the Proof of Concept (PoC) architecture that has been defined for the TIMES project, including the different hardware-based sub-systems and how they will be integrated towards the PoC realization.

1. Introduction

1.1 Scope

This deliverable provides the definition of the PoC, and the hardware behind it, used for the TIMES project. The general scope is the technical description of the PoC: principle, required hardware functions, the related key performance indicators (KPIs) and usefull metrics.

1.2 Audience

This report is intended for public use.

1.3 Structure

The rest of the document is structured as follows:

- Section 2 presents the overall description of the THz-enabled link, on which the PoC is based, with the list of the different sub-parts.
- Section 3 describes the hardware sub-parts/systems required for the PoC. Each part or sub-system is detailled and associated Key performance Indicators (KPIs) are listed. This also applies for the network interfaces that make the link between THz hardware and network-level/connectivity.
- Section 4 presents the possible PoC scenarios related to the hardware capabilities, according to the targeted performances.

2 Scenario for Hardware demonstrations and PoC

2.1 Overall description

This section includes a description of the different hardware types that are at the essential building blocks for the experimental demonstrations. This includes several types of hardware, active/passive, static/dynamic.
Among the different building blocks of a THz link, that is the physical layer (PHY) associated to the PoC, the following hardware is to be part of the link:

- **Antenna**, used as an interface from waveguide-based to free-space. Two types of antennas are considered here: i) fixed/high gain and ii) beam-steerable antenna.

- **Transmit and receive (T/R)** integrated circuits (integrated in modules), that make the link with MODEMS. These units have to up or down-convert the signals from the MODEMS to the 300 GHz band and include the required local oscillators (LO) as well as the amplification stages at Tx side (MPA) and Rx (LNA).

- **MODEMS**, that enable to connect the network interfaces to the IF front-end interfaces of the T/R modules, before up/down conversion to the 300 GHz band.

- **IRS** (Intelligent Reflective Surfaces), that are inserted within the THz channel (in the THz path), enabling non-line of sight (NLoS) connections using THz frequencies (here the 300 GHz band).

Based on these components, the initial overview of the end-to-end assembly that is targeting to connect any machine using the 300 GHz radio spectrum is given hereafter by the figure 1:

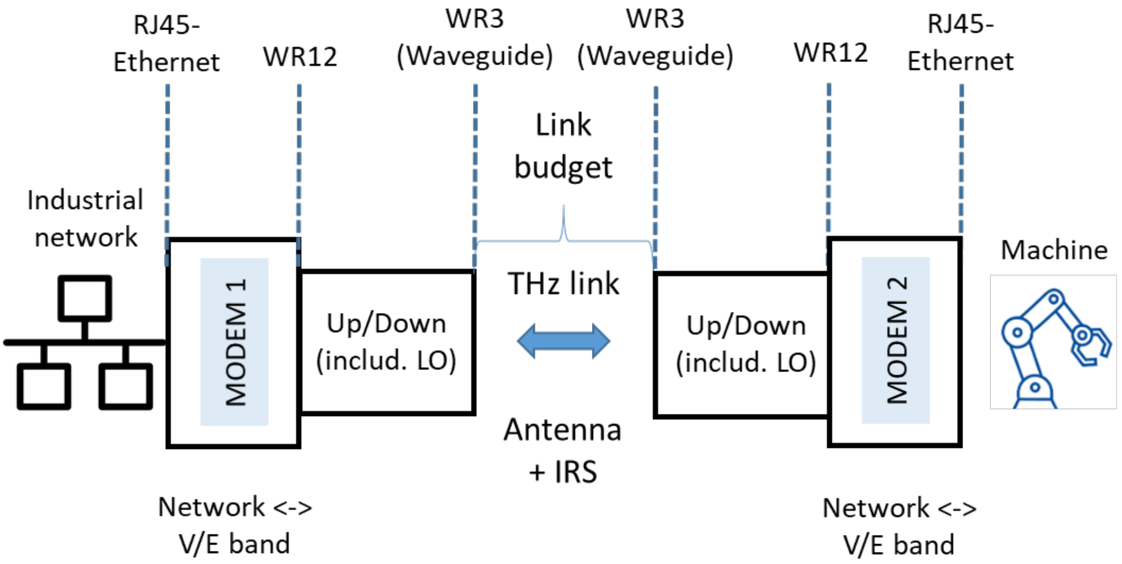


Fig. 1. End-to-end connection of a machine using ethernet/THz/ethernet bridge. The modem architecture needs to be duplexed, and could be time domain (TDD) based for frequency domain (FDD)

In this approach, each sub-system must be defined in terms of specifications and KPIs, including the proper interface definitions that enable to connect the different sub-systems to each-other. The THz link budget targeted for the TIMES project will strongly depend on the chosen scenario. However, in any case, the link budget will be the key figure to assess for each scenario.

In addition, as the different sub-systems will be designed and fabricated in parallel during the project, the final metrics and measured KPIs are obviously not known at the time of writing this report.

In the following parts, hardware-oriented descriptions are given for the different sub-systems (Antenna/IRS, Front-ends, MODEMS and network interfaces). These different sub-systems are the key-enabling THz technologies behind the PoC for TIMES project.

3 Key enabling technologies

3.1 Antennas & IRS

3.1.1 High gain – Fixed antennas

For data communication between fixed points, high-gain antennas are necessary to reach the required distances in the long-distanced PoC tests. High gain also implies high directivity and therefore a narrow beam. Such beam characteristics are necessary in a complex environment like the one considered, where multipath propagation with multiple reflections from the surroundings is critical. Similarly, high gain is also necessary to compensate for channel losses.

There is a wide range of high-gain antenna types available [BAL], such as Yagi-Uda antennas, parabolic antennas, horn antennas, arrays, slotted antennas, etc. However, not all of them are suitable for communication in the 220-330 GHz band. Firstly, not all types are manufacturable, either due to their topology or manufacturing tolerances. Secondly, high losses at high frequencies must be considered. Additionally, the RF signal generation ultimately determines the antenna feeder, which also defines or restricts the type of antenna.

At these frequencies, when high gain is required, it is common to use reflectors or horn antennas fed by waveguides. For this project, horn antennas with lenses will be used. Adding a lens allows reducing the size of the horn antenna while achieving the same beamwidth. To achieve high directivity, very long horns would be required, which might exceed manufacturing limits. For the project, horn antennas will be designed where a very short feed efficiently illuminates the lens. The feed-lens system is enclosed in a metallic cylinder to prevent radiation at undesired angles and reduce the level of the secondary lobes. However, adding a lens increases propagation losses, so it will be necessary to use materials with low losses in this frequency range for the lens. Possible candidates are Teflon or high-performance polymers like PEEK. Horn antennas have been chosen over reflectors for their ease of manufacturing and their compact and robust design.

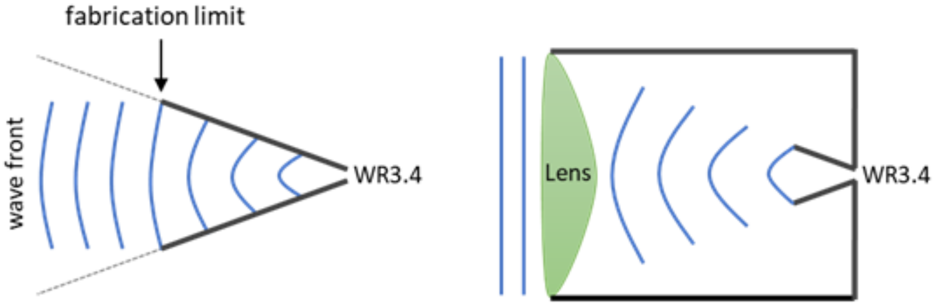


Fig. 2. Sketch of a classical horn and proposed lens horn antenna.

Among the types of dielectric lenses, hyperbolic or elliptical profiles allow better wavefront correction and less aberration with frequency. In this project, the hyperbolic profile will be initially explored as it provides a lens with a lower effective volume, resulting in lower losses.

