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Tera**h**ertz end-to-end wireless systems supp**o**rting ultra-high data **R**ate applications

ThoR

Deliverable D4.7

Final report of the RF front-end developments

Coordinator (EU): Thomas Kürner
Organisation: Technische Universität Braunschweig

Coordinator (Japan): Tetsuya Kawansihi
Organisation: Waseda University

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Contents

Change register

Version	Date	Author	Organisation	Changes
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B	July 22th, 2022	Guillaume Ducournau, Pascal Szriftgiser	ULIL	Revision

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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.

Confirmation by Authors: Guillaume Ducournau, Pascal Szriftgiser ULIL

2. Abbreviations (TO BE UPDATED)

AWG	Arbitrary Waveform Generator
BW	Bandwidth
Gbps	Giga bits per second
EVM	Error Vector Magnitude
FE	Front End
FWG	Flexible WaveGuide
InGaAs	Indium Gallium Arsenide
LNA	Low Noise Amplifier
LO	Local Oscillator
MPA	Medium Power Amplifier
NF	Noise Figure
PA	Power Amplifier
PSG	Performance Signal Generator
QAM	Quadrature Amplitude Modulation
QPSK	Quadrature phase shift keying
RF	Radio Frequency
SHM	Sub-Harmonic Mixer
SNR	Signal to Noise ratio
SSPA	Solid State Power Amplifier
TWTA	Travelling Wave Tube Amplifier

3. Executive summary

The TeraHertz end-to-end wireless systems supporting ultra-high data Rate applications (ThoR) project aims at providing a technical solution for back- and fronthauling operating in the 300 GHz frequency range. These high frequencies offer the advantage of a high available bandwidth, which directly translates into high data rates. The final ThoR front-end has been designed and has been operated using either 4 modems in the E-band from SIKLU, Israel [1], or TDD modems from HRCP, Japan [2].

The main focus of the D4.7 is to summarize the full RF Front-end developed in the ThoR project. The final RF Front-end is composed of three main elements:

- Photonics-based local oscillator, described in the D4.1 [3]
- RF modules for up/down conversion, and medium power amplification, described in D4.2 [4], D4.3 [5], D4.4 [6].

As reported in the D4.5 [7] and D4.6 [8], the travelling-wave tube amplifier (TWTA) was not available, and integrated in the final RF front-end. Nevertheless, this was not a show-blocker for the validation of the overall ThoR architecture. Indeed, as the TWTA was intended to be used to extend the range of the transmission system, the final transmission distance was set according to the final measurements carried out on the RF front-end (e.g. with a reduced distance related to the available system margin without TWTA).

In the D4.6 [8], the tests of these elements were done:

- Photonic LO
- THOR Medium Power Amplifiers modules
- THOR Transmitter

The general conclusion of the D4.6 was the validation of the different sub-systems that define the full ThoR RF front end:

- The photonic LOs has been re-checked and are compliant to the requirements (phase noise and power performance).
- The ThoR receiver was successfully pumped by the photonic LO. The optimum LO powers, RF power were determined using modulated data signals in the THz range, leveraging a dedicated setup established in Lille. The down-conversion of up to QAM-16/50 Gbit/s data-rate was validated, with EVM around 9%.
- The ThoR transmitter was successfully pumped by the photonic LO. The linearity of the ThoR Tx was determined and IF signals, up to 32 and 40 Gbit/s were successfully up-converted to the 300 GHz band. IF power optimum is found to be close to -12/-10 dBm (QAM-16). The degradation of the EVM from IF to THz band is found to be very low at the optimum point.
- The medium power amplifiers were tested in terms of gain, linearity in CW and degradation of the EVM with input modulated data was evaluated using several modulation formats and baud-rates. Available power at MPA output with no significant impairments on the EVM of the IQ map is found to be close to 1-2 dBm for QAM-16.

In this deliverable D4.7, the description of the final front-end assembly is done, i.e. the assembly of the two pairs of Tx/Rx to be used in **duplex links at 300 GHz**. The system was setup and different tests carried out in Lille, before the use in the demos stages (Berlin, at Deutsche Telekom and Braunschweig, TUBS).

We also report on the verification of the FDD and TDD hardware to the final RF Front-end, as a milestone prior to the final demo stages.

4. Introduction

Although it is a big technological challenge, communication systems operating at extremely high frequencies, above 100 GHz, are experiencing an exponential development due to the continuously increasing demand for high data rates. Wireless links with centre frequencies around 300 GHz (so called terahertz band) have been successfully built in the last decade and impressive data rates have been reported in [9-11]. Until now all these successful data transmissions have been realized in a laboratory environment transmitting only pseudo-random bits sequences. Also, almost all demonstrated systems are leveraging AWGs and complex digital signal processing (D.S.P.), which is interesting to evaluate the overall performances.

However, while future THz systems may not use this advanced D.S.P. processes, approaches that are compliant to real signals used in networks is of utmost importance. In addition, the target distance of the demonstrators in the ThoR project is up to km range rather than lab distances (10-15 meters).

In this context, the goal of ThoR project was to design and develop a terahertz (THz) communication system which can be used in real environments supporting a deployment of 5G and beyond 5G networks. Such a communication system implies the combination of fast baseband and cutting edge terahertz devices. Fig. 1 shows the scenario of a real-life application in which the ThoR system can be successfully integrated. The main building blocks of ThoR communication device are modems, in orange, the combining/splitting structures (in blue) and the 300 GHz transmitter (TX) and receiver (RX), in green.

