>87% Complexity Reduction at 25-GS/s, 50-Gbps and 30-dB Loss Budget LR-OFDM PON using Digital Predistortion

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Abstract: We demonstrate the digital predistortion (DPD) at a reduced sampling rate in high-loss-budget 10G-class LR-PONs. A >50-Gbps transmission was achieved over 30-70 km using fixed DPD with >87% complexity reduction, compared to fully optimized DPD.

1. Introduction

The introduction of fifth-generation (5G) and future access networks will impose new challenges on passive optical networks (PON) in terms of data rates, loss budget, and transmission reach. Achieving these goals will require dramatic advances in optics technologies and the reconstruction of entire network architectures. In IEEE 802.3, the new 50 Gb/s/λ Ethernet PON has been standardized for 400G Ethernet [1]. Such high-capacity systems would require high-order modulation to reduce the bandwidth requirements for optical components. For instance, 4-level pulse amplitude modulation (PAM4) is widely viewed as a candidate solution to meet growth requirements. In addition to lower bandwidth requirements, orthogonal frequency division multiplexing (OFDM) imposes superior bit-rate scalability and higher tolerance to non-flat response resulting from power fading in long-distance dispersive transmission. This has led to the development of OFDM-PONs to support the data rates required for 5G networks [2]. Extended-reach links will enable the proliferation of small cells for fiber-optic-based backhaul systems [3]. The preferred approach to cost-sensitive systems is intensity modulation and direct detection (IMDD), which permits low cost and power consumption. Note however, that the capacity of IMDD LR-PON is limited by severe power fading and high transmission loss. The use of high launch power to induce strong self-phase modulation (SPM) has been proposed to mitigate severe fading and enhance the loss budget without the need for optical inline- or pre-amplification [4]. Unfortunately, SPM tends to aggravate dispersion-induced nonlinear distortion, which can seriously degrade system performance. Compensation for nonlinear distortion can be achieved using digital nonlinear equalizers (NLE), such as Volterra-based equalizers or artificial neural network-based equalizers [5], [6]. Note that all such schemes implemented in the form of post-compensation necessitate the use of additional hardware and/or software at the receiver, which can greatly increase costs and energy consumption, particularly when dealing with large-scale optical network users (ONUs).

In this work, we introduce a >50 Gbps OFDM LR-PON with the loss budget of 30 dB using digital predistortion (DPD) based on Volterra filter at a reduced sampling rate. Specifically, while the Nyquist sampling rate is 21 GS/s in this work, the sampling rate was reduced from 50 GS/s (oversampling by $\sim$2.4$\times$) to 25 GS/s (oversampling by only 1.2$\times$); such reduction is particularly important in decreasing power consumption and implementation costs. Compared to the optimal performance using DPD at 50 GS/s, it is possible to reduce the complexity by >87% using DPD at 25 GS/s, when still satisfying a target data rate of >50 Gbps. Note that these benefits were achieved with only a <9.6% decrease in the maximum achievable data rate over all testing distances. Moreover, a fixed DPD exhibited excellent tolerance to transmission distance, achieving >50 Gbps at all distances of 30-70 km.

2. Experiment setup an digital predistortion optimization

Fig. 1 illustrates the experiment setup of the proposed LR-PON system. The OFDM signal comprised 216 subcarriers with an FFT size of 1024 (50 GS/s) or 512 (25 GS/s), a cyclic prefix (CP) of 1/64, and a signal bandwidth of $\sim$10.5 GHz. The modulation format of the training signals was 16 QAM, and that of the testing signal was adaptively adjusted in accordance with the signal-to-noise ratio (SNR) using the bit- and power-loading (BPL) algorithm. The baseband signal was loaded into an arbitrary waveform generator (AWG; Tektronix AWG70001A). The light source was a 1541 nm DFB laser (Thorlabs WDM8000) and modulated by an electro-absorption modulator (EAM; CIP 10G-LR-EAM-1550). An Erbium-doped fiber amplifier (EDFA) was used with a variable optical

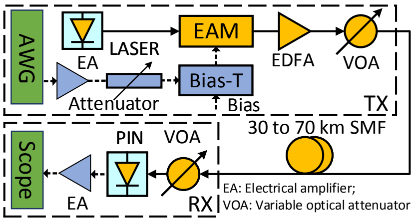

Fig. 1: Schematic of experiment setup.

