616-Gbit/s Single Line Rate Fiber-THz-Fiber Seamless Transmission Utilizing Cascaded MIMO Equalization

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Abstract: We experimentally demonstrate 56-GBaud PS-64QAM signal fiber-THz-fiber seamless communication by employing photonic up-/down-conversion technique and cascaded MIMO equalization algorithms, achieving a record-breaking single-carrier line rate of 616 Gbit/s.

1. Introduction

THz-wave communication, with sufficient spectrum resources (0.3 THz~10 THz), can meet the needs of future 6G large-capacity mobile communication services [1-7]. Recently, the seamless integration of existing fiber-optic networks and THz-wave wireless links has attracted great attention [8-10]. THz wireless bridge can establish effective and low-cost high-speed connections in areas where fiber deployment is difficult or very expensive, or in situations where catastrophic events cause damage to the fiber-optic networks. Therefore, such a flexible fiber-THz-fiber transmission architecture has great potential in the application of 6G mobile fronthaul and backhaul. Based on DCO modules and MMIC-based direct-conversion I/Q mixers in THz transceiver, 100-Gbit/s net-capacity real-time fiber-THz-fiber delivery over two spans of 103-km SSMF and 0.5-m wireless distance at 300 GHz has been demonstrated [8]. Real-time transparent fiber-THz-fiber delivery over two spans of 20-km SSMF and 3-m wireless distance using commercial DCO modules and photonics-aided scheme with single-channel 103.125-Gbit/s and dual-channel 2×103.125-Gbit/s net capacity has been reported [9,10]. However, it is still a technical challenge to achieve ultra-high-speed fiber-THz-fiber transmission with single-channel throughput of hundreds of Gbit/s or even Tbit/s.

By employing photonic up-/down-conversion technique, PS technique and cascaded MIMO equalization algorithms, we have experimentally demonstrated fiber-THz-fiber seamless integrated transmission system with single line rate of 616 Gbit/s under 0.83-NGMI threshold. As far as we know, it is the first time to achieve above 600-Gbit/s/channel fiber-THz-fiber seamless communication, which paves the way towards future ultra-high-speed 6G mobile fronthaul and backhaul.

2. Experimental setup

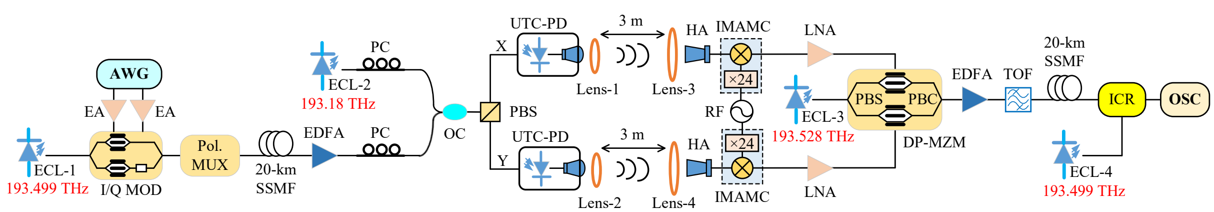

Fig. 1. Experimental setup.

The experimental setup for broadband fiber-THz-fiber communication system is illustrated in Fig. 1. Photos of optical transmitter, THz wireless transmitter and receiver, 3-m 2×2 wireless link, optical receiver of the test-bed setup are shown in Figs. 2(a)-(d), respectively. In the Tx-side offline DSP, we generate the PS-64QAM symbol sequence with 5.5-bit/symbol information entropy via probabilistic amplitude shaping (PAS) scheme [7], which is then ×2 up-sampled and sent into RC filter with 0.01 roll-off factor. We utilize an AWG with 112-GSa/s sampling rate for the electrical baseband I/Q signals generation, which are boosted and fed into an I/Q modulator (Fujitsu, FTM7961EX) biased at the null point. The tunable ECL-1 with linewidth less than 100 kHz provides the optical carrier at 193.499 THz for the I/Q modulator. Then, a polarization multiplexer (pol. MUX) is deployed to realize polarization-division multiplexing (PDM), which consists of a PM-OC, a 2-m optical delay line (ODL) and a PBC. After 20-km SSMF link, an EDFA is added to compensate for the insertion loss and control the input power into the THz wireless transmitter. The optical signals are then coupled with the optical local oscillator (LO) from ECL-2 operating at 193.18 THz through an OC. The X- and Y -polarization diversities of the PDM optical signals are achieved via a PBS. The optical-to-THz conversion is realized via the UTC-PD (NTT IOD-PMAN-13001). Two PCs are deployed to control the optical polarization state before the polarization-sensitive UTC-PDs. The frequency space between the optical carriers from the free-running ECL-1 and ECL-2 is 319 GHz. Therefore, the center frequency of the generated THz-wave signals is 319 GHz. Fig. 3(a) depicts the optical spectra of a 56-GBaud PS-64QAM optical signal and optical LO into the UTC-PD.