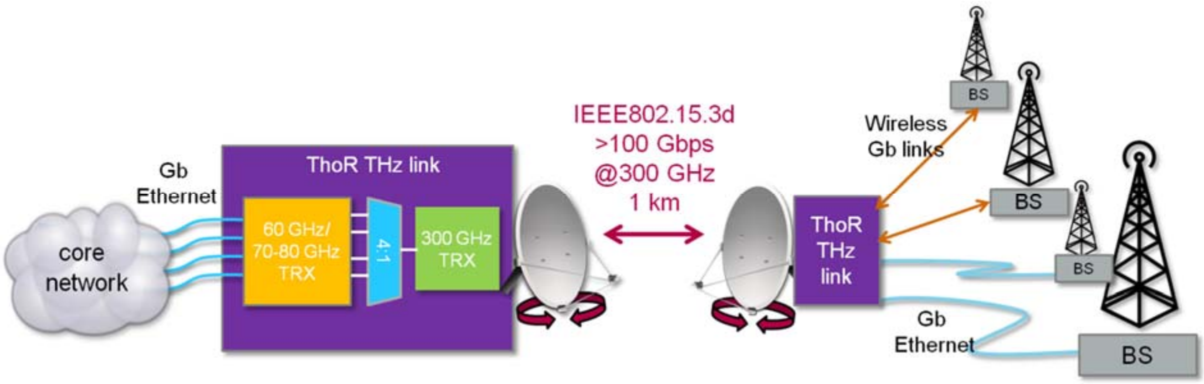


Fig. 1: The example of a deployment scenario of the ThoR system. The ThoR communication device integrates baseband electronics, 60/70-80 GHz modems, 300 GHz RF transmit/receive modules (in green) and TWTA. [4]

The present deliverable is focused on the description of the final configuration of the ThoR developed hardware to reach the objectives of duplex THz links, using two pairs of up/down conversion of V/E bands signals to the 300 GHz range.

5. Final ThoR RF front-end assembly

5.1. General overview – Overall RF Front end

This paragraph is a reminder of the architecture of the overall RF front-end based on the combination of photonics-based LO, RF up/down converters and MPA. This is given in the figure 2.

In this overall architecture, the photonic-LO, after being multiplicated by 3, is mixed with IF input in V or E-band. Then the ThoR up converter is used to reach the 300 GHz band, before a final amplification stage using an SSPA (Solid State Power Amplifier) or MPA (Medium Power Amplifier). Then signal is sent to the ThoR Rx, composed of LNA, mixer, also pumped by a second photonics-based LO, to down convert to IF-out.

In this configuration, a simplex link is realized. Duplex link is then achieved using a second set of Tx/Rx circuits, pumped per link terminal by the same photonic-LOs. In this approach, 2 photonic LO are used for duplex link (1 each site for the duplex link).

In the simplex link (figure 2), one photonic LO stands at each site.

