100 Gb/s Real-Time Transmission over a THz Wireless Fiber Extender Using a Digital-Coherent Optical Modem

Carlos Castro[(1)], Robert Elschner[(1)], Thomas Merkle[(2)], Colja Schubert[(1)], Ronald Freund[(1)]
(1) Fraunhofer Institute for Telecommunications Heinrich-Hertz-Institute, Einsteinufer 37, 10587 Berlin, Germany
(2) Fraunhofer-Institut für Angewandte Festkörperphysik IAF, Tullastraße 72, 79108 Freiburg im Breisgau, Germany
carlos.castro@hhi.fraunhofer.de

Abstract: We demonstrate the real-time transmission of a 34-GBd PDM-QPSK signal over two fiber-optic links interconnected by a THz wireless fiber extender at 300 GHz carrier frequency, with joint impairment compensation by a single-carrier DSP.

1. Introduction

Terahertz (THz) wireless communications, i.e. transmission systems in the frequency band spanning from 0.1 to 10 THz, have been getting a lot of attention in the last few years as a way of preemptively addressing the high data rate demands of future wireless/mobile applications [1]. In this regard, THz communications are expected to bring wireless data rates on par with fiber-optical systems by offering link throughputs in the range of hundreds of Gb/s or even Tb/s [2]. This will also enable new network design options using seamless combinations of fiber-optical and THz wireless links. Such a *THz Wireless Fiber Extender* (or alternatively *THz Wireless Bridge)* will allow to bypass areas where fiber deployment is difficult or prohibitively expensive, and therefore might soon find applications e.g. in back- and fronthaul links of 5G macro stations [2,3].

Recently, several demonstrations of high-speed transmission over THz links with ~100 Gb/s throughput have been carried out, typically for wireless carrier frequencies between 250 and 450 GHz. While some of them focus on the THz transmission using purely electronic THz generation and reception [4,5] there have also been several experiments that explore THz communication using photonic-based methods such as broadband photo-mixing to interface fiber-optic and THz wireless systems for high-speed communications [3,6-9].

In this paper, we investigate an alternative THz wireless fiber extender configuration that is based on the seamless interconnection of two standard fiber-optical links by an electronic THz wireless link through a linear analog optic-THz baseband interface [2,10]. We demonstrate, for the first time to the best of our knowledge, the digital-coherent real-time transmission of a 34-GBd PDM-QPSK signal providing 100-Gb/s net capacity over such a system configuration, where we use a single high-speed digital-coherent optical real-time modem [5] to jointly compensate for all combined impairments of the 3 different links. This is possible because the 2-times spatially multiplexed THz wireless link at a carrier frequency of 300 GHz provides a flat channel response with sufficient bandwidth to carry the two polarization tributaries of the 34-GBd PDM-QPSK signal. We show that the THz wireless fiber extender is transparent towards accumulated chromatic dispersion, random polarization rotations and phase noise, thus allowing for the joint compensation of all combined link impairments by the single-carrier real-time DSP.

2. Experimental setup

The experimental setup used in this investigation is depicted in Fig. 1. At the transmitter side, a standard broadband digital-coherent optical modem generates four electrical signals corresponding to the in-phase and quadrature (I/Q) components of the two polarization tributaries of a 34-GBd PDM-QPSK signal. These signals are fed into a dual-polarization Mach-Zehnder modulator (DP-MZM), where they are modulated onto an optical carrier with a frequency of 192 THz. The polarization-multiplexed optical signal is launched into a standard single-mode fiber, whose length varies between 1 m (back-to-back connection) and up to 103 km, with a fixed launch power of 1 dBm.