In summary, the proposed fixed high-gain antennas have the following characteristics:

- **Type**: Horn antenna with hyperbolic lens
- **Material**: Aluminum (body), low-loss dielectric (lens)
- **Frequency bandwidth**: 220 – 330 GHz
- **Input**: rectangular waveguide WR-3.4

And the following KPIs are considered:

1. **Return loss**: < -10 dB at full frequency bandwidth
2. **Directivity**: > 45 dBi
3. **Mean beamwidth**: < 2 deg
4. **Losses**: < 1.5 dB
5. **Sidelobe level**: < -30 dB

3.1.2 Beam-steerable antenna

Antennas with beamforming or beam-steering [MON23] capabilities are of particular interest in the PoC due to their ability to selectively direct the radiation beam towards a specific direction without physically moving the antenna. The ability to focus and adjust the radiation beam has several benefits in the communication system, such as improving signal quality, increasing range and transmission capacity, and reducing interference.

The ability to steer the beam can be achieved either analogically or digitally [MON23]. Analog beamforming is achieved with antennas that have multiple radiating elements, where each element has adjustable delay and amplitude. By controlling the delays and amplitudes of each element in the antenna, a directional beam can be generated in a specific direction. On the other hand, digital beamforming uses an array of antennas and signal processing systems to digitally manipulate the phase and amplitude of each antenna element. Sophisticated algorithms are employed to calculate the optimal weights applied to each element, allowing for precise formation and adjustment of the radiation beam.

In the project, analog beamforming antennas have been chosen due to the following reasons:

- Lower complexity: Analog beamforming generally requires fewer components and processing compared to digital beamforming. By using adjustable delays and amplitudes in the radiating elements of the antenna, beam formation can be achieved without the need for complex digital signal processing. This results in a simpler and less expensive system.
- Reduced latency: Analog beamforming tends to have no latency compared to digital beamforming because it does not involve digital signal processing. This is beneficial in real-time applications such as wireless communications or radars, where fast response is crucial.
- Greater bandwidth: Analog beamforming can handle a higher signal bandwidth compared to digital beamforming. There are no restrictions on sampling frequency and digital processing that can limit the bandwidth in the case of digital beamforming.
- Lower power consumption: In general, analog beamforming consumes less power compared to digital beamforming since it does not require intensive digital processing.

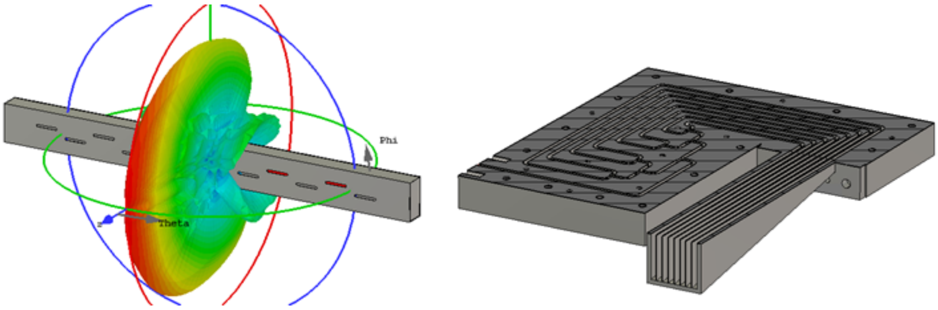
Therefore, the proposed antennas for the different PoCs are antennas that contain different radiating elements where, depending on the emission frequency, the phase in each element varies, and thus, the final formed beam points in a specific direction.

Like high-gain antennas, there are different types of antennas with analog beamforming capabilities, such as radiating element arrays, slotted waveguides, MEMS (Micro-Electro-Mechanical Systems) systems, etc. Mainly due to the complexity involved in manufacturing high-frequency antennas, the antennas designed and fabricated during the project will be of these two types:

1. *Slotted waveguide antenna* is a type of antenna that uses a waveguide structure with slots or openings to control the direction of the radiated or received electromagnetic waves. The antenna design typically consists of a rectangular waveguide with a series of narrow slots or openings along

its length. By varying the excitation of the slots or openings, the antenna can steer the beam of radiation in a specific direction. By properly controlling the phasing and amplitude of the signals fed to each slot, the antenna can create constructive interference in the desired direction and suppress radiation in other directions. The input is a standard WR3.4 rectangular waveguide.

2. *Phase delay line antenna* consists of an array of individual antenna elements, each with its own phase shifter or delay line. By manipulating the phase of the signals applied to each element, constructive or destructive interference can be achieved, resulting in the desired radiation pattern. This phase adjusting will be done by varying the length of the phase delay line. The performance depends on factors such as the number and spacing of the individual elements, the frequency of operation, the accuracy of the phase shifting components, and the overall system design. In this antenna, the phase lines are different rectangular waveguides which end in an aperture-like antenna, forming a final aperture array. The input is also a WR3.4 waveguide.



(1) (2)

Fig. 3. (1) Slotted waveguide antenna. (2) Phase delay line antenna.

Both types of antennas will be manufactured using metal by high accuracy manufacturing process (milling and/or DRIE) with the aim to reduce losses to the minimum. Such antennas must deal with low losses. The main challenge is to achieve high directivity for the design steering angles. Therefore, adding a dielectric lens as a complement to the aperture with the aim of increasing the directivity is also under consideration.

The following KPIs are considered:

1. **Return loss**: < -10 dB at full frequency bandwidth.
2. **Directivity**: > 14 dBi.
3. **Steering angle**: 20 to 50 degrees.
4. **Losses**: < 2 dB.

3.1.3 300 GHz Intelligent Reflecting Surface

Most of the IRS works available in the bibliography are related to indoor 5G scenarios (X-, Ku-Bands) [KAM17, OKO22, MAR22], where a large variety of layer configurations, patch geometries and reconfigurability options can be found. Also, it can be noted that, even with less presence, IRS working at higher frequencies (100 GHz, 1 THz) have been analyzed [HAS17, CHE21], but these IRS technologies still are in early phases. Here, the development of such a technology at 300 GHz is proposed and analyzed.

First, passive structures (100mm (4”) diameter silicon wafers, loaded with patch arrays capable of redirecting an incident normal beam to a certain direction) will be designed. Each patch presents a different size, so the locally impinging wave is reflected with a local specific phase. This local phase variation for each patch results in the deflection of a fan beam to a certain angle, although the specular reflection beam is also expected [ENC07].

For the PoC, two IRS designs for two different scenarios are considered:

- If the incident beam impinges normally ([θ,φ]= [0, 0] deg) it will be directed to a certain [θ’,φ’]= [-X, 0] deg (θ value “X” used to calculate the patch sizes), in the plane that contains the unit patch array (*yz*).

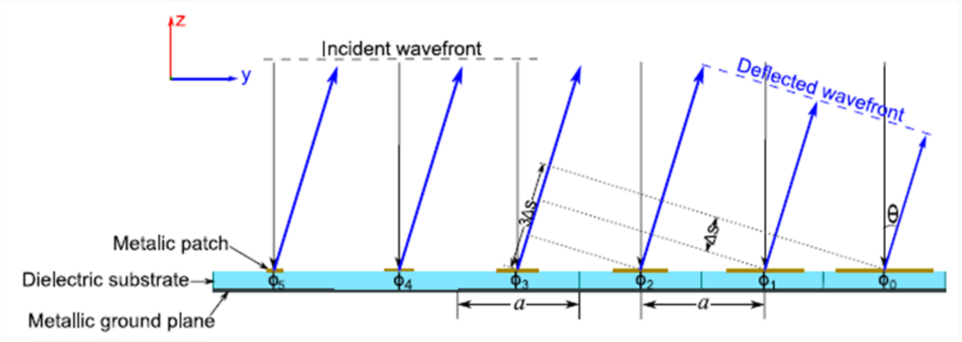


Fig. 4. Illustration of an IRS working under normal incidence.