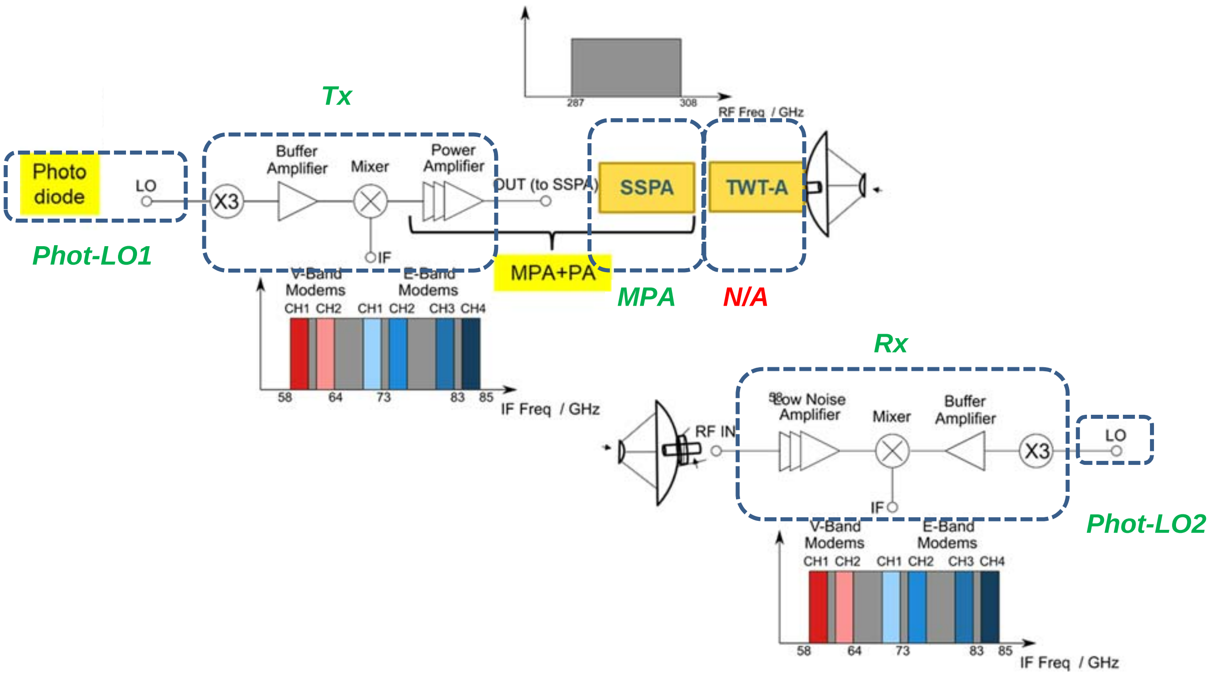
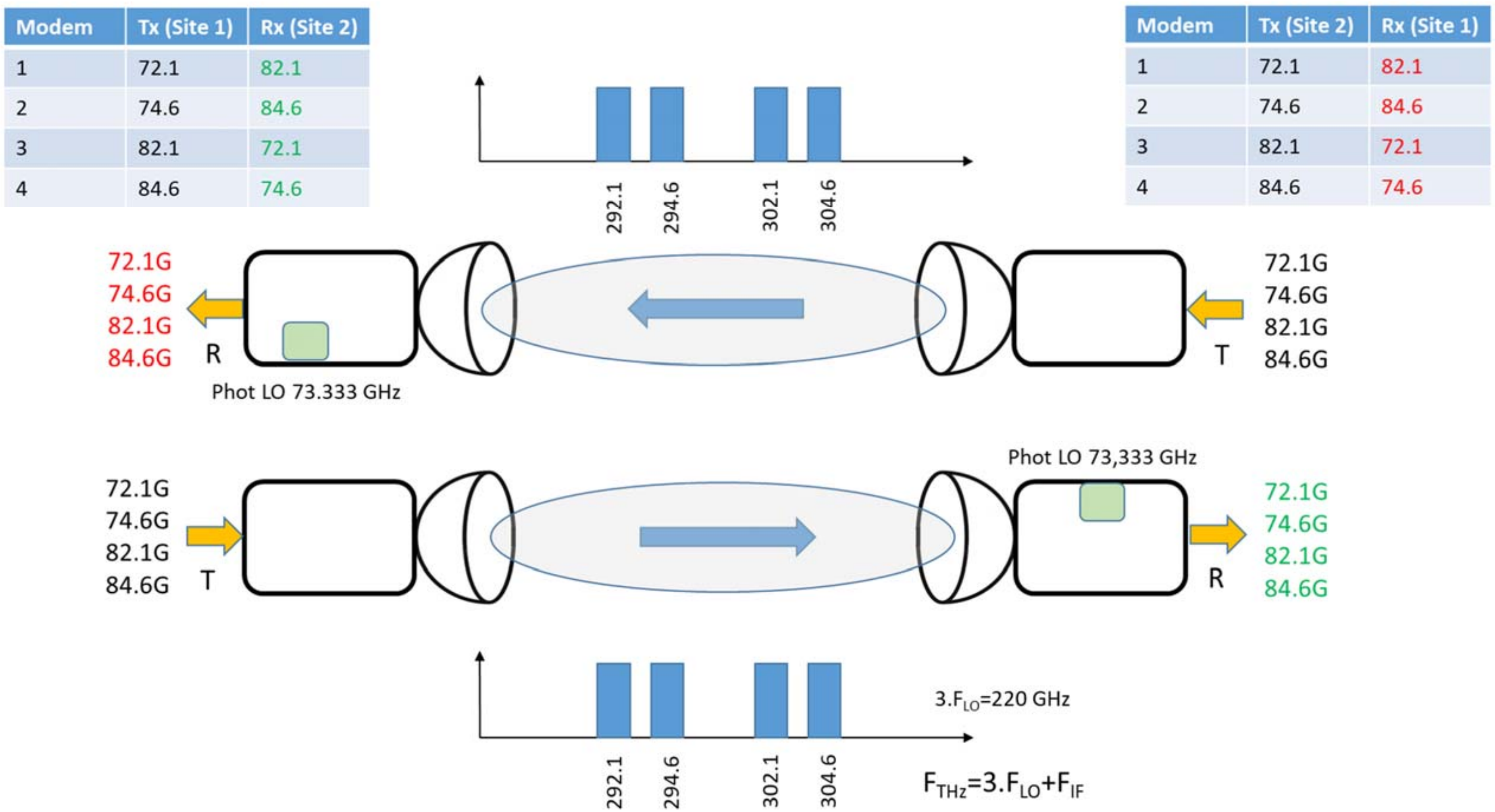


Fig. 2: Overall RF Front end of the ThoR 300 GHz transmission system (Simplex case).

In the final ThoR front-end, a pair of Tx/Rx is to be used to achieve a duplex link. This is shown in the figure 3 for the use case of the SIKLU MODEMs connections at both ends.



Modem	Tx (Site 1)	Rx (Site 2)
1	72.1	82.1
2	74.6	84.6
3	82.1	72.1
4	84.6	74.6

Modem	Tx (Site 2)	Rx (Site 1)
1	72.1	82.1
2	74.6	84.6
3	82.1	72.1
4	84.6	74.6

Fig. 3: ThoR duplex link using a pair of Tx/Rx front-ends, defined from final RF Front-end measurements at ULIL.

 Named Distribution Only

5.2. Final performances of the RF Front end (System margin)

To validate the full RF front end, several tests have been carried out, for step-by-step validation of the different sub-systems, most of the stand-alone developments and associated measurements were described in the other deliverables (D4.1 to D4.6 [3-8]).

In this paragraph we report on the final measurements done on THOR RF front-ends, where the system margin in the 300 GHz range was evaluated. The estimation of the system margin was done using simplex case with only 1 back-to-back (waveguide) direction, ie corresponding to figure 3 without any antenna system. This configuration is shown on figure 4, with no MPA included, ie with direct connection of the Tx to the Rx, with attenuator in between to simulate the Free Space Path Loss (FSPL) at 300 GHz.

