Grand Agreement No: 101096307

Full Title: THz Industrial Mesh Networks in Smart Sensing and Propagation Environments

Start date: 01/01/2023

End date: 31/12/2025

Duration: 36 Months

DeliverableDeliverable D6.1

Validation of MODEMS and joint PHY/MAC Implementation

Document Type	Deliverable
Title	Deliverable D6.1 - Validation of MODEMS and joint PHY/MAC Implementation
Contractual due date	30/06/2025
Actual submission date	dd/06/2025
Nature	Report
Dissemination Level	PUB
Lead Beneficiary	University of Stuttgart
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Revision history

Version	Issue Date	Changes	Contributor(s)
v0.1	28/05/2025	Initial Version	Simon Haussmann (USTUTT), Lukas Gebert (USTUTT), Steffen Kroos (TUBS)
v0.2	30/06/2025	Initial Version after internal review	Simon Haussmann (USTUTT), Guillaume Ducournau (CNRS), Varvara Elesina (TUB)
v1.0	03/07/2025	Final review and acceptance	Luca Sanguinetti (CNIT), Thomas Kurner (TUB)

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Table of Contents

List of Abbreviations

THz Terahertz

RF Radio Frequency

IF Intermediate Frequency

MIMO Multiple Input Multiple Output

PoC Proof of Concept

PAPR Peak to Average Power Ratio

FDD Frequency Division Duplex

TDD Time Division Duplex

CotS Commercial-of-the-shelf

PoE Power over Ethernet

RIS Reflective Intelligent Surface

ODU Outdoor Unit

CINR Carrier to Interferer and Noise Ratio

RSSI Received Signal Strength Indication

Executive Summary

This deliverable provides a summary of the validation of the modems, that are used in the system-demonstrators. On one hand we provide information and measurement data, validating the compatibility of the modems with the targeted Radio Frequency (RF) hardware. On the other hand, we provide preliminary information, on how the modems will be used and implemented in the Proof of Concept (PoC).

1 Introduction

1.1 Scope

This deliverable provides a summary of the validation of the modems, that are used in the system-demonstrators in the project TIMES. On one hand we provide information and measurement data, validating the compatibility of the modems with the targeted Radio Frequency (RF) hardware. On the other hand, we provide information, on how the modems will be implemented in the Proof of Concept (PoC).

The general compatibility of the employed modems has already been demonstrated within the project ThoR (Horizon 2020, grant number 814523). So the principle of up-converting signals from mmW-Modem to THz and down-convert it again with non-phase coherent local oscillator sources has been already demonstrated and is viable. A system-description and key findings have been summarized in the publication [1]. This deliverable is mostly related, if the modems are compatible with the TIMES related PoC and the specific requirements for industrial networks:

- PoC-1: High-Gain antennas Point-to-Point link over a reflective surface. In this PoC mostly the Frequency Division Duplex (FDD)-modems will be used.
- PoC-2: Frequency-selective (leaky-wave) antenna with beam-steering capabilities. In this PoC mostly the Time Division Duplex (TDD)-modems will be used.

A detailed description of the PoC is available in the TIMES deliverable D2.3 [2].

Further, according to the project proposal, the modems need to reflect the developments of joint PHY/MAC schemes from work-package WP4, which are documented in deliverable D4.3 [3]. As the modems are commercial products the physical layer is not fully accessible. Also both PoC are quite complex setups, so not all PHY/MAC functionalities will be reflected in the setups. The "Beam Alignment and Tracking with Leaky Wave Antennas" (Chapter 6 in [3]) will be implemented in PoC-2. The other developed functionalities, that are not compatible with the hardware and the modems are verified in simulation or with distinct measurements as part of WP4. Examples for verification in simulation are the Multiple Input Multiple Output (MIMO) functionalities. Examples for verification in distinct measurements are the waveform-design and the mitigation of hardware impairments.

1.2 Audience

This Deliverable is intended for internal use by the TIMES Consortium.

1.3 Structure

The rest of the document is structured as follows:

- Section 2 presents the validation of the Frequency Division Duplex Modems and their possible implementation in the PoC-1.
- Section 3 presents the validation of the Time Division Duplex Modems and their possible implementation in the PoC-2.
- Section 4 presents the conclusions.

