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Table of Contents

List of Abbreviations

AWG arbitrary waveform generator

AWGN arbitrary white gaussian noise

b2b back-to-back

BPF band pass filter

BER bit error rate

CCU compact converter unit

CG conversion gain

CINR carrier to interference plus noise ratio

CW continuous wave

DUT device under test

EVM error vector magnitude

FDD frequency division duplexing

FoM figure of merit

HPA high power amplifier

IF intermediate frequency

LNA lower noise amplifier

LO local oscillator

MMIC monolithic microwave integrated circuits

MODEM modulator-demodulator

OP1dB output-referred 1-dB compression point

OTA over-the-air

PoC Proof of Concept

PLL phase locked loop

RF radio frequency

RSSI received signal strength indication

RX receiver

SNR signal to noise ratio

TDD time division duplexing

TX transmitter

VCA vector component analyzer

VCO voltage controlled oscillator

VNA vector network analyzer

VNAX VNA extender

VSA vector signal analyzer

Executive Summary

This deliverable documents the validation of the TIMES proof of concepts by using the millimeter wave modems and front-ends that have been designed within the project. Using split-block RF front-ends housed in modular indoor units connected to commercially available modems, we performed back-to-back and over-the-air measurements to determine optimal operating conditions and verify the functionality of all system components. The first proof of concept employs frequency division duplex modems and the second one uses time division duplex modem, resulting in different experimental setups. The tests confirm that the systems meet the required performance and are ready for implementation in the actual system demonstrators. In both scenarios the system is able to maintain a real-time fully transparrent IP-connection with path attenuation of more than 50 dB. One remaining task is the integration of transmitter and receiver with a broadband waveguide coupler.

1 Introduction

1.1 Scope

This deliverable provides the validation of the modulator-demodulator (MODEM)/radio frequency (RF) front-end. This includes lab-validation of real-time duplex communication systems for the TIMES Proof of Concept (PoC)-1 and TIMES PoC-2. For testing we employ the RF front-ends in split-block packages, encapsuled in modular indoor units from WP5, connected to commercially purchased MODEM. A measurement-based link budget determination in back-to-back (b2b) configuration of the modules as well as over-the-air (OTA) communication is conducted. The setup of the two PoC are fundamentally different: PoC-1 makes use of FDD Modems and PoC-2 makes use of TDD modems. This results also in different intermediate frequency (IF) connection setups.

1.2 Audience

This deliverable is intended for public use.

1.3 Structure

The rest of the document is structured as follows:

- Section 2 presents b2b measurements of the housed RF front-ends and a characterization using the MODEMs in an over-the-air transmission experiment.
- Section 3 presents the verification of PoC-1 with FDD-modems.
- Section 4 presents the verification of PoC-2 with TDD-modems.
- Section 5 presents the conclusions.

2 Back to Back Module Characterization using Modulated Data

This section describes the initial characterization of the stand-alone TIMES modules using modulated data. Therefore, b2b measurements were performed. This is done to get an impression of the module capabilities for communication link use cases. Here, the modules used are introduced, and the validation and measurement setup is introduced.

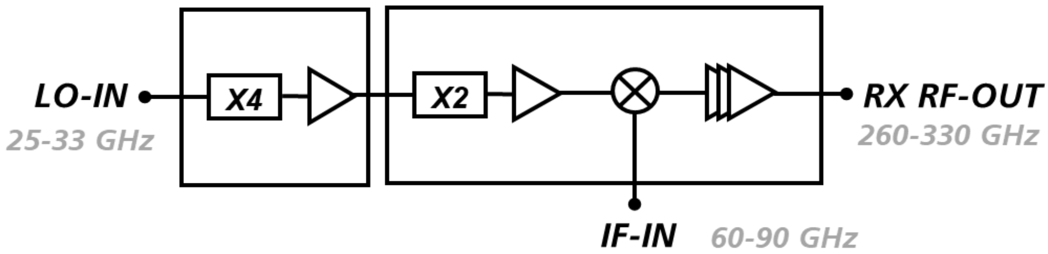
2.1 TIMES Modules and Continuous Wave Characterization

The TIMES RF front-ends monolithic microwave integrated circuits (MMIC) were already described in Deliverable 5.1 [1]. Those Front-end chipsets were packaged in a split-block waveguide package. Integration and a first continuous wave (CW) characterization were done by the Fraunhofer IAF. In Fig. 1, a photograph of one of the manufactured TIMES modules is shown. The benefit of this type of packaging is the superior robustness

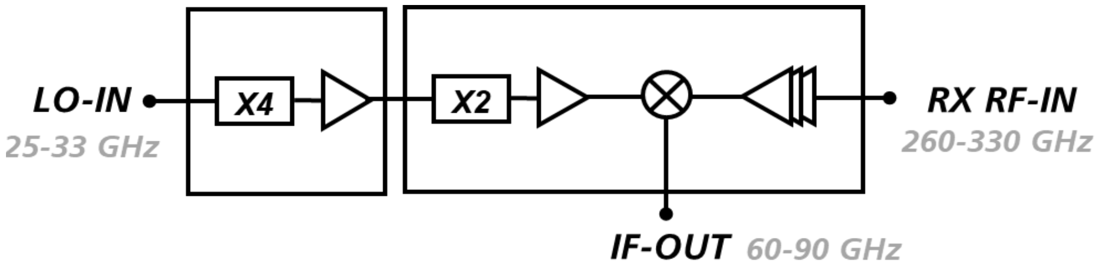
Figure 1: Photograph of a split-block waveguide module.

and easy handling, which allows for easy reuse for several use case scenarios and environments, which is needed for the different POCs in the TIMES project. The most important benefit is the superior performance, which is outstanding compared to other commercially available packaging techniques, which is important for prototype development, even though the cost of the split-block packaging is comparably high.

For full functionality of the modules in addition to transmitter (TX) or receiver (RX) MMIC, an additional frequency multiplier by four is integrated into the split-block. This multiplier allows the module to use local oscillator (LO)-frequencies in a range of 25-31 GHz. This is necessary to be able to use the off-chip LO-signal generation, which is done using a voltage controlled oscillator (VCO) in combination with a phase locked loop (PLL), which is provided by IAF. In Fig. 2, the block-diagrams for the TX- and RX-modules are shown. As seen there and as already described in Deliverable 5.1, the LO signal generation is done using a separate frequency multiplier by 4, which achieves an up-conversion from 25 - 33 GHz up to 100 - 132 GHz. A subsequent LO-buffer amplifier is inserted to guarantee sufficient LO-power. On the TX and RX chips, a frequency multiplier by 2 with subsequent LO-buffer generates a LO-signal from 200 - 240 GHz with a power larger than



(a) Block diagram of the transmitter split-block module.



(b) Block diagram of the receiver split-block module.

Figure 2: Block diagrams of the transmitter (a) and receiver (b) split-block modules.

2 dBm for sufficient mixing operation. The frequency translation is achieved by using single-ended resistive mixers. A 7-stage high power amplifier (HPA) for the TX and a 3-stage lower noise amplifier (LNA) with a subsequent amplification stage for the RX is used for sufficient operation of the front-ends. The operation bands of the modules are shown in the frequency plan seen in Fig. 3 and listed in Tab. 1. As seen there, the targeted IF frequency band is the E-band from 60-90 GHz, the RF frequency band inside the WR 3.4 waveguide band goes from 250-330 GHz and the LO band is from 100-120 GHz.

The performance specifications of the TX and RX are summarized in Tab. 2. As seen there, the targeted fre-

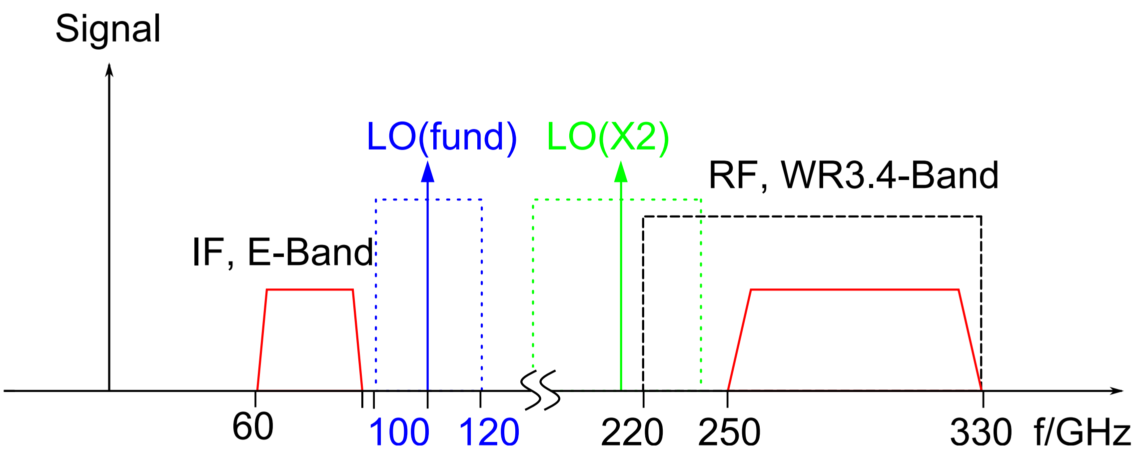


Figure 3: Frequency plan of the TIMES Front-ends.

	Transmitter	Receiver
RF / GHz	250-320	250-320
IF / GHz	60-90	60-90
LO / GHz	100-120	100-120

Table 1: Relevant operation frequency bands of the modules

quency bands are well covered by the produced split-block modules. The IF- and LO-bandwidths are covering the targeted frequency bands. In the RF performance, a shift towards higher frequencies can be observed. An RF operational bandwidth from 270-325 GHz is measured, which is not exactly covering the targeted frequency range but is still sufficient for the targeted use cases. The modules achieve a conversion gain (CG) of more than 10 dB, with an output-referred 1-dB compression point (OP1dB) of 0 dBm. Those CW characterizations indicate a useful module performance for later PoC use cases.

FoM	RF-BW / GHz	IF-BW / GHz	LO-BW /GHz	CG / dB	Psat / dBm	OP1dB / dBm
TX	275-325	<70...>90	25-31	11	3	0
RX	270-325	<65...>90	25-32	12	3	-14

Table 2: figure of merit (FoM)s of the TX and RX modules.

2.2 TIMES Modules Back-to-Back Characterization

The b2b characterization with the transmission of modulated data have given a first impression of the performance and communication link capabilities of the TIMES modems. The characterization was performed at the University of Stuttgart in the Institute of Robust Power Semiconductor Systems ILH using their unique state-of-the-art measurement system, which is referred to as CrossLink-System [2]. This system allows for characterization in frequency and time domains and the digital predistortion of modulated signals in various frequency bands and is therefore well-suited for the characterization of the TIMES modems.

2.2.1 Description of the used Measurement Setup

The measurement setup is shown in Fig. 4. It consists of a vector network analyzer (VNA) (Keysight PNA-X N5244B) including a so-called millimeter Wave test set (mmW Test Set), which is responsible for the communication and data transmission/conversion between the VNA and the extension modules. The extension modules are frequency converting units, which are able to up- and down-convert signals in their respective frequency band region. For the generation of modulated signals, an arbitrary waveform generator (AWG) is used, which is controlled by the VNA and operated in clock lock mode with the VNA. The modulated signal is upconverted into the E-band region using a compact converter unit (CCU) with a multiplication factor of 6. The modulated E-band signal is then fed into the vector component analyzer (VCA) module. The VCA is in the CrossLink-System used as a coupler, which allows the VNA to measure the modulated signal at the output of the VCA, therefore a predistortion of the modulated signal can be applied and an error vector magnitude (EVM) of < 1 % can be achieved at the reference plane. Between the CCU and the VCA a band pass filter (BPF) from 81 - 86 GHz is implemented. The BPF is needed due to large LO feed through and LO-harmonics of the CCU, which would drive the TX into compression and therefore would restrict the usable modulation format to QPSK. A major drawback of the needed filtering is the restriction of the usable modulation bandwidth to 5 GHz, even though the modules would be able to transmit much more broadband signals. The modulated signal will be received at the VNA extender (VNAX) in E/W-band. From there, the signal is transmitted into the mmWave Test

Set and from there into the VNA. Using vector signal analyzer (VSA) software directly addressable from the VNA real-time measurements and signal processing can be performed. A picture of the used setup is shown in Fig. 5.