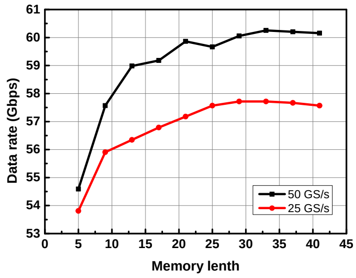

Fig. 2: Optimization of NPC at 50 GS/s and 25 GS/s.

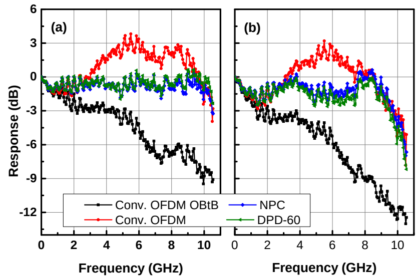

Fig. 3: Responses before and after 60-km SMF: a) Scenario 1; b) Scenario 2.

attenuator (VOA) to establish a launch power of 18 dBm. Following transmission over standard single mode fiber (SMF) at distances of 30-70 km, the received signal was detected using a 10G PIN and then captured using a digital oscilloscope (Tektronix DPO 71254) with a bandwidth of 12 GHz. Note that the sampling rates of the AWG and oscilloscope were fixed at either 50 GS/s or 25 GS/s, which corresponding to the oversampling by 2.4 or 1.2, respectively. In experiments, the received optical power was fixed at -12 dBm, resulting in a loss budget of 30 dB.

During training, the received waveform was used to optimize the NLE for either NPC or DPD applications by minimizing the mean square error (MSE) between the output and target waveform [7]. Fig. 2 presents the achievable data rates with NPC after 60-km SMF as a function of memory length. Note that the Volterra series in this work was of the 3rd order without any 3rd-order cross terms. The data rate was measured at the target bit error rate of 3.8×10^{-3} (i.e., a limit of 7% hard-decision forward error correction), based on the BPL algorithm. At a sampling rate of 50 GS/s, the data rate increased with memory length before reaching saturation at $\sim$ 60 Gbps, at which the memory length exceeded 29. Due to the effects of aliasing, reducing the sampling rate to 25 GS/s reduced the effects of compensation for nonlinearity, resulting in 2.5 Gbps decrease in data rate, except when the memory length was less than 10. In the remainder of this work, we compare two scenarios with different NLE settings. Scenario 1 maximizes the performance of the NLE without considering complexity at a sampling rate of 50 GS/s. Thus, the Volterra memory length was 29, in accordance with Fig. 2. Scenario 2 minimizes NLE complexity with a target of 50 Gbps at a sampling rate of 25 GS/s. As described in [7], the achievable data rate using the DPD was roughly 8% lower than that of NPC. Thus, to achieve the target data rate using DPD, we selected the memory length of NLE such that the data rate with NPC was roughly $\sim$55 Gbps. Thus, the Volterra memory length in Scenario 2 was 9.

3. Experiment results and discussions

Fig. 3 presents the responses of OFDM systems after 60-km transmission using NPC or DPD. This figure also presents the frequency responses of conventional OFDM (i.e., the signal without any NLE) at optical back-to-back (OBtB) and after 60-km SMF. Note that the abbreviation DPD-xx (e.g., DPD-60) in Fig. 3 denotes the application of xx-km transmission signals to train the NLEs. In both scenarios, the responses at OBtB are limited primarily by the bandwidth of the AWG. Compared to the response at OBtB, the interaction between the SPM and dispersion increased the response following transmission over 60-km SMF. As applying NLEs in the first scenario, the best compensation for nonlinear impairment resulted in relatively flat responses, except for subcarriers near the band edge, as shown in Fig. 3(a). The dramatic drop in response indicates that NLEs are less effective in overcoming severe nonlinear distortion near the band edge. The responses using the NLEs in Fig. 3(b) present more fluctuation, particularly at frequencies exceeding 7 GHz, indicating that minimizing the complexity of NLEs undermines equalization ability.

