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

ThoR

Deliverable D6.1

Initial hardware demonstration DEMO1

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Change register

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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

5G	5th generation of cellular mobile communication systems
AWG	Arbitrary Waveform Generator
b2b	back-to-back
B5G	Generation(s) Beyond 5G
BER	Bit Error Rate
bps	Bit per second
DSP	Digital Signal Processing
EVM	Error Vector Magnitude
FET	Field Effect Transistor
FSPL	Free Space Path Loss
GBd	Giga Baud
GbE	Gigabit Ethernet
ICT	Information and Communications Technology
IF	Intermediate Frequency
LCP	Liquid Crystal Polymer
LO	Local Oscillators
MMIC	Monolithic Microwave Integrated Circuit
mm-wave	Millimetre Wave frequencies (30 to 300 GHz; wavelength 1 cm to 1 mm)
PHY	Physical layer (interface)
PRBS	Pseudo Random Binary Sequence
QAM	Quadrature Amplitude Modulation
QPSK	Quadrature Phase Shift Keying
RF	Radio Frequency

RX	Receiver
SNR	Signal-to-noise ratio
THz	Terahertz
TWTA	Travelling Amplifier Tube
TX	Transmitter
VSA	Vector Signal Analyzer

3. Introduction

Data traffic densities of several Tbps/km^2 are already predicted for 5G networks. The 5G networks are widely expected to enlarge the usage of the electromagnetic frequency spectrum to the lower mm-wave range below 100 GHz, covering such frequency bands as 26-42 GHz (Ka-band), 57-66 GHz (V-band), 71-76 and 81-86 GHz (E-band). However, limited exploitable bandwidth of this fully regulated range of the electromagnetic spectrum below 252 GHz can only provide an incremental, mid-term alleviation to the accelerating growth of capacity requirements. The advance into the yet unregulated terahertz (THz) and sub-mm-wave frequency range around and above 300 GHz opens up unprecedented bandwidths and improvements of spectral efficiencies [1] for wireless communication systems, supporting advanced high bitrate and low latency applications, e.g. wireless backhauling, augmented reality, or virtual reality services. Market readiness of THz communication solutions are expected soon, pushed by current technological improvements [2].

Furthermore, the potential for a disruptive and fundamental change in the information and communications technology (ICT) platforms for wireless communication enables beyond 5G generations. Moreover, the seamless combination of IEEE 802.3 [3] standardized digital baseband 1GbE, 10GbE, 100GbE, 200GbE, or 400GbE Gigabit Ethernet interfaces with THz links through the intermediate of, for example, parallelized V-band and E-band modems in a so called superheterodyne architecture, would pave the way for bit-transparent high-performance THz wireless links in a real network environment, further extending the omni-present Ethernet eco system.

In order to provide Exabyte global traffic [4], the wireless THz link capacity has to be increased well beyond 100 Gbps. Therefore, advanced technologies providing high channel bandwidth at high frequencies, high level modulation schemes, e.g. beyond QAM-256, and high signal to noise performances are needed. Such advanced technologies may include the optical generation of THz carriers by photonic local oscillators (LO) with very low phase noise performance [5].

Fig. 1. ThoR wireless transport link integration in a live network, as the first use of THz frequencies in an operational network.

Fig. 1 shows the overview of the ThoR concept. All technological building blocks developed by ThoR partners will be integrated on the physical layer (PHY) to demonstrate 300 GHz high performance, outdoor deployable wireless links, leveraging state-of-the-art gigabit modems and channel aggregation in the standardized 60 GHz and 70-80 GHz bands. Demonstration activities will include laboratory stage experiments (DEMO1 and DEMO2 in Fig. 2) for versatile data rate and modulation format testing, providing valuable scientific insights into the PHY limitations of THz links. In addition, ThoR will show the very first operational demonstration of a THz wireless link of actual user data in a mobile communication network testbed with real-time modems (DEMO3).

