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Terahertz end-to-end wireless systems supporting ultra-high data Rate applications

ThoR

Deliverable D6.4

Laboratory Transmission Experiments (DEMO2)

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Change register

Version	Date	Author	Organisation	Changes
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1. Statement of independence

The work described in this document is genuinely a result of efforts pertaining to the ThoR project. Any external source is properly referenced.

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2. Abbreviations

CINR	Carrier-to-Interferer-plus-Noise Ratio
RSSI	Receive-Signal-Strength Indicator
Tx	Transmitter
Rx	Receiver
SSPA	Solid-State Power Amplifier
LO	Local Oscillator
RF	Radio Frequency
IF	Intermediate Frequency
QAM	Quadrature Amplitude Modulation
QPSK	Quadrature Phase Shift Keying
PSK	Phase Shift Keying
WP	Work Package
DRO	Dielectric-Resonator Oscillator
EVM	Error Vector Magnitude
SNR	Signl-to-Noise Ratio

3. Executive summary

This deliverable summarizes the results of the laboratory-based hardware demonstrations DEMO2-1 and DEMO2-2. In DEMO2-1, the successful operation of the developed H-band Tx and Rx modules has been demonstrated applying CW and modulated signals. Additionally, the successful operation together with SSPA and SIKLU modem hardware was successfully verified in short-range wireless simplex and full-duplex scenarios. DEMO2-2 proved the compatibility of the RF hardware together with specifically developed photonic LO generation and provided the final link budget calculations for the long-range outdoor demonstrations, based on measurements of the entire RF chain.

4. Introduction

After the initial feasibility study on the super-heterodyne link architecture done in DEMO1, which has been reported in D6.1 [1], new H-band hardware modules have been developed and manufactured within WP4 and reported in D4.4 [2]. With the successful basic characterization of the standalone devices further characterization and demonstration of the entire wireless link are the focus of WP6.

This document reports on the demonstrations DEMO2-1 and DEMO2-2 which are performed in a laboratory environment at the University of Stuttgart and University of Lille, respectively. DEMO2-1 combines H-band Tx and Rx modules in a back-to-back configuration, driven by electronic LO generation, in order to evaluate the optimum operating conditions of the modules using broadband modulated signals. Applying various complex modulation formats, the corresponding required back-off from the 1dB-compression point of the respective modules is determined.
Adding separate SSPA modules to the transmitter RF port, short range wireless experiments, simplex and full-duplex with transmission distances up to 1.5m, are carried out to also verify the compatibility of the RF hardware with modems, which are intended to provide and process the data to and from the THz link. Simultaneously the compliance with the IEEE802.15.3d channel scheme is tested. For performance evaluation the data throughput as well as the receive signal strength indicator (RSSI) and carrier-to-signal-plus-noise ratio (CINR) are taken into account.

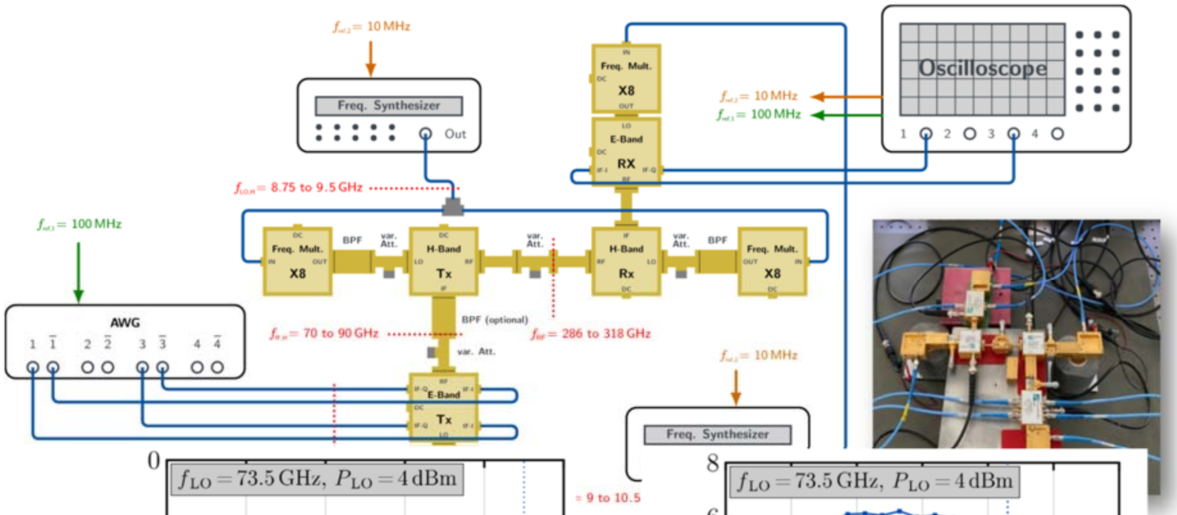
While in DEMO2-1 a purely electronic LO generation is used to drive the frequency converters, DEMO2-2 adds a specifically developed photonic LO generation, designed in WP4 and reported in D4.1. This way optimum operation points for the entire RF chain as well as the final link budget is calculated for the setup as it will be used in the following outdoor transmission experiments within DEMO2-3 and DEMO3.