Two cases have been distinguished:

Case 1: without the MPA. This is to assess the maximum data-rates/minimum EVMs

Case 2: with the MPA (for maximum system margin, i.e. to assess optimum scenario for the demonstrations to be done at TUBS, i.e. 160 m or km-range).

In terms of integration of the experimental setup, the integration of MPA is done at Tx output, with a direct waveguide connection, while ensuring that the MPA is operated in the linear range (described in the D4.6 [8]).

Figure 5 shows the experimental testbed used to qualify the two simplex links in their final configuration, feed by the photonic local oscillator (PHOT LO).

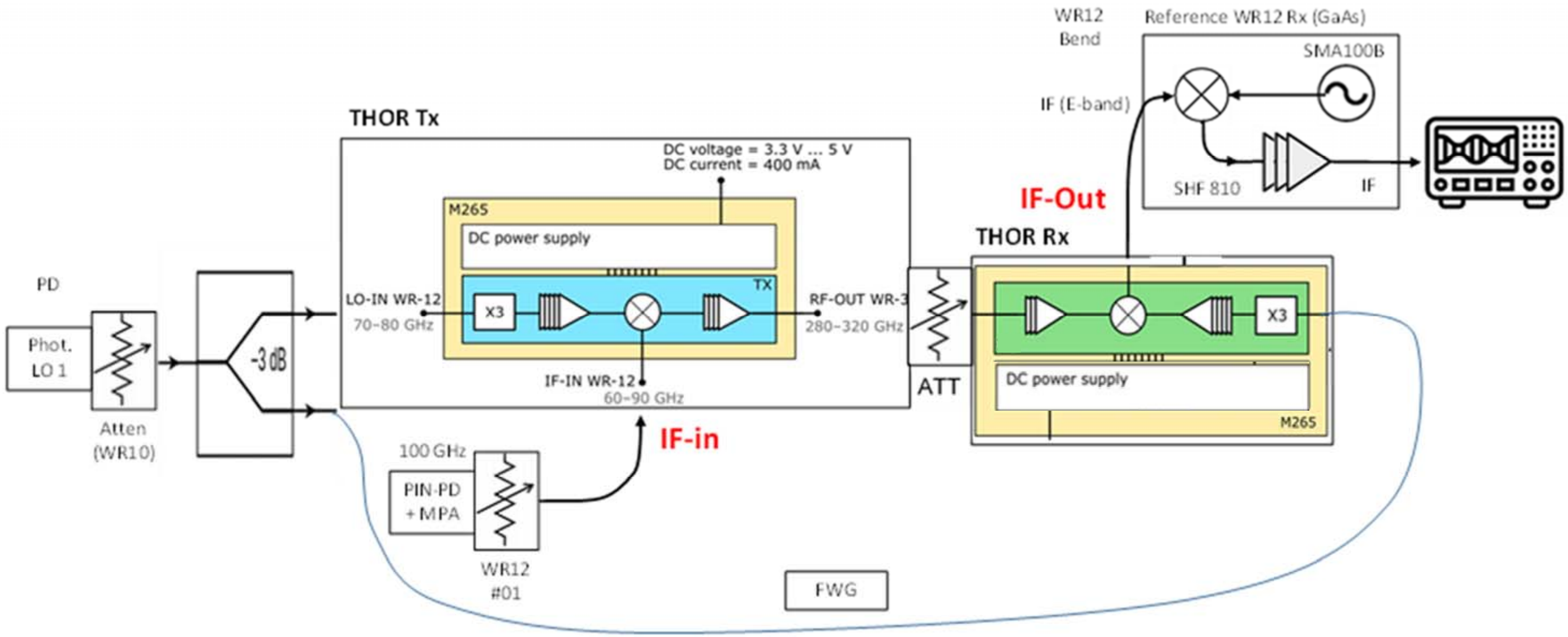


Fig. 4: Final configuration of ThoR simplex link using a pair of Tx/Rx front-ends, to assess the 300 GHz system margin (MPA not represented).