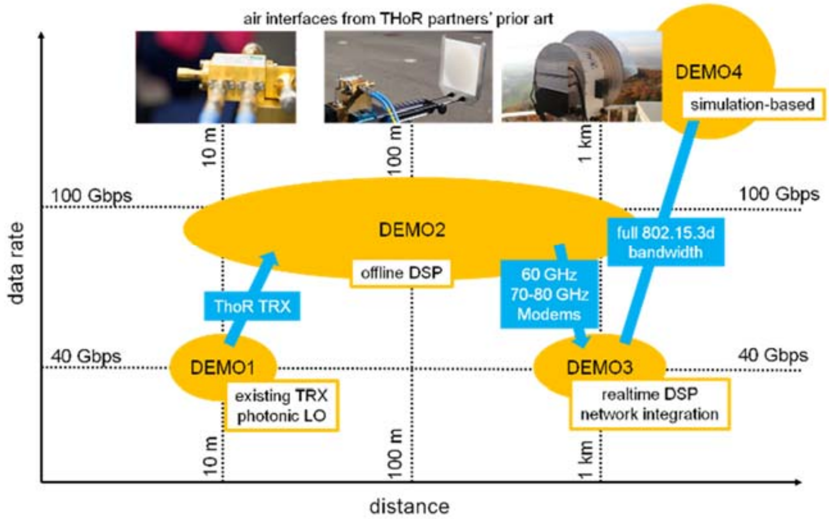

Fig. 2. Overview of the ThoR demonstrations.

This deliverable provides the results of the DEMO1. Using the available devices in the consortium, the DEMO1 validated the technological proof of concept of the ThoR project, including (1) wireless THz system architecture for > 40 Gbps bitrates, (2) a THz superheterodyne transmission system and (3) the use of a photonic local oscillator (LO). To validate the THz system architecture and superheterodyne transmission, DEMO1 combined high performance 300 GHz MMIC-based electronic transmitters and receivers with commercially available baseband mixers. Furthermore, the requirements on the final LO generation are derived from DEMO1 in which an optical frequency comb was used as a photonic LO in the superheterodyne transmission. The experimentally derived requirements on the final LO generation will play an important role towards DEMO2 and DEMO3.

4. Experimental Setup

To validate the ThoR concept, a wireless transmission experiment has been realized in a laboratory environment. Fig. 3 shows the setup used in this transmission and the spectrum of the transmitted radio frequency (RF) signals. All the components will be described in the following sections. The LO signal, generated at 8.33 GHz, can be provided by a stable frequency synthesizer or by an optical frequency comb (photonic LO). The setup can be coherent, like in Fig. 3 or incoherent, using two different LO sources for the transmitter side and receiver side.

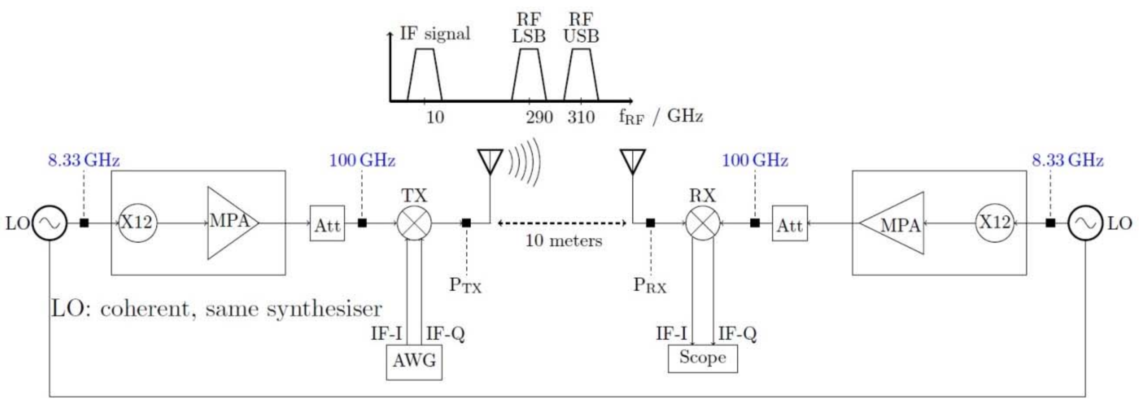

Fig. 3. Schematic of the wireless transmission experiment.

4.1. The 300 GHz Transmit-Receive System

The 300 GHz system includes a total of four modules: two frequency-multipliers by twelve, one transmitter (TX) and one receiver (RX). All modules and the integrated MMICs are fabricated at Fraunhofer IAF. The used technology has remarkable low noise characteristics and excellent high frequency performance and is described in [1].