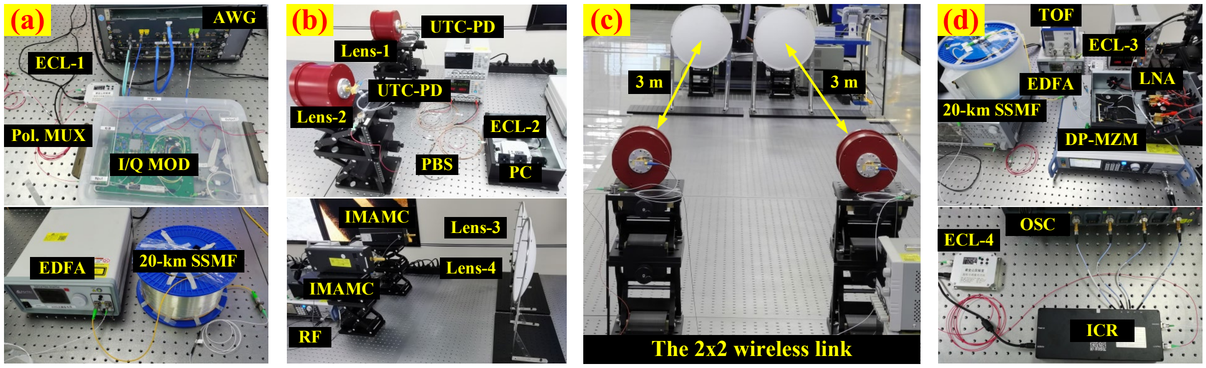

Fig. 2. Photos of setup: (a) optical transmitter, (b) THz wireless transmitter and receiver, (c) 3-m 2×2 wireless link, (d) optical receiver.

In the 3-m 2×2 wireless transmission link, two pairs of parallel PTFE lenses are utilized to focus the THz beams. In the THz wireless receiver, an integrated mixer/amplifier/multiplier chain (IMAMC) in each path is utilized to realize the analog down conversion of THz-wave signals, which includes a mixer and a ×24 frequency multiplier, driven by a 14.5-GHz RF source. Two IF signals obtained with 29-GHz center frequency are amplified via parallel LNAs to drive the DP-MZM (Fujitsu, FTM7980EDA) biased at the optical-carrier-suppression point. ECL-3 operating at 193.528 THz provides the optical carrier for the DP-MZM. The generated PDM optical double-sideband (DSB) signals are then amplified via an EDFA and sent into a band-pass TOF. The TOF is utilized to select the optical upper sideband (USB) for homodyne coherent detection, which filters out the optical lower sideband (LSB) and the ASE noise. Fig. 3(b) depicts the optical spectra of optical signals before and after the TOF, where the resolution is 0.03 nm. After 20-km SSMF link, the PDM optical USB signals are homodyne detected via an integrated coherent receiver (ICR). The optical LO of the ICR generated by ECL-4 operates at 193.499 THz, which is consistent with the center frequency of the initial optical baseband signal. Finally, the electrical baseband signals are captured by a 4-ch oscilloscope with 128-GSa/s sampling rate and 59-GHz bandwidth.

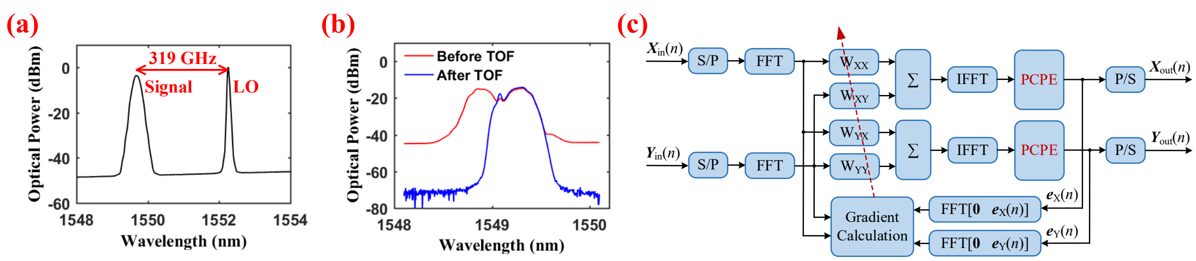

Fig. 3. (a) Optical spectra of optical signal and optical LO into UTC-PD; (b) Optical spectra of optical signals before and after TOF; (c) Block diagram of MIMO-FDE-PCPE algorithm.