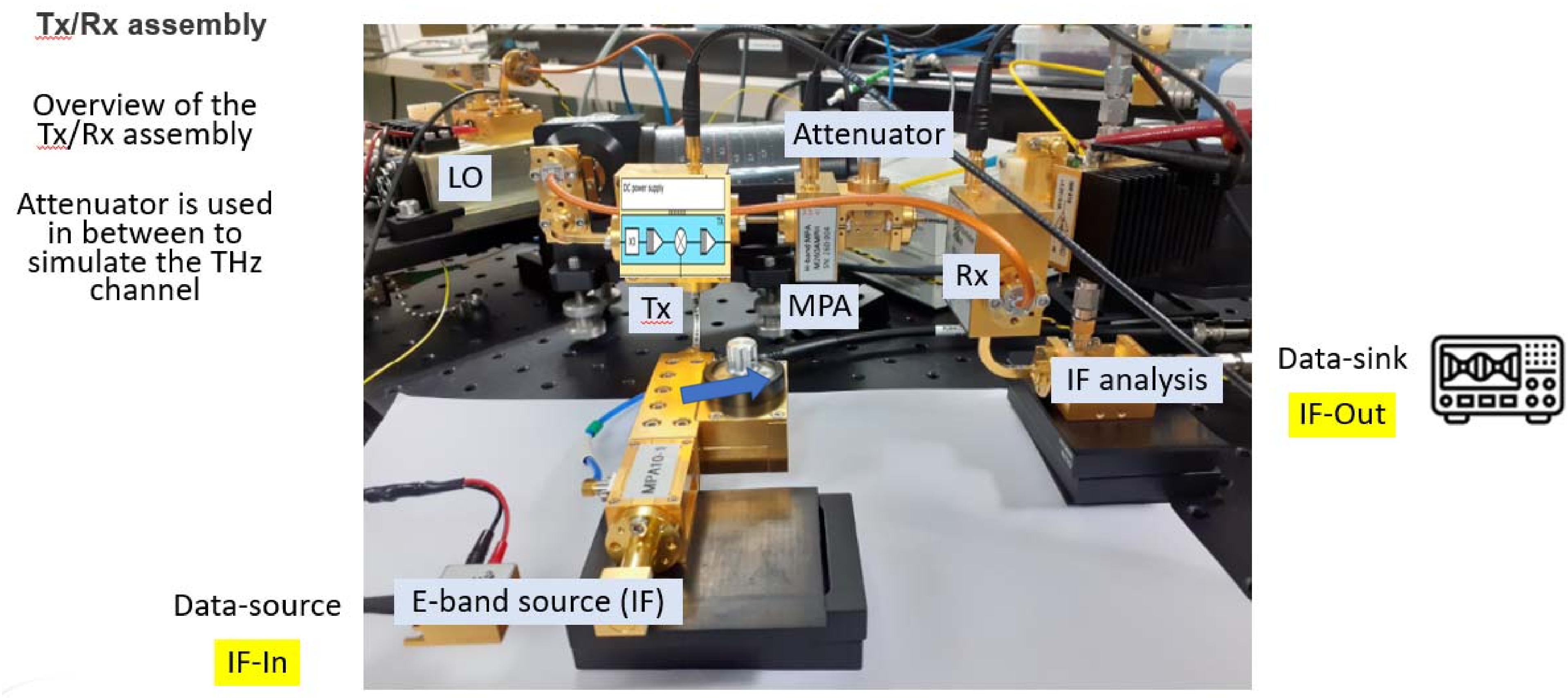


Fig. 5: Experimental setup of the THOR simplex (1 Tx, 1 Rx) testbed, with MPA connected, used to determine the system margin of the final RF Front-ends.

System margin measurements

In figure 6, the system margin is determined by evaluating the error-vector magnitude (EVM, %) of the overall THOR link for different data-rates, at 8 GBaud. QPSK and QAM-16 signaling was used in this case, for the system with and without MPA placed at final Tx stage.

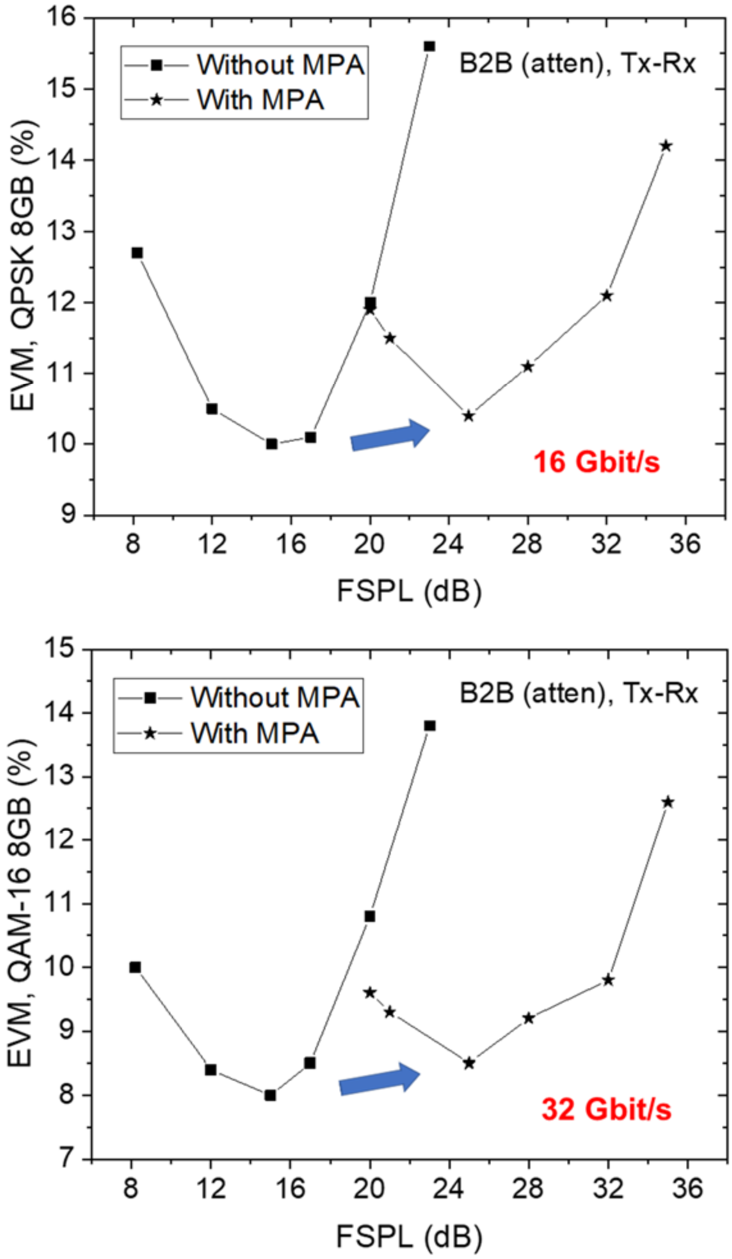


Fig. 6: Performance of ThoR simplex link in QPSK and QAM-16 at 8 GBaud. The FSPL (dB) is corresponding to the calibrated attenuation placed in between Tx and Rx modules. IF is fixed in this case at 75 GHz.