The frequency-multiplier by twelve integrates a cascade of three frequency-multipliers on a single chip: one multiplier by two, followed by a multiplier by three, and again by a multiplier by two. The buffer amplifier at the output compensates for the multiplier losses and provides enough power at the 100-GHz LO input of the 300-GHz TX and RX modules.

The transmitter and the receiver use identical sub-circuits for LO generation, which consists of a frequency-tripler from 100 to 300 GHz followed by a two-stage buffer amplifier. A single-balanced quadrature resistive FET mixer is used as an up- and down-converter stage. The RF signal is post-amplified in the transmitter by a three-stage medium power amplifier, whose final stage uses a balanced topology to combine the power of two parallel amplifier branches. All amplifier stages employ cascaded gain cells. Both the mixer and the power amplifier use 90° couplers that are implemented as tandem-X couplers, featuring a simulated operating frequency range from 280 to 360 GHz, an insertion loss of 1 dB and output port phase relation of 88° to 91°. The particularity of the mixer is that the quadrature IF signals are applied on the isolated ports of the drain-side coupler. Equal length coplanar transmission lines preserve the phase balance of the IF signals and route the broadband signals to the contact pads of the mixer cells. In the receiver, the single-balanced quadrature resistive mixer is preceded by a four-stage low-noise pre-amplifier. Fig. 4 shows the 300 GHz integrated receiver schematic described above. More details about each stage of the module and measurement results can be found in [2].

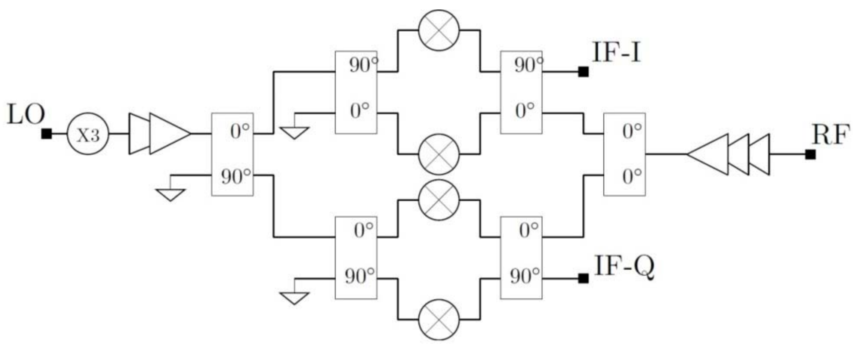

Fig. 4. Schematic of the 300 GHz receiver including a frequency multiplier by three, a buffer amplifier, a single-balanced quadrature resistive mixer and a low-noise pre-amplifier.

The transmitter and the receiver are packaged in split-block waveguide modules. The MMIC-to-waveguide transitions are realized by quartz substrates, thinned down to the thickness of the MMICs which is 50 µm. For this reason, ultra-short wedge-wedge bond wire connections can be placed between the MMIC bond pad and the microstrip transmission lines used on the quartz substrate. The rectangular waveguide mode is coupled by an E-plane probe to the microstrip mode.

The insight view of a 300 GHz TX module is shown in Fig. 5. V-connectors and a liquid crystal polymer (LCP) substrate provide the TX MMIC with the I and Q baseband data signals. A bandwidth of 50 GHz was measured for the IF path up to the MMIC. The LO (100 GHz) and RF signals (300 GHz) use a rectangular waveguide interface to connect to the X12 multiplier module and the transmit antenna.

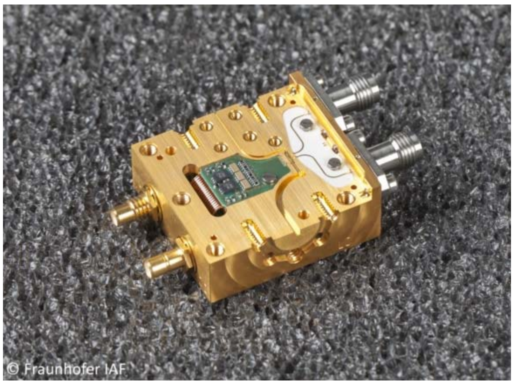

Fig. 5: Inside view of the 300 GHz TX module [Picture credits: Fraunhofer IAF].