5. DEMO 2-1

The results achieved within DEMO2-1 are essentially based on three separate measurement setups. For all three scenarios a purely electronic generation of LO signals, required in the frequency range of 70 to 76 GHz, is used. It consists of frequency synthesizers or dielectric-resonator oscillators (DRO) as signal sources, providing output in the X-band. In conjunction with frequency multiplier modules with a multiplication factor of eight, the targeted frequencies in E-band are reached. Except for the simplex wireless link in 5.2.1, the LO signals are applied coherently to the pairs of Tx and Rx modules. To suppress unwanted harmonics arising from the frequency multiplier modules, additional band-pass filters are used. The LO power is adjusted to 3 dBm, based on the measurements reported in D4.4 [2], which ensures maximum conversion gain (CG) independently from the used LO frequency within the frequency range from 72 to 76 GHz.

5.1. Tx / Rx back-to-back Setup

In order to determine the optimum operating point in terms of IF input power to the Tx as well as RF input power to the Rx, the link is operated in a back-to-back configuration. The corresponding block diagram in Figure 1 as well as the shown results are part of [4] where a more detailed description can be found. To up- and down-convert the IF signals to and from the E-band frequency range, custom frequency extensions are used.



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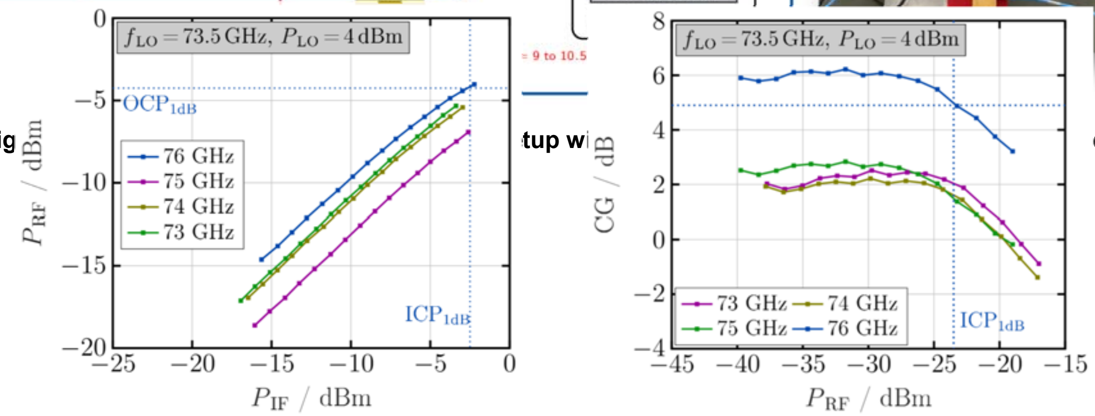


Figure 2: Measured linearity of the Tx (left) and sensitivity of the Rx (right) using CW signals and a LO frequency of 73.5 GHz.