2 Frequency Division Duplex Modems

The PoC-1 will be implemented as a static point-to-point link. The Terahertz (THz) front-ends are connected to a high-gain antenna and is transmitting in a static scenario to the other terminal. In the radio path, a Reflective Intelligent Surface (RIS) is added to enable signal paths around obstacles and allows to redirect the beam. The modems, that have already been successfully implemented in a THz-link in the ThoR-project, are the Siklu Etherhaul-8010 FX (the enterprise had been acquired by "Ceragon Networks" in 2023).

The Commercial-of-the-shelf (CotS) E-band (60 - 90 GHz)-modems have a channel assignment according to IEEE-Standard. The FDD architecture has the advantage, that it is continuously transmitting data without interruptions. The modems are delivered in two Outdoor Unit (ODU) configurations: ODU-H and ODU-L, for the higher and lower transmit channel. This defines, in which band the modems are sending or receiving. ODU-H is transmitting data in the frequency range of 81 – 86 GHz and receiving in 71 – 76 GHz. In the ODU-L version this assignment is inverted. This can not be altered by software as this is a hardware configuration of the modem. The modems are able to transmit up to 10 Gbit/s with a channel bandwidth of 2 GHz. The modulation formats range from QPSK to 128-QAM. From the available bandwidth of 5 GHz, two sub-channels can be chosen. The modems can be configured per software, to send/receive centered at 72.125/82.125 GHz or 74.625/84.625 GHz. So the channel spacing is always 10 GHz, that leaves taking into account the bandwidth of 2 GHz a 8 GHz window for H-band (220 - -330 GHz) diplexing filter-transition. The validation of applicability is summarized in the subchapter 2.3. Fig. 1 is showing a rendering of a FDD modem. There are three relevant interfaces:

- RF-interface as rectangular waveguide in WR-12 standard.
- 10 Gbit/s Ethernet interface, that is used for data-connection towards the equipment.
- 1 Gbit/s Ethernet interface with Power over Ethernet (PoE), that is used for power supply and to apply the settings (output power, channel assignment, modulation format) to the modems.

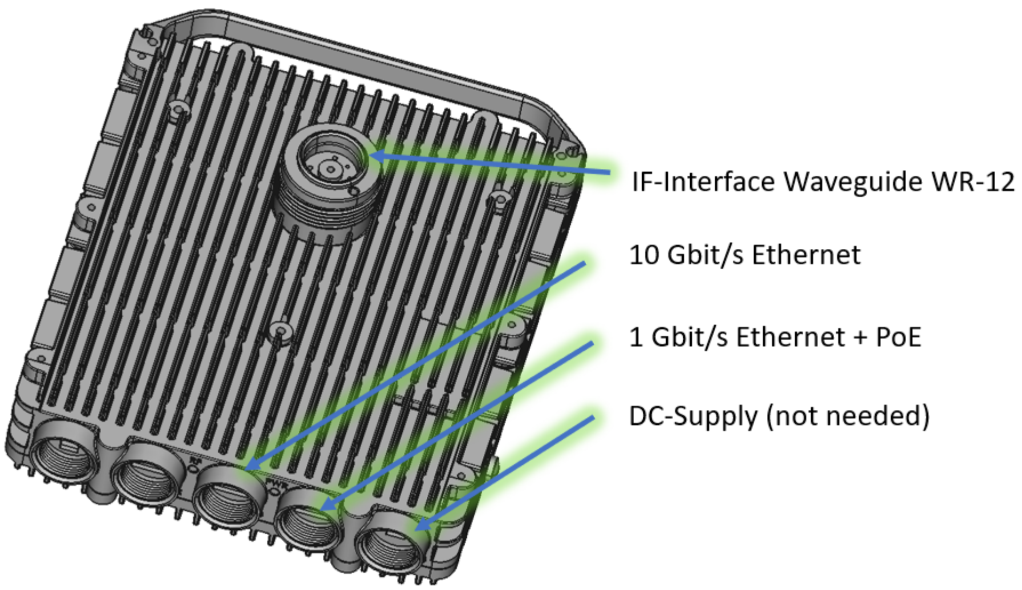

Figure 1: 3D-CAD rendering of the E-band modem with FDD-architecture. The most important interfaces are highlighted, like the power supply, the interface to the wired 10G Ethernet and the Waveguide interface, that will be connected to the H-Band hardware.