4.2. Signal Generation and Analysis

To generate the complex I/Q-data signals for this experiment, a 15th-order pseudorandom binary sequence (PRBS15) was generated in the arbitrary waveform generator (AWG). This bit stream is used as data source. In the next step, the bits are mapped to complex symbols by taking two bits per symbol for quadrature phase shift keying (QPSK) modulation, four bits per symbol for 16-quadrature amplitude modulation (16-QAM) and five bits per symbol for 32-QAM.
The I and Q-part of the complex signals are digital-to-analog converted by two channels out of the AWG and fed to the transmitter module with an offset carrier frequency of 10 GHz. Hence, the TX radio system is in a superheterodyne architecture. On the receiver side, analog-to-digital conversion is done by the vector signal analyzer (VSA). The received signal is analyzed in offline digital signal processing (DSP) using custom software developed by ULIL based on the Keysight VSA software. The DSP performs the carrier recovery and frequency equalization to compensate for the frequency and phase drift of the LO signals and for the frequency response of the overall transmission system. The received signal is investigated in terms of error vector magnitude (EVM) and bit-error-rate (BER), which serve as measure for the analyzed signal quality.
The spectrum of the generated IF signal and of the resulting RF signal can be seen in Fig. 3 above the schematic of the setup. Since no filters are applied in the RF, both the lower and the upper side-bands are transmitted.

4.3. Link Budget Parameters

This link was realized at ULIL, by radiating the 300 GHz beam in the free space using conical horn antennas, fed by a WR3.4 (220-325 GHz) band. Such antennas provide a typical gain of about 25 dBi. Then the signal was collimated using a 100 mm Teflon lens. Using a free-space VNA setup we estimated that the gain of such a system (horn + lens) is featuring a total gain around 38 dBi. The same configuration of lens/horn is used at the receiver, for signal detection in the receiver. Fig. 6 shows a view of the TX, RX and lenses. The 10-meter transmission is obtained with a reflection on a mirror placed at 5-meter distance from the emission/detection circuits.

The link budget of the transmission is presented in Table 1. The output power of the TX module has been measured for signals with different modulation types, symbol rates and IF input powers and varies between -10 and -5 dBm. For simplicity, an average of -7 dBm is used for the link budget calculation. At 310 GHz carrier frequency the free space path loss (FSPL) over 10 meters is 102 dB. The atmospheric losses can be neglected. To achieve an optimum input power for the receiver a variable attenuator is placed between reception horn and RX module. The attenuation value is set to 10 dB, which leads to an RF input power of -43 dBm, which corresponds to the optimum point of the receiver's sensitivity curve measured previously and presented in [3].

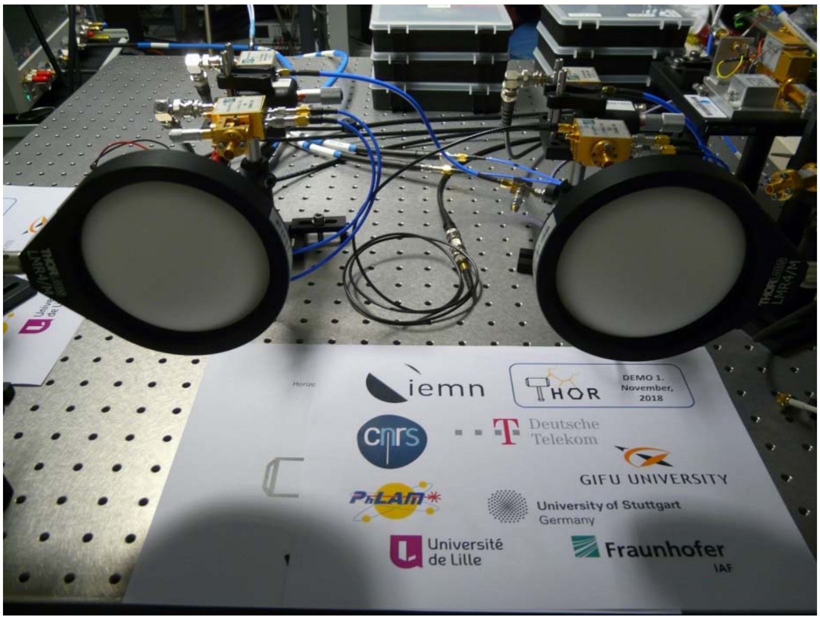

Fig. 6. View of the 300 GHz transmit-receive system including collimating lenses.

