Experimental Demonstration of Single-wavelength, Single-polarization 102-Gb/s DMT Signal Transmission over 105-km Single-span SMF in an IM-DD System

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Abstract: We experimentally demonstrate a 102-Gb/s DMT signal transmission over 105-km single-span SMF in an IM-DD system. This work reports the highest single-wavelength and single-polarization net data rate × single span length product in IM-DD systems.

OCIS codes: (060.2330) Fiber optics communications; (060.4080) Modulation

1. Introduction

Driven by the rapidly increasing demands for broadband services such as cloud computing and high definition video, the bandwidth requirements in metro networks and data center interconnects (DCIs) have grown tremendously in recent years [1]. Since these scenarios are sensitive to cost and power consumption, coherent systems face challenges despite their high capacities. Compared to coherent systems, direct detection (DD) systems are preferred in metro/DCI applications [2], considering the advantages of low cost, low power consumption, and easy implementation.

However, high-capacity DD systems suffer from limited system bandwidth and impairments from fiber chromatic dispersion (CD) and nonlinearities. Recently, to satisfy the requirements of higher net data rate beyond 100 Gb/s per wavelength, various digital signal processing (DSP) techniques have been proposed to solve these problems. It was reported that pre-emphasis and duo-binary filtering at the transmitter can alleviate the inter-symbol interference (ISI) caused by limited system bandwidth, with an improved system performance [3,4]. In order to deal with the dispersion-related power fading, Hilbert transforming-based single sideband (SSB) modulation and digital CD pre-compensation were used in DD systems [5,6]. Signal-signal beating interference (SSBI) cancellation schemes, such as iterative cancellation and Kramers-Kronig (KK)-based cancellation [7,8], can greatly mitigate the effect of SSBI. Volterra nonlinear equalization (NLE) algorithm was also employed to compensate the nonlinearities of the DD systems [5].

Moreover, multiple advanced modulation formats, such as pulse amplitude modulation (PAM), carrier-less amplitude phase modulation (CAP), and discrete multi-tone modulation (DMT), have been extensively studied in metro/DCI systems [3,9]. Among these formats, DMT is a promising candidate due to its high spectral efficiency, high tolerance to dispersion and flexible bandwidth allocation.

In this paper, we experimentally demonstrate a 102-Gb/s DMT signal transmission over 105-km single-span single mode fiber (SMF) in an intensity modulation-direct detection (IM-DD) system at C band. In the experiment, bit loading is performed to acquire the maximum capacity under the limited bandwidth. Then, to overcome the inherent high peak-to-average power ratio (PAPR) for DMT signals, partial transmit sequence (PTS) technique is used, leading to a higher transmit power efficiency [10]. NLE algorithm is also implemented to improve the system performance and increase the transmission capacity [5]. Enabled by these advanced DSP techniques, a large net data rate × single span length product, i.e., 102.08 Gb/s × 105 km = 10718.4 Gb/s*km, is achieved. To the best of our knowledge, this is the highest single-wavelength and single-polarization net data rate × single span length product in IM-DD systems at C band.

2. Experimental setup

Fig. 1(a) shows the experimental setup of the 102-Gb/s DMT IM-DD system. The digital DMT data is generated offline by Matlab and converted to an analog signal using an arbitrary waveform generator (AWG) (Keysight M8195A), with a 64-GSa/s sampling rate and a 25-GHz analog bandwidth. The output signal is then amplified by an electrical amplifier (EA) with a bandwidth of 45 GHz. A continuous wave (CW) light from a distributed feedback laser (DFB) at 1550 nm is fed into a 25-GHz intensity modulator (IM). The IM is biased at the quadrature point, to obtain the linear electrical-to-optical (E/O) conversion. In the modulator, the electrical DMT signal is linearly converted to an optical DMT signal. After amplified by an erbium-doped fiber amplifier (EDFA), the optical signal is fed into a 105-km single-span SMF, with an optimal 7-dBm launch power. The CD of the 105-km fiber is compensated by a dispersion-compensating fiber (DCF). Another EDFA is used to exactly compensate the DCF loss, due to the constraint power budget of the system. At the receiver, the received optical signal is first amplified by an EDFA and then filtered by an optical band-pass filter (OBPF), to suppress the amplified spontaneous emission (ASE) noise. A following 40-GHz photodetector (PD) converts the optical signal to an electrical signal, which is then captured by a digital storage oscilloscope (DSO) (LeCroy 36Zi-A) at 80 GSa/s. Finally, the offline processing is performed to retrieve the original data and calculate the bit error ratio (BER). The end-to-end frequency response of the system is measured by performing the frequency sweeping of the AWG, as shown in Fig. 1(b). According to the results, the 3-dB bandwidth of the system is ~2.9 GHz, while the 10-dB bandwidth is ~21.7 GHz. The limited bandwidth will introduce strong ISI and high-frequency attenuation, thus degrading the system performance.