In these curves a system margin close to 15 dB is obtained without MPA and 24-25 dB with the MPA connected. The same values were obtained for the second set of THOR modules.

5.3. Estimation of the link range

Looking on transmission equation, where R is the distance in km, α the attenuation (dB/km), and G_e/G_r the antenna gains (dBi) the overall losses L is defined by:

$$L_{dB} = P_{e,dBm} - P_{r,dBm} = \underbrace{92.4 + 20.log(f) + 20.log(R)}_{\text{Free space propagation losses (FSPL)}} + \alpha.R - G_e - G_r$$

The antenna gains of the two Cassegrains (one pair from Stuttgart, one pair from Lille) used in the final demonstration are estimated to 50 and > 55 dBi, respectively, corresponding to 105 dB FSPL compensation. Figure 7 is giving the estimation of the overall losses (L dB) at 300 GHz for a medium at 10 dB/km. In this conditions, a 180 m distance could be expected. However, it should be noted that 10 dB/km is a quite pessimistic attenuation range at 300 GHz, ie in a sunny weather attenuation is likely lower.

As antenna gains are concerned, we assume, even if we didn't measured it, that larger Cassegrain (Lille's antennas) is close to be 60 dBi, corresponding to the 2 additional cases considered (10 dB/km and 5 dB/km) in the figure 7.

Beyond weather effect, the final demonstration including channel aggregation is using a multiple channel, a couple of dB from the limit should be taken into account. The last chosen value for the distance was 160 m for the final demo of the THOR project, which comes with a sufficient margin for the measured limit (24-25 dB as shown on the figure 6), considering that for disturbed weather (10 dB/km), the system would be close to the measured limit.

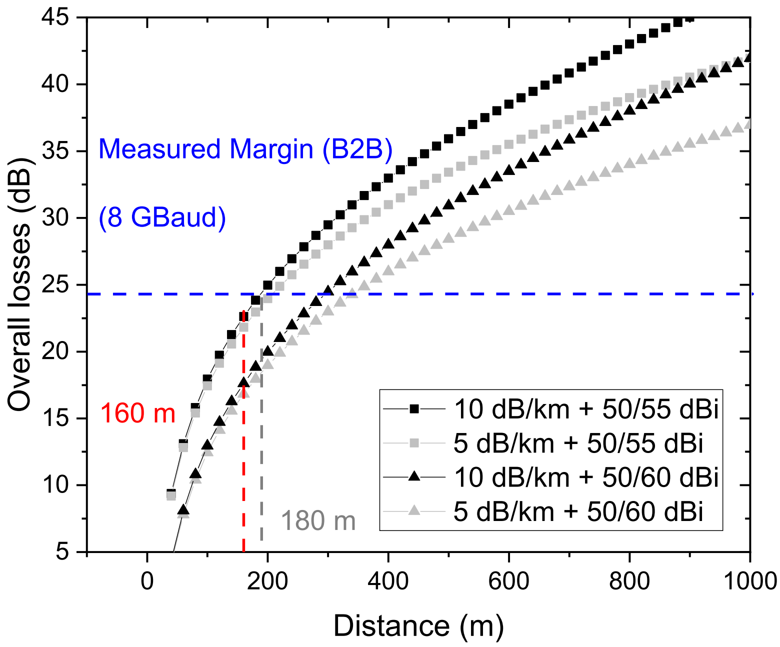


Fig. 7: Estimation of the link range in the simplex case, using 1 carrier (1 channel @ 8 GBaud) from link budget analysis.

5.4. Duplexing system for the validation of the Front-end for bidirectional link

In addition to the tests conducted in simplex links, the system was also tested in the duplex configuration. In the final demo of the ThoR project, a set of two antenna pairs are to be used in the duplex link, enabling full bi-directional transmission. In order to enable the test of ThoR system in waveguide, a duplexing system was developed at ULIL for the validation of the RF front-ends with the ThoR MODEMS (TDD mode from HRCP partner [2], and FDD mode from SIKLU partner [1]).

The concept and system testbed are shown on the figures 8 and 9.

The duplexing system was optimized and calibrated to be able to cover the equivalent FPSL range measured previously. In addition, the test was done using Gbit/s SIKLU ports in the duplexed link, with 74.6 and 84.6 GHz carriers at IF ports, corresponding carriers at 295 and 305 GHz, respectively.