Table 1 Link Budget Parameters

Parameter	Unit	Value	Comment
Centre frequency	GHz	310	LO plus carrier offset
TX output power	dBm	-7	Measured
TX and RX overall antenna gain	dBi	38	Including horn antennas, collimating lenses and mirror
Link distance	m	10	
Free space path loss (FSPL)	dB	102	
Extra attenuation	dB	10	to drive the RX in its optimum sensitivity point
RX input power	dBm	-43	Value expected from the receiver design

5. Superheterodyne Transmission using an Electronic LO Source

The superheterodyne transmission is ensured by applying a carrier offset of 10 GHz to the baseband signals generated in the AWG. As a first step an electronic stable frequency synthesiser is used to generate the 8.33 GHz LO signal.

In addition to the transmission described in section 4, a back-to-back transmission is carried out and will be referred to as the reference measurement. This measurement is realized by directly connecting the transmitter and the receiver using a variable attenuator. The input power in the receiver remains the same as in the case of the 10-meter transmission, namely -43 dBm.

The results of the 10-meter transmission in comparison to the reference measurement can be seen in Fig. 7. The quality of the transmission is evaluated in terms of EVM. Following modulation formats were successfully transmitted: QPSK, 16-QAM, 32-QAM and 64-QAM.

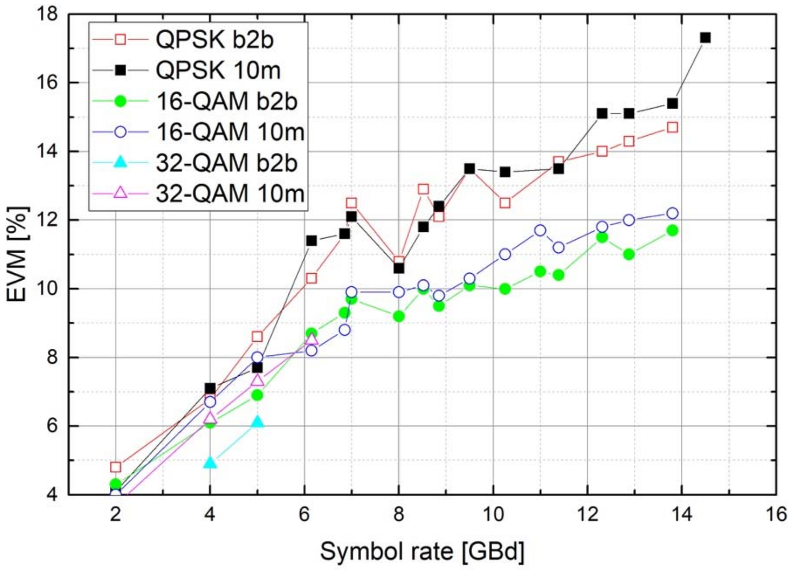

Fig. 7. Signal quality versus symbol rate for different modulation formats and transmission scenarios.

For all modulation formats, a linear degradation in dependency of symbol rate can be observed. The difference between the reference measurement and the 10-meter transmission is minimal, less than 2 %. The highest symbol rate achieved is 14.5 GBd, which, considering the applied raised cosine filter with a roll-off factor of 0.5, corresponds to a bandwidth of 22.5 GHz. At this symbol rate the upper side-band overlaps the lower side-band and therefore higher symbol rates cannot be achieved because of interferences.

The highest data rate is achieved with a 16-QAM modulated signal: 55.2 Gbps. Fig. 8 and Fig. 9 show the constellation diagrams of this signal for the reference measurement and the 10-meter measurement.

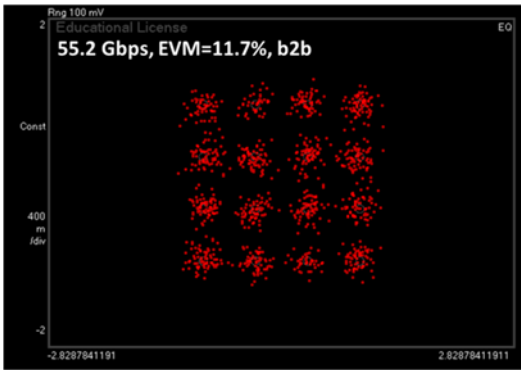

Fig. 8. Constellation diagram of a 16-QAM detected signal in b2b configuration.