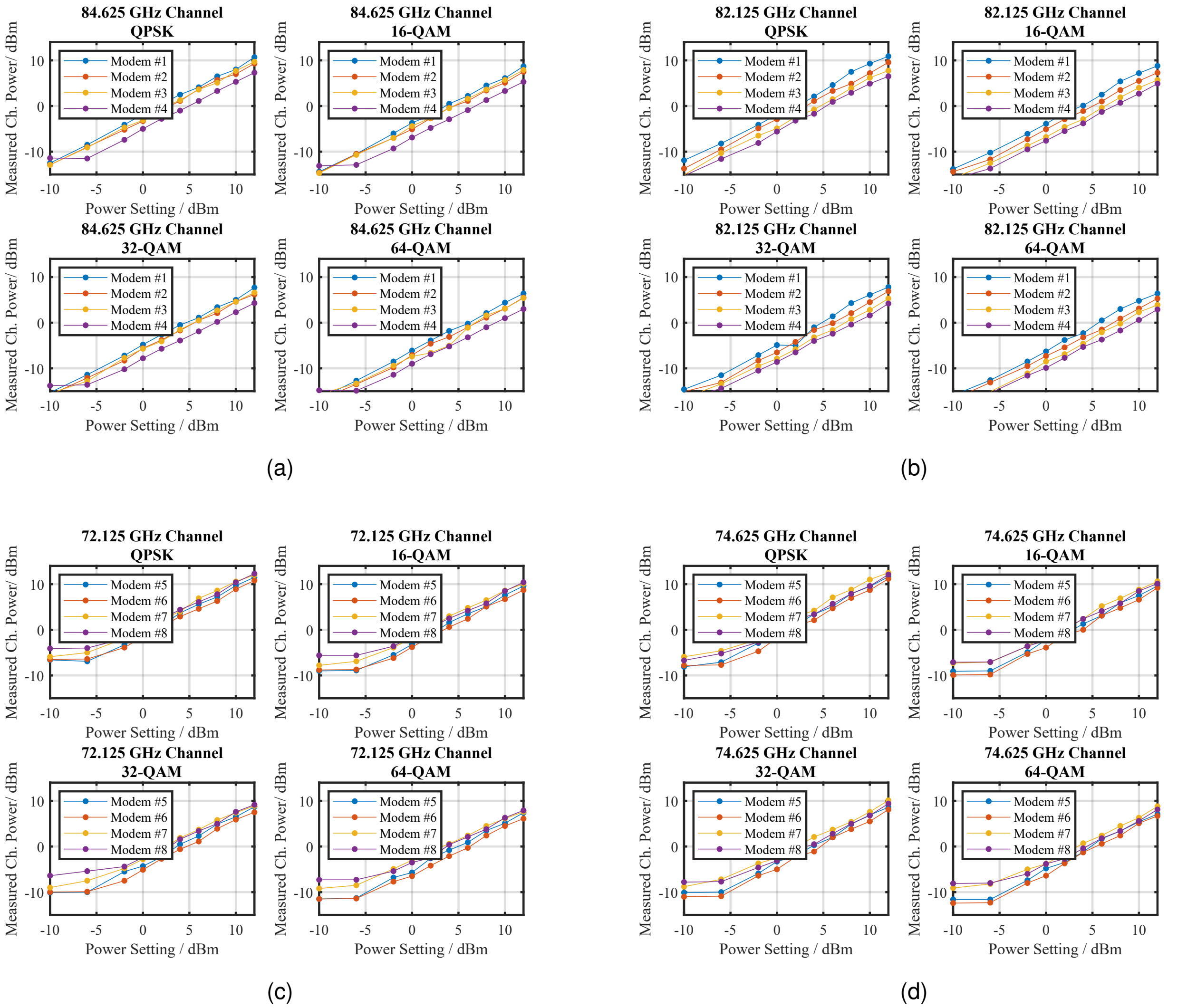

Figure 2: Measured IF-power of the available E-band modems at different modulation formats and power settings. (a) and (b) are showing the performacne of the ODU-H modems in both channel configurations. (c) and (d) are showing measurements of the ODU-L modems, for both channel configurations as well.

