# 107.1-GBPS NET-RATE TRANSMISSION OVER A JOINT 51km-FIBER-AND-10.7m-WIRELESS LINK FOR TERAHERTZ RADIO ACCESS NETWORKS

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## Abstract

107.1- and 93.9-Gbps net-rate (gross-rate 133.9- and 101.3-Gbps) OFDM transmission on a 408-GHz carrier frequency is experimentally demonstrated over a joint fiber-wireless link, 51-km single-mode fiber and 10.7-m free-space, with bit-error-rates below the 20% soft- and 7% hard-decision FEC thresholds of $2.7\times10^{-2}$ and $3.8\times10^{-3}$, respectively.

## 1 Introduction

While mobile communications move towards the fifth generation (5G), it has become obvious that networks beyond 5G (B5G) will have to tackle fundamental performance limitations related to the available bandwidth in the wireless spectrum, transmission and processing delay, cost and energy consumption [1]. Considering that the currently allocated frequency spectrum for 5G has almost reached its limits, the terahertz-wave band (0.1 – 10 THz) is gaining more attention for the upcoming B5G [2]. As a result, research on THz and sub-THz radio access networks is of great importance to utilize the unlicensed bandwidth in higher wireless frequency bands [3]. *First*, the THz wireless technology has a potential of delivering fiber-optic speeds “out of the fiber” offering terabits per second (Tbps) wireless connectivity for base-band units (BBUs) or even for radio remote units (RRUs). *Second*, THz communications are expected to be used for wireless access and backhaul networking to ensure high-speed Internet access everywhere, including areas where an optical fiber cannot be deployed due to geographical and infrastructure operator cost issues [4]. Moreover, such areas will expand due to the increasing number of RRUs per base-station. Hence, hundreds of gigabits per second will be required in transmission to or between BBU pools or between BBU pool and RRUs.

The THz channel itself is important to explore and develop, and several demonstrations have been reported in the 300 GHz range, e.g., [5], and in the 400 GHz range, e.g., [6], [7], focusing on capacity and wireless reach. However, if the application scenario is related to the reach extension in access networks, apart from the targeted high data rates and long wireless transmission, an overall reach for the joint fiber and wireless link is another critical parameter. Such joint fiber-wireless links should consist of at least two segments: *(i)* an optical fiber link, where two optical wavelengths (one carries data, the other is for THz generation) separated by the desired THz carrier frequency are transmitted; and *(ii)* a free-space segment for THz wireless transmission. Both these segments should be long enough, but they share an optical budget and contributes to an overall signal-to-noise ratio (SNR), which impacts a transmission performance. Seamless integration of radio and optical networks in a physical layer reduces network complexity and ensures high capacity in the upper transport and application layers, by reducing the need for additional signaling and management, especially considering a small-cell configuration [4]. In spite of that, only a few demonstrations report considerably high net-rates for joint fiber-and-THz-wireless links: in [8], a net-rate of 59 Gbps is demonstrated for a link that consists of short fiber span (the length is not mentioned) and 5 cm short wireless transmission at a carrier frequency of 325 GHz; and recently, in [9], a gross-rate of 132 Gbps with bit-error-rate (BER) under $4\times10^{-2}$ is experimentally demonstrated for a single carrier signal at 450 GHz after transmission over a 20 km fiber and 1.8 m wireless distance. However, both solutions have very limited applications due to a relatively low distance and/or signal quality performance.

In this context, we modify our THz-wireless link presented in [6] by substituting a THz-wave generation setup and by adding a 51 km long single-mode fiber (SMF) span to construct a joint fiber-wireless link operating with carrier frequencies in the >400 GHz band and wireless reach above 10 m. The single carrier at 408 GHz was generated by an optical frequency comb generator (OFCG) using a so-called photonic radio setup, and we use orthogonal frequency division multiplexing

