Hybrid fiber-optical/THz-wireless link transmission using low-cost IM/DD optics

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Abstract: Hybrid fiber-optical/THz wireless transmission of 16 GBd 16-QAM is demonstrated over 20 km of fiber. Transmission of 50 Gb/s net rate is achieved using low-cost IM/DD optics and wireless front-ends operating at 306 GHz.

1. Introduction

Digital data consumption growth is a defined trend for the past and upcoming years where internet protocol traffic is expected to triple in 5 years [1]. In order to keep up with these demands, operators need to update their network infrastructure and investigate new fixed and wireless solutions capable of serving user demands while maintaining the service at the expected cost and power consumption targets. Recently, researchers have shown that terahertz (THz) wireless technologies can be used to realize communication systems to keep up with the increasing data rate requirements [2, 3]. At carrier frequencies around 300 GHz, it is possible to combine the advantages of wireless links such as flexibility with the higher data rates of fiber-based optical networks, i.e. several tens or hundreds of Gb/s per link, allowing seamless integration between optical and wireless links. THz wireless links and their hybridization has been under study over the past years with reports of transmission records being published, ranging from a 100 Gb/s THz-wireless real-time link [4], to THz links demonstrating Ethernet transmission [5]. Furthermore, several research groups are studying the use of photonics for THz wireless technologies [6-9], showing that photonics can play a major role in THz frontends and ease the connection to hybrid systems.

Some of the above-mentioned reports use, for the optical transmission, advanced modulation formats and coherent reception to transmit/receive the signals to/from the THz converters. However, an alternative path is the use of Intensity Modulation and Direct Detection (IM/DD) schemes for the optical links supporting THz systems. A solution based on optical IM/DD links allows to take advantage of the reduced complexity compared with coherent solutions as well as of the maturity and the diverse commercial availability of IM/DD transceivers which will pave the way to affordable optical-THz frontends. Combining the use of optical IM/DD links with wavelength multiplexing, both In-Phase (I) and Quadrature (Q) components of the THz signal can be propagated in parallel over an optical fiber, using multiple amplitude levels in order to achieve m-ary modulation signals in the wireless link. To allow for further integration and reduced complexity of THz front-ends, Photonic Integrated Circuits (PICs) should be considered to implement THz front ends either by co-designing the optical and THz converters or by co-packaging the optical and THz front-ends.

To the best of our knowledge, in this paper we demonstrate for the first time an hybrid optical-THz link based on IM/DD optical link reaching 50 Gb/s over 20 km of Standard Single Mode Fiber (SSMF) and a wireless 50 cm-long line-of-sight (LoS) point-to-point-connection. Our analysis explores two configurations for a hybrid system: an optical-THz and a THz-optical link. Beyond the beforementioned comparison, we studied 16 GBd (QPSK and 16-QAM) and 32 GBd (QPSK) signals, achieving a successful fiber-optic/THz-wireless transmission at a maximum net data rate of 50 Gb/s with a bit error ratio (BER) below the soft-decision forward-error correction (SD-FEC) threshold of 2.2×10^{-2}.

2. Experimental setup

Fig. 1(a) and (b) represent the setup used for the experimental demonstration of the hybrid THz-optical IM/DD link. Whereas Fig. 1(a) depicts the hybrid link where the IM/DD is the first transmission block, in Fig. 1(b) the THz plays the initial transmission role. The former will be referred as downstream and the latter as upstream, considering the use case where the THz link is used as a wireless fiber extender [2]. Using the downstream case, the wavelengths of two external cavity lasers (ECLs) are set to ~1533.47 nm (λ_1) and ~1534.25 nm (λ_2) according to the ITU C-band grid standard and fed into two Mach Zehnder modulators (MZMs) with a bandwidth of 40 GHz. A two-channel 84 GSa/s digital-to-analog converter (DAC), where the two channels represent the I and Q components of the electrical baseband signal, drives both MZMs simultaneously. In our experiments, we employ QPSK and 16-QAM