For an exemplary LO frequency of 73.5 GHz the measured EVM is shown in Figure 3 for QPSK, 8-PSK, and 16-QAM modulated signals with a baudrate of 1 GBd. For the characterization of the Tx, the IF input power is swept from -13 to -2 dBm with the RF attenuation kept constant at 25 dB to ensure linear operation of the Rx. The resulting curves indicate the optimum operating point including a required back-off from the ICP1dB, which increases with higher order modulation formats. This is expected due to the increasing peak-to-average power ratio (PAPR) of the complex modulation schemes. The back-off is calculated with respect to the CW linearity and sensitivity measurements depicted in Figure 2. The characterization of the Rx is done by using a constant RF power while varying the RF attenuation between 10 and 40 dB. Combining both results a tolerable loss between Tx and Rx of about 16 dB is calculated, with slight dependency on the used modulation scheme.

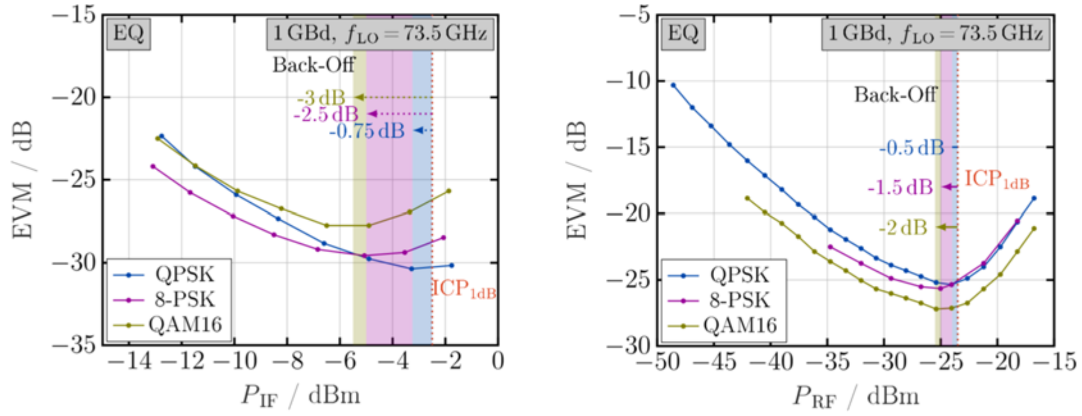
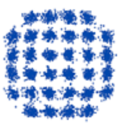
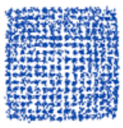
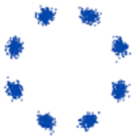
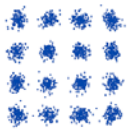
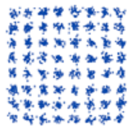


Figure 3: Measured EVM for different modulation formats as a function of the IF input power (left) and RF input power (right).

Using this setup, the link is also tested for higher order modulation formats as well as for increased baud rates. The latter are primarily limited by the available bandwidth of the used E-band extensions. Selected results of those measurements are shown in Table 1, demonstrating a maximum data rate of 32 Gbit/s using 32-QAM modulation. Simultaneously the linearity of the whole link proves to be sufficient for modulation schemes with ultra-high spectral efficiency, such as 128-QAM or 256-QAM. However, here the maximum achieved baud rate is limited to 1.6 GBd.

Table 1: Selected constellation diagrams demonstrating maximum performance as well as IEEE802.15.3d conformity.

	Maximum performance		IEEE802.15.3d			
Channel ID	-	-	44	54	25	26
$f_{IF,center}$ / GHz	79.1	79.25	85.7	79.1	84.6	84.6
$f_{RF,center}$ / GHz	301.2	304.25	302.4	300.2	305.6	307.8
Bandwidth / GHz	8.64	1.35	4.32	8.64	2.16	2.16
Data Rate / Gbit/s	32	8	9.6	25.6	9.6	11.2
Modulation Scheme	32-QAM	256-QAM	8-PSK	16-QAM	64-QAM	128-QAM
Constellation						
EVM / dB	−23.6	−30.8	−20.9	−21.4	−27.1	−30.5
SNR / dB	19.6	26.3	20.6	19	23.5	25.6

5.2. Short-range wireless transmissions (with modems)

To demonstrate the capability of the developed RF hardware not only to deal with signals provided by laboratory-grade arbitrary waveform generator but also with commercial modems, two separate short-range wireless transmission scenarios are used. In both of them additional SSPA modules are used to further increase the available transmit power. The air interface is realized by WR-3.4 horn antennas with an antenna gain of 20 to 25 dBi.