(OFDM) for data transmission over the joint link. We achieved a BER below the 20% soft-decision forward error correction (SD-FEC) threshold of 2.7×10$^{-2}$ [10] for a gross-rate of 133.9 Gbps using 16-level quadrature amplitude modulation (16QAM)-modulated subcarriers of the OFDM signals, yielding a transmitted net-rate of 107.1 Gbps. The 7% hard-decision FEC (HD-FEC) threshold of 3.8×10$^{-3}$ is achieved for a gross-rate of 101.3 Gbps using quadrature phase-shift keying (QPSK)-modulated OFDM subcarriers, leading to a net-rate of 93.9 Gbps. Furthermore, we highlight that the BER requirement of 4×10$^{-2}$ for 27% SD-FEC [9] is met for a gross-rate of 159.6 Gbps; it brings a slightly higher net-rate of 116.5 Gbps, but at a cost of complexity that may be too high for optical and radio networks beyond 5G. In any case, these results, to the best of our knowledge, demonstrate for the first time the joint fiber-wireless link with net-rates above 100 Gbps after more than 50 km long fiber and 10 m long THz-wireless transmission using a carrier frequency above 400 GHz, which overwhelms the previous demonstrations.

## 2 Experimental Setup

The experimental setup is shown in Fig. 1. *First*, we generate two optical tones using an optical frequency comb generator based on an external cavity laser (ECL) and phase modulator that are driven by a 24 GHz radio frequency (RF) signal from an electrical local oscillator (LO). The generated comb signal is amplified by an Erbium doped fiber amplifier (EDFA) before two tones spaced by 408 GHz are filtered and separated by a wavelength selective switch (WSS).

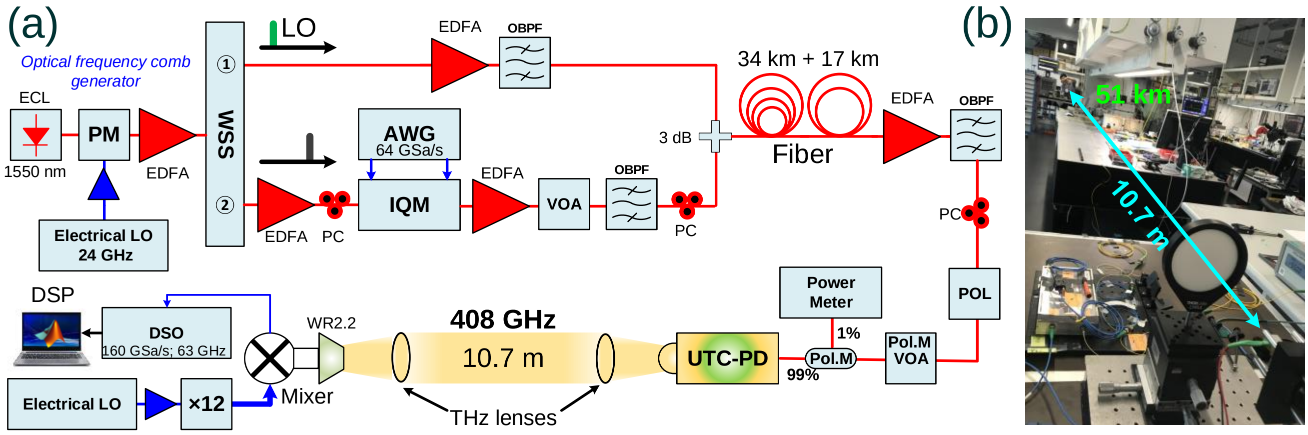

Fig. 1 (a) Experimental setup of the fiber-THz-wireless link used for the simultaneous transmission of the OFDM-modulated data; and (b) the moment from the experiment. Acronyms: ECL – external cavity laser; PM – phase modulator; EDFA – Erbium-doped fiber amplifier; LO – local oscillator; WSS – wavelength selective switch; PC – polarization controller; AWG – arbitrary waveform generator; IQM – In-phase and quadrature modulator; VOA – variable optical attenuator; OBPF – optical bandpass filter; POL – polarizer; Pol. M. – polarization maintaining; UTC-PD – uni-travelling carrier photodiode; DSO – digital storage oscilloscope; DSP – digital signal processing