The Rx-side offline DSP includes resampling, chromatic dispersion compensation, I/Q orthogonalization, T/2-spaced likelihood-based selection radius-directed equalizer (LBS-RDE), frequency offset estimation (FOE) and data synchronization. Afterwards, cascaded MIMO equalization algorithms are utilized to eliminate the linear and nonlinear interference and damage between X-polarization and Y-polarization generated during the fiber-THz-fiber transmission, which consists of 2×2 MIMO hybrid frequency domain equalization and principal component-based phase estimation (MIMO-FDE-PCPE) algorithm, 2×2 MIMO Volterra nonlinear equalization (MIMO-VNLE) algorithm, and 2×2 MIMO LBS decision-directed least mean square (MIMO-LBS-DD-LMS) algorithm. The block diagram of MIMO-FDE-PCPE algorithm is illustrated in Fig. 3(c), where block-by-block PCPE with low computational complexity is integrated with adaptive FDE. MIMO-FDE-PCPE uses FDE with FFT size of 256 for inter-polarization crosstalk cancellation and PCPE with covariance window length of 128 for carrier phase estimation. The phase error of all symbols within the block is compensated prior to FDE, which mitigates the effect of equalization-enhanced phase noise. MIMO-VNLE with 210 second-order nonlinear kernels is employed to reduce the nonlinear damage between two polarizations. The probability-aware MIMO-LBS-DD-LMS with 53 taps is utilized to eliminate the residual inter-polarization linear impairment and I/Q imbalance for PS-QAM signals.

3. Results and discussion

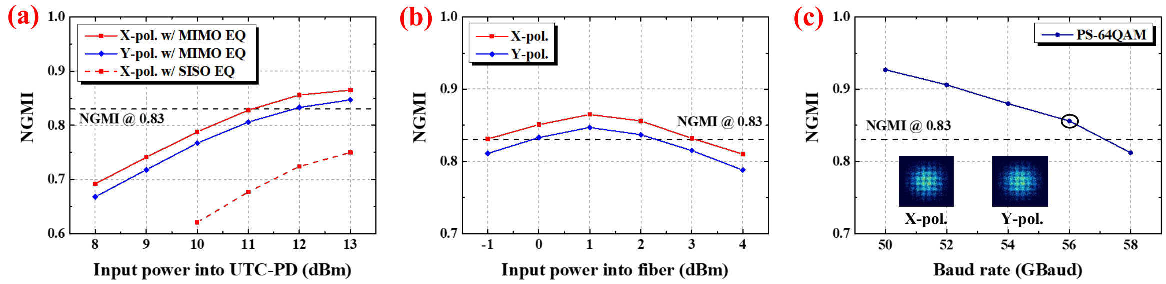

Fig. 4. (a) NGMI of 56-Gbaud PS-64QAM signals versus input power into UTC-PD; (b) NGMI of 56-Gbaud PS-64QAM signals versus input power into fiber before the ICR; (c) NGMI versus baud rate for PS-64QAM signals.

We analyze the NGMI performance in the fiber-THz-fiber transmission system under various conditions. When we deploy the DVB-S2 LDPC with 4/5 code rate in the PAS scheme for PS-64QAM format generation, 0.83-NGMI threshold can be applied to indicate the error-free decoding results [7]. Fig. 4 (a) depicts the NGMI performance of the received 56-Gbaud PS-64QAM signals in X-polarization and Y-polarization versus input power into the UTC-PD. Here, we compare the NGMI performance using cascaded MIMO equalization and cascaded SISO equalization. With the aid of cascaded MIMO equalization, to reach the 0.83-NGMI threshold, the required UTC-PD input power is at least 12 dBm. As the input power increases, the NGMI performance will be affected by the saturation effect of UTC-PD. The slight difference in NGMI performance of signals in X-polarization and Y-polarization is mainly caused by the polarization-dependent loss and the difference in insertion loss between devices in two paths. However, when MIMO equalization is replaced by SISO equalization, NGMI performance will deteriorate and decrease from 0.865 to 0.75 at 13-dBm input power. It embodies the advantages of MIMO equalization in eliminating inter-polarization interference.

When the input power into UTC-PD remains at 13 dBm, Fig. 4 (b) gives the measured NGMI performance of 56-Gbaud PS-64QAM signals versus input power into the 20-km fiber before the ICR. The result shows that the optimal launch optical power is approximately 1 dBm. Moreover, we investigate the transmission rate in the fiber-THz-fiber transmission system. Fig. 4 (c) illustrates the overall NGMI performance versus baud rate for PS-64QAM signals. As the baud rate increases, the limited bandwidth of devices and the crosstalk between the two sidebands of the DSB signals lead to deterioration of NGMI performance. To achieve the error-free decoding results, the highest baud rate is 56 GBaud. The recovered constellation diagrams of 56-GBaud PS-64QAM signals in X-polarization and Y-polarization are also given. The highest single line rate obtained in the fiber-THz-fiber transmission system is 616 Gbit/s (5.5×2×56=616 Gbit/s). After removing LDPC overhead, the net rate is 481.6 Gbit/s ([5.5-6×(1-4/5)]×2×56 = 481.6 Gbit/s).

4. Conclusions

We have experimentally demonstrated a promising ultra-high-speed fiber-THz-fiber seamless integrated transmission system for future 6G mobile fronthaul and backhaul. Thanks to the photonic up-/down-conversion technique, PS technique and cascaded MIMO equalization algorithms, 616-Gbit/s/channel single line rate (481.6-Gbit/s/channel net rate) transmission can be successfully achieved, under the 0.83-NGMI threshold.

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