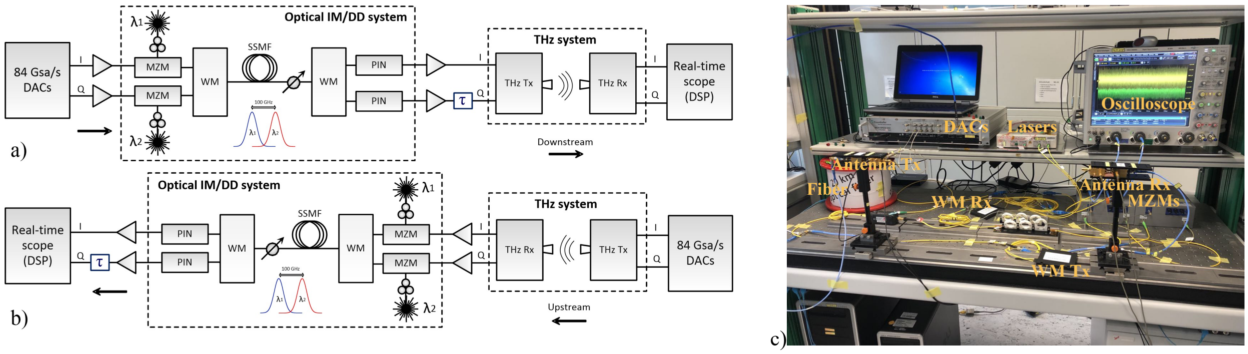

Fig. 1. Experimental setup using a hybrid approach with IM/DD optical and THz-wireless link for (a) downstream and (b) upstream directions; (c) Photo of the experimental setup.

formats at symbol rates of 16 and 32 GBd signals. The data signal corresponds to a randomly generated 2^{15}-bit-long binary sequence, to which a training sequence has been added for processing purposes. Furthermore, a root-raised cosine pulse shape with a roll-off factor of 0.35 has been applied digitally before entering the DAC.

After modulation, the two optical signals are combined using a wavelength multiplexer (WM), resulting in two wavelength division multiplexing (WDM) channels with a frequency separation of 100 GHz which carry the I and the Q component of the THz signal. In the optical domain, the signals take the form of non-return-to-zero (NRZ) in case of QPSK modulation in the THz domain, and 4-pulse amplitude modulation (4-PAM) in case of 16-QAM modulation. The optical power per channel at the fiber input is approximately 7 dBm. This signal is then propagated over a SSMF of various lengths. The attenuation value of the fiber is 0.2 dB/km and the dispersion parameter is around 16 ps/nm/km at λ_1 and λ_2. At the receiver side, a variable optical attenuator (VOA) adjusts the received power to a constant value (approximately 0 dBm/channel). Subsequently, both WDM channels are then separated using a WM and individually detected using two photodiodes with ~40 GHz bandwidth. Afterwards delay lines are applied to compensate the delay between the I and Q components induced by chromatic dispersion. After opto-electrical conversion, both signals are fed into the THz transmitter, which is based on monolithic microwave integrated circuits (MMIC) [10], and modulated onto a THz carrier using direct-conversion I/Q mixers resulting in a ~-15 dBm radiated output power. To generate the carrier in the THz band, a synthesizer generates a sinusoidal wave at 8.511 GHz. This is then increased by a factor of 36 in the internal multiplication stages of the THz modules to achieve a carrier frequency of ~306 GHz. Simultaneously, this signal is fed into the THz receiver front-end to downconvert the signal back into the baseband. The signal is transmitted over a 50 cm-long LOS wireless link using horn antennas with 23 dBi gain values. At the receiver side, we employ a single-chip I/Q direct-conversion THz receiver with a conversion gain > 5 dB and a noise figure < 9 dB. This device exhibits ~50 GHz bandwidth in the frequency range between 270 and 320 GHz [11].

After down-conversion, both I and Q signals are sampled at 80 GSa/s by a real-time oscilloscope with ~33 GHz bandwidth, and digital signal processing (DSP) is carried out offline [12]. The DSP includes resampling of the signal into two samples per symbol, I/Q imbalance compensation, frame-synchronization with the transmitted training sequence, and signal equalization using the minimum mean-square error approach supported by the training sequence. The signals are then down-sampled to one sample per symbol and the carrier phase recovery is performed using the blind phase search (BPS) algorithm. Finally, once the symbols have been decoded, BER is estimated via bit error counting. The considered BER threshold is 2.2×10^{-2} assuming a SD-FEC with 20% overhead. Combined with the training sequence, this enables a net bit rate of 50 Gb/s using 16 GBd 16-QAM and 32 GBd QPSK signals. For reference, a photo of the experimental setup in the upstream case is shown in Figure 1(c).