- If the incident beam impinges at an angle other than the normal ([θ,φ]= [Y, 0] deg), the deflected angle will be observed at ([θ’,φ’]= [-(X+Y), 0] deg) as well as a specular reflection at ([θ’’,φ’’]= [-Y, 0] deg). For the moment, a maximum of X+Y=50 deg is considered.

Once the 100 mm diameter wafer analysis is concluded as a short distance proof of concept, a larger block is intended to be built for the long-distance PoCs. The idea is to attach several wafers together, like a mosaic, to obtain a larger block. Two wafer geometries are for now considered: side by side circular or square wafers. The square wafer market is not as a developed as the circular wafers one, but the process of cutting and shaping the latter is quite challenging.

The KPIs considered for both short and long distance PoCs are:

1. Deflected beam pointing angle: 10 to 50 degrees.
2. Magnitude difference between deflected and specular beams: < 10 dB
3. Magnitude difference between deflected and undesired side beams: > 15 dB
4. Frequency bandwidth: > 15 GHz.
5. Reflection losses (substrate and metal): < 2 dB.

Three main challenges are identified both related with design and fabrication:

1. Reduction of the specular beam magnitude.
2. Increase of the deflected beam magnitude.
3. Reduction of undesired side lobes magnitude.

The second part of this study and a challenge on its own, is the implementation of intelligence in the passive structure, I.e., development of an active structure. Two methods are contemplated:

- On/Off configuration: in which specific patches are, by means of different voltages, changed from insulation to metal state (and vice versa) to obtain a new patch distribution and, consequently, a new pointing angle [JUN14].

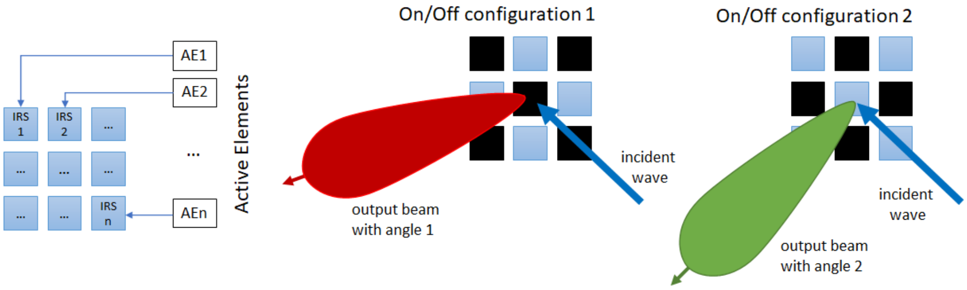


Fig. 5. IRS based on ON/OFF concept

- Liquid Crystal: in which an intermediate liquid crystal layer, over which the metallic IRS parches are placed, changes its dielectric constant when a certain voltage is applied, consequently changing the deflected beam direction [PER23, ISM07].

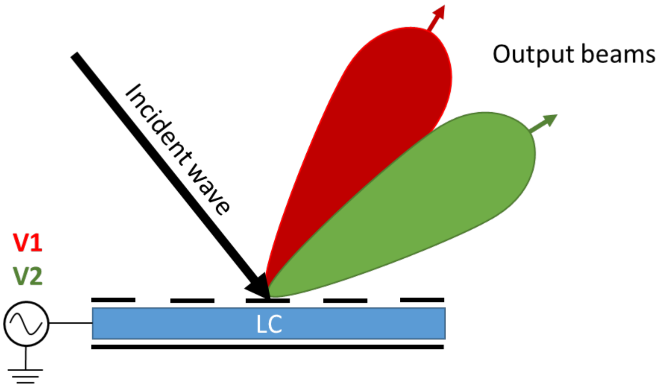


Fig. 6. IRS base on liquid crystal concept

For the moment, the main focus is being given to the latter technology, for its rather lower complexity.

In any case, one of the key metrics related to the PoC will be the reflectivity of the surface and the beam collimation impact. These effects will directly impact on the link-budget by introducing an extra loss. This metric is not known at this moment; however, it is considered as an extra loss in the last part of the document, dedicated to link budget estimations.

3.2 THz front ends

Up to date, most THz front-end (FE) demonstrators consist of a larger number of waveguide modules (amplifiers, multipliers, up-/down converters) that are screwed together. In contrast, Fig. 7 illustrates a preliminary drawing of the TIMES FE modules, consisting of a low-cost single FE package that is mounted on a back-end (BE) carrier. The FE package incorporates the millimeter-wave monolithic integrated circuits (MMICs) and the BE package will include all relevant components and interfaces for the control and generation of the LO signal as well as the bias control of the THz circuits. A simplified block diagram is depicted in Fig. 8.

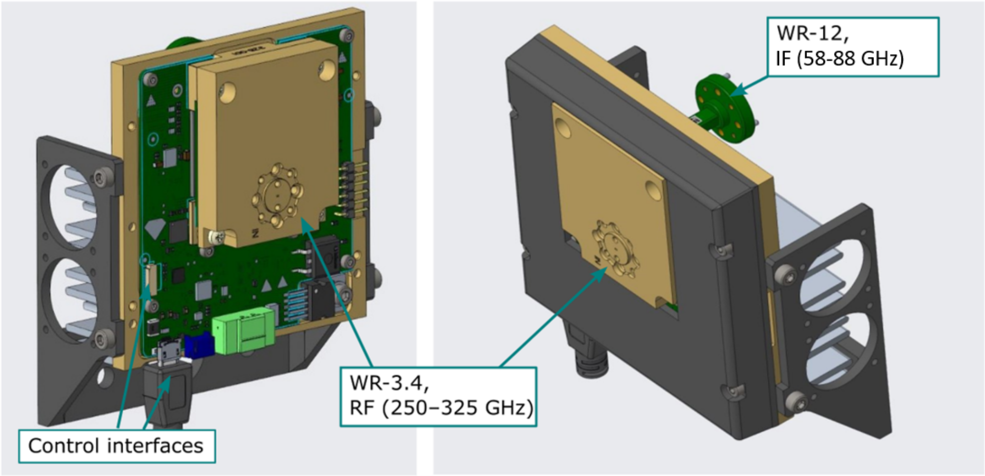


Fig. 7: Preliminary drawing of the 300-GHz FE modules.

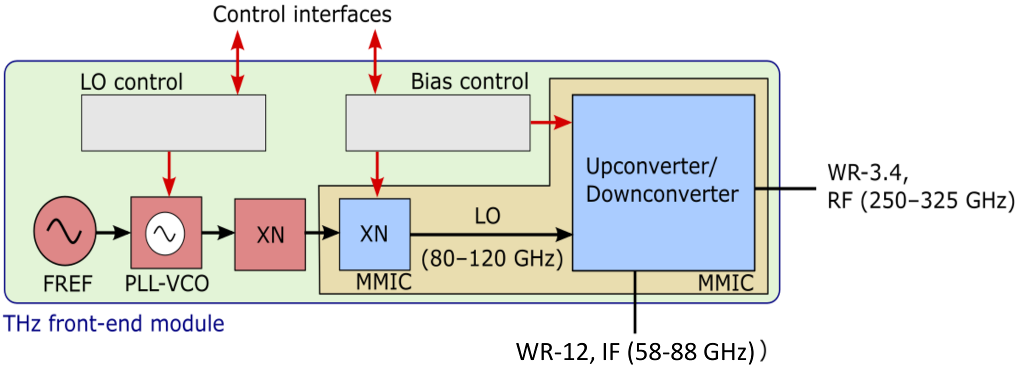


Fig. 8: Simplified and preliminary block diagram of the 300-GHz FE modules. *'FREF' is frequency reference, 'XN' states for the multiplication factor of an integer N.*

The targeted RF frequency range is 250 to 325 GHz, using the standard WR-3.4 waveguide flange. The IF frequency range has to cover the frequency bands of the TDD and FDD modem frequency ranges, which is approximately 58 to 88 GHz, compliant to the WR12 range. All relevant interfaces are listed in the table below. The interface and specifications for the LO control still needs to be defined, however without changing the concept of the PoC.