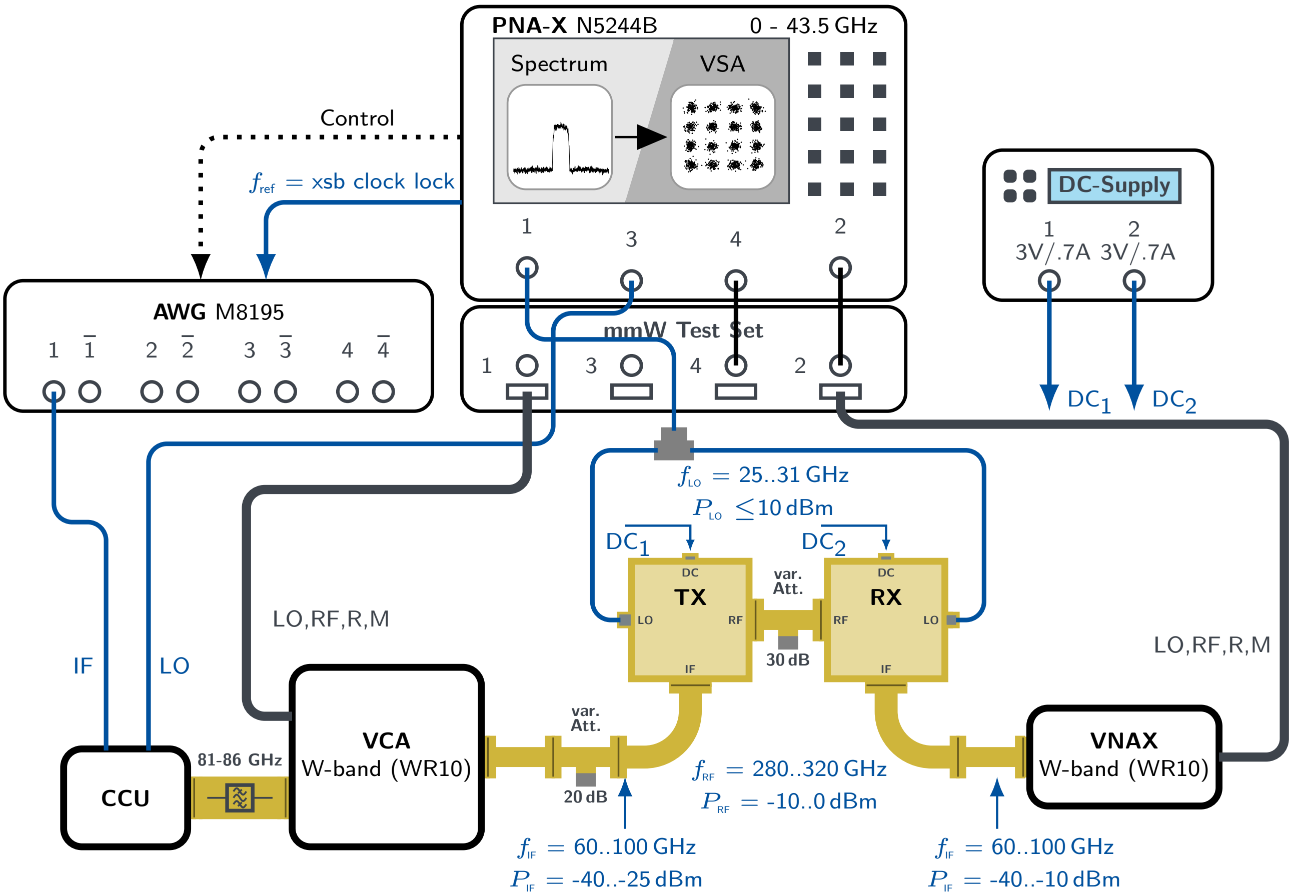


Figure 4: Measurement setup of the CrossLink-System, which is used for the b2b characterization using modulated data.

The characterized device under test (DUT) consists of the TIMES modules TX and RX connected together b2b using a variable attenuator, in order to set the attenuation between the modules manually. At the IF input of the TX an additional variable attenuator is used to set the power level at the input. A reason for this configuration is, that the CCU provides the best signal to noise ratio (SNR) and EVM values, when it's driven with a high power level. At this operation region a spectral power of >-10 dBm is achieved, what would drive the TX into strong saturation. The input level is chosen in 5 dB back-off from the OP1dB at -30 dBm and a RF attenuation of 20 - 30 dB is chosen for a linear operation of the RX. This way a power level of -30...-20 dBm can be received at the VNAX modules. Depending on the chosen modulation format, the optimum operation region can deviate.

2.2.2 Measurement Results

The different measurements were performed using identical operation setups, which are listed in Tab. 3. As already mentioned, the data-rate limiting factor in this setup is the bandwidth limiting BPF, which is needed due to the spurs of the CCU. In Fig. 6, the constellation diagrams for the different modulation formats are shown. The here seen measurements are achieved using additional equalization in the VSA. The measured FoM of the here shown measurements are summarized in Tab. 4.

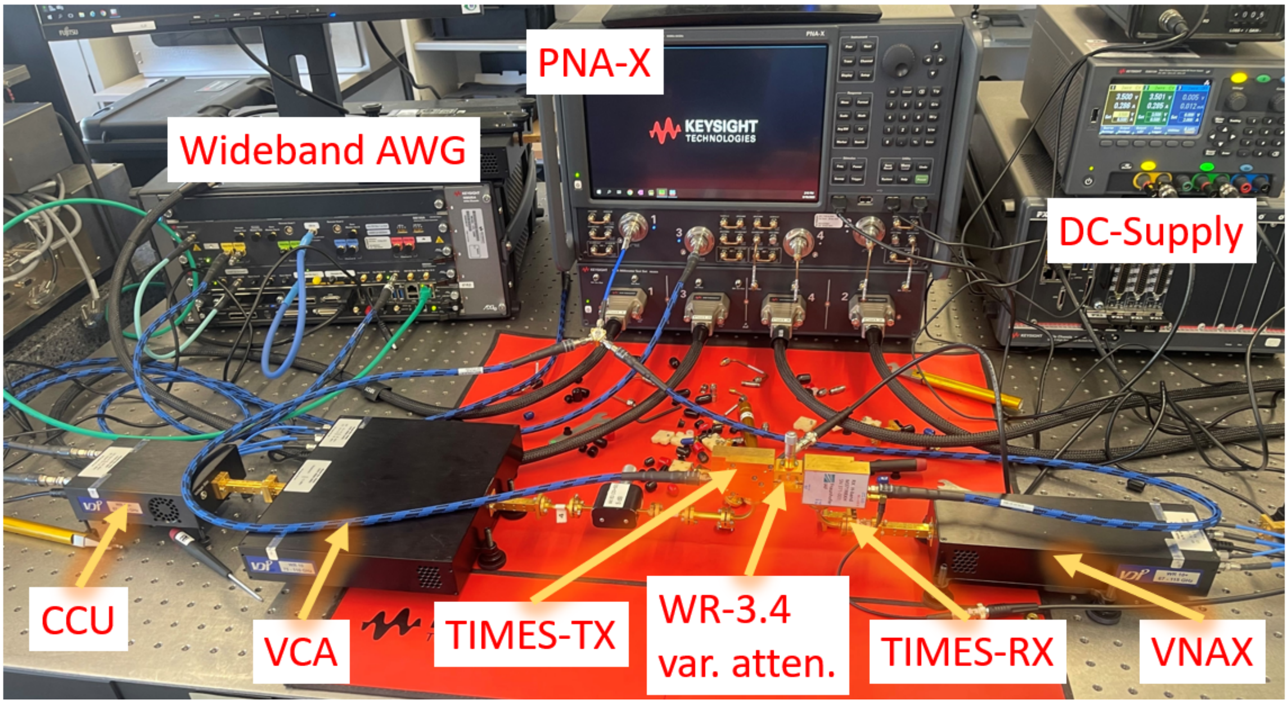


Figure 5: Measurement setup of the CrossLink-System, which is used for the b2b characterization using modulated data (VNA on top of the mmW Test Set).

Modulation	**16-QAM**	**64-QAM**	**128-QAM**
LO-Power / dBm	5	5	5
IF-Power TX / dBm	-20	-20	-20
RF-Attenuation / dB	30	30	30
Symbol-Rate / Gbaud	6	6	6
LO-Frequency / GHz	27.25	27.25	27.25
IF-Frequency / GHz	81-86	81-86	81-86
RF-Frequency / GHz	295-305	295-305	295-305

Table 3: Settings of the b2b measurements for the different modulation formats.

Modulation	**16-QAM**	**64-QAM**	**128-QAM**
EVM / %	3	2.59	2.43
SNR / dB	28	28.1	27.6
Data-Rate / Gbits^{-1}	24	30	36

Table 4: Measurement results for the different modulation formats.

As seen there, a demodulation of the transmitted signal up to a modulation format of up to 128-QAM could be demonstrated.A higher modulation format was not investigated du to the limitation of the available symbol memory of the used AWG. The achieved SNR of > 27 dB would allow for a modulation format of up to 256-QAM with a bit error rate (BER) < 10^{-3} in a arbitrary white gaussian noise (AWGN) channel. The SNR is only slightly degraded by going for a higher modulation format. A EVM of < 2.5 % for 128-QAM could be achieved.

As shown in this chapter, the produced TIMES modules are well suited for the intended use cases.

- The intended frequency regions are covered well within an IF-band from > 60 to < 90 GHz. The RF region from 270 - 325 GHz and the LO region from 100 - 120 GHz. A CG of > 10 dB and an OP1dB of up to 0 dBm allow for distance OTA communication.
- The performed b2b measurements show, that the modules are able to use modulation formats of over 128-QAM with at least 6 GHz of signal bandwidth. The bandwidth limitation is due to the needed BPF for the CCU, the modules themself should be capable of handling higher signal bandwidths. The achieved SNR and EVM agree with this statement, and indicate that even higher modulation formats and bandwidths could be used. The here demonstrated data-rates are already beyond the achievable data-rates of the modems and are therefore well suited for the use in the PoC's.

The communication link demonstrations, including the combination of modems and TIMES indoor units are covered in the following chapters.

