100 Gbit/s Terahertz-Wireless Real-Time Transmission Using a Broadband Digital-Coherent Modem

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Abstract—In this paper, we demonstrate for the first time 100 Gbit/s real-time THz-wireless data transmission at a carrier frequency of 300 GHz using a single broadband real-time modem originally designed for 2x2 Polarization-MIMO digital-coherent fiber-optical transmission. As a reference, the performance of the 50-cm-long, LoS, spatially multiplexed (tx2) wireless link is also evaluated using offline DSP algorithms optimized for the THz setup. During the real-time operation of the system, we have recorded the pre-FEC BER over 100 hours of continuous operation to demonstrate the stability of the system.

Keywords—real-time transmission, THz communications, wireless communication

I. INTRODUCTION

Terahertz (THz) wireless communication technologies are currently gaining a lot of attention as a possible way to upgrade existing and upcoming wireless solutions beyond 5G due to the large available bandwidth at THz carrier frequencies [1,2], potentially capable of supporting data-hungry applications such as virtual and augmented reality [3], and internet of things [4]. The available bandwidth is even comparable to channel bandwidths typically found in optical communication systems [1,5], where high-speed m-ary quadrature amplitude modulated (QAM) signals such as 4-QAM and 16-QAM at data rates of 100 Gb/s and 200 Gb/s, respectively, are currently used. Therefore, the possibility of a seamless integration of THz wireless technologies into fibre-optical networks could result in the realization of highly flexible hybrid network supporting new applications like THz wireless fiber extension or high-capacity THz wireless backhauling [6,7].

The integration of fibre-optical and THz-wireless technologies at high data rates (beyond 100 Gbit/s) has been investigated by a variety of research groups [8-11], effectively demonstrating the possible interoperation of both communication techniques by means of a common digital signal processing (DSP) scheme at the receiver end. This joint correction of transmission impairments is the key to ensuring the seamless interconnection of the optical and the THz transmission links and elements. Thereby, our own previous work [6,8] has focused on the assessment of the joint transmission performance of such hybrid fibre-optical / THz-wireless transmission links in theory and offline experiments.

In this paper, we demonstrate for the first time, to the best of our knowledge, a real-time 100 Gbit/s, 34 Gbd 4-QAM THz wireless transmission link using a single broadband real-time modem, originally designed for 2x2 Polarization-MIMO digital-coherent fibre-optical transmission. The signals are transmitted over a 50 cm-long line-of-sight (LoS) wireless THz link with 2x spatial multiplexing, using a 300-GHz carrier. We prove the long-term stability of the system by recording the pre-FEC BER for over 100 hours of uninterrupted operation. Furthermore, we also evaluate the performance of the transmission link using offline DSP algorithms to compare the system performance to the performance in real-time operation.

II. OFFLINE EVALUATION OF THE THZ WIRELESS LINK

A. Experimental setup

The THz setup used in offline experiments is illustrated in Fig. 1. We carry out the experiments in the THz band using modules based on monolithic microwave integrated circuits (MMIC) [8,12]. As these modules are designed for SISO transmission, i.e. do not support polarization-multiplexed data transmission in the moment, we are using two pairs of THz Tx-Rx modules in a 2x spatially multiplexed configuration; one for each polarization component generated by the broadband modem.

In the offline Tx DSP, random binary sequences of length 2¹⁵ are generated at the transmitter and then coded into 4-QAM symbols at a rate of 34 Gbd, which results in a net data rate of 100 Gbit/s when taking into account the overhead of 25% for FEC and ~10% for framing. The symbol sequence is pulse-shaped using a root-raised cosine pulse with a roll-off factor of 0.35 and then uploaded to the digital-to-analog converter (DAC, 8 bit nominal resolution, 80 GS/s, ~30 GHz electrical bandwidth). After adjusting the voltage of the electrical output signals to ~110 mVpp, they are fed into the THz transmitters and upconverted to 300 GHz using direct-conversion I/Q mixers. This results in a radiated output power of ~17 dBm. In order to generate the 300-GHz local oscillator signals in all THz transmitters and receivers, an external signal generator produces a sinusoidal wave with a frequency of 8.31 GHz, which is multiplied by a factor of 36 via two multiplication stages in each of the MMIC modules.

The transmission distance of the LoS wireless link is 50 cm, which is bridged using horn antennas with gain values of 23 dBi. In the THz receivers, the received signals are downconverted into the baseband also using direct-conversion I/Q mixers. The received baseband waveforms are captured...
using an oscilloscope (Osc.) (8 bit nominal resolution, 80 GS/s, electrical bandwidth of ~32 GHz). Afterwards, the channel impairments are corrected using offline Rx DSP algorithms [13,14]. The received waveforms are first resampled to two samples per symbol. Then, front-end I/Q imbalances as well as carrier frequency offset are corrected. To correct any delay between the polarizations as well as inter-symbol interference, a 2x2 MIMO T/2-spaced equalizer with a blind coefficient update using the constant-modulus algorithm (CMA) [15] is used. After downsampling to 1 sample per symbol, the phase noise is removed using the blind phase search algorithm [16]. Subsequently, a second, T-spaced 4x4 equalization stage with a decision-directed least-mean squares (DD-LMS) update criterion is used to mitigate delays within the in-phase (I) and quadrature (Q) components of a single polarization as well as I/Q imbalances at the transmitter [17]. Finally, the symbols are decoded and the bit error rate (BER) is estimated by counting the erroneous bits.

B. Experimental results

The constellation diagrams in Fig. 2 show the received data after the offline DSP alongside the corresponding average BER value. After analyzing more than 5 million bits, the average BER of the system operated with 4-QAM has been estimated to be $8.8 \times 10^{-4}$.