Interface specifications RX/TX modules	
RF frequency range (GHz)	250 – 325
RF WG flange	WR-3.4
IF frequency range (GHz)	58 – 88
IF WG flange	WR-12
Interface for beam steering (LO control)	TBD
LO control speed	TBD

Tab. 1: General specifications of the Rx/Tx modules. The interface for beam steering, ie the way to adjust the LO frequencies, is not yet defined.

The only difference between the RX and TX FE modules will be the integrated up- and downconverter circuits of the THz FE. The package dimensions, interfaces and positions of the interfaces will be identical for both the RX and TX modules. The preliminary electrical specifications, like input and output power level of the RX and TX modules, are summarized in the following subsections.

3.2.1 Tx (up-converter)

Electrical specifications TX FE	
RF frequency range (GHz)	250 – 325
RF output power (dBm, OP1dB)	> 6
IF frequency range (GHz)	58 – 88
IF input power (dBm, IP1dB)	-5 … 0
IF input power (dBm, damage)	5 … 10

Tab. 2: General specifications of up-converter. Values in range for IF power to be confirmed (compression/damage levels).

3.2.2 Rx (down-converter)

Specifications LO generation	
RF frequency range (GHz)	250 – 325
RF input power (dBm, IP1dB)	-30 … -20
RF input power (dBm, damage)	< – 15
IF frequency range (GHz)	58 – 88
IF output power (dBm, OP1dB)	-18 … -13

Tab. 3: General specifications of the down-converter. IF output power to be confirmed (compression level).

3.2.3 Local oscillator specifications

The PLL can be controlled via a Serial Peripheral Interface, e.g., an additional controller for the LO control can be implemented. This, however, will reduce the switching speed of the LO generation. The required switching speed for the application at hand as well as the required interface needs to be considered as a part of the beam-tracking implementation in the PoC specification.

Electrical specifications of the LO	
LO output frequency PLL-VCO (GHz)	25 – 35
LO multiplication factor on the BE (unfiltered xN)	4
LO multiplication factor on the FE (unfiltered xN)	4
LO output frequency at up/downconverter MMIC (GHz)	80 – 120
LO switching speed	TBD

Tab. 4: General specifications of the local oscillator (LO) that is to be coupled to the up/down converters.

3.2.4 Front-End requirements for the implementation of the different PoCs

There are two main PoC scenarios planned, as described in Section 4. Scenario 1 will be using the high-gain antennas and Scenario 2 will be utilizing the beam-steerable antennas.

Scenario 1 – Using high-gain antennas: In this scenario, due to the larger antenna dimensions, a single antenna should be used for both the R_X and T_X path at each node. This antenna has to handle the transmitted and received signals. In addition, when FDD approach is used, the R_X path has to be separated from the T_X path, and a 300 GHz diplexer will be required between antenna and FEs. Only a diplexer can provide the required isolation above 50 dB between the R_X and T_X path. The isolation of other components such as couplers is typically limited to the same range as the return loss, which is typically in the range of 25 dB and much too low for the targeted application.

The diplexer needs to be realized as a separate waveguide component to connect the R_X and T_X path/modules and to be able to choose the R_X/T_X frequency bands at each note separately. Hence, to provide maximum flexibility, separate RX and TX modules will be developed and can be merged into a single transceiver module if required (see Fig. 9):

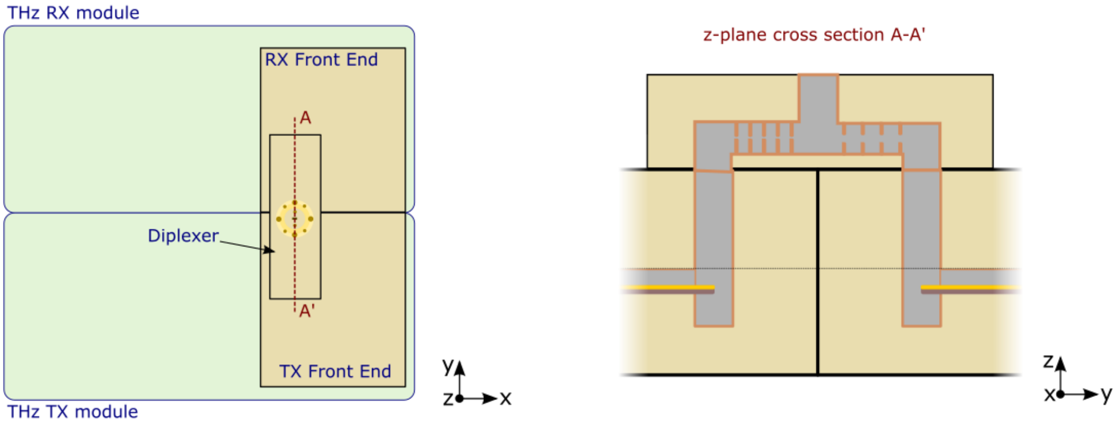


Fig. 9 Preliminary schematic view of the waveguide diplexing structures to combine two separated FEs (Rx and Tx) in a single waveguide fed (WR3.4) antenna.

Scenario 2 – Using beam-steerable antennas: In this scenario, RX and TX front ends need to be used with a separate antenna each, since both must be able to use the whole and same frequency range provided by the antenna. Hence the stand-alone RX and TX modules described above can also be used in unidirectional demo scenarios.

3.3 MODEMS

For the demonstrator setups, two types of commercial E-/V-band modems will be used in the project. Both types contain modem functionality as well as integrated E-band frontends, which are connected to the 300-GHz frontend modules via WR-12 waveguides.

3.3.1 FDD Modem

To achieve duplex-link functionality by FDD, commercial SIKLU EH-8010 FX modems will be used. The FDD modems operate in the 71-76 GHz and 81-86 GHz frequency bands. Channels centred at 72.125, 74.625, 82.125 or 84.625 GHz are selectable with bandwidths between 250 MHz and 2 GHz. The transmit and receive channels are separated using waveguide diplexers. The modems support complex modulation formats BPSK, QPSK, 8-PSK, 16-QAM, 32-QAM, 64-QAM, 128-QAM, enabling traffic up to 10 Gbit/s injected/extracted via RJ-45 or SFP+ interface. The transmit power at the modem waveguide port is adjustable in the range of –5 to +18 dBm, with slight dependencies on the used modulation format. KPIs are the carrier-to-interferer plus noise ratio (CINR) as well as the received signal strength indicator (RSSI). Both can be observed in the modem GUI (accessible via browser) or SNMP application. The modems are powered either by Power over Ethernet (PoE) or a dedicated DC supply. A more detailed description, block diagrams and a testing report can be found in the deliverable D3.6 from the ThoR-Project [THR20].

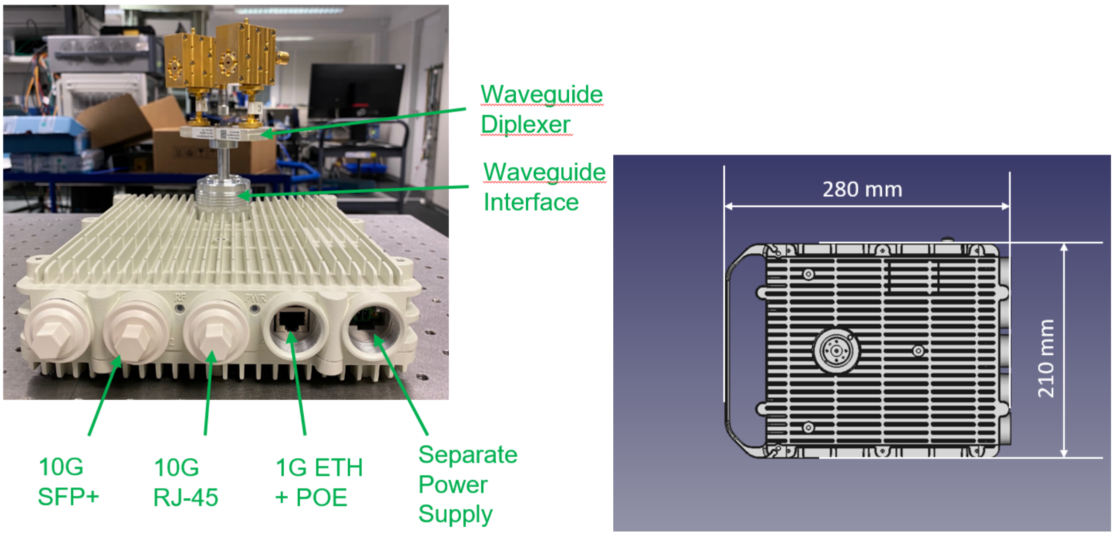


Fig. 10: Interfaces of SIKLU EH-8010FX modems.