5.2.1. Simplex wireless link with custom E-band frequency extensions and baseband modems

First experiments use the same custom E-band frequency extensions which are connected to either an AWG or a set of baseband modems which use channels with a RF bandwidth of 2.5 GHz and modulation capabilities up to 256-QAM. The corresponding block diagram of the simplex link in Figure 4 as well as the shown results are part of [6] where a more detailed description can be found.

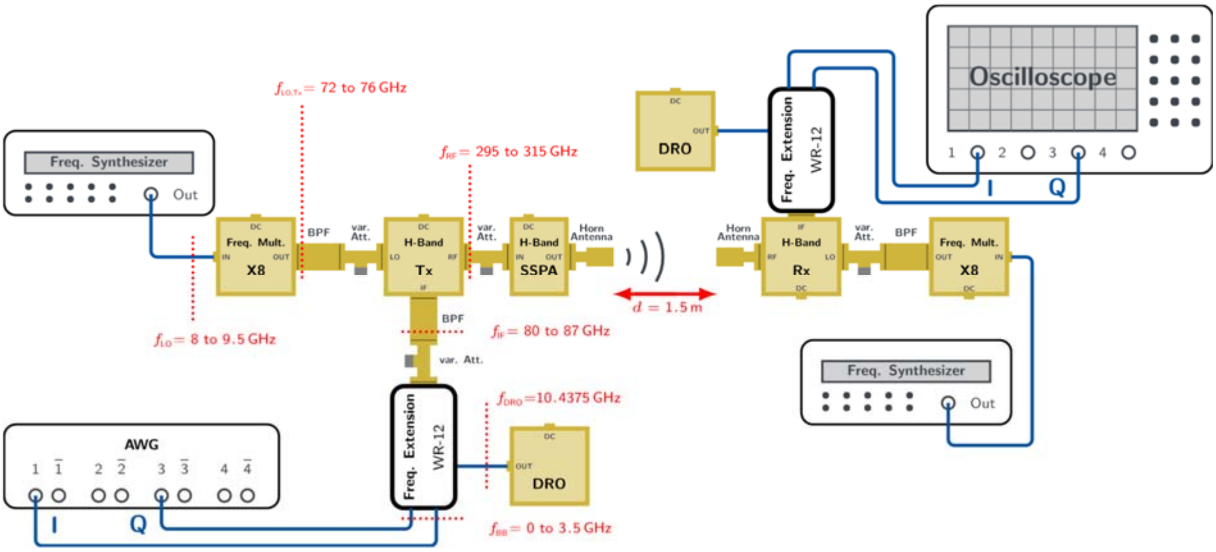


Figure 4: Block diagram of the measurement setup for the simplex wireless link.

With the AWG setup, the link is evaluated for its compliance with the IEEE802.15.3d channel scheme by sweeping the LO frequency. As shown in Figure 5 channels 22 through 28, each expanding over a bandwidth of 2.16 GHz, are successfully addressed using QPSK, 8-PSK and 16-QAM modulation. Additionally, channels 44 to 46, each with 4.32 GHz of bandwidth, are successfully tested with QPSK signals. The shown results are thereby extracted without adaptive frequency equalization applied.