As the two pairs of THz Tx/Rx elements stem from different chip generations, they have noticeably different characteristics w.r.t. frequency response, output power radiated into free-space, electrical amplification at the receiver module, noise figure, etc. The observed differences in the constellations for the X- and Y-spatial channel are partly attributed to this fact. Another reason are the different I/Q imbalances in the setup, as discussed later. Additionally, the THz frontends show non-linear limitations that impair the transmitted signal. In this regard, to realize high-capacity systems above 100 Gb/s that operate using 16-QAM or 64-QAM, the linearity of the RF mixers must be improved and I/Q distortions kept to a minimum [6].

In addition, the offline DSP allowed to estimate some characteristics of the system in terms of I/Q imbalance and delays, which are summarized in Table I. The estimated I/Q amplitude imbalance and I/Q skew values before correction in the T-spaced 4x4 DD-LMS equalizer show that channel 2 (Y) is more impaired than channel 1 (X), which can explain the observed differences in the constellation diagrams, as the correction of those impairments is not ideal.

![Fig. 2. Constellation diagrams corresponding to the two spatially multiplexed 34 Gbd 4-QAM signals (referred to as X (left) and Y (right)) after transmission over a 50 cm-long LoS THz wireless link and subsequent processing with offline DSP.](image)

![Fig. 1. Experimental setup for the offline THz transmission system operating at ~300 GHz.](image)

TABLE I. ESTIMATED CHARACTERISTICS OF THE THZ SYSTEM

<table>
<thead>
<tr>
<th>Impairment</th>
<th>Estimated value</th>
</tr>
</thead>
<tbody>
<tr>
<td>I/Q Amplitude Imbalance</td>
<td>0.3</td>
</tr>
<tr>
<td>I/Q Skew</td>
<td>3.3</td>
</tr>
<tr>
<td>Differential group delay</td>
<td>14.3</td>
</tr>
</tbody>
</table>

Furthermore, there is some differential group delay (DGD) between the two channels amounting to almost half a symbol. This DGD is compensated for by the T/2-spaced 2x2-MIMO CMA equalizer.

III. REAL-TIME EVALUATION OF THE THZ WIRELESS LINK

A. Experimental setup

The experimental setup used for real-time data transmission is depicted in Fig. 3. The main difference compared to the setup in Fig. 1 is the use of the broadband real-time modem originally designed for 2x2 Polarization-MIMO digital-coherent fiber-optical transmission.

At the transmitter end, the modem generates the electrical signals corresponding to the in-phase and quadrature components for a polarization-multiplexed transmission. The I/Q signals are passed through configurable delay lines to equalize the observed I/Q skews that might impair the transmission, and are fed into the THz modules with a voltage of ~100 mVpp.

The operational parameters of the system have not been modified from the offline system experiment, i.e. the carrier frequency lies at approximately 300 GHz, and 23 dBi horn antennas are used to transmit data over a 50 cm-long wireless link.

At the receiver, the amplitude of the downconverted data signals is ~40 mVpp in average. For this reason, we utilize broadband baseband amplifiers (~20 dB gain, 40 GHz
bandwidth) to increase the power of the signals. The real-time modem performs DSP similar to the algorithm scheme used for the offline evaluation of the THz link described above [15]. Additionally, the modem includes a soft-decision forward error correction (SD-FEC) block with ~25% overhead and a BER threshold at a value of $3.4 \cdot 10^{-2}$.

**B. Experimental results**

For the live traffic real-time demonstration, we have captured the BER performance of the system over 100 hours of continuous operation. The results of the real-time transmission over the THz link have been summarized in Fig. 4. This experiment demonstrates that the THz system performs in a stable matter. The pre-FEC BER values remain well below the SD-FEC threshold (represented by the dashed line in Fig. 4) for the whole duration of the experiment, which resulted in an error-free post-FEC signal. The 4-QAM constellation diagrams of both channels after the DSP stages performed by the broadband real-time modem are shown in Fig. 5.

As a reference, the pre-FEC BER observed in the offline experiment presented in Section II is plotted as a dash-dotted line in Fig. 4. The comparison shows that the performance using the offline DSP techniques is significantly better than that using the DSP algorithms used in the real-time modem. Here, the main difference comes from the additional degrees of freedom permitted by the offline DSP, since we are able to freely adjust the algorithms’ parameters individually and perform I/Q imbalance and I/Q skew compensation at both Tx and Rx by means of an additional symbol-spaced 4x4 DD-LMS equalizer [17]. This shows that there is still room for improvements of the performance of the real-time transmission, which eventually will be also needed to address specifics of the THz part of the link, e.g. rate adaptivity to address time-varying channel loss etc.

**IV. CONCLUSIONS**

As research into THz technologies continues, several potential applications are under investigation. Some particularly interesting use cases would result from the seamless combination of fibre-optical and THz-wireless communication technologies allowing the construction of hybrid transmission systems and networks. To make such scenarios practical, a joint impairment compensation scheme for both the fibre-optical part and the THz-wireless part is required. Towards this goal, we have demonstrated for the first time 100 Gbit/s real-time THz-wireless data transmission at a
carrier frequency of 300 GHz using a single broadband real-time modem originally designed for 2x2 Polarization-MIMO digital-coherent fiber-optical transmission. We evaluated the pre-FEC BER performance after transmission in the 300 GHz band over a 50-cm long, LoS, spatially multiplexed (x2) THz wireless link. The evaluation both with real-time and offline DSP resulted in BER performances of at 8.8 \times 10^{-4} and at 9.9 \times 10^{-3} for the offline and real-time systems, respectively. The real-time system was stable for more than 100 hours. These results will pave the way towards the realization of hybrid fibre-optical / THz-wireless transmission systems.

REFERENCES