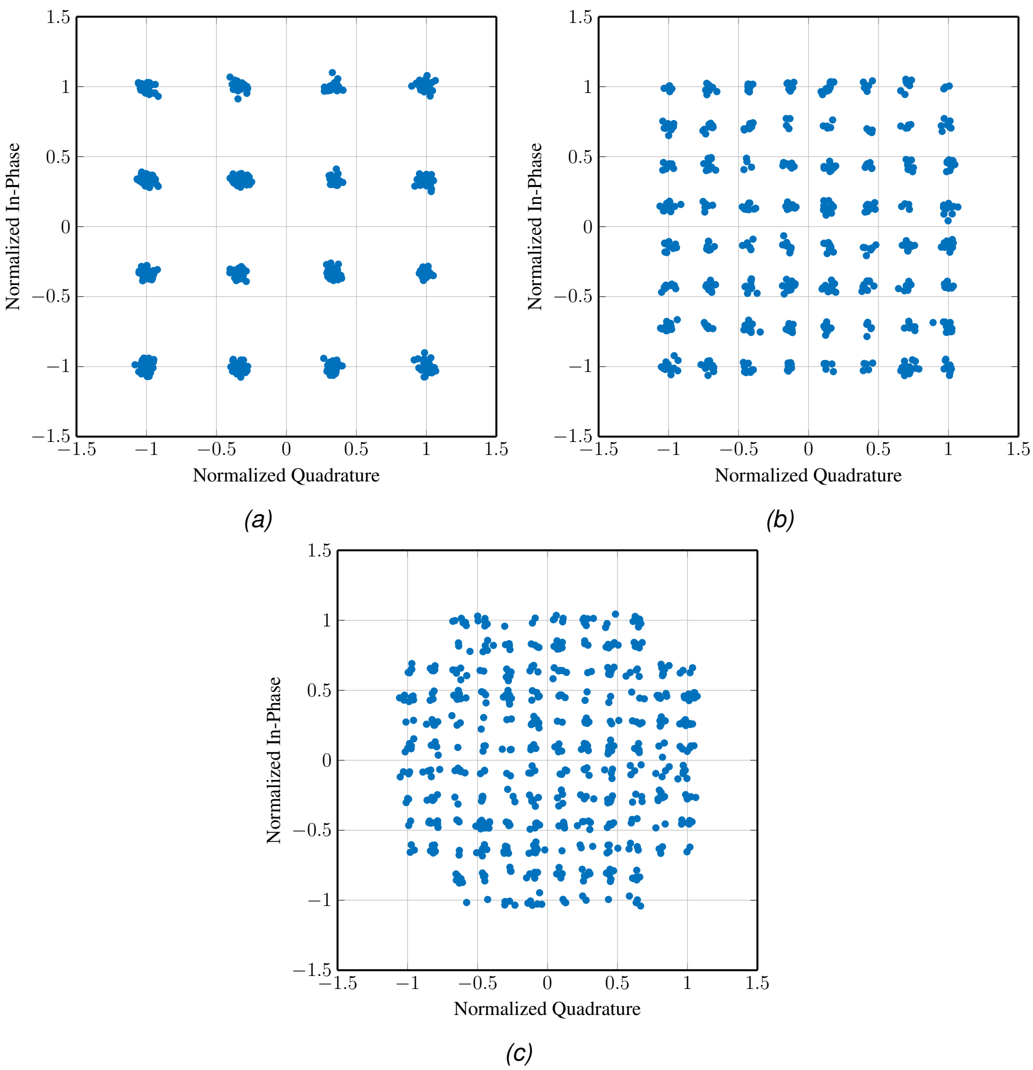


Figure 6: Constellation diagram of the measured modulation formats (a) 16-QAM, (b) 64-QAM, (c) 128-QAM.

3 System Verification with FDD-Modems

This section describes the verification for the TIMES PoC-1. The PoC should demonstrate two THz-Indoor-Units, equipped with high gain horn-lens antennas, that are communicating in frequency division duplex over a reflective intelligent surface.

The PoC-1 includes the operation of new THz-transceiver unit, that has been developed within the TIMES project, in conjunction with frequency division duplexing (FDD)-real-time modems, manufactured by the company Siklu [3].

This validation is structured as follows: First, we present the validation setup. Then we show consecutively the assessment of the frequency scheme, the TX linearity and the RX linearity. Finally, we conduct OTA tests in order to validate the operation of the real-time wireless link.

3.1 Measurement Setup

The system consitists of two terminals. Each terminal is built with following components:

- TIMES Indoor-Unit, consisting of
  - 2 x PLL
  - 1 x RX
  - 1 x TX
  - 1 x HPA
  - Controller
- TIMES H-band diplexer
- FDD-Modem (Siklu), with additional equipment
  - Power-over-Ethernet supply
  - 2 x CAT-6 Ethernet cable
- IF-waveguide components, connection modems to front-end, namely
  - WR-12 waveguides
  - E-band diplexer
  - WR-10 variable Attenuator, to reduce output power of modems.
- Computer with connection setup
  - USB-connection from computer to indoor-unit
  - 10-GBit Ethernet connection towards modem

The measurement setup in b2b configuration with the labeled components is shown in Fig. 7. The modems are connected with WR-12 waveguides to an E-band diplexer, which splits the TX and RX-signal, based on their carrier frequency. Depending on the modem configuration, the frequency band 71 - 76 GHz as TX-band and 81 - 86 GHz as RX-band (or vice-versa) is then fed towards the TX-IF input of the indoor unit or to the RX-IF output of the indoor unit. The RF output of the TX and the RF input of the RX are further combined with an additional H-band diplexer, that is employed to guarantee sufficient isolation between the TX and the RX. If the modems output is configured as high-channel (81 - 86 GHz) then also the high-channel of the diplexer (283 - 300 GHz) is connected to the TX. The indoor-units RF-input is similarly connected to the low-channel of the H-band diplexer (265 - 278 GHz).

The indoor-units are supplied with 6 V laboratory supply. Further, they are connected to a computer via USB-interface in order to control the LO-frequency settings within the indoor modules.

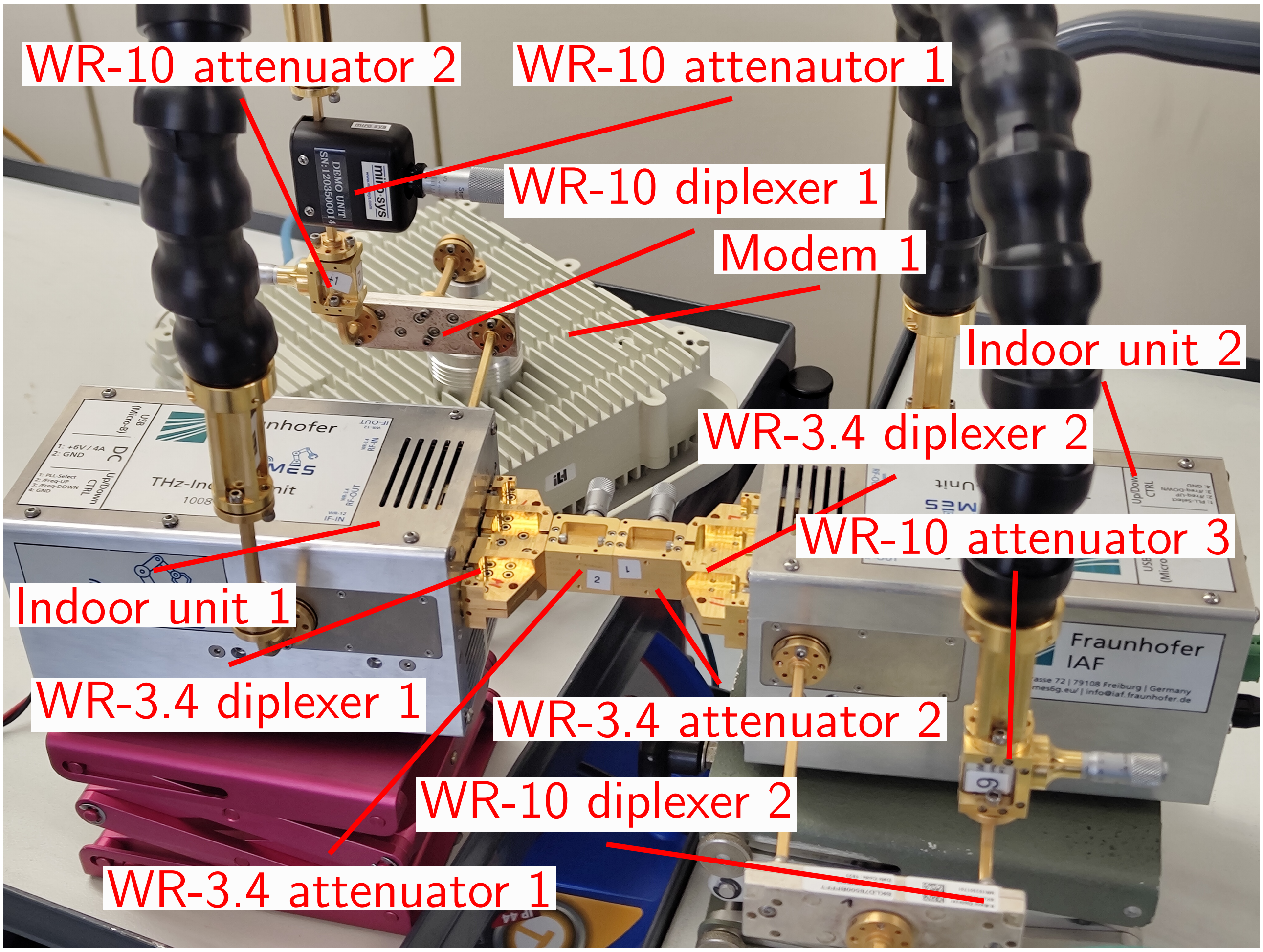


Figure 7: Picture of the setup for the b2b measurements.

Each modems is connected via Ethernet to an individual computer, that is equipped with 10-GBit Ethernet card. The computers are able to access the modems performance metrics in terms of received signal strength indication (RSSI) and carrier to interference plus noise ratio (CINR). Further with a standard iperf-software we can measure the possible data rates between the computers in each direction independently.

For the first tests, to derive the optimum operation conditions of the setup, we connected both terminals back-to-back with variable WR-3.4 variable waveguide attenuators (WR-3.4 attenuator 1 and 2). Later, the attenuators are replaced by two conical waveguide horn antennas, and the free-space-path.

In the system verification, it shows, that the modems are not able to sufficiently reduce their output power in order to drive the THz transmitter in a linear operation point. Thus, additional WR-10 variable waveguide attenuators are employed, in order to improve system performance. We used WR-10 attenuators, because of pressure of time and availability in our facilities as no WR-12 waveguide attenuators have been available.

3.2 Performance versus Operational Frequency

Firstly, to confirm the design and manufacturing of the diplexers, a characterization with a VNA-setup is conducted. Two pieces are fabricated, as each of the two terminals have to be equipped with an diplexer in order to provide the required isolation between input of RX and output of TX. As shown in the S-parameters in Fig. 8 and Fig. 9, the diplexers have low insertion loss of 2 dB and good input matching. The isolation is sufficiently

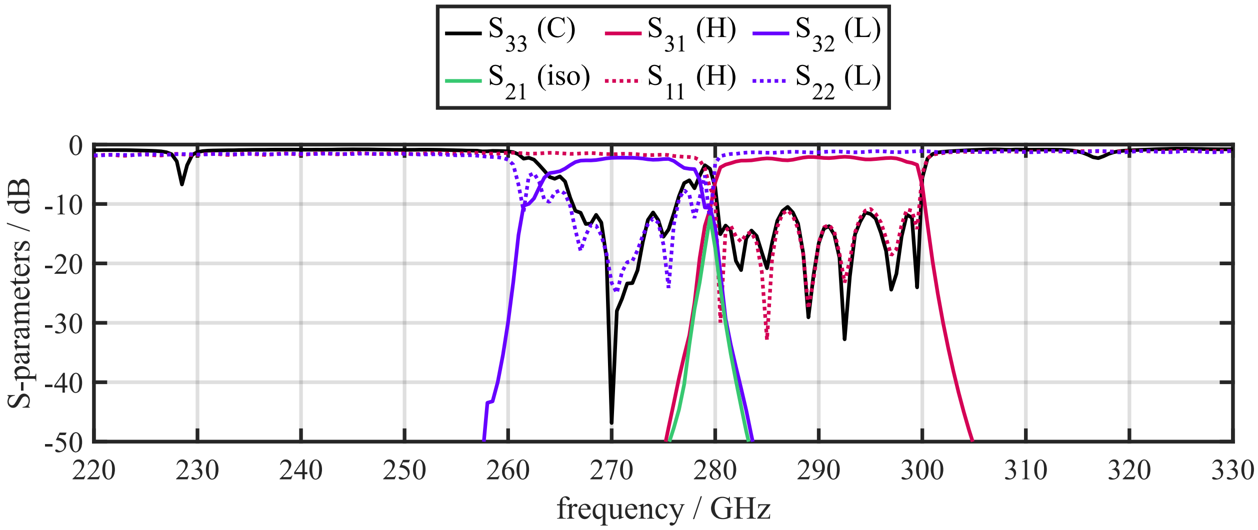


Figure 8: S-parameters of the diplexer M386-001.