*Second*, one tone (port 1) is used as an optical LO signal for heterodyne mixing to generate the THz carrier but is first amplified by an EDFA and filtered by an optical bandpass filter (OBPF) to get rid of excessive noise from the amplifier. The other tone (port 2) is used for carrying data. This tone is amplified, aligned in polarization (polarization controller, PC), and launched to an in-phase and quadrature modulator (IQM). A two-channel arbitrary waveform generator (AWG, 64 GSa/s) is used to generate an IQ-QFDM signal having the length of the inverse fast Fourier transformation (IFFT) and a cyclic prefix (CP) set to 1024 and 16, respectively. A MATLAB generated random binary sequence is used to generate the OFDM symbols. The modulated QPSK-/16QAM-OFDM optical signals are amplified, their power levels are adjusted by the variable optical attenuator (VOA) to keep the best power ratio for the highest photo-mixing efficiency in the uni-travelling carrier photodiode (UTC-PD) [11], then the out-of-band noise is filtered by an OBPF, and, finally, the polarization state is controlled by a PC.

*Third*, after an optical combiner, the optical LO and the IQ-OFDM-modulated signals are jointly transmitted over two single-mode fiber (SMF) spans – a 34 km super-large area (SLA) fiber and a 17 km inverse dispersion fiber (IDF). These two spans were dispersion matched. After the fiber transmission, the optical signals are amplified, filtered, and their polarizations adjusted. In addition, a polarization maintaining (Pol. M.) VOA is used to control the optical power launched into the UTC-PD for THz wave generation and wireless transmission. The UTC-PD generates the THz wave at a 408 GHz carrier frequency and emits it into a 10.7 m line-of-sight wireless link, where a pair of THz lenses (having 100 mm diameter and 200 mm focus length) are used to collimate the THz beam.

*Fourth*, at the receiver, the THz signal is down-converted to an intermediate frequency by a sub-harmonic Schottky mixer driven by a 12-times multiplied RF signal from an electrical LO. The IF signal at radio frequency 30 GHz is amplified, detected and then converted to digital samples by a real-time digital storage oscilloscope (DSO, 160 GSa/s and 63 GHz) for digital signal processing (DSP). Finally, we use a typical DSP stack for the OFDM signals. Besides the linear equalization (LE), phase noise compensation (PNC) and nonlinear equalization (NLE) are also used for channel equalization. The LE is used to compensate for the linear response and reduce the additive noise influence of the system. Subsequently, the PNC is implemented using a least-squares method. Finally, a simplified Volterra series nonlinear model, which considers the 2nd-order and the 3rd-order distortion terms, is used for mitigating the nonlinearity impairment.

## 3 Results and Discussion

After the fiber-THz-wireless transmission, we evaluate the single-channel QPSK-/16QAM-OFDM signal. *First*, we analyze how the channel pre-FEC bitrate (gross-rate) changes with pilot symbol overhead (see Fig. 2 (a)). The results here are after the nonlinear channel equalization (Volterra filtering) and phase compensation. A pilot symbol overhead of 10% means that every symbol per 10 OFDM symbols are followed by a pilot symbol. Figure 2 (a) also shows how the BER changes with the pilot symbol overhead. For the considered channel and the first OFDM configuration (1024 IFFT points, 900 QPSK-modulated subcarriers), we find that a pilot symbol overhead (OH) of 10% achieves a BER below $3.8\times10^{-3}$. This corresponds to a pre-FEC gross-rate of 101 Gbps (a net-rate 93.9 Gbps). The second OFDM configuration (1024 IFFT points, 560 16QAM-modulated subcarriers) achieves a BER below $2.7\times10^{-2}$, which yields a net-rate of 100.8 Gbps. However, these results are obtained for the highest optical power to the UTC-PD, which may lead to saturation. Therefore, optical power sweep is required to check the BER *vs.* optical power performance for a lower OH and for a larger number of OFDM subcarriers. Consequently, Fig. 2 (b) presents the BER versus optical power to the UTC-PD for four selected cases that fulfills a number of BER threshold set by a different type of FEC: *(i)* 101.3 Gbps gross-rate, which corresponds to a pilot symbol overhead of 10% and fulfills the HD-FEC requirement ($3.8\times10^{-3}$); *(ii)* 126 Gbps gross-rate and 10% OH; *(iii)* 133.9 Gbps gross-rate, which corresponds to a 4% OH and fulfills the 20% SD-FEC requirement ($2.7\times10^{-2}$); and *(iv)* 159.6 Gbps gross-rate, which corresponds a OFDM configuration with 684 16QAM-subcarriers and a 7% OH and fulfills the 27% SD-FEC requirement ($4\times10^{-2}$).