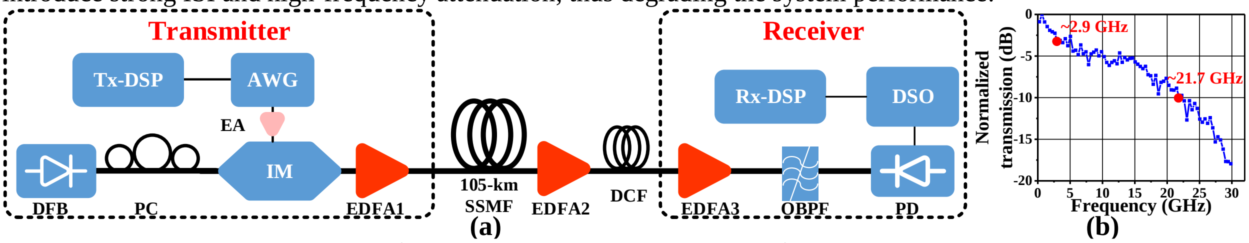

Fig. 1. (a) Experimental setup of the DMT system; (b) Frequency response of the system. PC: polarization controller.

The DSP flow charts at the transmitter side and the receiver side are depicted in Fig. 2 (a). At the transmitter side, a pseudo-random binary sequence (PRBS) is mapped onto the subcarriers with different quadrature amplitude modulation (QAM) orders, according to the bit loading results, as shown in Fig. 2(b). The bit loading is carefully designed by estimating the electrical signal to noise ratio (ESNR) of each subcarrier at the receiver. After the serial to parallel (S/P) converting, training symbols and one synchronization symbol are added. The PTS algorithm is then applied to reduce the PAPR of the real DMT signal, which is obtained by using Hermitian symmetry. Following the 512-point inverse fast Fourier transform (IFFT), 8-point cyclic prefix (CP) is added. After the parallel to serial (P/S) converting, the acquired DMT signal is sent to the AWG. The frame structure of the DMT signal is shown in Fig. 2(c), consisting of one synchronization symbol, 39 training symbols and 1000 data symbols. At the receiver side, the signal captured by the DSO is first down-sampled to the sampling rate of the AWG. Then the synchronization operation is performed to obtain the DMT symbols, by sliding window and calculating correlation function. Subsequently, the NLE algorithm is employed to effectively alleviate the nonlinearities, especially the interplay between CD and direct detection. After the S/P converting and CP removing, fast Fourier transform (FFT) is used to transform the signal from the time domain to the frequency domain. In the frequency domain, the 1-tap equalizer is implemented to compensate the residual CD due to the mismatch of the DCF and other linear distortions. Finally, the de-mapping and P/S converting are performed, following the BER calculation.

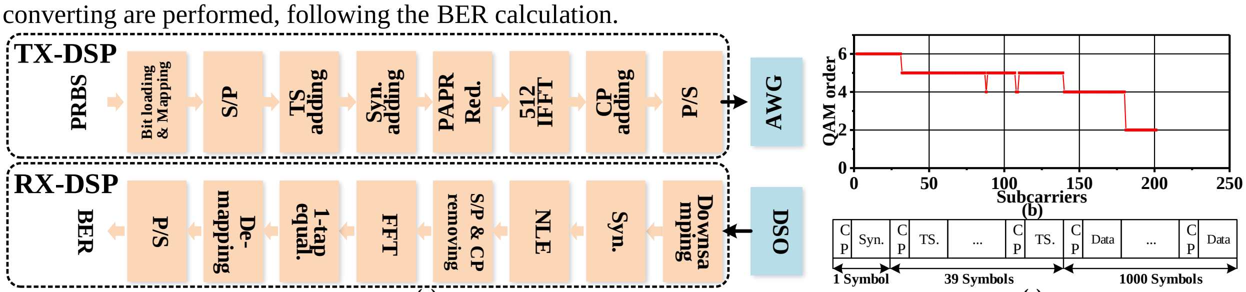

Fig. 2. (a) DSP flow charts at the transmitter side and the receiver side; (b) Bit loading; (c) Frame structure of the DMT signal. TS.: training symbol; Syn.: synchronization; PAPR Red.: PAPR reduction; 1-tap equal.: 1-tap equalization.

In the experiment, the first 200 subcarriers are loaded with data, leading to a valid signal bandwidth of 25 GHz. The corresponding date rate is 109.23 Gb/s ($64\times\frac{6\times30+5\times105+4\times44+2\times21}{512}\times\frac{512}{512+8}\times\frac{1000}{1000+1+39}$). Considering the 7% forward error correction (FEC) overhead, the net data rate is 102.08 Gb/s ($109.23\times\frac{1}{1+0.07}$).