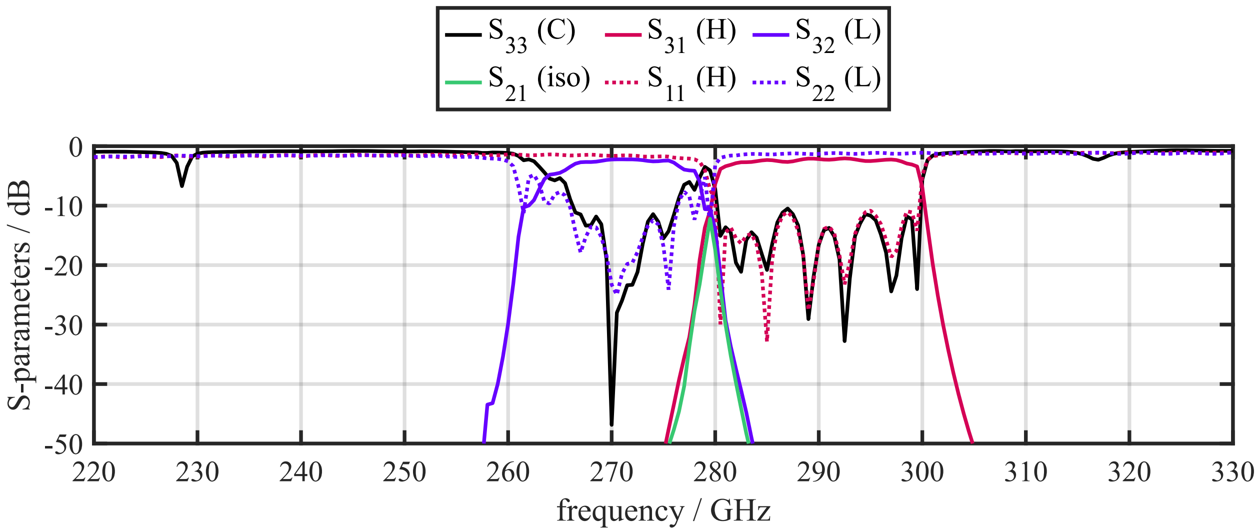


Figure 9: S-parameters of the diplexer M386-003.

high as well, only in the transition from high-band to low-band there is a limited isolation, as the bands are overlapping. A paper on the design process has been published in [4].

The frequency of the internal LO sources of the THz indoor modules can be set via an USB interface. In order to verify the operational frequency of all employed devices, the systems power levels are set close to optimum conditions. Then, the LO frequency is swept in order to observe the influence on signal quality, signal strength and data-rate. To ensure robust link establishment and quick synchronization, we are conducting the test with a fixed QPSK modulation setting. The modems offer the possibility to change the frequency assignment: They are able to operate either with an TX/RX-frequency of 72/82 GHz or at 74/84 GHz. The testing of the LO-frequency is repeated for each frequency. Because of an integrated frequency multiplier by four and a subharmonic mixer, the RF frequency of the super-heterodyne mixer can is calculated by

$$f_{\mathrm{RF}} = 8 \cdot f_{\mathrm{LO}} + f_{\mathrm{IF}}. \tag{1}$$

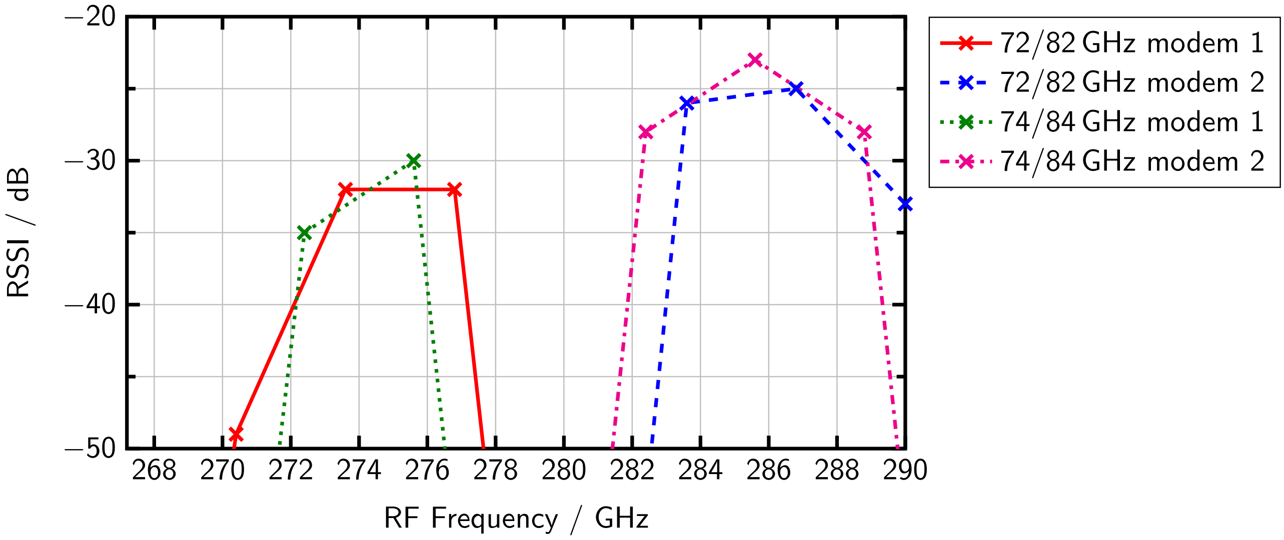


Figure 10: RSSI as a function of the RF frequency.

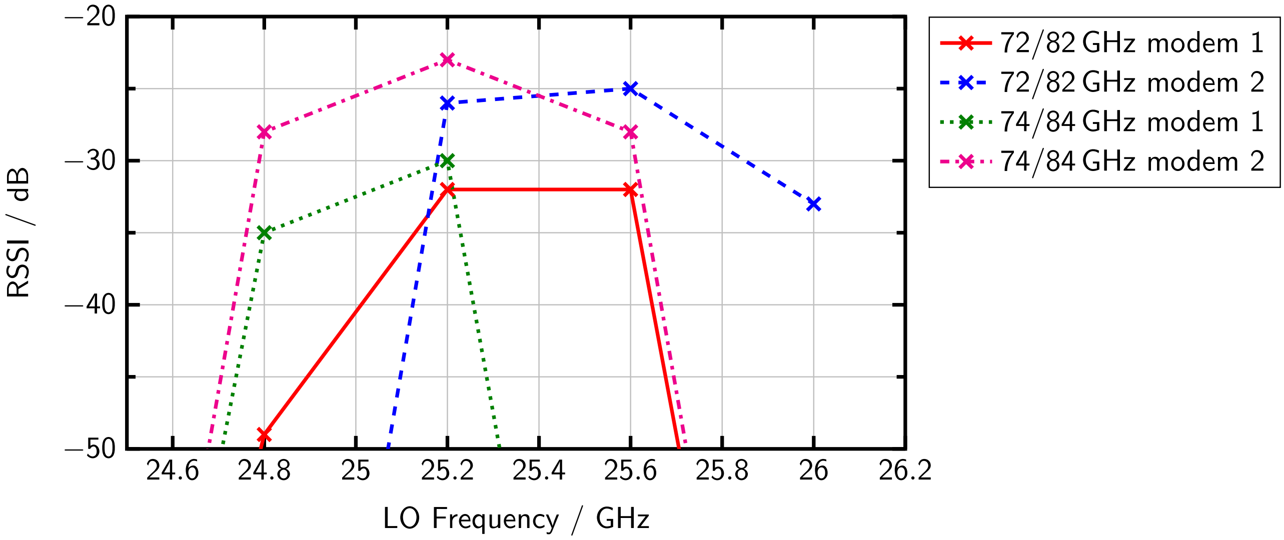


Figure 11: RSSI as a function of the LO frequency.

Fig. 10 shows the received signal strength of both modems in both IF-configurations vs the RF carrier frequency. In the evaluation, the influence of the diplexing filters can be observed, that omits operation out of band. When the RSSI is displayed versus the LO frequency setting, it is clear, that the system is only operational at all IF frequency bands in one particular LO setting, namely the 25.2 GHz setting.

3.3 TX Linearity

For optimal signal transmission, we have to ensure to operate the **Tx!** (**Tx!**) at optimum signal power. Especially for higher modulation formats as 16-QAM or 32-QAM it is essential to operate the transmitter in its linear region. On the contrary, with reduction of the transmit power, the system margin decreases, which worsens the system performance. This tests are conducted with 16-QAM modulation, as it is still quite robust in terms of synchronization but on the other hand, amplitude compression is degrading this modulation format, because

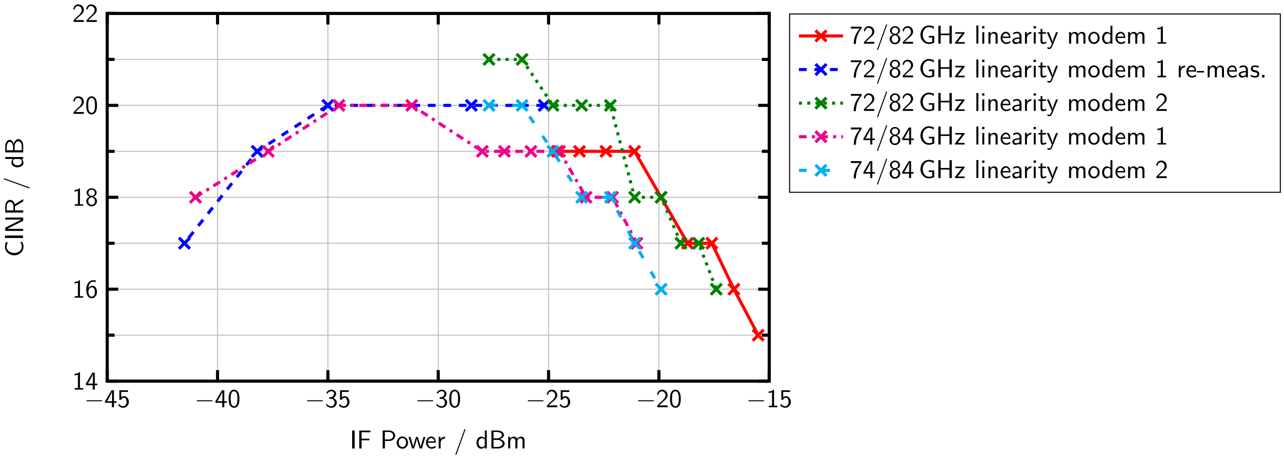


Figure 12: Transmitter linearity measurements using both MODEMs for different IF frequencies.