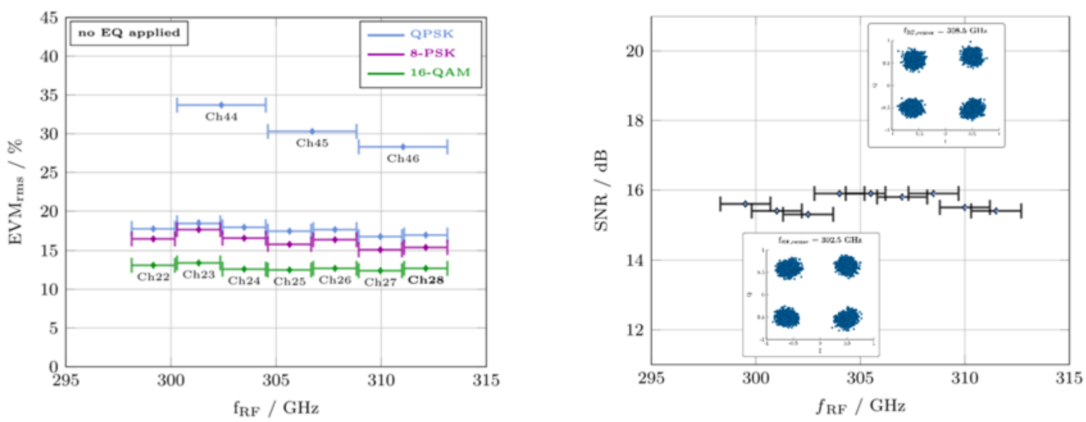
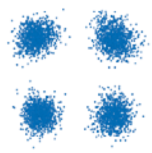
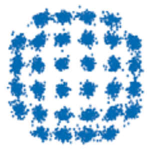
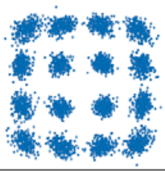
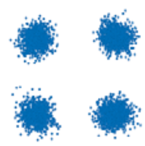


Figure 5: Measured EVM for different IEEE802.15.3d channels using the AWG setup (left) and measured SNR provided by the baseband modems for different RF channels (right).

Using the modems, a simplex real-time transmission is established with the back-channel being realized by a coaxial wired connection of the modems. As displayed in Figure 5 the modems did not manage to increase the modulation to more than QPSK as the signal-to-noise ratio (SNR) did not significantly exceed the threshold value of about 16 dB, which is required for 16-QAM.

Selected constellation diagrams in Table 2, which are captured using the AWG setup, show a maximum data rate of 10 Gbit/s that is achieved using QPSK modulation. The highest spectral efficiency is achieved using 32-QAM modulation with a baud rate of 1 GBd as displayed.

Table 2: Selected constellation diagrams of the achieved maximum performance as well as IEEE802.15.3d compatibility.

	Maximum performance		IEEE802.15.3d		
Channel ID	-	-	27	46	46
$f_{\mathrm{RF,center}}$ / GHz	308.5	309.5	309.96	311.04	311.04
$f_{\mathrm{IF,center}}$ / GHz	83.5	84.5	84.6	83.5	83.5
Bandwidth / GHz	6.75	1.35	2.16	4.32	4.32
Data Rate / Gbps	10	5	6.4	9.6	6.4
Modulation Scheme	QPSK	32-QAM	16-QAM	8-PSK	QPSK
Constellation					
$\mathrm{EVM_{rms}}$ / %	23.7	6.5	10	19.9	19.7
SNR / dB	12.5	19.7	17.4	14	14.1

5.2.2. *Full-Duplex with SIKLU modems*

To verify the compatibility of the RF hardware in conjunction with the E-band modems reported in D3.6 [3], which also will be used for outdoor demonstrations in DEMO2-3 and DEMO3 of the project, a full-duplex real-time wireless link is set up. Using two pairs of Tx and Rx modules as well as Two SSPA modules and one set of modems the link over a distance of 0.5 m is build according to the block diagram shown in Figure 6. The diagram as well as the shown results are part of [5] where a more detailed description can be found.

Figure 6: Block diagram of the full-duplex real-time wireless link including two pairs of Tx+SSPA and Rx modules as well as one set of modems.

Figure 7: Photograph of the full-duplex real-time wireless link set up in the laboratory.

The performance evaluation is done using open-source traffic generation tools running on two PCs, one per link terminal. Additionally the CINR provided by the modem graphical user interface