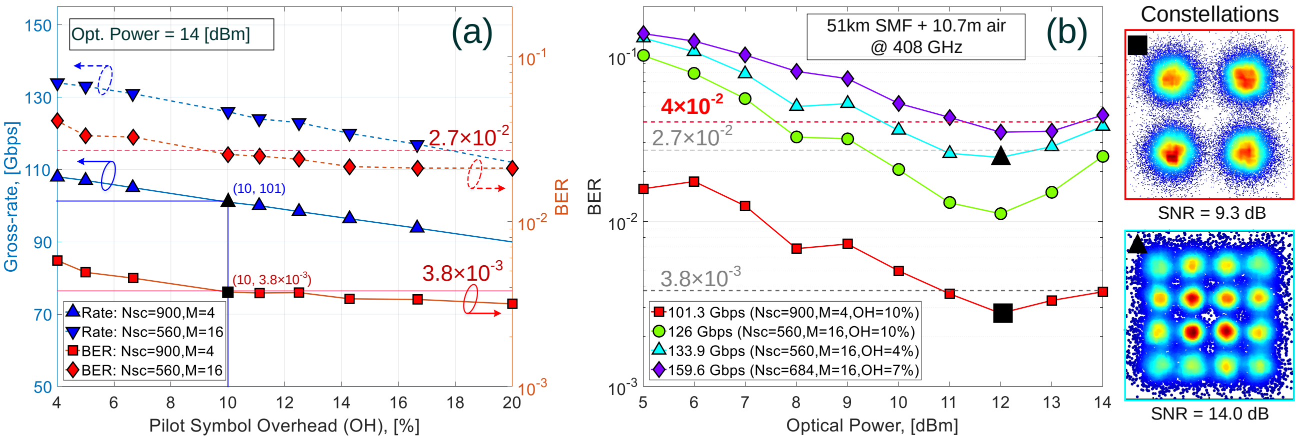

Fig. 2 Experimental results showing (a) the OFDM channel pre-FEC gross-rate) and corresponding BER vs. the pilot symbol overhead for the 14 dBm optical power launched into the UTC-PD; and (b) BER vs. the optical power launched into the UTC-PD for four cases: 101.3 Gbps, 126 Gbps, 133.9 Gbps, and 159.6 Gbps gross-rates

The lowest BERs are observed for the +12 dBm optical power, and the highest average signal-to-noise-ratio (SNR) of *(i)* 9.3 dB, *(ii)* 14.5 dB, *(iii)* 14.0 dB, and *(iv)* 13.2 dB are achieved for the considered cases. Such low SNR is not only due to the performance of the THz components, such as the Schottky mixer and the UTC-PD with its poor conversion efficiency (0.15 A/W), but also due to fiber transmission loss. The constellation diagrams for the most significant cases are shown as insets in Fig. 2 (b) and stamp the transmission performance of the joint fiber-and-THz-wireless link.

## 4 Concluding Remarks

We have demonstrated the joint THz fiber-wireless link in the >400 GHz carrier frequency range by transmitting a single channel 408 GHz carrier with 93.9 Gbps and 107.1 Gbps (gross-rates: 101.3 Gbps and 133.9 bps) QPSK-/16QAM-OFDM over 51 km SMF and 10.7 m free space with BER below the 7% HD-FEC threshold of $3.8\times10^{-3}$ and below the 20% SD-FEC threshold of $2.7\times10^{-2}$. The THz carrier at 408 GHz was generated via photonic heterodyning of two tones from an optical frequency comb generator based on phase modulator. The presented results pave the way towards the delivering of fiber-optic speeds "out of the fiber", while extending the radio access networking for future B5G communications.

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