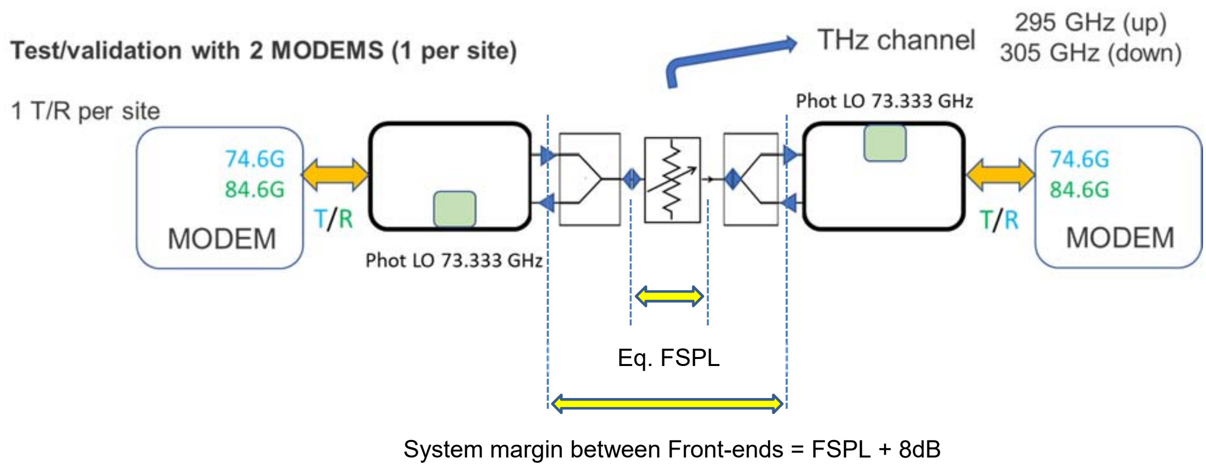


Fig. 8: Measurement of the ThoR front-end using a duplexing system and variable attenuator in between (SIKLU MODEMS case, with 74.6/84.6 GHz E-band channels). The duplexing system has a typical loss of 8 dB at 295 and 305 GHz carrier frequencies.

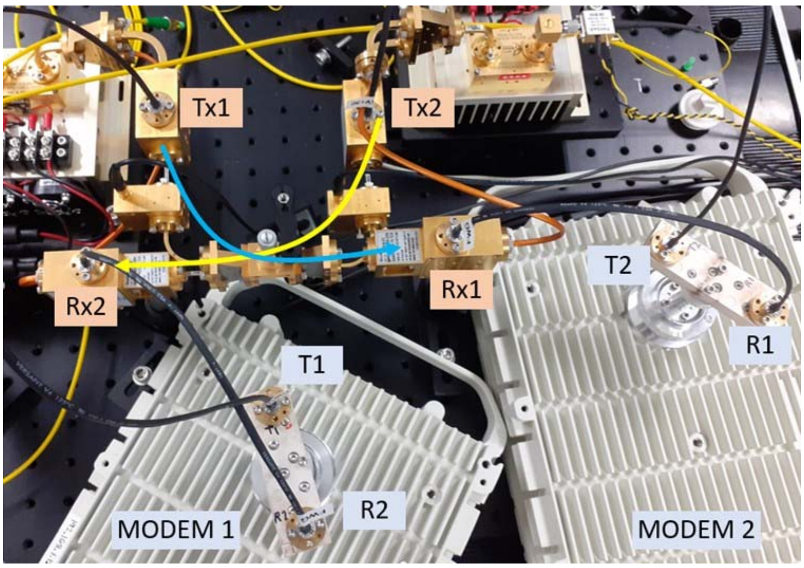


Fig. 9: Experimental testbed: measurement of the ThoR front-end using a duplexing system and attenuator in between (SIKLU MODEMS case, with 74.6/84.6 GHz E-band channels).

5.5. Validation of the ThoR system, SIKLU FDD modem case

To assess the functionality of the link, the two MODEMS were run at each terminal site, and CINR/RSSI (dB/dBm) were measured for different modulations schemes. Figure 10 is giving the result for a QAM-16 signal. While the performance shows CINR close to 21 dB, for two channels @ 16 dB FPSL, the channels suffers from small imbalance between the two channels, mainly due to the fact that one of the MODEMS was worse in power performances. Here, as the duplex link is reached with waveguide-based elements, extra-losses of close to 8 dB is affecting the signal. It means that in the final demos, where the duplexing system is not used, eq. FSPL of 16 dB in fig. 10 will correspond to 24 dB losses between front-ends (figure 8)

This confirms that the final front-end is compatible with a duplex link in FDD, and CNIR close to 21 dB is expected (channel bandwidths 2 GHz). In the final demos, the losses of the duplexing system will not affect the system as 4 antennas will be used, and there is no need for the duplexing waveguides elements used in the schematic (figures 8 and 9).

Fig. 10: FDD duplex link: validation of the dual channel operation, using the final RF ThoR front-end, for 2 GHz channel bandwidth Ifs signals in the E-band. The eq. FSPL is the attenuation between the duplexing system ports.

To confirm that the 16 dB FSPL was in-line with expectations a 100 meter link was realized with the final configuration of the ThoR front-end, with the Cassegrain antennas available in Lille, which features gains > 55 dBi.

At 300 GHz, 120 dB isotropic losses are expected, thus 110 dB total total antenna gain would be compliant to meet the system margin range (figure 7).

To confirm this, a test of 100 meter was validated.