2.1 Measured Performance IF-Interface

Before employing the modems in a THz-setup a baseline characterization is concucted to verify the specifications and to identify the settings, the modems have to be configured with. Fig. 2. The modems have slightly less output power, than the setting, also depending on the modem, the channel-assignment and the chosen modulation format. However, this will not influence the PoC. The THz-hardware is designed for IF-input powers up to 1 dBm. In conclusion, this is met for all modems. However, the input-damage level of the THz-hardware will be around 4 dBm of input power. So the modems can potentially damage the THz-hardware when the power settings are chosen to high.

2.2 Linearity Considerations for Channel Aggregation

To increase the achievable data-rate in the PoC, a so called channel aggregation can be applied. For this, multiple modems are combined at the IF-interface of the THz transmitter/receiver, in order to multiply the data rate, as shown in Fig. 3a. This has two major influence on the design of the demonstrator. One impact is the reduced channel spacing for the diplexer in H-band, leaving only a 5.5 GHz spacing to separate the up- from the down-link signal, which complicates the diplexer design. Another impact is the influence on the systems linearity. One key finding of our experiments of the PoC is, that if channel aggregation is used, this decision affects the Peak to Average Power Ratio (PAPR) of the signal. When superposing multiple FDD channels at the Intermediate Frequency (IF), this increases the PAPR and leads to an earlier compression of the transmitter. With the low system-margins of THz-links this might influence the link budget and needs to be considered in the system design. Fig. 3 shows the laboratory measurement setup, that is used to verify the increase in PAPR. Fig.4 shows linearity measurements, based on preliminary hardware from the ThoR-project using the FDD-modems. In red and green, we observe a degradation of the data-rate at overall input power of -11 dBm. When applying two signals, the data-rate degrades already at -14 dBm. Which means, that the PAPR is following approximately the formula:

$$\mathrm{PAPR} = \mathrm{PAPR}_{\mathrm{base}} + 10 \cdot \log_{10}(N) \tag{1}$$

with $\mathrm{PAPR}_{\mathrm{base}}$ being the PAPR of the used modulation format and N being the number of the aggregated channels. The finings are reported in [4].

2.3 Compatibility with Diplexing Filters

An important part of the PoC-1 is the implementation of an duplex link. As the modems-architecture is FDD, frequency division has to be implemented as well in H-band. For this purpose we developed in scope of the project diplexing filters. However, these filters add additional impairments to the signals. Not only additional insertion loss or slight amplitude ripple. Also, group delay distortions towards the edges of the filter-bands can distort the signals. To check the modems functionality for the use with these filters, we implemented a link, based on previous hardware and ran the link close to or even in the filter flanks. We did not observe a influence on link quality, only when the attenuation in the stop band causes a drop in signal quality due to a reduced signal strength. However, these experiments channel aggregation and the use as a frequency duplex in THz validates the FDD-Modems for PoC-1. Fig. 5 is showing a picture of the experiment setup with a picture of some newly developed H-band filters. With laboratory synthesizers we swept the RF center frequency, to assess the influence of the filter flanks on the signal quality. The filter flanks are at 298 GHz for the down-link-filter and at 305 GHz for the up-link-filter. In the plot of the signal quality (CINR) in Fig.5 (c) we did not observe additional impairments, until exceeding the filter flanks. Then the signal quality degrades, due to the additional insertion loss in the filter flanks.

The design of the filters (a sketch is shown in Fig. 6)and the assessment of the influence on the real-time communication had been published in [5].