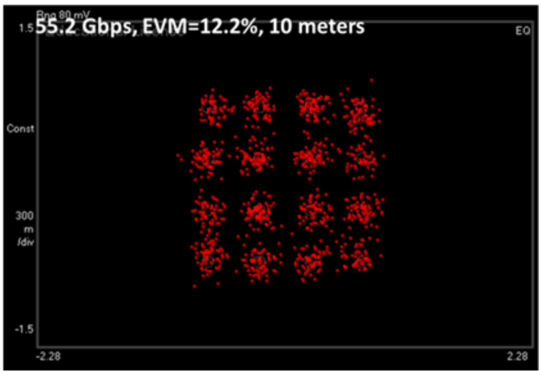

Fig. 9. Constellation diagram of a 16-QAM detected signal for the 10-meter transmission.

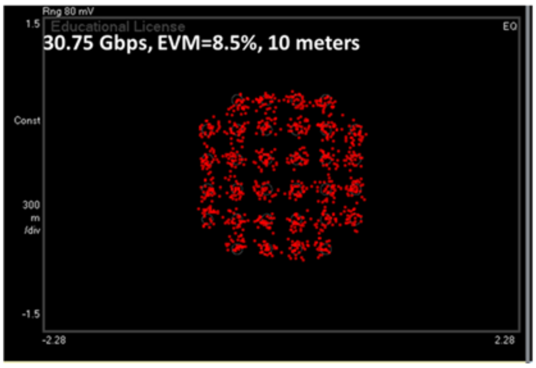

Fig. 10. Constellation diagram of a 32-QAM detected signal for the 10-meter transmission.

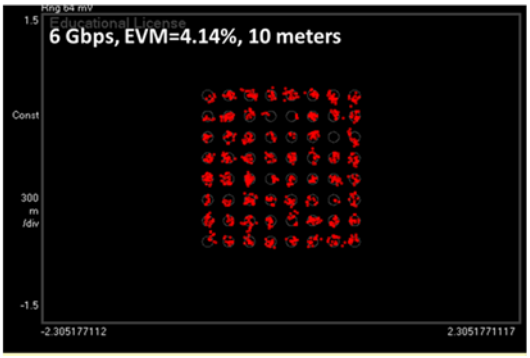

Fig. 11. Constellation diagram of a 64-QAM detected signal for the 10-meter transmission.

For 32-QAM the highest symbol rate reached was 6.15 GBd, which corresponds to a data rate of 30.75 Gbps, shown in Fig. 10. 64-QAM modulated signals were also transmitted. For this modulation type, a symbol rate of 1 GBd was reached, as shown in Fig. 11.

The successful usage of higher modulation formats shows the good linearity of the system. Especially in multi-channel transmissions, it is desirable to use higher modulation formats with a smaller symbol rate, as the bandwidth available for each channel decreases.

6. Photonic based LO

As the ThoR architecture is using a superheterodyne approach, the system is using frequency-multiplication stages to increase in frequency up to the mm-wave/THz band around 300 GHz. In order to enhance the system performance, we target to use for the LO a photonic-based signal to feed the transmit and receive solid-state circuits. This will enable to work with LO frequencies directly in the W-band, i.e. around 77 GHz rather than multiplying the frequency from the microwave range. However, the use of a photonic LO, combined with the superheterodyne approach being a novelty of the THoR system concept was to be validated during DEMO1.

In the DEMO1, one initial scheme to generate the photonic LO was tested. It is composed of an electrical signal that drives an optical modulator to generate an amplitude modulation, further detected by a photodiode. Then this signal is amplified to reach the LO required level of the devices used for up and down conversion. Fig. 12 shows an example of comparison of LO phase noise for photonic and electronic-based generation. The phase noise obtained is good, however the signal-to-noise ratio (SNR) in the DEMO1 photonic LO was limited, due to available components.