3.3.1.1 Accessories FDD-Modems: Power Supply and Maintenance ETH

The power supply of the modems can be combined with a maintenance ETH-connection. Over this Ethernet connection the SNMP-Functions of the modems can be used to monitor and track the link-quality in terms of RSSI and CINR. DC power consumption of a single modem is 50 W.

3.3.1.2 Accessories FDD-Modems: Waveguide Diplexer

The FDD-Modems are sending and receiving on different carrier frequencies. To feed the R_X-Channel to the 300 GHz receiver and to feed the T_X-Channel to the 300 GHz transmitter, frequency diplexers have to be used. The diplexers are commercially available. In Fig. 11 [WRA22] the two passbands of the diplexer and the available channels of the Modems are displayed.

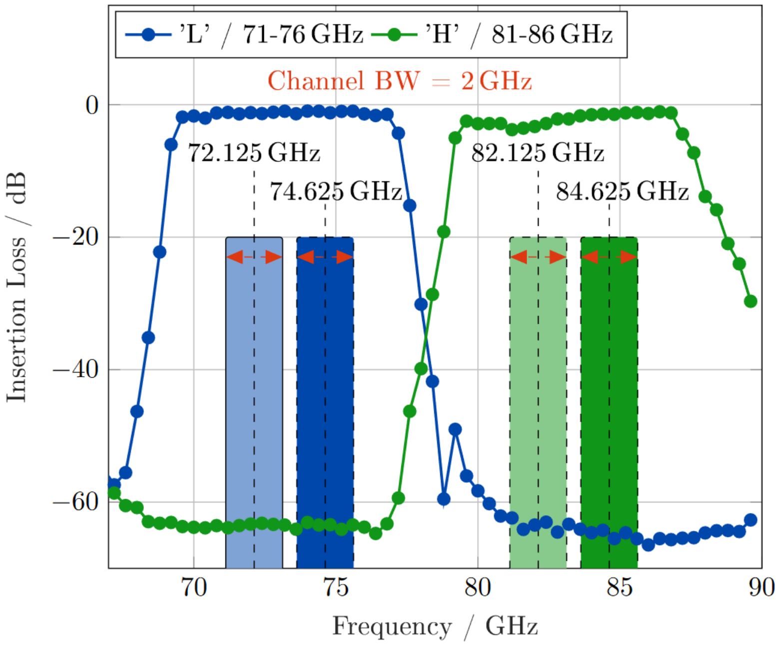


Fig. 11: Characteristics of waveguide diplexer for TX/RX separation in FDD modems.

3.3.1.3 Accessories FDD-Modems: Waveguide combining Structure "Spider"

For the parallelization of multiple FDD-Modems external waveguide structures must be applied to combine/split the RF-Signals from and to up to 4 FDD-Modems. A picture of the waveguide structure used in the ThoR-Project can be seen in Fig. 12.

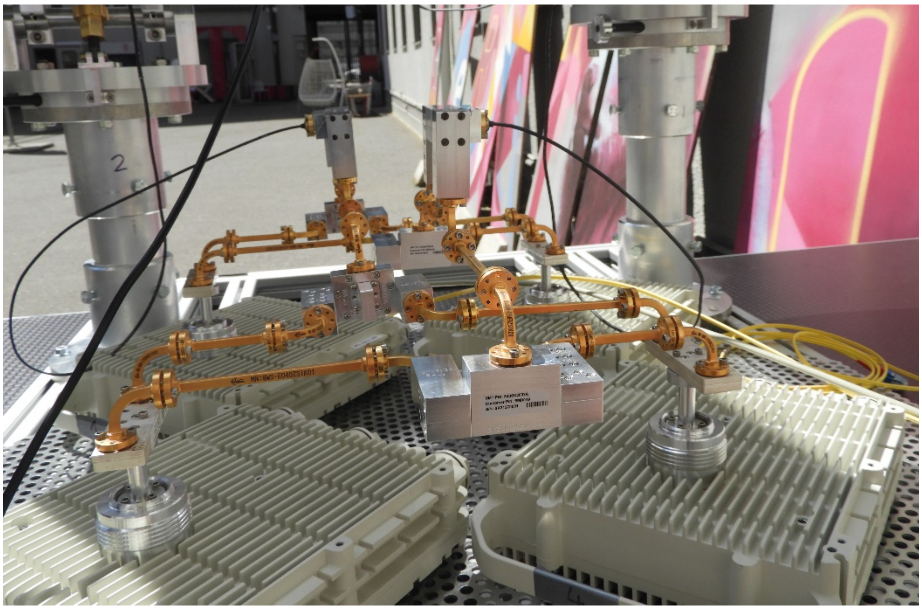
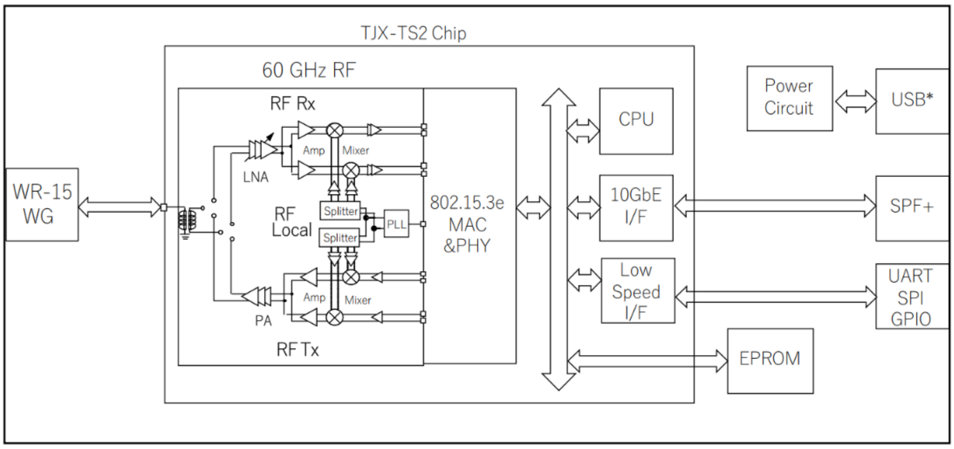