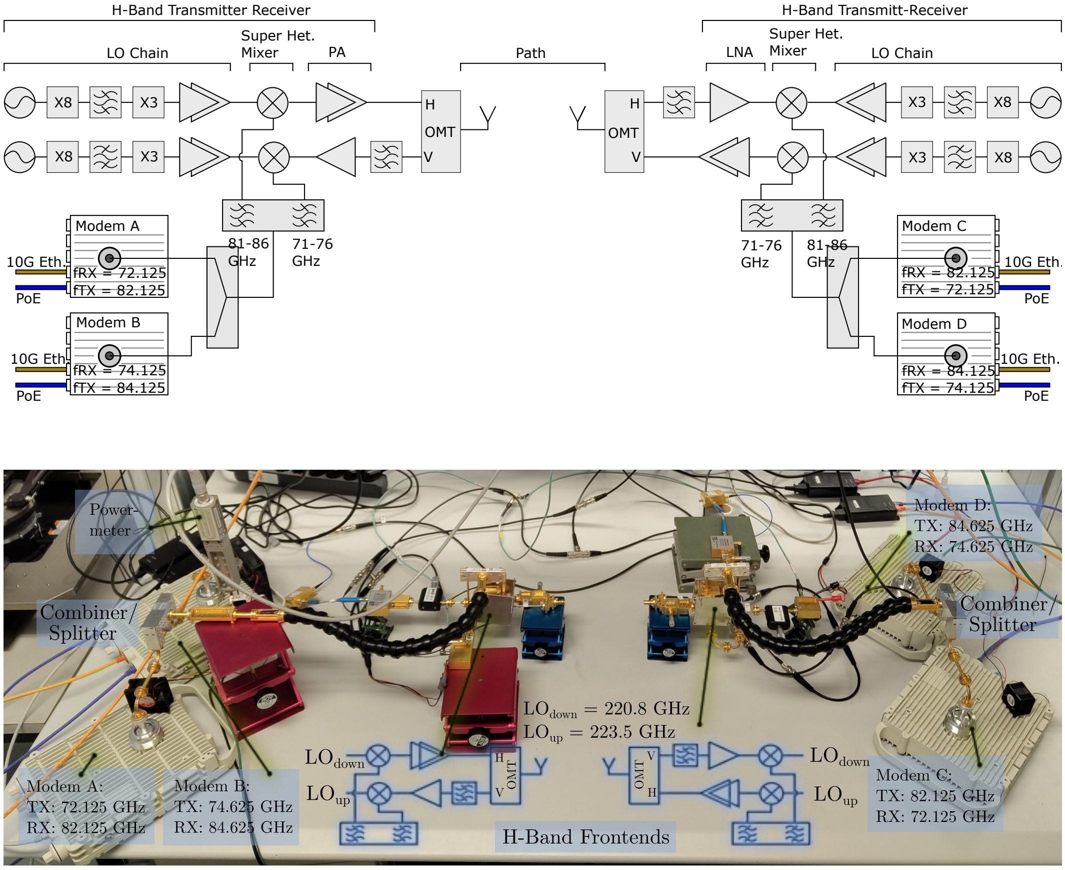

Figure 3: Experimental setup of the full electronic point-to-point link. Modem A and B are connected to the downlink terminal, modem C and D are connected to the uplink terminal. Combination and rerouting of the aggregated channels at the IF-interface is done by waveguide combining and diplexing. Figure from [4]