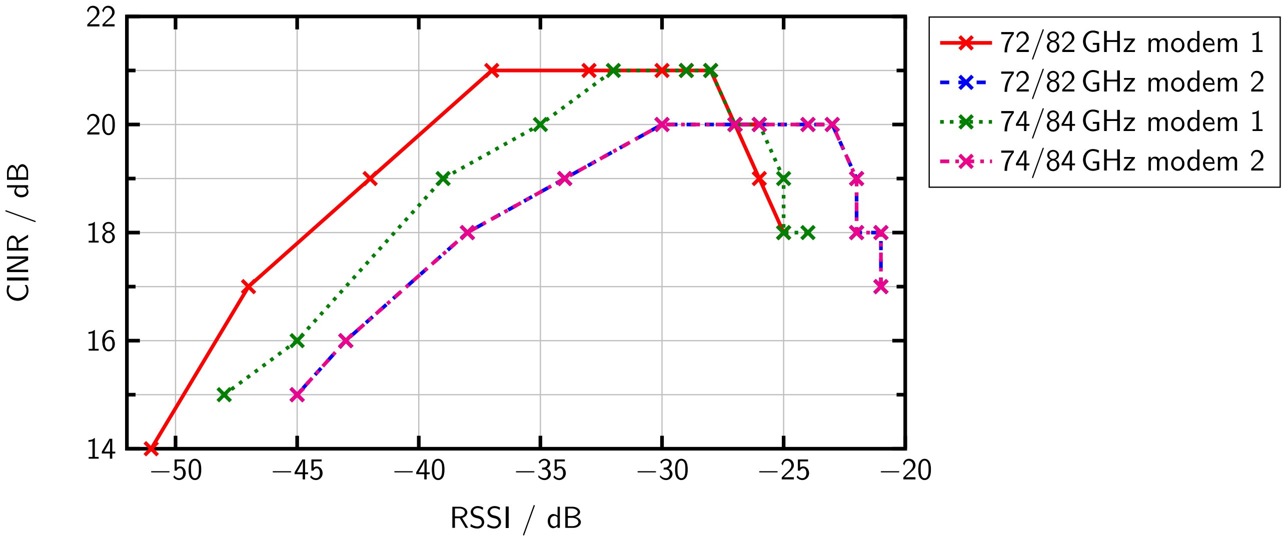


Figure 13: Receiver linearity measurements using both MODEMs for different IF frequencies.

parts of the information is modulated on the amplitude. Fig. 12 shows the dependency of the signal quality from the IF power. To exclude the influence of the RX linearity, the WR-3.4 (RF) variable attenuators are set to reduce the signal power to a level of -30 dBm at the receiver. This ensures linear operation of both, the THz RX and the RX within the FDD modem. The output power of the modems can be configured with a graphical user interface. The settings permit to reduce the output power to -10 dBm. However, with this input power, the THz TX is already in its saturation. Thus, additional waveguide attenuators are employed to reduce the modems output power further. Fig. 12 shows, that for high CINR above 20 dB, which is needed, for 32-QAM, an additional attenuation of 15 to 20 dB has to be inserted, as the compression starts at -25 dBm of input power.

3.4 RX Linearity

In a second step, the TX is operated under constant, optimal conditions. By sweeping the RF-Attenuation, we extract the systems RX linearity and are also able to estimate the system margin. Fig.13 shows the measured signal quality (CINR) versus the RSSI. It can be seen, that over a wide range of input power a high CINR of

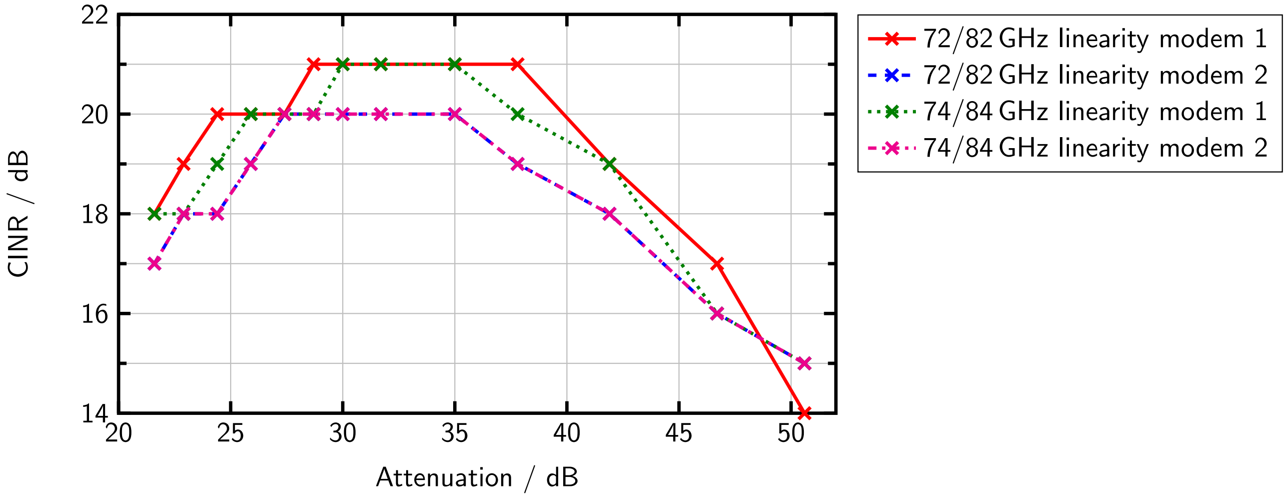


Figure 14: Receiver linearity measurements using both MODEMs for different IF frequencies.

20 dB can be achieved. Also the link can be established over a wide range of RF attenuation.

Fig. 14 shows the same data over the inserted RF attenuation. It can be observed, that the plateau with the optimal operation conditions is between 28 and 35 dB.

3.5 Over-the-Air Measurements

Fig. 15 is showing the OTA measurement setup for a distance of 18 m. The WR-3.4 attenuators are removed from the setup. Instead, WR-3.4 horn antennas are connected to the diplexers. The antennas are conical corrugated horn antennas for laboratory purposes with 21 dBi of antenna gain. Both terminals are placed on movable carriages and the distance is successively increased. At nearer distances up to 5 m higher order modulations are possible and thus a higher data rate of 5 Gbit/s(simplex) can be achieved. This results in 10 GBit/s duplex data rate, if both directions are considered. If the modulation format is reduced to QPSK, long range transmissions of over 25 m are possible, which is quite high, considering the small antenna gain of only 21 dBi at each terminal.

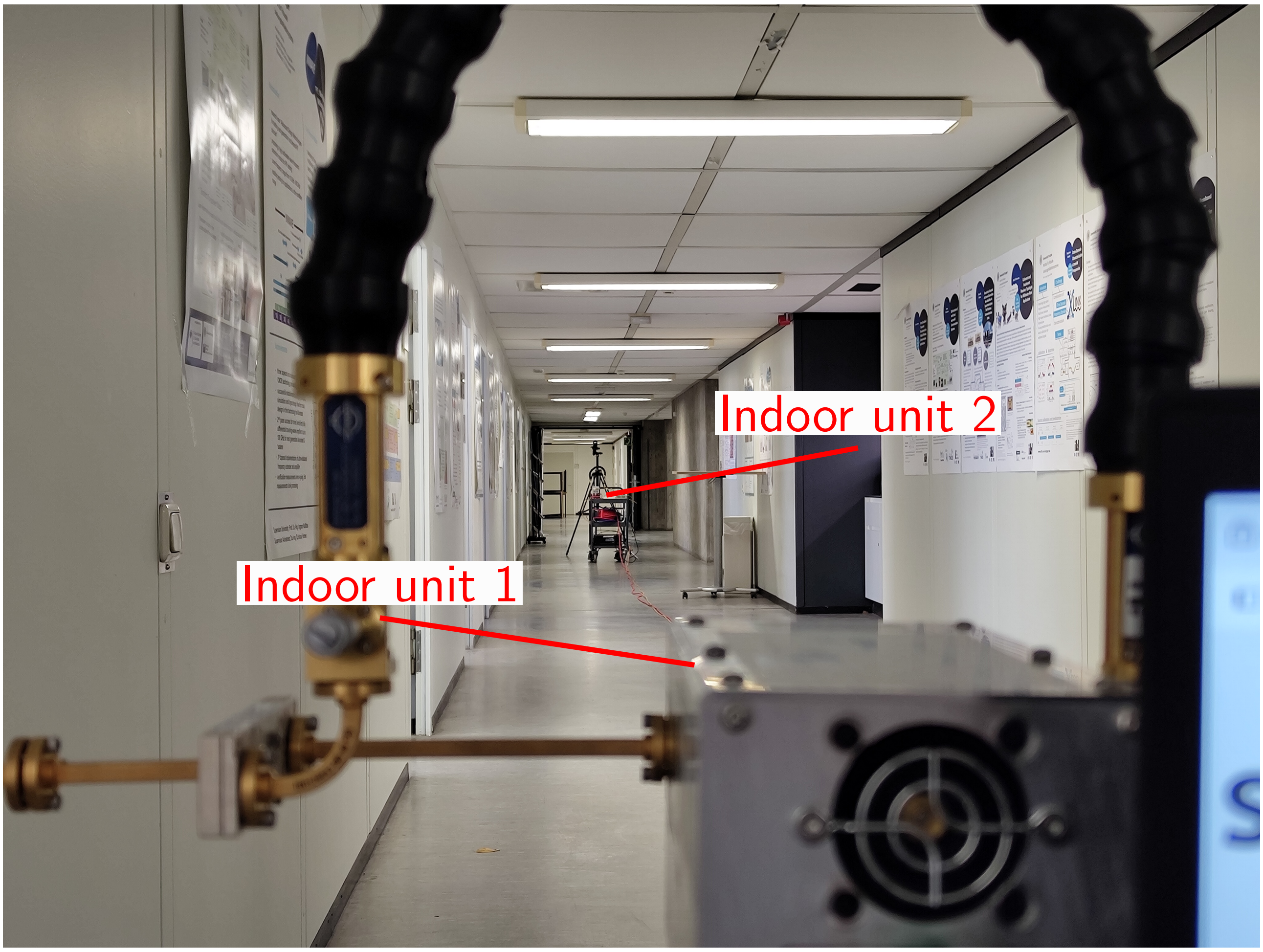


Figure 15: Picture of the setup for the OTA measurements.

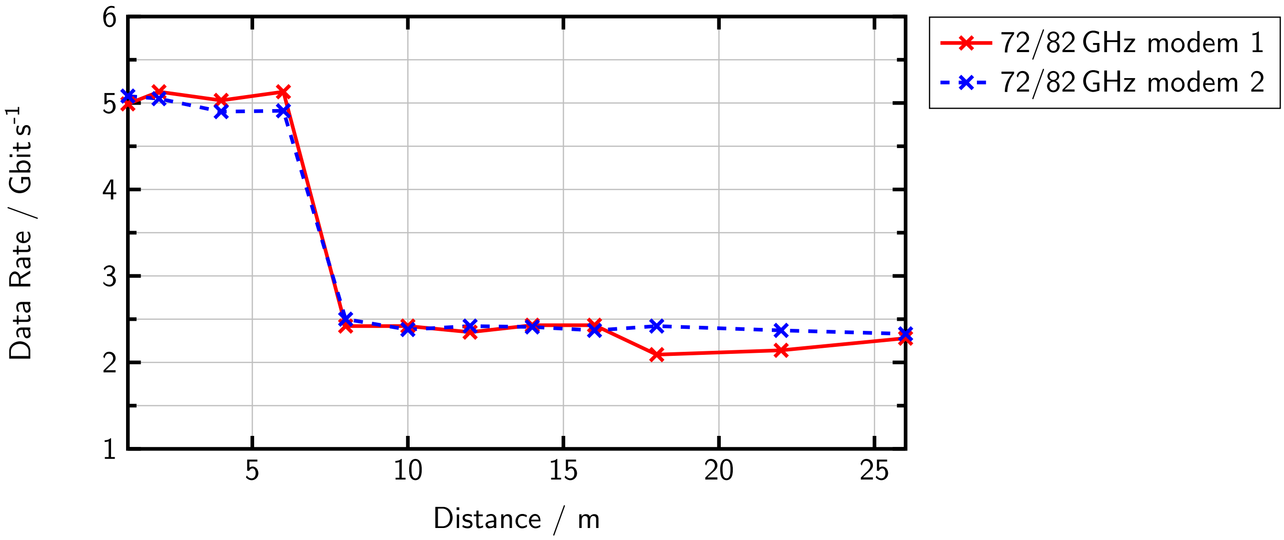


Figure 16: Transmission capabilities using both MODEMs.