At the receiver end of the first fiber-optical link, the fiber connects to the receive-side of the optic-THz baseband interface, where a standard dual-polarization coherent receiver frontend (DP-CoRx) with a free-running local oscillator laser is used to convert the incoming optical signal back into 4 analog electrical baseband tributaries. Subsequently, these analog baseband signals are directly fed into the two THz transmitter front-end modules (THz Tx) of a 2-times spatially multiplexed THz wireless link, which comprise direct-conversion I/Q mixers on a monolithically microwave integrated circuit (MMIC) with a 3-dB bandwidth of ~25 GHz in the frequency band centered around 300 GHz [11]. For the generation of the required THz local oscillator, a signal generator provides a sinusoidal wave with a frequency of 8.311 GHz, which is then multiplied by 36 in order to achieve a carrier frequency ~300 GHz. After up-conversion into the THz band, the signal is transmitted over a 50 cm-long wireless link with a THz power >-17 dBm using horn antennas with a gain of 23 dBi. The lateral separation between the antenna pairs and their height from the base are ~12.5 cm and >19 cm, respectively. The total path loss of the THz-wireless link is about 30 dB. At the receiver end of the THz wireless link, a second signal generator generates the LO for the two MMIC-based receiver THz front-ends (THz Rx) based on direct-conversion I/Q mixers to down-

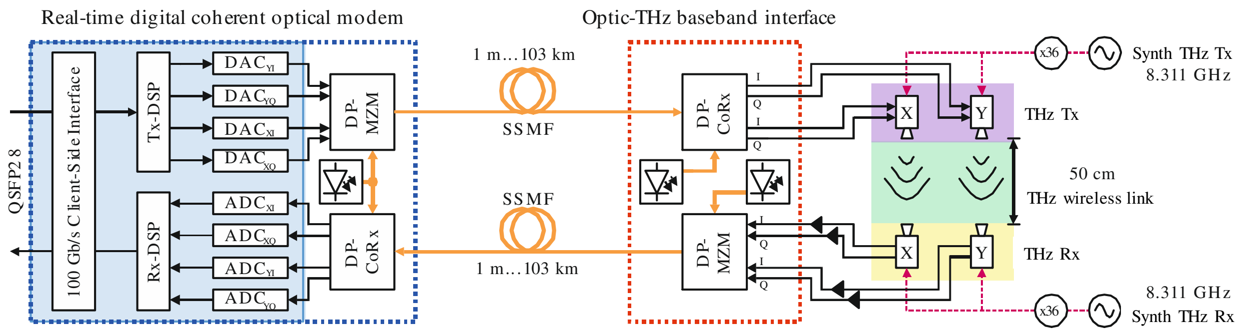

Fig.1. Experimental setup depicting the optic-THz baseband interface that translates the polarization-multiplexed optical signal into the electrical domain, so that data can be transmitted over a THz wireless link, which operates at a carrier frequency of ~300 GHz.

convert the THz signals back into the analog electrical baseband. These devices exhibit 3-dB bandwidths of ~50 GHz [11]. At the transmit side of the second optical link, four baseband amplifiers with 32 GHz bandwidth and 17 dB gain are used to reach a suitable voltage to drive a DP-MZM in the optic-THz baseband interface. There, the four analog baseband signals are modulated onto a free-running optical carrier at 192 THz and are transmitted over a standard single-mode fiber, whose length varies between back-to-back and 103 km. At the receive side of the second optical link, another DP-CoRx and analog-to-digital converters (ADC) in the digital-coherent real-time optical modem detect the signals and transform them into digital samples to be processed in real-time using a standard single-carrier DSP comparable to [12]. The real-time modem uses a soft-decision FEC with a threshold corresponding to a bit-error rate (BER) of $3.4 \cdot 10^{-2}$ (25% overhead) to correct erroneous bits after transmission.

3. Experimental results

To investigate the THz wireless fiber extender scenario, we considered different link configurations: a fiber link before the THz wireless link (‘Fiber–THz wireless’), a fiber link after the THz wireless link (‘THz wireless–Fiber’), and (symmetrical) fiber links before and after the THz wireless link (‘Fiber–THz wireless–Fiber’). Please note that it is also possible to artificially construct another configuration from the configuration ‘Fiber–THz wireless–Fiber’ by inverting the in-phase components of the two polarization tributaries at the analog baseband interface before the second fiber link. We will refer to this configuration as ‘Fiber–THz wireless–Fiber (PC)’ (where ‘PC’ stands for phase conjugation), and will later use it to demonstrate the transparency of our THz wireless fiber extender.

The experimentally obtained BER performance for all cases is shown in Fig. 2 (a) for different total (i.e. added) lengths of the fiber links. We observe that the BER is well below the SD-FEC threshold for all measured cases, and therefore neither the length nor the positioning of the fiber links play a major role in affecting the BER performance of the overall transmission system. This is in agreement to our previous numerical analysis [10], where we estimated that the noise accumulated in our THz wireless link is the main limiting factor regarding the system performance.