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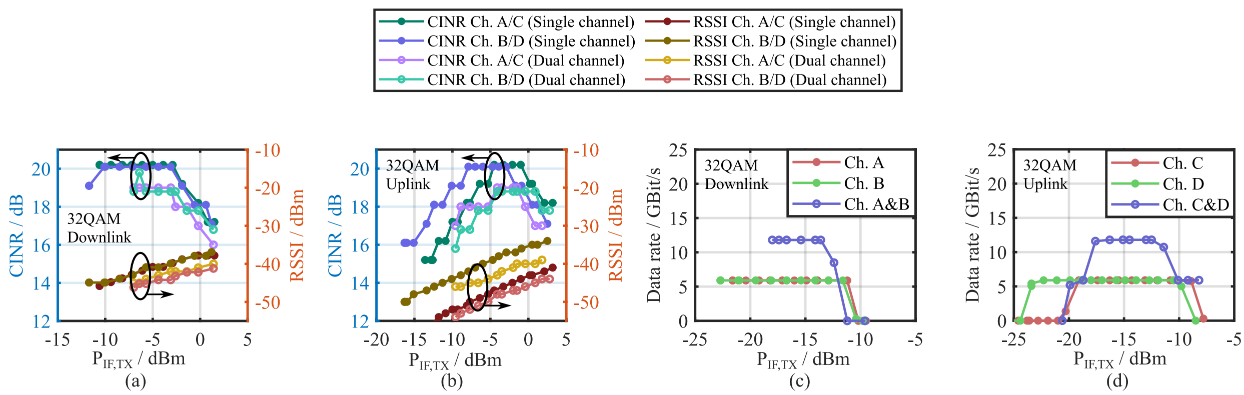
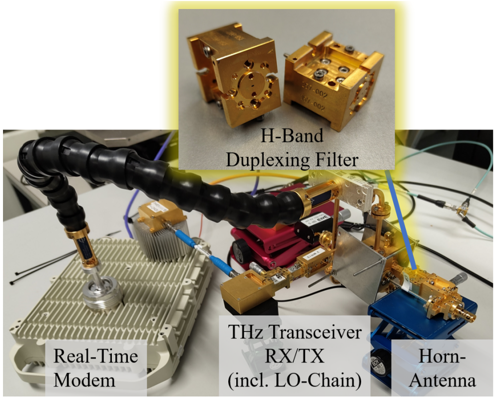
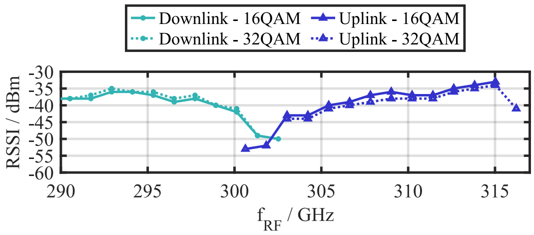


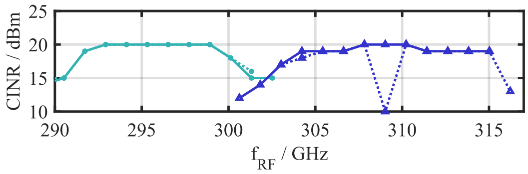
Figure 4: Performance of the real-time modems vs. the input power at the TX. (a) and (b) are showing the Carrier to Interferer and Noise Ratio (CINR) and Received Signal Strength Indication (RSSI) versus the IF input power at the TX for up- and downlink. (c) and (d) are showing the achieved real-time data-rate per direction over the IF input power. Data rate of dual channel operation drops 3 dB sooner due to compression compared to single channel. Figure from [4]



(a)

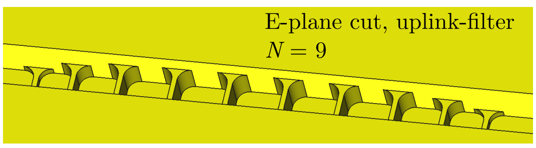


(b)

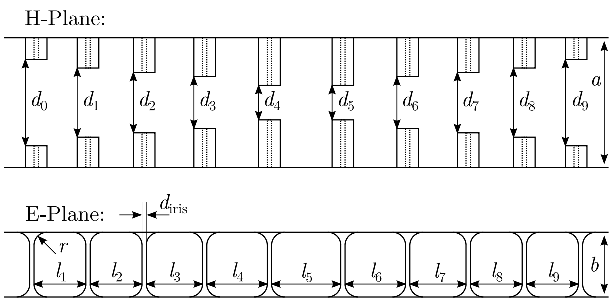


(c)

Figure 5: Setup for validation of the broadband filters for communication. Duplex wideband measurements with 2 GHz channel bandwith while sweeping the RF-center frequency over the filter edge. Figures from [5]. (a) is showing a picture of the setup. (b) and (c) are showing the RSSI and CINR over the center frequency, respectively.



(a)



(b)

Figure 6: Technical sketch of the iris filter dimensions. (a) shows a 3D-rendering of one half of the split-block design. (b) shows a sketch of the design parameters l_k, d_k, a, b, d_{Iris} and r (not true to scale). Figure from [5]

3 Time Devision Duplex Modems

For time division duplex communication the TJX-Ethernet modules by HCRP are available and used for the second PoC experiments. The second PoC consists also of a point-to-point scenario, with one of the terminals fixed and the other one mobile/moving. In order to maintain connectivity, the beam is steered by a leaky-wave-antenna. By changing the center-frequency of the data-stream, the angle of departure/angle of arrival can be tuned.