4 System Verification with TDD-Modems

This section describes the verification for the TIMES PoC-2. The PoC should demonstrate two THz-Indoor-Units. One of which is equipped with a leaky-wave antenna, that is able to steer the THz-beam, based on the carrier frequency. The other terminal is equipped with a medium gain antenna with approximately 35 dBi of gain. Because the leaky-wave antenna is based on frequency-dependent angle of arrival/departure, the up-link and down-link channel have to occupy the same frequency channel. Thus, only the operation of real-time time division duplexing (TDD)-Modems is viable within this PoC. The antenna design is summarized in the Deliverable D5.3 [5]. The modems are commercially available and are manufactured by the company HRCP [6]. This results in the fact, that the RF-ports of the TX and RX have to be combined with a broadband H-band combiner without a frequency selective behavior, that allows to operate the leaky-wave antenna over a wide frequency range. So, the WR-3.4 diplexer of PoC-1 is not applicable. Also a high isolation of > 20 dB is needed in order to prevent damage from the RX of too much input power. As this kind of combiner is at the time of publication of this deliverable not available, we conduct a reduced validation in order to verify the system: based on waveguide components, we build two separate channels with variable attenuators. Thus, also the OTA validation is currently not possible, but will be conducted as soon as all parts are available.

This validation is structured as follows: First, we present the validation setup. Then we show consecutively the assessment of the frequency scheme, the TX-linearity and the RX-linearity.

4.1 Measurement Setup

The measurement setup consists of two terminals, that are each composed of:

- TIMES Indoor-Unit, consisting of
  - 2 x PLL
  - 1 x RX
  - 1 x TX
  - 1 x HPA
  - Controller
- TDD-Modem (HRCP), with additional equipment
  - 12-V supply
  - 2 x CAT-6 Ethernet cable
- IF-waveguide components, connection modems to front-end, namely
  - WR-12 waveguides
  - WR-12 coupler (magic-tee)
  - WR-10 variable Attenuator, to reduce Output power of modems.
- Computer with connection setup
  - USB-connection from computer to indoor-unit
  - USB-connection from computer to TDD-modem
  - 10-GBit Ethernet connection towards modem

For the b2b configuration, we use additional equipment, to connect the both indoor-units with each other.

- 4 x WR-3.4 waveguide straight section
- 2 x WR-3.4 variable attenuator

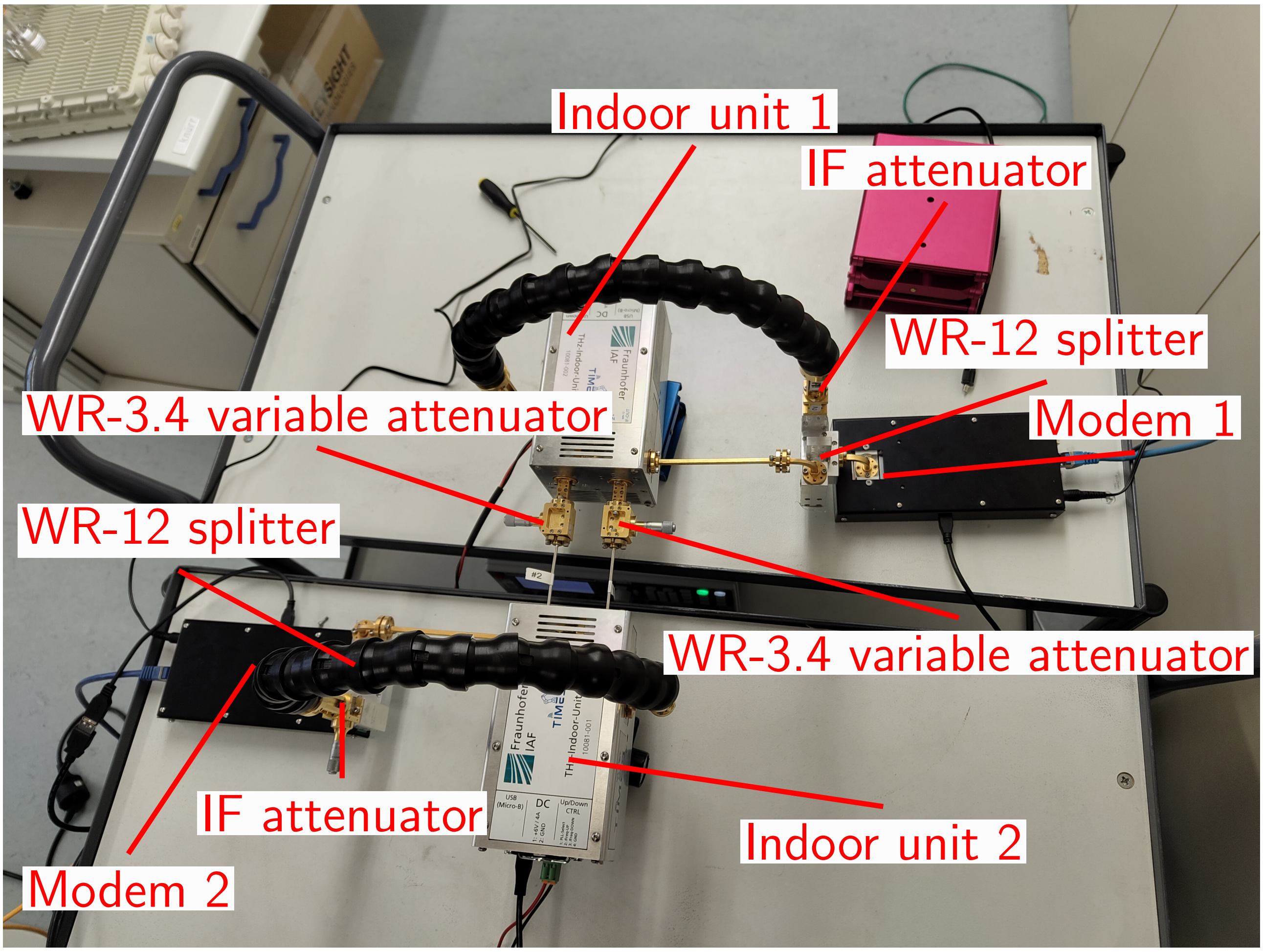


Figure 17: Picture of the measurement setup used for the characterization of the TDD modems.

The setup of the measurement is shown in Fig. 17. The modems are connected to a WR-12 coupler to split the interface without frequency selection into two ports, one to connect to TX, the other to connect to the RX. In order to optimize the system, instead of the coupler, a circulator could be included to avoid coupling loss from the THz-RX IF output towards the modem. The insertion loss from modem to THz-TX and the insertion loss from THz-RX to the modems is both 4 dB in the current configuration. The indoor unit is then connected b2b to the second indoor unit, which is then connected with the same waveguide configuration to the second modem. The modems are connected each to a computer with a 10-GBit Ethernet connection in order to measure real IP traffic over the system. The computers are further connected each to their corresponding modems via USB to establish the link and to retrieve data regarding the link quality. An additional USB connection is used to connect the computer to the indoor unit, which is needed to alter the LO settings.

As already introduced, the indoor units are connected via a provisional waveguide structure. A close-up of said structure is displayed in Fig. 18. Both directions are assembled with individual waveguide channels, also the attenuation of both paths can be altered independently. The individual paths are necessary to separate the TX and RX of each indoor-unit, to prevent damage the RX with high power levels. In the final demonstrator setup, this path will consist of WR-3.4 waveguide coupler, with two S-bend waveguide pieces, that combine TX and RX to a single port with sufficient isolation between each other. This combined port will then be connected to the antenna units.

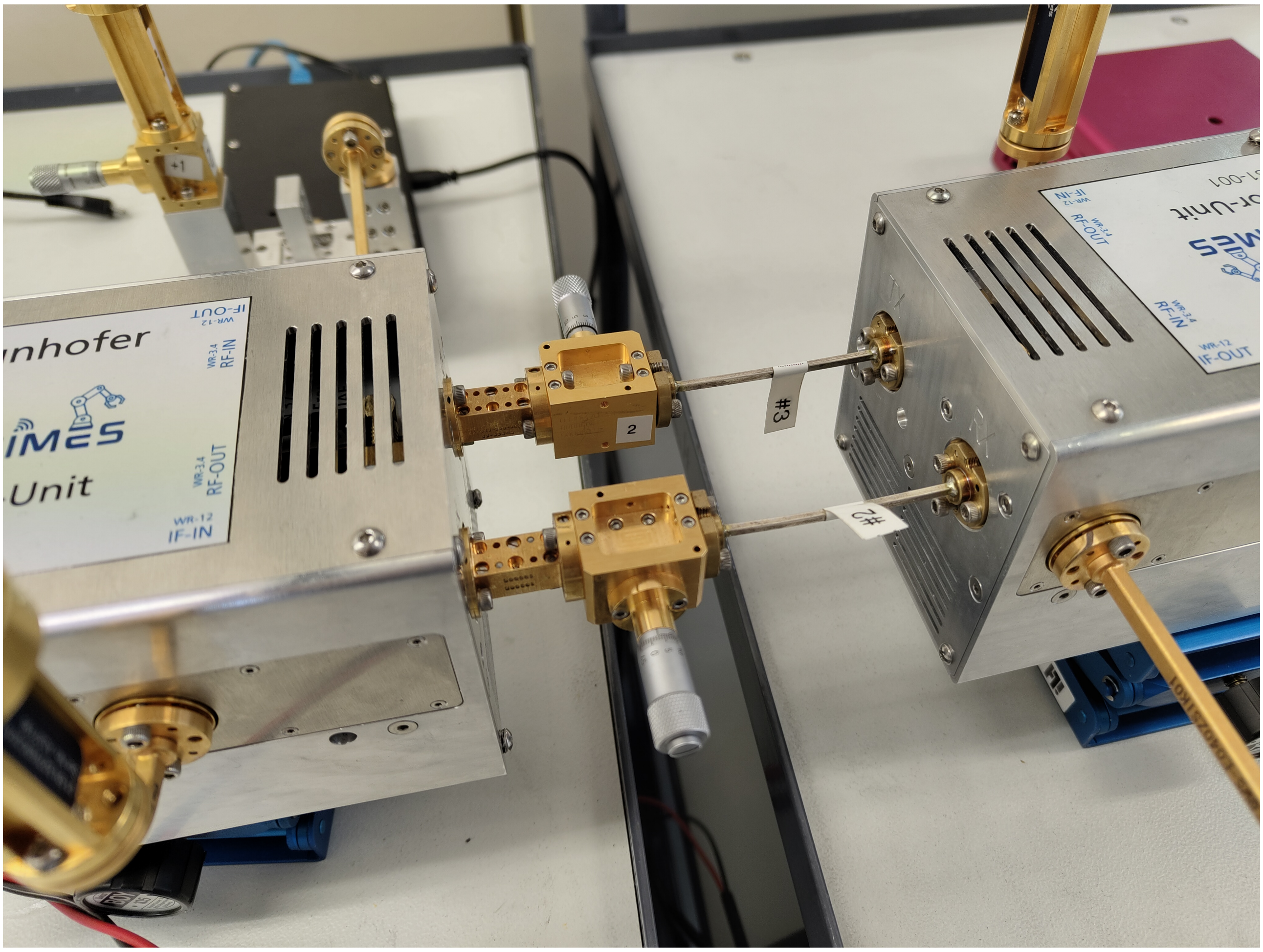


Figure 18: Detail view of the WR-3.4 variable attenuators applied in the measurement setup for the characterization of the TDD modems.