Fig. 12: Waveguide structure "Spider" for parallelization of multiple modems

3.3.2 TDD Modem

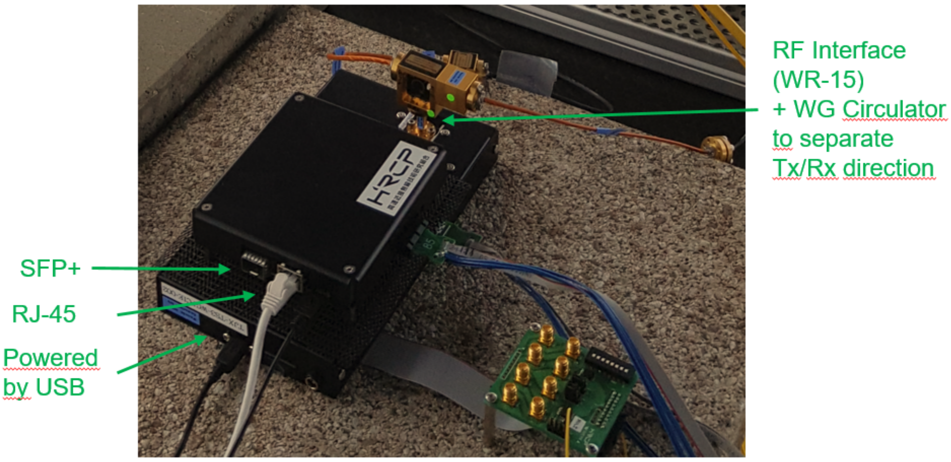
To achieve duplex-link functionality by time-division duplex (TDD), commercial V-band modems manufactured by HRCP will be used. The TDD modems operate at V-band frequencies, offering two channels with a bandwidth of 2.16 GHz, centered at 60.48 GHz and 62.64 GHz. The available transmit power at the modem waveguide port is around -5 dBm. Available modulation schemes are QPSK and 16-QAM, supporting up to 6 Gbit/s. The modems connect to the network via RJ-45 or SFP+ interface. KPI is the received signal strength indicator (RSSI) monitored in the console, which is also used to control the modem. A more detailed description, block diagrams and a testing report can be found in the deliverable D3.5 from the ThoR-Project [THR21].

The general architecture of this TDD MODEM is depicted by the Fig. 13, and Fig. 14 shows the package of the TDD modem. This TDD modem is also to be combined with external waveguide devices to connect the IF waveguide interfaces of the T_x and R_x FEs.



*for power supply only

Fig. 13: 60 GHz band TDD modem architecture [THR21]



RF Interface (WR-15) + WG Circulator to separate Tx/Rx direction

SFP+

RJ-45

Powered by USB

Fig. 14: Interfaces of the HRCP V-band TDD modems.

3.4 Requirements for the network interfaces

In this part, a description of the network interfaces is given in relation to the requirements of the associated industrial (end-to-end) scenarios.

For the PoC, the following are the hardware specifications of a bridge box composed of an antenna that receives and transmits data through the air and forwards the communication through a cabled connection.

Ethernet Standard: IEEE 802.3

The physical layer of the cabled communication must implement the Ethernet standard IEEE 802.3.

That is usually achieved through an ETH PHY (physical layer) electronic circuit.

The use of this standard ensures the compatibility with a wide range of networking equipment.

Connector Type:

At least one connector of type RJ-45 needs to be exposed from the device.

RJ-45 is the most widely used connector for ETH connections and is commonly used for 10/100/1000 Mbps connections.

Power Requirements: 24V DC

Voltage: The operating voltage required is 24V DC. This choice aligns with the common power standards employed in industrial environments. It ensures compatibility with existing power infrastructure and simplifies integration into industrial systems.

Power Connector: The power connector required is a simple 2pin spring terminal block

Heat dissipation:

To ensure efficient heat dissipation and avoid the use of mechanical parts prone to failure, the device should be designed to dissipate heat passively without the need for fans. This fan-less design offers several benefits, including improved reliability, reduced maintenance requirements, and silent operation.

The design should feature a heat sink, typically made of thermally conductive materials like aluminium or copper, to absorb and distribute heat evenly across its surface. The enclosure should be designed with sufficient surface area and heat sink contact to facilitate effective heat dissipation.

Resistance to Shock and Vibrations

The device should pass the most used standard tests for shock and vibration, described in the IEC 60068 directives. Specifically, IEC 60068-2-27 and IEC 60068-2-29 for the shock testing, IEC 60068-2-6 and IEC 60068-2-64 for the vibration testing.

Regulatory Compliance and Safety Standards:

For the device to be used in an industrial environment in the European Union, it needs to comply with various regulatory and safety standards:

- **CE Marking**: the device meets essential health, safety, and environmental protection requirements.
- **Electromagnetic Compatibility (EMC) Directive**: the electromagnetic emissions of the device must not interfere with other equipment or suffer from interference.
- **Radio Equipment Directive (RED)**: the wireless components operate safely and efficiently

Optionally, it may pass the tests described in the **IEC 60068** standard, to ensure that the device has adequate reliability and performance for the real-world operating conditions.

Optional specifications

Outside the scope of the PoC and classified as ‘nice to have’, the following specifications may need to be followed to ensure the compatibility of the bridge in a specific industrial context.

Form Factor

A. Designed to be mountable on a metal plate or a DIN rail

For a piece of equipment to be freely installable in a standard industrial environment, it needs to be set-up to be mountable onto a metal plate through screws or rivets. In case the device was composed of a freely installable antenna, cable connected to the box part, an installation inside the electrical cabinet through DIN rail, a standard metal rail widely used for this type of mounting, may be considered.

This design choice enables flexibility and ease of installation in different industrial settings, and behind the shielding of the cabinet, the device does not need more protection than an IP20.

B. Resistant to harsh ambient conditions

If the device is installed outside a cabinet in an environment that may be harsh, it must be IP67 rated. This means that the device's shell and connectors must be designed to prevent dust and airborne particles from entering the device, and to protect the device from water and liquids, including immersion in up to one meter of water.

ETH Connectors: The classic RJ-45 connector is only IP20, so to satisfy IP67 requirements a different connector must be used in its place, named D-coded M12. These connectors provide ETH connection in a rugged and weather-resistant interface. They are designed to withstand vibration, moisture, and contaminants commonly encountered in industrial settings, ensuring reliable data transmission and reducing the risk of connection failures.

Electrical Connectors: for the same reasons above, a specific power connector, 4-pin M12 circular connector, needs to replace the standard power connector.

Real Time PHY Layer protocols implementation: In addition, to the Ethernet IEEE 802.3 implemented standard, it may be needed to also implement specific Industrial Ethernet standards, like PROFINET, to allow a seamless integration into industrial automation systems that rely on these protocols, especially if the communication in place has a motion control purpose or real time requirements.

Analog Input for sensor

To read process data from a sensor (for acceleration, temperature, electro-magnetic field, etc.) the device needs to expose an analogue input configurable in 0-10V or 4-20mA, the same interface used in a standard industrial analogue input card for PLC.

Flexibility to connect Fibre or Copper cables

The device, to provide flexibility in terms of network connectivity options may offer a Small Form-factor Pluggable (SFP) connector, also known as Mini-GBIC (Gigabit Interface Converter). It supports both copper and fibre optic connections, allowing for seamless integration into different network infrastructures. The modular nature of SFP connectors enables easy replacement and upgrade of network interfaces without requiring extensive reconfiguration or replacement of the entire equipment.

The SFP connector supports high-speed data transmission, making it suitable for bandwidth-intensive industrial applications, such as real-time monitoring, video surveillance, and data-intensive processes. It also facilitates long-distance connectivity, being compatible with a wide range of fibre optic transceivers.

Mobile Industrial Robot (MIR) requirements

Fig. 15: Mobile robot example

Given the maximum battery capacity of 26053 mAh (48V), it is essential to select a modem for the mobile robot's 6G network connection that minimizes power consumption. Considering the convenience of wireless connectivity, it is preferable to choose a WIFI communication for the robot. As the robot is designed for carrying objects, in case of taking the modem implementation option a careful consideration should be given to the placement of the modem to ensure it does not interfere with the robot's object-carrying capability. Please refer to the accompanying figure to visualize how the robot carries objects.

Fig. 16: Mobile robots in a factory.