(GUI) is taken into account. Using IF channels with 2 GHz of bandwidth, the up-link and down-link are centered at 72.125 and 82.125 GHz in the IF domain, respectively. The corresponding throughput and CINR with respect to the IEEE802.15.3d channels are displayed Figure 8. Again the addressing of the different channel is achieved by variation of the LO frequency of the H-band modules. The modems are capable of establishing the duplex-connection in all of the tested scenarios. Using modulation schemes up to 64-QAM a maximum per-channel throughput of around 7 Gbit/s is reached. 128-QAM transmission are prevented by the CINR not sufficiently exceeding the required threshold of 23.6 dB. The reduced performance in channels 16, 17, and 18 is due to the fact that the fourth harmonic of the frequency multipliers, integrated in the H-band modules, is present at the RF port as well. This creates in-band interferers at 285.43 GHz, 288.31 GHz, and 291.19 GHz. Therefore the modulation scheme and thus the achievable throughput is limited. Since the modems are not capable of applying different modulation schemes to the up- and downlink at the same time, channels 22, 23, and 24 are simultaneously limited with respect to the achievable throughput.

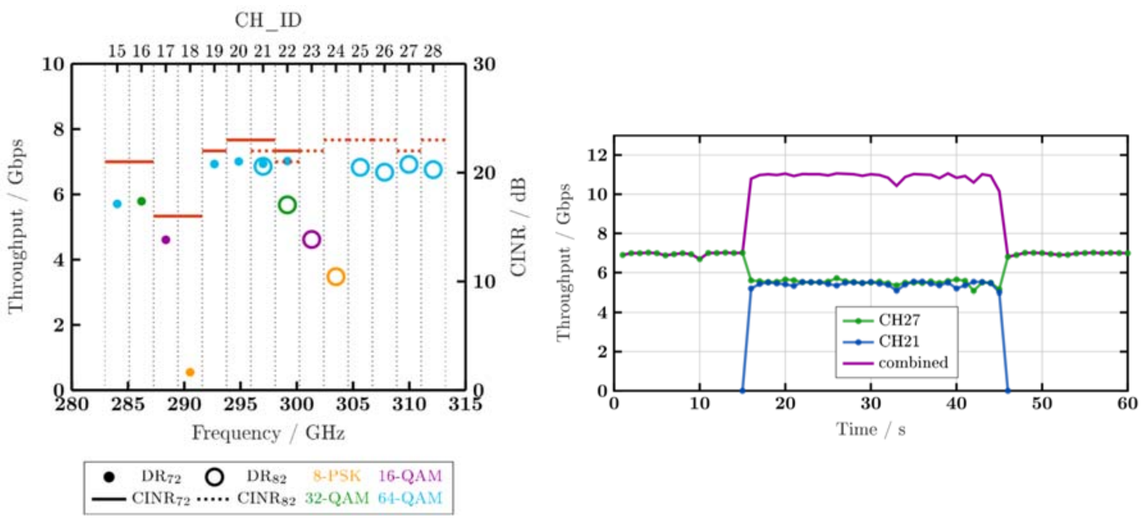


Figure 8: Measured throughput and CINR using various IEEE802.15.3d channels (left) and maximum duplex throughput (right).

The maximum duplex-throughput is evaluated by sequentially initiating and terminating the traffic generation at both terminals as displayed in Figure 8. Using channels 21 and 27 of the IEEE802.15.3d scheme, a total throughput of 11.09 Gbit/s is achieved, while the individual channels both use half of the traffic.

6. DEMO 2-2

In contrast to DEMO2-1 the electronic LO generation is replaced by the specifically designed photonic LO generation for DEMO2-2. This way again optimum operating points for the Tx, Rx and SSPA modules are determined in the dependency of the LO power. Additionally, the available link budget is calculated including the system gain.

6.1. Standalone characterization of Tx / Rx module using photonic LO

Targeting the association of the THOR Tx and Rx to set-up a full directional link in the 300 GHz band, using the photonic LO, several steps are taken:

- to feed the Tx and Rx with the photonic LOs
- to realize an IF to IF transmission, qualified using a referenced IQ generator.
- to investigate the maximum losses that can be supported between the Tx and the Rx, in order to determine the system gain of the full association.

Figure 9 is presenting the experimental setup used for the realization of the data-link.