Pictures of the modules are shown in Fig. 7 The modems can be configured for two channels at 60 GHz. The first channel is centered at 60.48 GHz and the second at 62.64 GHz.

Figure 7: TJX Modems by HCRP

3.1 Interfaces

The TJX-modules provides different types of interfaces. The main output interface is a waveguide (WG) connector with the waveguide ratio of 15 (WR-15), for output signals centered around 60 GHz. For the connection to the user interface and control purposes a USB port can be used on the backside of the modem. The provided USB connector is of typ micro B. For the network integrability and data traffic two Ethernet connections are provided, one SFP+ and one RJ45, each providing a data rate up to 10 Gbit/s. For each connection an UTP CAT7 cable is recommended. The modem can be powered using a power SW connector or a 5 V DC pin connector. In Fig. 8 a photograph of the provided interfaces is shown.

3.2 Setup and Commands

After powering and connecting the modem to a windows computer, a new COM port is going to be connected. After the connection of the new port, a terminal application has to be installed, in order to communicate with the TJX modem using the COM port. The port settings are shown Fig 9.

In table 1 and 2 the available commands and environmental variables are shown.

3.3 RF Performance Evaluation

In order to evaluate the RF performance of the modems the rfdmystart command can be used. This command initiates a dummy data TRX (Transmit-Receive) function. During the dummy data TRX mode, a module assigned as PRC itself generates test data and sends them to another module assigned as PRDEV. With this function, the RF throughput can be evaluated without any external data sources. By setting progress to1, the current TRX status can be seen. The data size is given in MiB. If you set it to 0, it sends data continuously, a soft reset is needed to stop the command. If it set to 1, the TRX status is shown periodically. In order to setup a connection between two modems the rfstart command has to be used. By running rfstart–prc on a

Figure 8: Interfaces of the TJX modems

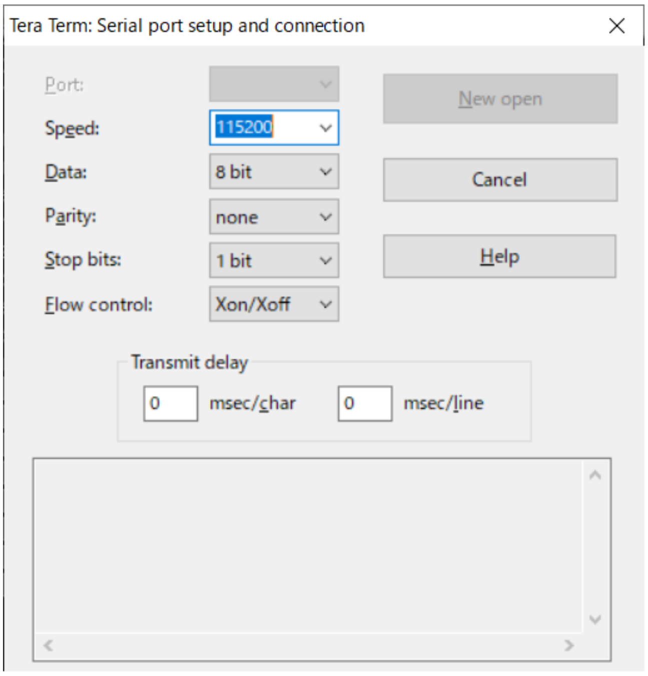


Figure 9: Setting for the connection to the TJX modems

device and running rfstart–prdev on another enables the Ethernet bridge mode between these two devices. Once the ether bridging is enabled, the network throughput between two PC connected via two TransferJetX modules can be evaluated. You can evaluate Ethernet throughput using iperf3. The connected link is illustrated in Fig 10.