3. Results and Discussion

Fig. 3 (a) plots the ESNR results at the receiver with and without the NLE algorithm, respectively. The ESNR of each subcarrier is estimated by transmitting the DMT signal with quadrature phase shift keying (QPSK) modulation and calculating the received constellations. It can be observed that a maximum ~2.5-dB improvement is achieved by using the NLE algorithm. With the carefully designed bit loading, BER curves of the DMT signals for back-to-back and after 105-km single-span fiber transmission are measured respectively, as shown in Fig. 3 (b). At the 7% hard decision-FEC threshold of 3.8×10^{-3}, the receiver sensitivity is –19 dBm in the back-to-back case. After the 105-km single-span SMF transmission, the FEC threshold is achieved at the –13.4-dBm received optical power, with a 5.6-dB power penalty. Limited by the constrained power budget of the 105-km fiber link, higher received optical power cannot be obtained. The constellations of the 64-QAM, 32-QAM, 16-QAM and QPSK signals are shown in Fig. 3 (c), which were obtained at the –13.4-dBm received optical power for the case of 105-km fiber transmission. An error floor of 4.6×10^{-4} is noted in the back-to-back case, which is mainly caused by the qualification noise and the limited system bandwidth. Further performance improvement can be realized with more advanced DSP techniques.

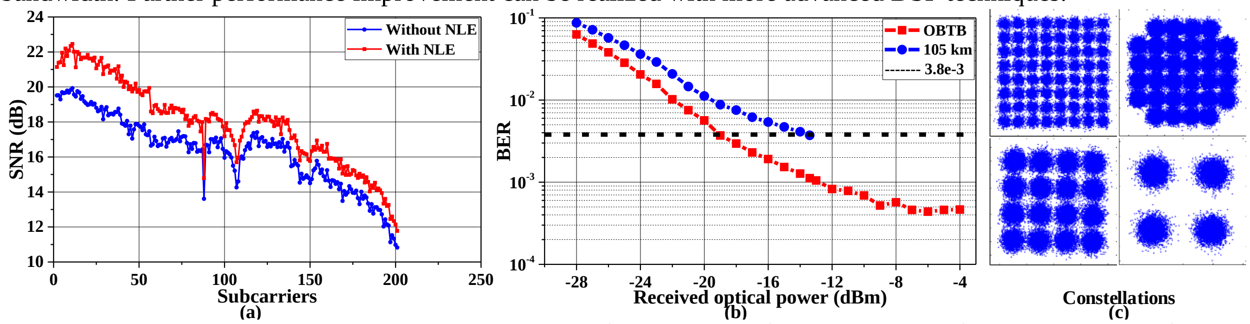

Fig. 3. (a) ESNR curves with and without NLE; (b) BER curves of the DMT signals for back-to-back and after 105-km single-span fiber transmission; (c) Constellations of the 64-QAM, 32-QAM, 16-QAM and QPSK signals. OBTB: optical back-to-back.

Previous experimental demonstrations of high-capacity IM-DD systems employing intensity modulators at C band are detailed in Table 1. Note that the systems using complex modulators (e.g., in-phase/quadrature Mach-Zehnder modulator and dual-drive Mach-Zehnder modulator biased at the quadrature point) are not included. Among these systems, our demonstration has the highest net data rate × single span length product under the condition of single wavelength and single polarization.

Table 1. Previous experimental demonstrations of high-capacity IM-DD systems employing intensity modulators at C band. OOK: on-off keying; DFT-S OFDM: discrete Fourier transform-spread orthogonal frequency division multiplexing; DCM: dispersion compensation module; VSB: vestigial sideband.

References	Modulation format	CD solution	Gross / Net data rate in Gb/s	Single span length × Span number in km	Net data rate × Single span length in Gb/s*km
This work	DMT	DCF	109.23 / 102.08	105 × 1	10718.4
[11]	OOK	DCM	140 / 130.84	80 × 1	10467.2
[12]	DFT-S OFDM	VSB	144 / 120	80 × 1	96000
[13]	PAM4	DCF	112 / 104.67	80 × 1	8373.6
[14]	PAM4	VSB	112 / 104.67	80 × 1	8373.6

4. Conclusion

In this paper, a single-wavelength and single-polarization DMT signal of 102 Gb/s is successfully transmitted in an IM-DD system over a 105-km single-span SMF at C band, enabled by advanced DSP techniques including bit loading, PAPR reduction and nonlinearity equalization. To the best of our knowledge, this demonstration has the highest net data rate × single span length product in IM-DD systems with single wavelength and single polarization.

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