Such a scheme was also successful. As an example, Fig. 13 hereafter shows a QPSK and 16QAM transmission using the photonic LO, for 1 GBd symbol rate. It should be noted here that the data-rate is limited here due to limited SNR of the LO, while validating the concept.

As the performances were lower with photonic LO than the electronic LO, for instance due to a limited SNR available on the photonic LO, it was checked that an electronic LO with limited SNR was leading to the same performance. This was confirming that both good SNR and phase noise performance need to be obtained to enable such an architecture, for both electronic and photonic LO. Thus, it should be noted that this result validates the use of photonic LO and also gives an important target and guideline for the dedicated ThoR developments. Also, we point out that the photonic LO architecture used here is not the one to be used within the final ThoR demonstration, since the WP4, dedicated to this development, is not yet started.

In a nutshell, the DEMO1 that uses the photonic LO was successful and strong guidelines were obtained for ThoR developments.

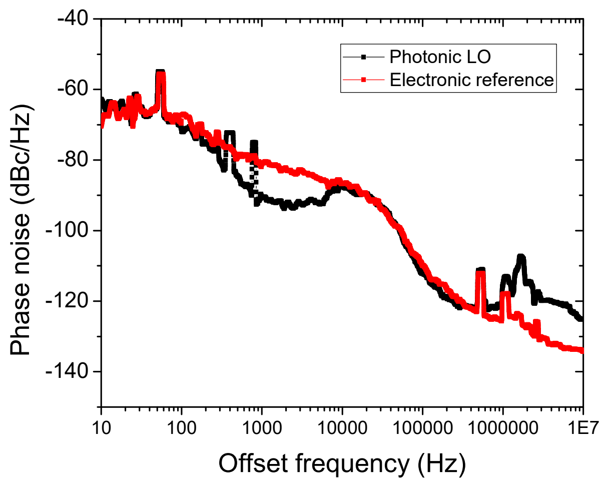

Fig. 12. Comparison of phase noise between electrical reference and photonic LO at a centre frequency of 8.3 GHz. Spikes around 50 Hz are due to power line noise.

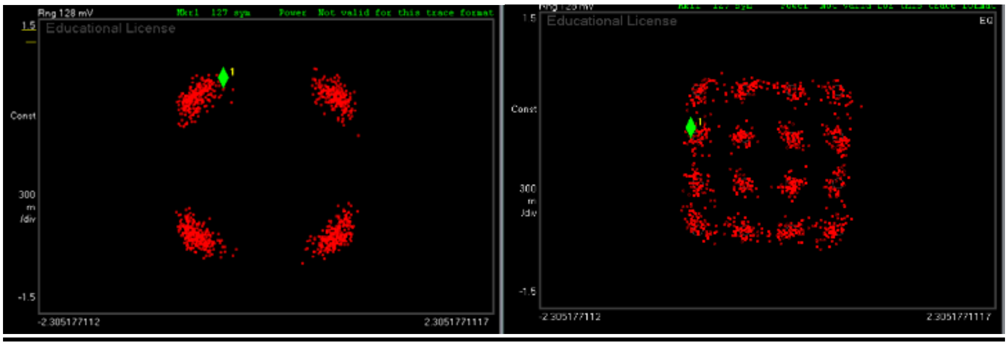

Fig. 13. QPSK and 16-QAM with a symbol rate of 1 GBd over the air (10-meter) using the photonic LO.

7. Dual channel transmission

Part of the concept of the superheterodyne transmission is to reach the possibility of transmission of a multiple frequency modulated signal at I and Q inputs (Fig 1), allowing for channel aggregation in line with the new frequency standard IEEE802.15.3d. This is of particular importance within the final integration with standard MODEMS in E and V bands, to reach a transparent THz integration with the existing MODEMS compatibility, and thus to obtain real-time user data transmission capability.

In the DEMO1, we took benefit from the AWG capability to enable the signal generation at I and Q of a dual carrier modulated signal, using two sub-carrier frequencies in the microwave range, with uncorrelated data (different PRBS sequences) as well as different modulation schemes and baud rates.

This demonstration was successful. As an example, Fig. 14 shows the dual channel transmission of two 16-QAM signals over the air (10-meter), using electronic LO.

Such an architecture was tested over several modulation schemes and baud rates. As a second example, Fig. 15 shows the transmission of 32 QAM and 64QAM, with a spectral separation of 4 GHz between the sub-channels.