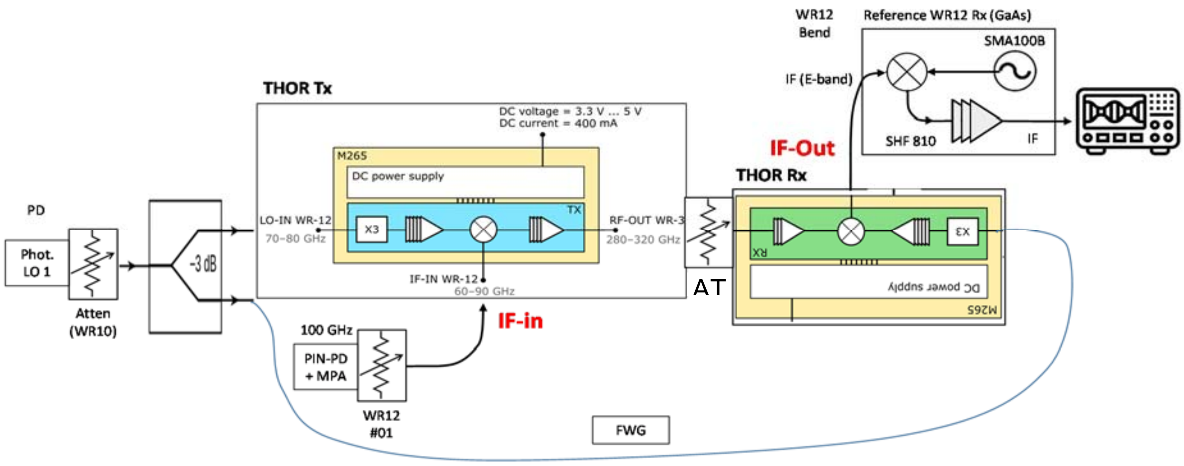


Figure 9: Test of the THOR Tx/Rx association: in this case, the same photonics-based LO is used for up and down-conversion. Here the 'IF-in' is transmitted towards 'IF-out'. FWG is a flexible waveguide, feeding the LO of the THOR Rx. The WR3 attenuator (ATT) is simulating a FSPL between the Tx and the Rx.

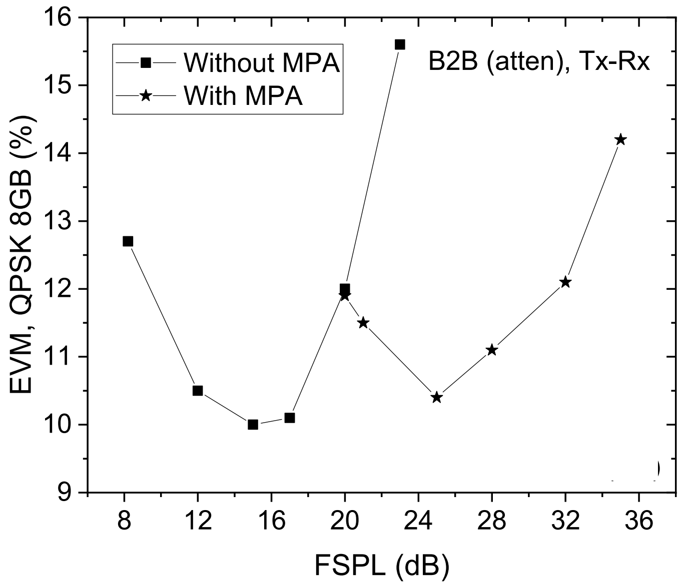
In this setup, the THOR Tx and Rx modules are connected thanks to an waveguide attenuator. A WR10 power splitter is used to split the photonic LO signal to pump the Tx and Rx, respectively. A flexible waveguide is used to realize this connection from the photonic LO to the LO-input of the THOR Rx.

IF-in to IF-out evaluation

To validate the THOR Tx/Rx full RF front-end, the transmission from IF-in to IF-out has to be evaluated. This is measured considering an I/Q generator which is used at the THOR Tx input, while the IF receiver is used to down convert the signal for analysis of the EVM parameter. Setting up a specific data baud rate, the attenuation value between the Tx and Rx is set using the WR3 attenuator placed in between.