3.4 Considorations for PoC-2

For PoC-2 an representative illustration of the modem setup is shown in Fig. 11. For this PoC two modems are mounted on a movable target, while the other modem pair is fixed in position. In order to achieve beam

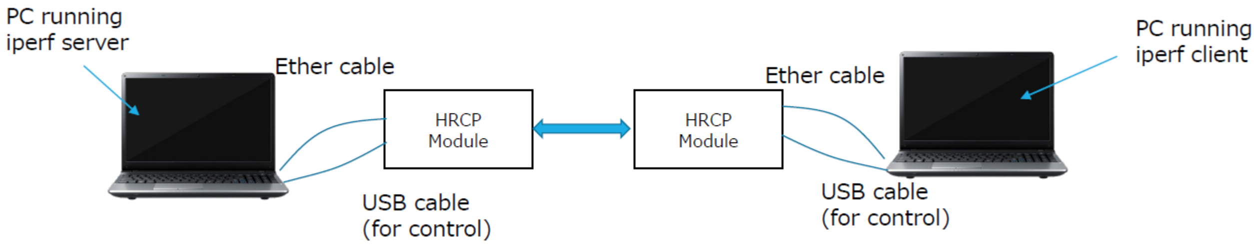


Figure 10: Setup example for a link between two modems using the ether bridge mode

steering in this PoC a leaky wave antenna is used, which allows for spatial beam steering by changing the center frequency of the transmitted signal. Using this antenna allows addressing different spatially separated targets by using different center frequencies.

The PoC will be implemented with two modems, running in parallel separated in H-band center frequency. By monitoring the signal quality and receive signal strength in both channels, a function/algorithm in a higher hierarchy can select the best channel and also reconfigure the center-frequency in THz to find the optimum angle of arrival dynamically.

As described in TIMES deliverable D5.3 the beam steering capabilities of the leaky wave antenna can be approximated by 0.3 deg/GHz. Considering the two available channels provided by the modems, which are separated from each other by Δf = 2.16 GHz, only 0.65 deg phase difference can be achieved using the leaky wave antenna. In order to increase the beam steering capabilities, a higher frequency separation of the two channels has to be applied. This can be done in the RF domain by using different local oscillator (LO) for the up-conversion of the IF channels. This way, a frequency separation up to Δf = 40 GHz and therefore a phase difference of up to 12 deg can be achieved.

Fig. 11 is showing a CAD-rendering of the planned system-setup with two modems running in parallel. A fixed terminal with leaky wave antenna is sending in TDD towards a movable structure, that hold the second terminal. This terminal will either have a more broad antenna with a broader beam or a leaky-wave antenna as well.

Table 1: Commands for the TJX-Modems

No.	Command	Arguments	Description
1	sreset	N/A	Initialize module
2	rfdmystart	-prc|-prdevlength (progress)	textPerform dummy data send receive for RF performance evaluation. TX: dstartdmy–prc2048 RX: dstartdmy–prdev If you need detailed status, add 1 after above commands, like TX: dstartdmy–prc2048 1
3	rfstart	-prc|-prdev	Enable Ethernet bridge function rfstart–prc rfstart–prdev
4	rfstop	A	Disable 60GHz RF connection
5	ssetenv	ssetenv environment variable value	Set value to an environment variable
6	sgetenv	sgetenv environment variable	Show value of an environment variable

Table 2: Environmental variables for the TJX-Modems

Name	**RW**	**Resart Required**	**Function**	**Description**
MU_FW_VER	R	no	Firmware Version	Shows FW version
MU_FW_NOECHO	R/W	no	Disable Echo	Echo control 1: Echo disabled 0: Echo enabled
MU_TJX_CHSEL	R/W	yes	60-GHz Channel Select	Selection of RF CH. 0: CH2 60.48 GHz 1: CH3 62.64 GHz
XG_HW_GPIO	R/W	yes	GPIO Configuration	Output TDD R/W signal

Figure 11: PoC-2 system setup view.

4 Conclusions

In this deliverable we provide information about the real-time modems used for the TIMES proof of concepts. Based on the obtained data, we conclude, that the chosen modems are applicable for both proof of concepts. With some limitations:

- Channel spacing of FDD-modems is limiting factor for the design of the diplexing filter for the H-band FDD-implementation. Dependant on the diplexer design, channel aggregation will be possible. However, single channel duplex communication is very likely to succeed.
- Channel spacing of the TDD-modems are not resulting in a significant angular difference in the leaky-wave PoC. Additional measures have to be taken to steer the center frequency of two modems independently with two independent THz-up-converters.

Apart from these limitations, the modems feature functionalities, that are enabling both PoC.

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