In this section, the demonstration of the ThoR concept, using superheterodyne approach and multi-channel was achieved. From the DEMO1 outcomes, the concept is validated.

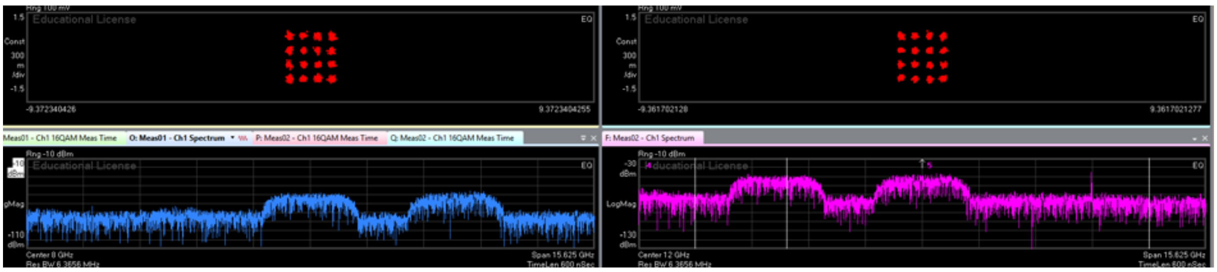

Fig. 14. Constellation diagrams of a measured 16-QAM dual channel signal, transmitted over 10 meter. Channel 1 is shown on the left, channel 2 is shown on the right. The baud rate is 2 GBd, total data-rate = 16 Gbps. The carriers lie at 8 and 12 GHz in the I path.

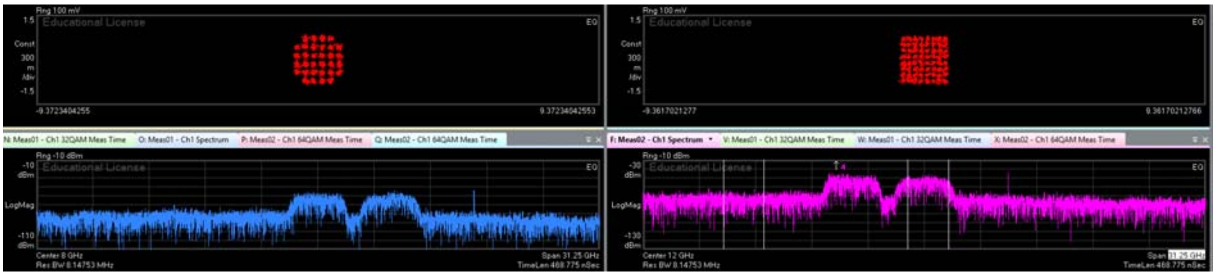

Fig. 15. Transmission of a dual frequency signal, carriers at 8 and 12 GHz, or 32-QAM with 2.56 GBd (left) and 64-QAM with 2.56 GBd (right). Total data-rate 5*2.56 + 6*2.56 = 28.16 Gbps.

8. Conclusion

This deliverable D6.1 provides the results of the DEMO1 proof of concept for the envisaged wireless THz system architecture and ultra-high data-rate transmission needed for beyond 5G networks. All DEMO1 objectives and expectations were reached, including the successful validation of

- the wireless THz system architecture
- the concept of the superheterodyne approach
- the combination of high performance 300 GHz MMIC-based electronic transmitters and receivers, provided by the ThoR project partners, with commercially available baseband mixers
- transmissions beyond 40 Gbps
- multi-level modulation-formats up to 64-QAM signals
- aggregation of sub-channels in line with frequency standard IEEE802.15.3d using 2 channel THz transmissions
- using an electronic LO for the THz signal generation
- using a photonic LO for the THz signal generation
- bridging a 10-meter reach THz link over the air supporting the above-mentioned items

These first encouraging results build up the basis for the planned and ongoing ThoR-project activities for further demonstrations of THz systems and applications towards data-rates beyond 100 Gbps, over the air reach up to 1 km with the association of TWTA (Travelling Amplifier Tube), network integration of photonic LO signal generation, network integration of real-time DSP, and full IEEE 802.3.15.3d standard compliant bandwidth transmissions.

9. References

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