Two scenarios are compared here: the first one is corresponding to the Figure 8, where no MPA is used. Then, the MPA module is placed in between and the IF power adjusted accordingly. In this tests, two modulation formats are used, QPSK and QAM-16, for 8 GBd. When varying the attenuator, the EVM is evaluated for several attenuation values, simulating the free space path loss (FSPL) of a 300 GHz link. The results of these characterisations are shown in Figure 9.a (QPSK) and Figure 9.b (QAM-16).

a)



b)

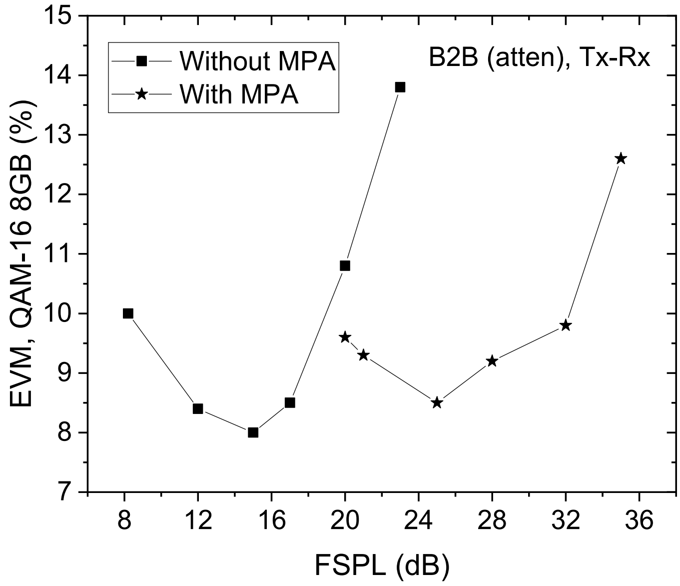


Fig. 9: Test of THOR Tx/Rx association, with 1 photonic LO pumping the Tx and Rx. Evolution of the EVM (%) of the detected QPSK (a) and QAM-16 (b) signal as a function of simulated FSPL.

Typical bathtub curves are obtained, where the EVM is high when the system is limited by non-linearities of the Rx or noise-limited when the received power is too low. For high FSPL, the received power is too low at the LNA input (receiver) and the EVM increases quite fast. For lower FSPL values, the saturation of the receiver is clear.

The obtained FSPL, without MPA, is around 16 dB for 8 GBd. The system margin obtained with the addition of the MPA is increased by around 9 dB, reaching 25 dB. The optimum point is considered to be +/- 1 dB around the optimum point. Using the MPA in the whole chain, system margin increase is coming with small EVM degradation. This can be due to the MPA noise figure and overall noise contribution.

It should be noted that the obtained values are close to estimated 22 dB margin, for 12.5 GBd, from stand-alone evaluations of the Transmitter (Tx) and Receiver (Rx) described in the THOR D4.6 [7]. A reduction of the baud rate from 12.5 to 8 GBd leads to an additional 2 dB margin (as the bandwidth is lower by a factor of 8/12.5), leading to a 24 dB margin, found very close to the obtained 25 dB in D4.6 [7]. The 1 dB variation can easily come from differences in the applied equalization, as the spectrums are different between 8 and 12.5 GBd.

6.2. Short-range wireless link including modems and phot. LO

Final association of the THOR Front-ends, combining photonic LO and MODEMs is ongoing at the time of writing this deliverable. The associated results will be reported in the final deliverables of the THOR project.

However, considering the FSPL of 200 m of air transmission, a 126 dB value is obtained without any air specific attenuation. This means that we can estimate that with 52 dB antenna gains at each site, the system should be able to work with QAM-16 12.5 GBd, according to the available system margin of 22 dB. The final performance will be determined considering the full association of Tx/Rx, photonic LOs (1 per site), and Modems.

7. Conclusion

This deliverable D6.4 provides experimental results of the laboratory-based transmission experiments conducted within DEMO2. Consisting of two sub-demonstrations (DEMO2-1 and DEMO2-2), the first focused on the joint operation of the developed H-band Tx and Rx modules in a back-to-back configuration as well as some short-range wireless transmissions, also including SSPA modules for increased transmit power as well as one set of modems as data signal sources, forming a full-duplex real-time link. The latter focused on the additional integration of the photonic LO generation, showing comparably results. Additionally, the final link budget has been determined. This way successful outdoor demonstrations are enabled.

8. References

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