4.2 Performance versus Operational Frequency

For the PoC-2 the frequency setting is an important aspect, as it plays a major role for the beam steering. The necessary frequency range of the radio system should be in agreement with the frequency range of the leaky-wave antenna, which is approximately from 260 - 290 GHz. Similar to the examination with the FDD-modems in section 3 we establish a link in between the modems close to the optimum operation power in terms of TX input power and RF input power and sweep the configuration of the LO within the indoor-units. The observed RSSI is displayed in Fig. 19 with respect to the RF frequency and in Fig. 20 with respect to the LO frequency. In the case of the TDD modems, only unit-less indication of the received signal strength is available, that has no direct relation to real-world power. More importantly, we display in Fig. 21 and Fig. 22 the measured data rate over the RF and LO frequency. In this test, we attest successful modem operation from RF-frequencies between 270 to 305 GHz, which is in line with the measured performance of the leaky-wave antenna.

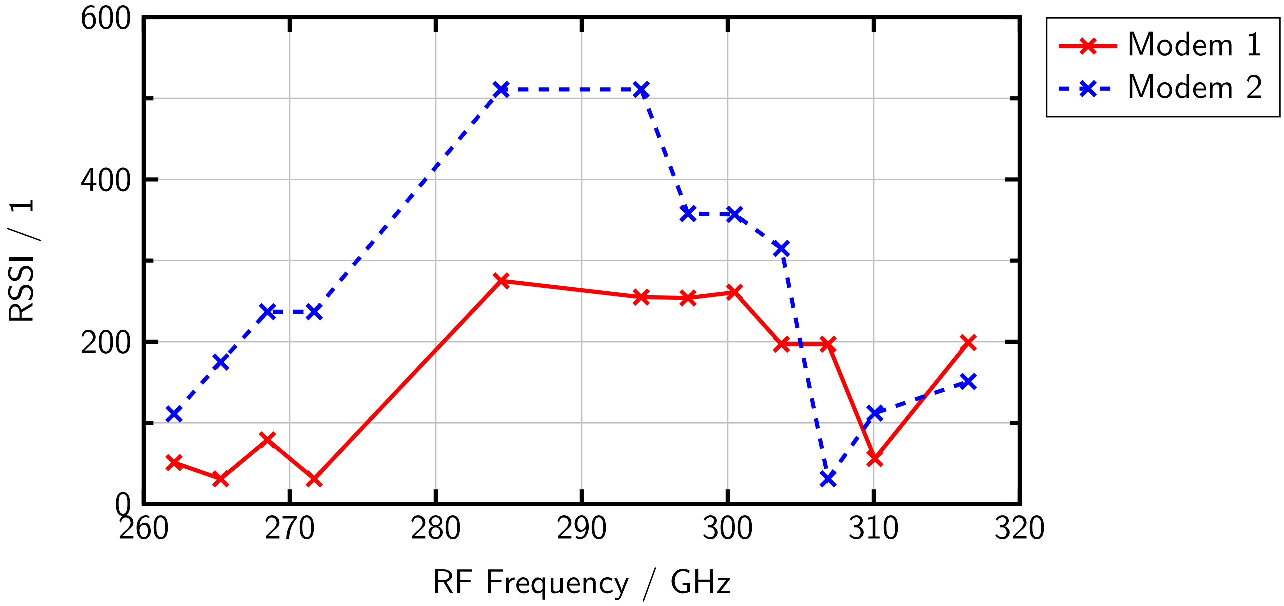


Figure 19: RSSI as a function of the RF frequency.

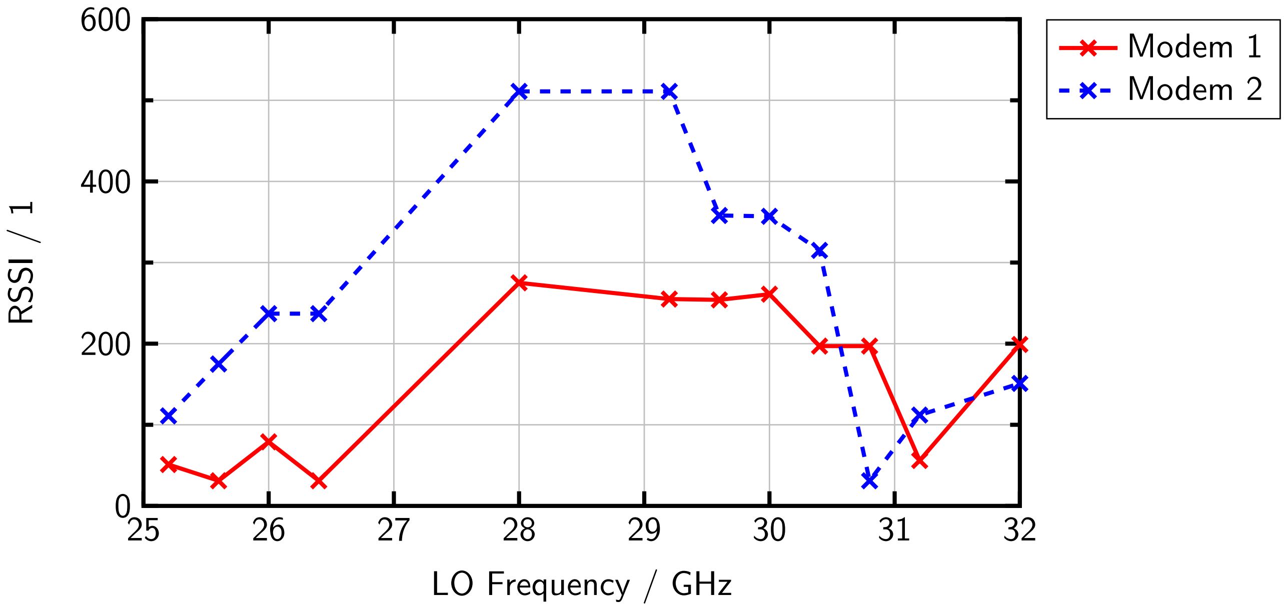


Figure 20: RSSI as a function of the LO frequency.

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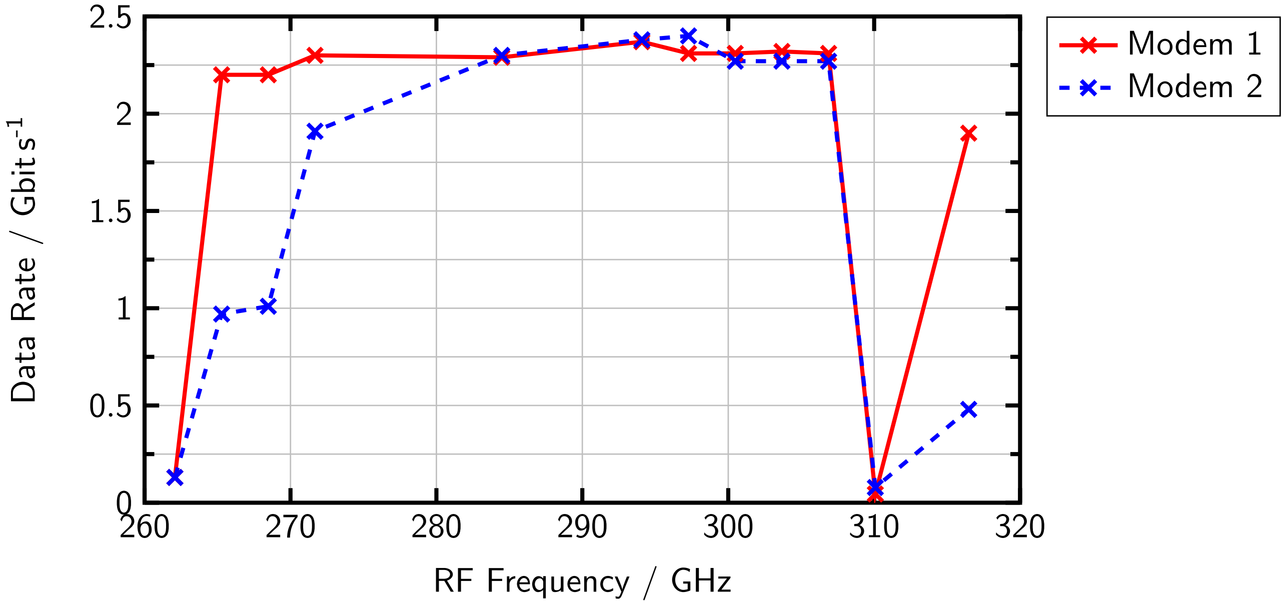

Figure 21: Data rate as a function of the RF frequency.

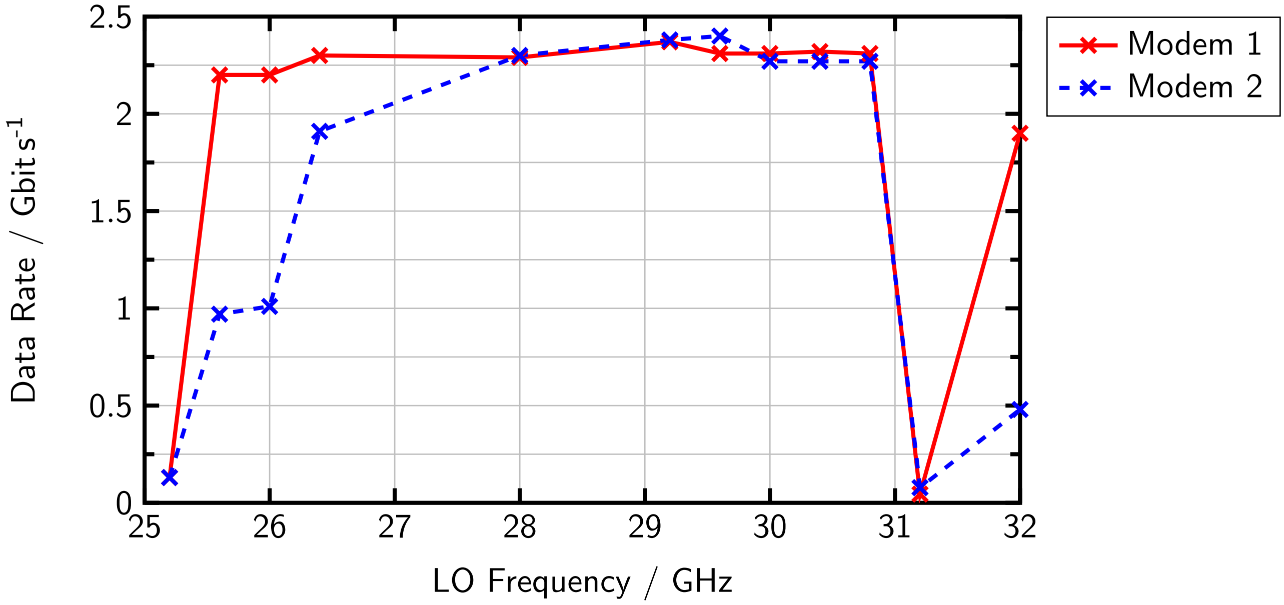

Figure 22: Data rate as a function of the LO frequency.

4.3 TX Linearity

In similar fashion as in section 3 with the FDD modems, we evaluate the modems TX-linearity. Opposed to the TDD-modems we do not have access to a direct indication of the signal quality, as the CINR. Hence, we make use of the data-rate as indication of signal quality. As a second indication, on how well the link is performing, we display the measured RSSI versus the IF-Power. Both can be seen in Fig. 23 and Fig. 24. For modem 1, the data rate is decreasing with the IF input power. Modem 2 does not seem to be influenced by the IF-power, probably because the adaptive modulation of the modem is anyways set to a lower modulation format because of other system impairment. Unfortunately, the modulation format can not be fixed to a certain setting, to resolve the issue further.