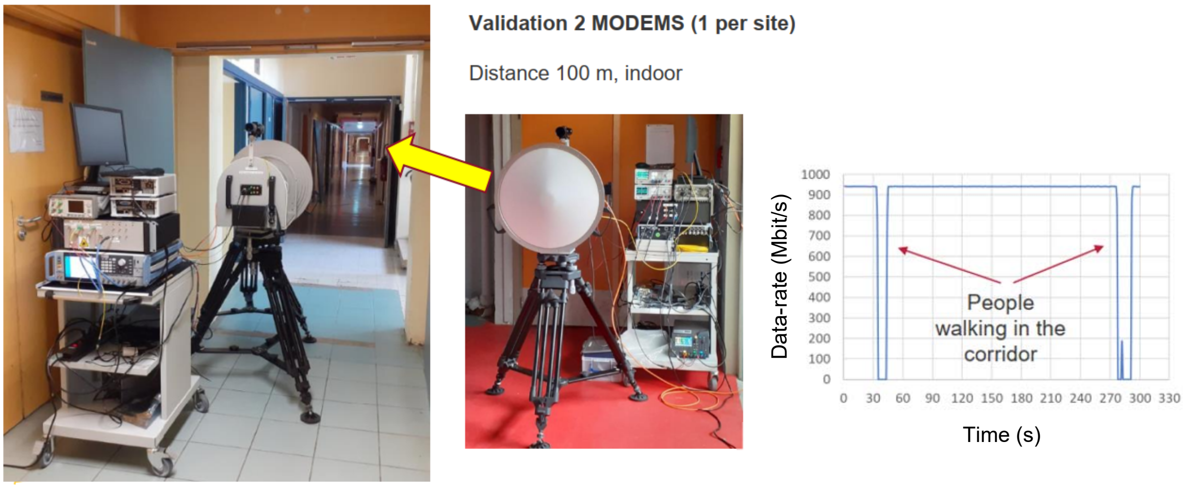


Fig. 11: FDD duplex link: validation of the dual channel operation, using the final RF ThoR front-end with photonic LOs, for 2 GHz channel bandwidth IFs signals in the E-band (74.6 GHz and 84.6 GHz), and corresponding THz carriers of 295 GHz and 305 GHz. Transmission distance is set to 100 m. Right plot: stability of the link over time.

5.6. Validation of the ThoR system, HRCP TDD modem case

The final RF Front-end was also tested using TDD modems. The same duplexing system was used to demonstrate that the system would work in the bi-directional configuration. The figure 12 is showing the obtained performances of the final RF Front end.

The curves in back-to-back (B2B) corresponds to the HRCP TDD Modems connected directly each-other, using an attenuator in between to simulate the FSPL/system margin.

These modems were described in [2]. At the time of the experiments, the output power of these modems was not controllable, thus the attenuator was used in order to determine the optimum power loss between Tx and Rx in the TDD case, obtaining data-rates, close to 4.5 Gbit/s. We can also observe an imbalance within Tx1-Rx1 and Rx1-Tx1 performance.

The association of the TDD modems was also done with the final RF front-end, in the same configuration that the one settled up for the SIKLU FDD modems. Similar to the B2B measurement, an attenuator was used to vary the attenuation level between the two duplexing systems, as shown in figure 9, but in the TDD case, single THz channel was 302.16 GHz.

The system margin found when combining the ThoR front end (FE) system with TDD modems was leading to feature > 2.5 Gbit/s for > 30 dB system margin, validating the concept of up/down conversion of the TDD system to the 300 GHz band.

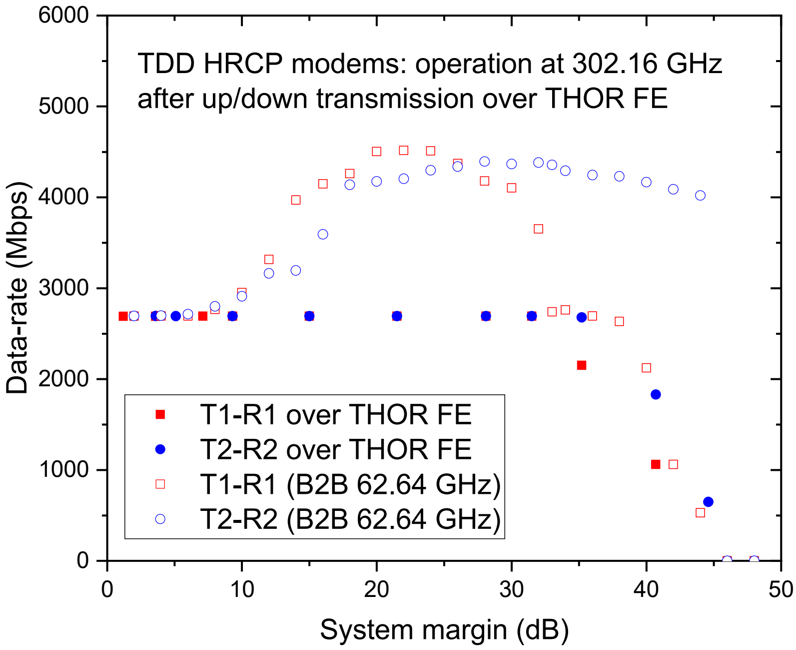


Fig. 12: Performance of the THOR system for up/down conversion of TDD MODEMS at 60 GHz to the 300 GHz band. TDD operation is successful with a data-rate up to 2.7 Gbit/s.

6. Summary and conclusions

The general conclusion of this document is the validation of the final ThoR RF front-end.

- The ThoR RF front-end has been characterized in terms of system margin.
- The estimation of link range has been done according to the scenario of the final demo.
- The ThoR front-end was successfully combined with the FDD modems, using a duplexing system in the 300 GHz range, to validate the concept while staying calibrated in the 300 GHz for the duplexed system with the SIKLU FDD modems [1].
- The TDD approach, validated in the 300 GHz band, using the MODEMS from HRCP partner [2].

The final steps is to use the final RF Front ends in the final demos (Berlin, and TUBS). This will be reported in the last deliverables of the ThoR project.

7. References

[1] ThoR Deliverable D3.6, available at https://thorproject.eu/results/deliverables/. "Testing Report of 70/80 GHz TRX Module"

[2] ThoR Deliverable D3.5, available at https://thorproject.eu/results/deliverables/. "Testing Report of 60 GHz TRX Module"

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[4] ThoR Deliverable D4.2, available at https://thorproject.eu/results/deliverables/. " RF Circuits design"

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[7] ThoR Deliverable D4.5, available at https://thorproject.eu/results/deliverables/. "TWTA Amplifier"

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