3. Experimental Results

In order to establish the benchmark performance of the system, we carried out measurements focusing exclusively on the IM/DD link. These results are presented in Fig. 2(a), where we can observe how the BER performance of the link depends on the length of the fiber. In this regard, four scenarios were evaluated: 16 and 32 GBd NRZ and 4-PAM signals. In the DSP the signals were processed as the I and Q components of the wireless system, i.e. as 16 GBd and 32 GBd QPSK and 16-QAM. In Fig. 2(a), one can observe that the IM/DD link operates below the defined SD-FEC threshold up to 20 km of fiber for 32 GBd QPSK, where distances of 15 and 20 km are already exhibiting some degree of degradation due to the dispersion along the fiber. Results for 32 GBd 16-QAM (net data rate of 100 Gb/s) are also presented in this graph. In this case, the degradation arising from dispersion limits the total reach before crossing the FEC threshold to 15 km. At 16 GBd QPSK and 16-QAM, no errors were observed in the number of symbols analyzed being represented at the bottom of the graph (at level -7 of the y-axis).

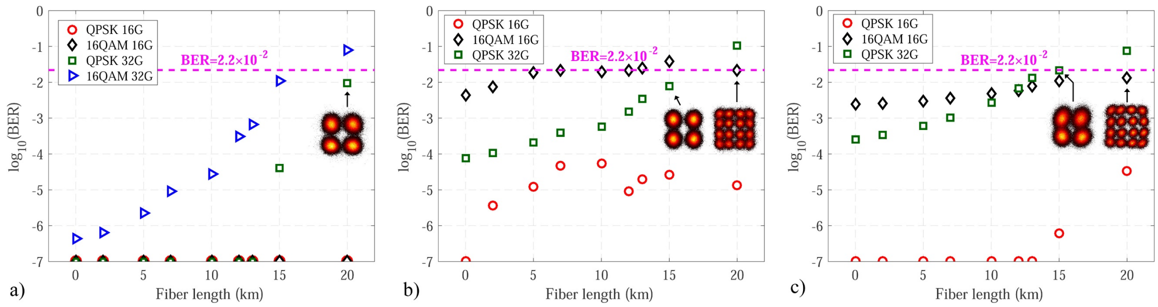

Fig. 2 – BER vs. fiber length for the (a) IM/DD system, (b) hybrid downstream and (c) hybrid upstream.

Fig.2 (b) and (c) depict the system performance in terms of BER versus fiber length for the downstream and upstream scenarios, respectively. In both cases, an increased degradation in the system performance is observed as the fiber distance increases, which originates from fiber impairments such as chromatic dispersion. For each fiber length analyzed, the time delay induced by the accumulated dispersion between the wavelengths of both I and Q signals was compensated using the delay lines. As expected, the overall performance of the system degrades further when increasing either the modulation order or the symbol rate for transmission. While the difference in performance between the two modulation formats is mainly coming from Signal to Noise Ratio (SNR) requirements, an increasing symbol rate incurs in an additional penalty mainly arising from the increased accumulated chromatic dispersion, but also from bandwidth limitations and nonlinearities of the THz frontends. Consequently, this did not allow to transmit 32 GBd 16-QAM signals over the hybrid optical-THz link in the current experiment. For both upstream and downstream scenarios a successful data transmission has been observed for a net bit rate of 50 Gb/s hybrid IM/DD-THz link up to 15 km for 32 GBd QPSK and 20 km 16 GBd 16-QAM.

4. Conclusions

We explored and demonstrated a hybrid optical-THz system using IM/DD optical links in two different configurations. Both configurations, where the wireless link was 50 cm-long and used a carrier frequency of 306 GHz, were shown to exhibit a BER performance below the FEC threshold for 20 km 16 GBd 16-QAM and 15 km 32 GBd QPSK signals, respectively. The total net data rate achieved on the hybrid system based on optical IM/DD and single THz channel was 50 Gb/s which, to the best of our knowledge, was demonstrated by the first time showing a path to exploit low-cost IM/DD optics for next generation optical-wireless networks.

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