4 PoC Scenarios options related to the HW performances

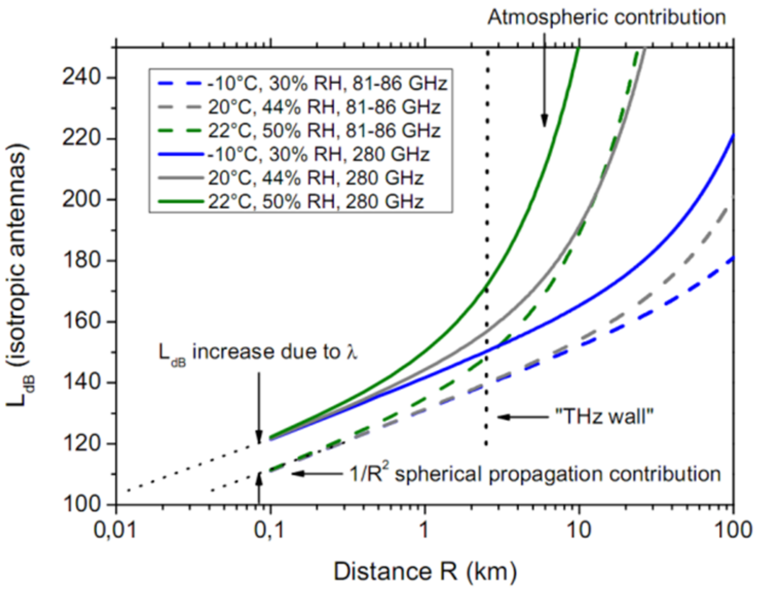
4.1 Preliminary Link budgets

The TIMES THz radio is targeting to up-convert the 58-88 GHz bands (TDD or FDD Modems) to the 250-325 GHz frequency range. The link budget is related to the Friis equation (1), which establish the connection between emitted and received powers. This is given by (1) and (2) is expressed in dB scale and including a constant atmospheric loss around the carrier frequency using in the link.

$$\frac{P_r}{P_e} = \frac{G_e{*}G_r{*}\mathrm{l}^2}{16{*}\mathrm{p}^2{*}R^2} \tag{1}$$

$$L_{dB} = 10{*}\log\left(\frac{P_e}{P_r}\right) = P_{e,dBm} - P_{r,dBm} = 92.4 - G_{e,dB} - G_{r,dB} + 20{*}\log(f) + 20{*}\log(R) + \mathrm{a}{*}R \tag{2}$$

In this relation, P_e and P_r are the respective emitted and received powers, G_e and G_r the transmit and receive antenna gains, f the frequency (expressed in GHz) and R the transmission distance between T_x and R_x. Moreover, α is the atmospheric attenuation (dB/km). Under standard conditions, this parameter is estimated to be around few dB per km [SCH12]. The next figure depicts the behaviour of L_{dB} for selected configurations of atmospheric attenuations using values in [ROS07]. E-band and around 280 GHz are considered, the last value being close to the frequency range defined for the TIMES project.



	α (dB/km)	α (dB/km)	α (dB/km)
Frequency (GHz)	-10°C/30% RH	20°C/44% RH	22°C/50% RH
81-86	0,09	0,3	3,8
280	0,4	3	9

Fig. 17: Link budget estimations (propagation in air, LoS configuration), RH is the relative humidity.

From these calculations, it is quite clear that for the distances related to the TIMES PoC, ie below 100 m, the propagation is mainly dominated by the well-known $1/R^2$ power evolution. That means that the THz path losses will have to be compensated mostly by the combination of the antenna gains.

Beyond this overall link loss, the presence of the IRS will impact the link budget and will be considered as 'extra-losses' contributors, while enabling the THz beam control/management. As an example, including 10 dB loss IRS (which is the maximal targeted loss as mentioned in the IRS section), at least the link budget would be affected by an additional 10 dB penalty.

4.2 Possible Scenarios

4.2.1 Scenario 1 - THz link with high gain antenna and static IRS

The first scenario considered is a link with one IRS, ie the beam is propagating in LoS from the T_x to the IRS in, then from the IRS to the R_x. Such a link is in NLos configuration thanks to the IRS. This kind of link can be considered as an equivalent LoS link with a fixed distance, including the IRS losses in the link budget. This first assumption assumes that the IRS will reflect the THz beam with a certain loss (in dB), while keeping the collimation of the THz beam. Considering a 100 m link, the rough estimation of losses using isotropic antennas is around 120 dB. Using 45 dBi antennas, the link-budget would be close to 30 dB, without considering antenna & IRS losses.

It should be noted that the estimated 10 dB losses induced by the IRS is a starting point. The refinement of this figure has to be confirmed by measurements, when the associated hardware (IRS) will be available. Such characterizations will be part of the goals of the WP3, task 3.2, starting at M17.

4.2.2 Scenario 2 - THz link with beam-steerable antennas

In the case of steerable antennas, it is currently not possible to estimate the link budgets as the structures and associated performances are not known. However, we believe that considering the potential gain reduction, the link budget and related scenario will have to be in-line with the THz link budget in the case of steerable antenna.

This second scenario, using steerable antennas is highly challenging. Beyond THz hardware performances that should be far beyond actual SoTA, additional challenges such as beam tracking and LO synchronization would arise. As the first scenario is already very challenging, ie demonstrating an operational static THz link including IRS, this scenario has been chosen to be the main TIMES target, and the next section presents link budget estimation according to the real use-case. As in the first scenario, the WP3-Task 3.2 and WP5-Task 5.4 will provide the measurement results of steerable antennas that are key devices for this scenario.

Using the outcome of the measurements and achieved KPIs, the potentialities to enable this second scenario will be investigated.

4.3 PoC scenario

4.3.1 PoC Description

The scenario chosen for the PoC is described in Fig. 18. It is composed of a THz link in NLoS case, including a reflection of the THz beam on the IRS and a static THz beam. The overall distance is 36+30 meters, estimated from implementation in industrial partner's premises.

The main goal of the PoC is the validation of the use of THz radio to connect 2 industrial equipment (using ethernet). While the network to RF connection is done by the FDD or TDD MODEMS, the THz hardware is enabling the use of the THz radio bands.