To investigate the effect of random polarization rotations on the system, we introduced a polarization scrambler directly after the transmitter of the first optical link. Fig. 2 (b) illustrates the BER performance of a ‘Fiber–THz wireless–Fiber’ configuration with a total fiber distance of 40 km. As a reference, we also show the BER performance of a purely optical transmission link of the same length and also with polarization scrambler, where the signal power was artificially decreased by an optical attenuator in order to achieve similar BER values. This reference case shows that, over an evaluation time of 5 minutes of continuous operation, the purely optical transmission system is not affected by the random polarization rotations, which indicates a correct operation of the PDM-QPSK real-time modem. Similarly, the performance of the system with the THz wireless fiber extender is stable and well below the FEC threshold under random polarization rotations, and only exhibits some small degree of variation over time, which shows that our THz wireless fiber extender is transparent to such a linear impairment.

To further analyze the small BER variations over time, we removed the polarization scrambler and instead compared the system performance for the case with two independent LOs at the THz transmitter and THz receiver (‘heterodyne’) and for the case of a common THz LO (‘homodyne’). The results are plotted in Fig. 2 (c) and show that the small fluctuations in the BER performance also occur without polarization rotations, but only in the ‘heterodyne’ case. As analyzed in previous experiments [5,7], the reason is a slight, phase-dependent nonlinear compression in the THz receiver front-ends which leads to a time-dependent signal degradation if the signal is exhibiting random phase noise in the THz link. In the ‘homodyne’ case, there is no random phase noise in the THz link, and we can set an optimal LO-phase to achieve the best possible performance without variations.

Finally, Figure 2 (d) depicts the accumulated chromatic dispersion as a function of the total optical link length, which is estimated by the real-time modem in order to compensate it adaptively [13]. In the plot, we observe a

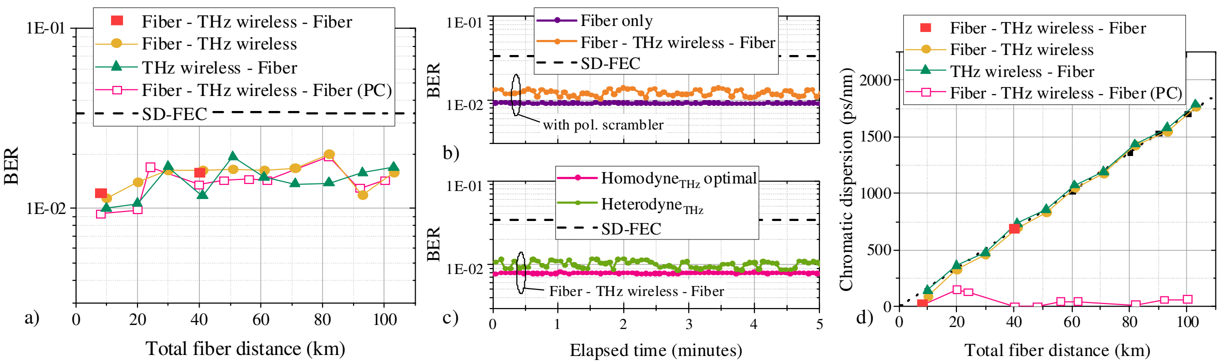

Fig. 2. (a) BER performance of the optical links with THz wireless fiber extender for different configurations (i.e. placement of the fiber in the transmission line). (b) BER performance of a purely optical transmission line compared against the performance of an optical link with THz wireless fiber extender in the presence of polarization scrambling. (c) BER performance comparison of the optical link with THz wireless fiber extender for independent THz LOs ('heterodyne') and a common THz LO ('homodyne') (d) Estimated accumulated chromatic dispersion of the optical link with THz wireless fiber extender for different cofigurations. The dotted line represents the accumulated chromatic dispersion for a single-mode fiber with a dispersion parameter of 17 ps/(nm·km)

linearly increasing curve with a slope of ~17 ps/(nm·km) which matches well to the actual chromatic dispersion coefficient of the used single-mode fiber. As the estimate is accurate for all configurations, this again indicates that our THz wireless fiber extender is transparent to this linear impairment. For the link configuration with 'Fiber–THz wireless–Fiber (PC)', i.e. if we invert the in-phase components at the optic-THz interface to achieve a phase conjugation of the signal, the modem correctly estimates almost zero accumulated dispersion due to the symmetric fiber lengths before and after the THz wireless link. This proves that the transparency of the THz wireless fiber extender could even be used to construct a phase conjugator to simplify the work of the DSP chain, depending on the length of the fibers and their configuration.