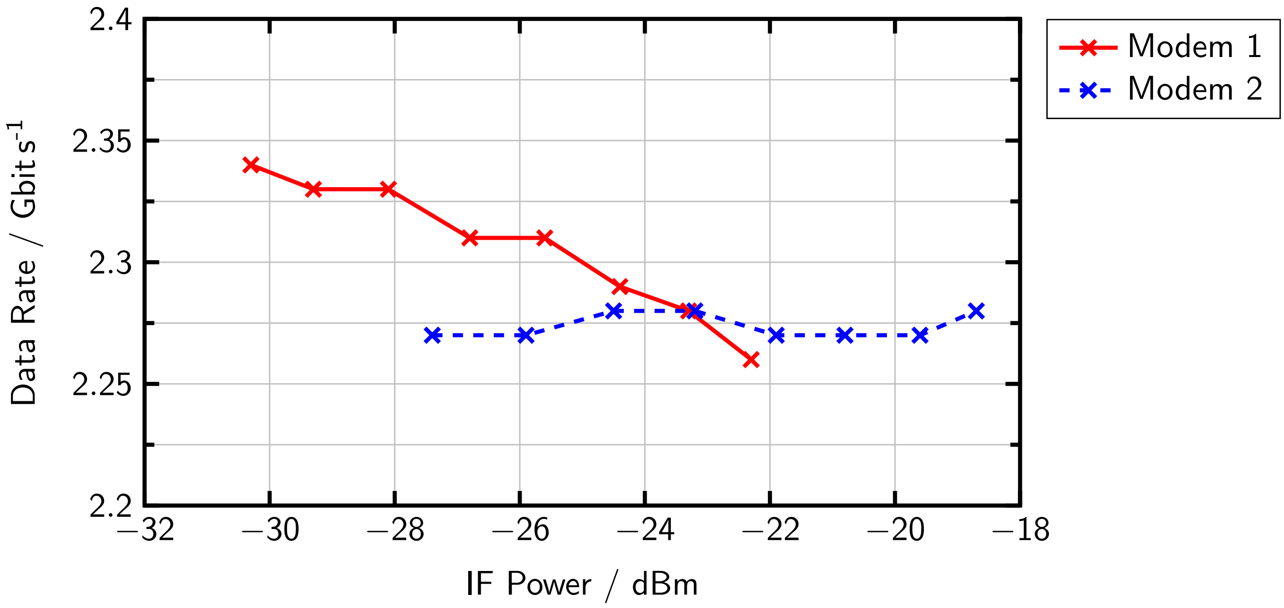

Figure 23: Data rate as a function of the IF power.

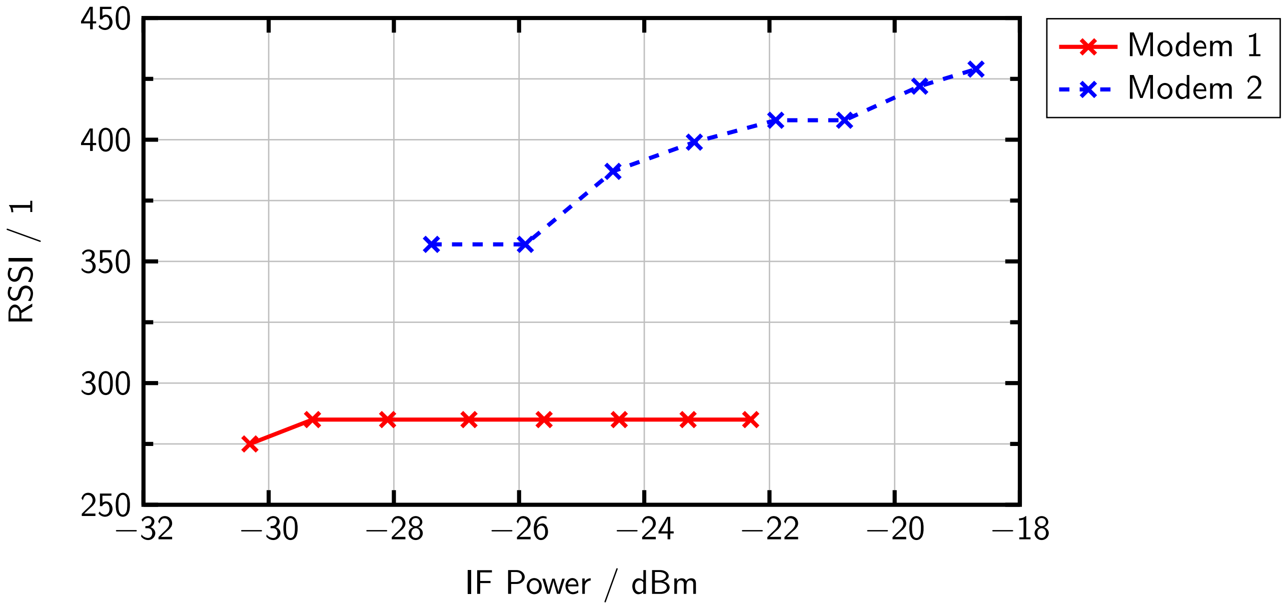

Figure 24: RSSI as a function of the IF power.

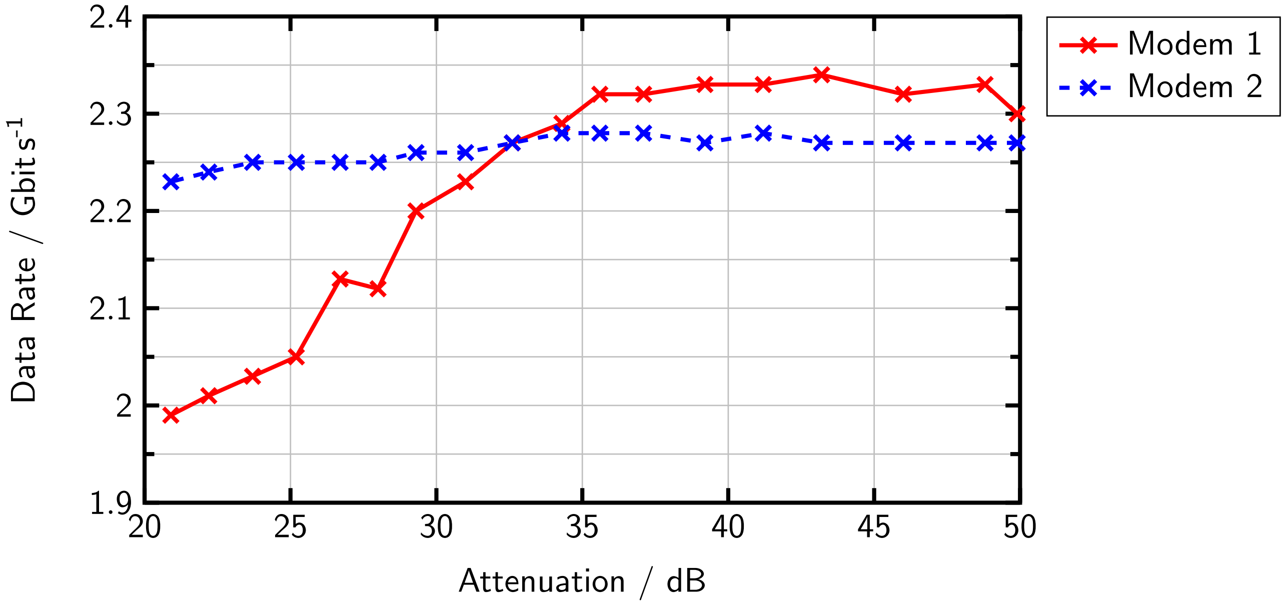

Figure 25: Data rate as a function of the attenuation.

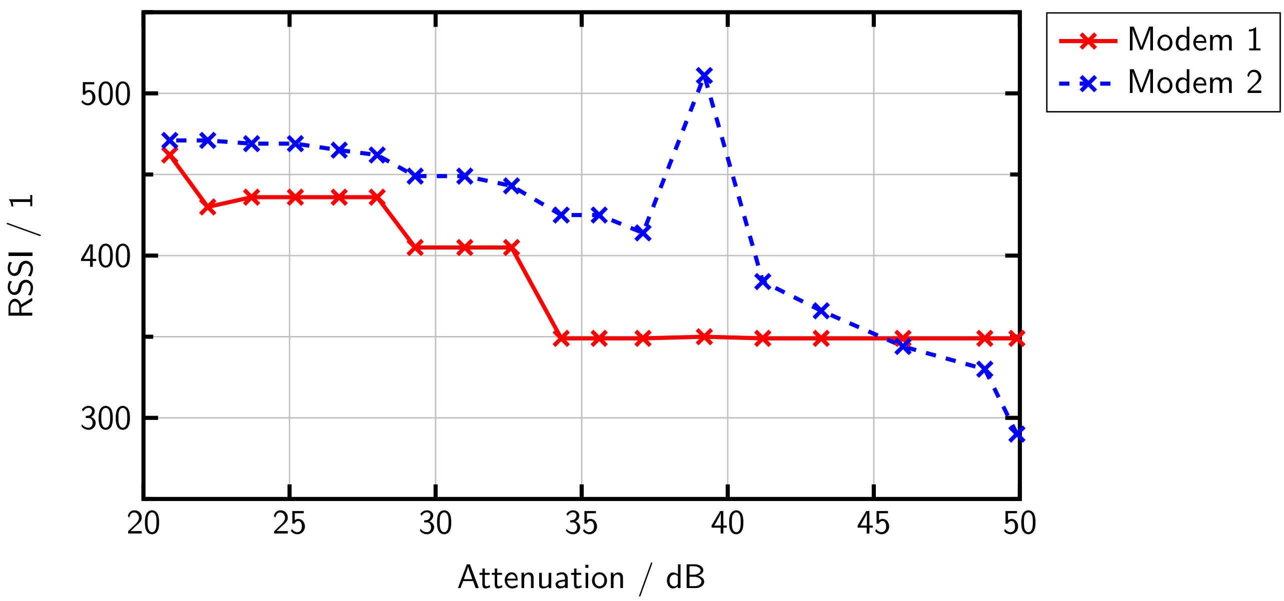

Figure 26: Data rate as a function of the RSSI.

4.4 RX Linearity

To directly assess the system margin, we measure, similar to the FDD-system testing, the data-rate under increasing RF-attenuation as can be seen in Fig. 25 and Fig. 26, respectively. With lower attenuation, the data-rate is decreasing, because of compression in the RX. As the attenuators have a maximum insertion loss of 50 dB, we can not determine the maximum path loss of this setup, but the system is still working for attenuation over 50 dB. In the real demonstrator, the link-margin has to be sufficiently high, to enable communication link OTA with a considerably low antenna gain from the leaky-wave antenna and potentially transmitting over a reflective intelligent surface, which has also quite significant loss.

4.5 Over-the-Air Measurements

No OTA measurements have been conducted in this setup due to the non-availabiltiy of some key components as mentioned earlier.

5 Conclusions

In this deliverable we document the validation of the TIMES PoC-a and TIMES PoC-2. With back-to-back and OTA measurements we retrieved the systems optimal operation conditions and validate the functioning of all the systems components.

The testing attests the necessary functionality and performance and the systems are ready to be implemented in the actual system demonstrators.

One aspect that has not been addressed yet is the combination of TX and RX with a waveguide coupler, as up to today, the relevant components have not yet been delivered. The installation of this detail will thus happen in the scope of the system demonstrations.

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