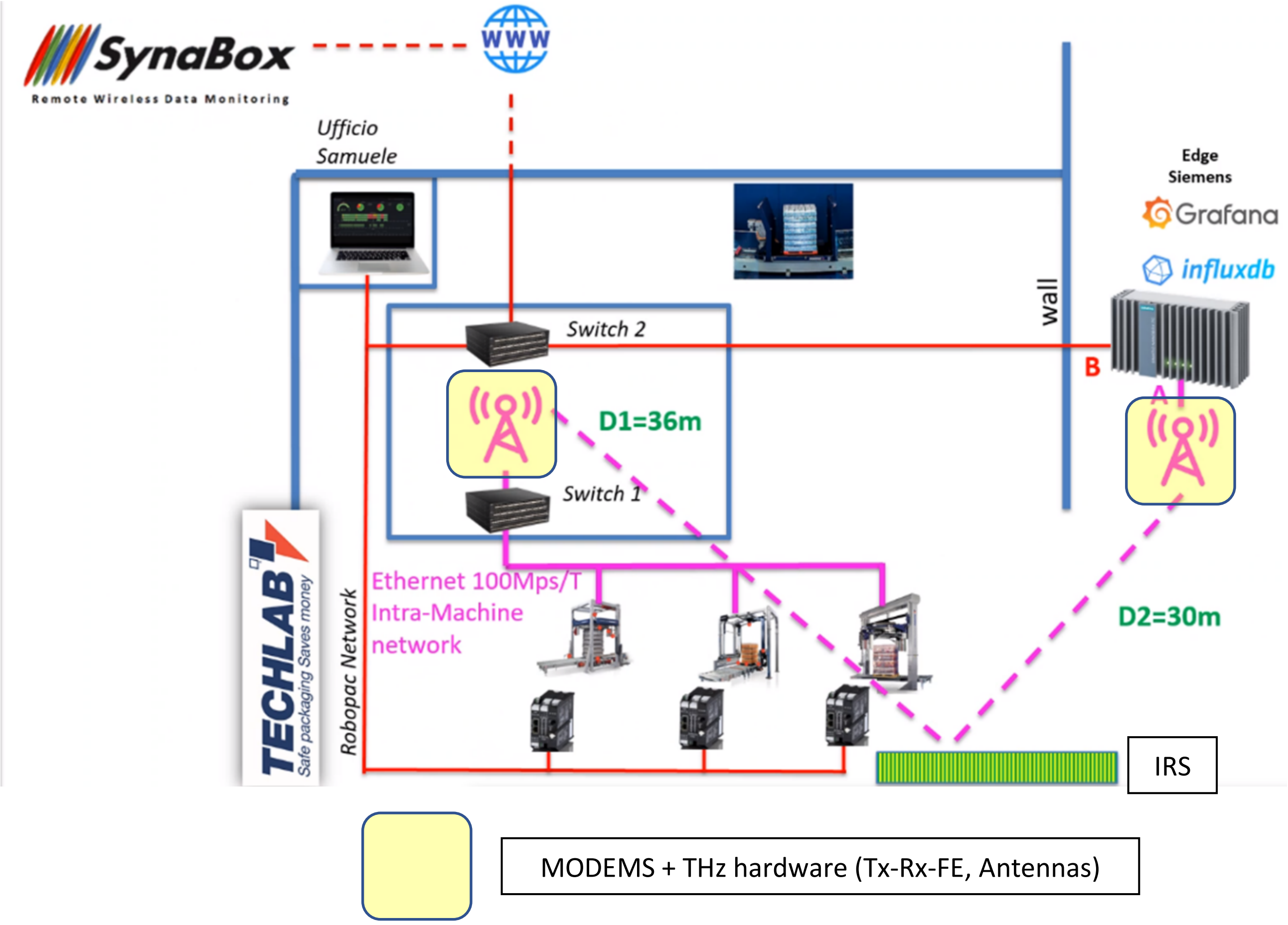


Fig. 18: PoC architecture: THz static link, including an IRS.

4.3.2 PoC link budget and required system-gain

The system-gain is the maximum loss that can be handled between a Tx and Rx. In other words, this is the overall maximum losses (in dB) that the system would have to live with, while end-to-end ethernet connection over the THz band is maintained between the two industrial equipment.

This parameter will have to be measured when Tx and Rx hardware will be available. It is generally measured in a back-to-back configuration where the Tx and Rx are directly connected, with a calibrated attenuator in between. This is scheduled in the T6.2 of the WP6.

In the case of TIMES hardware, when frequency-duplex case is used, the estimation of the available system-gain has to include the frequency-duplexing waveguide structures, externally connected to the THz FEs (Tx and Rx).

However, in real-cases, as the THz channel can be frequency-dependent, the performance can be a bit worse than back-to-back estimations.

Considering the general link budget equations, distances and antenna parameter (high directivity case), the link budget can be estimated and minimum system-gain between Tx and Rx has to be higher than the overall losses of the link budget.

Antenna	**Directivity**	45	dBi
	Losses	1.5	dB

THz link	**Distance**	66	m
	LdB (300 GHz)	118,3	dB
	IRS losses	10	dB
	Required link budget	39,8	dB

Tab. 5: Estimation of the required system-gain from PoC architecture and antenna parameters.

Considering the results of initial estimation of the link budget, a minimum system gain of 40 dB is required. Such a target will have to be reached using a data-rate up to 1 Gbit/s (even if the FDD MODEMS can over up to 10 Gbit/s) that is high-enough to cover the needs of the chosen scenario in relation to the industrial use-case considered. Such a data-rate will enable us to run the MODEMs in a low complexity modulation format, and by consequence to increase the system margin. As the chosen scenario is indoor, we don't expect strong effect of humidity/temperature over time.

As a rule of comparison, the available system gain achieved during the THOR project using a similar super-heterodyne architecture was around 25 dB [THR22], 15 dB lower compared to the required system gain for the TIMES PoC. However, the data-rate to handle in the TIMES industrial PoC is lower (1 Gbit/s), while higher output-power of the Tx is expected, and the 10 dB losses of the IRS might be reduced. According to all of these elements, we believe that the defined PoC could be enabled if the targeted performance is met.

5 Conclusions

This deliverable described the overall architecture of the PoC and the associated hardware behind it. This PoC scenario will be further refined as soon as real hardware performance is known, which is covered in the characterization and validation work-package. While the general architecture of the PoC is defined, the exact distances that can be covered could be adjusted in case of limited available system-gain, reduced antenna performances and IRS induced losses. However, considering previous partner's experience and THOR past project, the starting point is known, even if the link is well-more challenging as an IRS is integrated in the THz path for the first time.

6 References

[BAL] Antenna Theory: Analysis and Design. (ISBN-10: 1118642066)

[MON23] Terahertz Beam Steering: from Fundamentals to Applications. DOI: 10.1007/s10762-022-00902-1

[KAM17] A Review of Wideband Reflectarray Antennas for 5G Communication Systems. DOI: 10.1109/ACCESS.2017.2747844

[OKO22] Design and Application of Intelligent Reflecting Surface (IRS) for Beyond 5GWireless Networks: A Review. DOI: 10.3390/s22072436

[MAR22] Enhancement of 5G Millimeter-Wave Coverage in Indoor Scenarios by Passive Shaped-Beam Reflectarray Panels. DOI: 10.23919/EuCAP53622.2022.9769652

[HAS17] Reconfigurable metamaterials for terahertz wave manipulation. DOI: 10.1088/1361-6633/aa77cb

[CHE21] Intelligent Reflecting Surface Assisted Terahertz Communications toward 6G. DOI: 10.1109/MWC.001.2100215

[ENC07] Reflectarray Antennas. (ISBN-10: 047008491X)

[JUN14] Coding metamaterials, digital metamaterials and programmable metamaterials. DOI: 10.1038/lsa.2014.99

[PER23] Design and Experimental Validation of Liquid Crystal-Based Reconfigurable Reflectarray Elements With Improved Bandwidth in F-Band. DOI: 10.1109/TAP.2013.2242833

[ISM07] Phase agile reflectarray cells based on liquid crystals. DOI: 10.1049/iet-map:20070061

[ROS07] M. J. Rosker and H. B. Wallace, "Imaging Through the Atmosphere at Terahertz Frequencies," 2007 IEEE/MTT-S International Microwave Symposium, Honolulu, HI, USA, 2007, pp. 773-776, doi: 10.1109/MWSYM.2007.380054.

[SCH12] T. Schneider, A. Wiatrek, S. Preussler, M. Grigat and R. -P. Braun, "Link Budget Analysis for Terahertz Fixed Wireless Links," in *IEEE Transactions on Terahertz Science and Technology*, vol. 2, no. 2, pp. 250-256, March 2012, doi: 10.1109/TTHZ.2011.2182118.

[THR20] ThoR Deliverable D3.6: Testing report of 70/80 GHz TRX module, Yigal Leiba, Siklu Communication, https://thorproject.eu/wp-content/uploads/2020/12/ThoR-D3.6-Testing-report-of-70-80-GHz-TRX-module.pdf

[THR21] ThoR Deliverable D3.5: Testing report of the 60 GHz TRX modules, Keitarou Kondou, HRCP Research and Development, https://thorproject.eu/wp-content/uploads/2021/05/ThoR-D3.5-Testing-report-of-the-60-GHz-TRX-modules.pdf

[WRA22] D. Wrana, Y. Leiba, L. John, B. Schoch, A. Tessmann and I. Kallfass, "Short-Range Full-Duplex Real-Time Wireless Terahertz Link for IEEE802.15.3d Applications," 2022 IEEE Radio and Wireless Symposium (RWS), Las Vegas, NV, USA, 2022, pp. 94-97, doi: 10.1109/RWS53089.2022.9719954.

[THR22] ThoR Deliverable D4.7: Final-Report-of-the-RF-Front-End-Developments, Guillaume Ducournau, CNRS, https://thorproject.eu/wp-content/uploads/2022/08/ThoR-D4.7-Final-Report-of-the-RF-Front-End-Developments.pdf.