4. Conclusions

We have demonstrated, for the first time to the best of our knowledge, the digital-coherent real-time transmission of a 34-GBd PDM-QPSK signal providing 100 Gb/s net capacity over two fiber-optic links (up to 103 km total length) interconnected by a THz wireless fiber extender at 300 GHz carrier frequency. We have shown that the combined linear impairments from the 3 links, like polarization rotations, accumulated chromatic dispersion and phase noise, can be jointly compensated by the single-carrier DSP of the real-time optical modem because of the linearity and transparency of the THz wireless fiber extender. These promising results will pave the way towards new network architectures using seamless combinations of fiber-optical and THz wireless links.

5. Acknowledgment

This work was supported by the Fraunhofer Internal Programs under Grant No. MAVO 836 966 and by the EC Horizon 2020 Research and Innovation Program under grant agreement No. 761794.

6. References

[1] Cisco Visual Networking Index, "Global Mobile Data Traffic Forecast Update, 2017-2022 White Paper, 2019. [Online] Available: https://www.cisco.com/c/en/us/solutions/collateral/service-provider/visual-networking-index-vni/white-paper-c11-738429.html. [Accessed: 27-09-2019]

[2] A. Boulogeorgos et al., "Terahertz Technologies to Deliver Optical Network Quality of Experience in Wireless Systems Beyond 5G", IEEE Communications Magazine, Vol. 56, No. 6, pp. 144-151, June 2018.

[3] A. Udalcovs et al., "107.1-Gbps Net-Rate Transmission Over a Joint 51km-Fibre-and-10.7m-Wireless Link for Terahertz Radio Access Networks", in proc. 45th European Conference on Optical Communications (ECOC), Dublin, 2019.

[4] F. Boes et al., "Ultra-broadband MMIC-based wireless link at 240 GHz enabled by 64GS/s DAC", in proc. 39th International Conference on Infrared, Millimeter, and Terahertz waves (IRMMW-THz), Tucson, 2014.

[5] C. Castro et al., "100 Gbit/s Terahertz-Wireless Real-Time Transmission Using a Broadband Digital-Coherent Modem", in proc. IEEE 5G World Forum, Dresden, 2019.

[6] S. Koenig et al., "Wireless sub-THz communication system with high data rate", Nature Photonics, Vol. 7, pp. 977-981, 2013.

[7] C. Castro et al., "32 GBd 16QAM Wireless Transmission in the 300 GHz Band Using a PIN Diode for THz Upconversion", in proc. OFC, San Diego, 2019.

[8] T. Harter et al., "Generalized Kramers-Kronig Receiver for 16QAM Wireless THz Transmission at 110 Gbit/s", in proc. 45th European Conference on Optical Communications (ECOC), Dublin, 2019.

[9] T. Harter, et al., "Wireless THz link with optoelectronic transmitter and receiver", Optica, Vol. 6, No. 8, pp.1063-1070, August 2019.

[10] C. Castro, R. Elschner, and C. Schubert, "Analysis of Joint Impairment Mitigation in a Hybrid Optic-THz Transmission System", in proc. 20th IEEE International Workshop on Signal Processing Advances in Wireless Communicatiosn (SPAWC), Cannes, 2019.

[11] I. Kallfass et al., "MMIC chipset for 300 GHz indoor wireless communication", in proc. IEEE International Conference on Microwaves, Communications, Antennas and Electronic Systems (COMCAS), Tel Aviv, 2015.

[12] R. Elschner et al., "Data-aided DSP for Flexible Transceivers" (invited), in proc. Advanced Photonics Congress, San Diego, 2014.

[13] M. Kuschnerov, et al., "Adaptive Chromatic Dispersion Equalization for Non-Dispersion Managed Coherent Systems", in proc. OFC, San Diego, 2009.