We also examined NLE optimization in the context of SNR. Fig. 4 illustrates the improvements in SNR afforded as a function of frequency using the proposed scheme in Scenarios 1 and 2 after 60-km SMF. This figure also presents the SNR in cases without NLE over 60-km SMF. As shown in Fig. 4, the SNR curve in Scenario 2 was slightly lower than that in Scenario 1, (particularly at high frequencies), due mainly to a reduced response. Overall, all of the schemes provided significant improvements in SNR at frequencies exceeding 6 GHz, due to the fact that nonlinear distortion is less pronounced at lower frequencies. Optimizing NLE performance (i.e., Scenario 1) permitted a more pronounced improvement in the SNR at frequencies near the band edge, where nonlinear distortion was far more severe. Minimizing the complexity of the NLE (i.e., Scenarios 2) provided roughly the same benefit as Scenario 1 in terms of SNR at frequencies from 0 to 9 GHz. Note however that at frequencies exceeding 9 GHz, the improvement in SNR was less pronounced under the reduced sampling rate, due to the effects of aliasing and residual nonlinear distortion. These improvements correspond to the responses in Figs. 3.

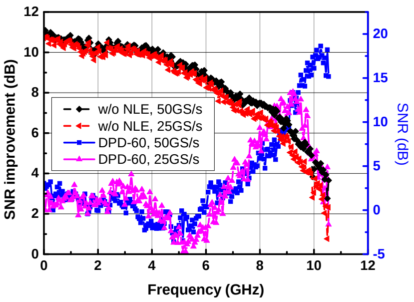

Fig. 4: Improvement in SNR and SNR at various sampling rates over 60 km.

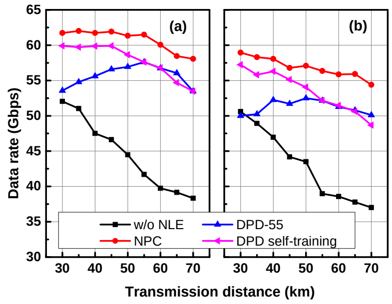

Fig. 5: Data rate comparison: a) Scenario 1; b) Scenario 2.

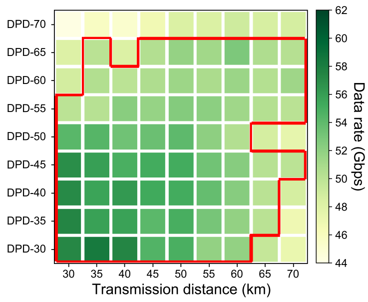

Fig. 6: Achievable Data rate using various DPDs at 25 GS/s.

Fig. 5 compares the fixed DPD with adaptively-varying NLEs in terms of transmission performance. Overall, reducing complexity of NLEs resulted in worse contribution. Without an NLE, the high data rate of >50 Gbps at 30 km dropped dramatically with increases in transmission distance, reaching <39 Gbps at 70 km regardless of the sampling rate. The capacity obtained using NPC in Scenario 1 was 61 Gbps at 30-55 km, which dropped to ∼59 Gbps at 70 km. When the complexity was reduced, the capacity obtained using NPC in Scenario 2 was ∼60 Gbps at 30 km and ∼55 Gbps at 70 km. The achievable data rate achieved using DPD with the same distance for training and testing (i.e., the adaptively-varying cases, name by DPD-self-training) was 1-5 Gbps lower than NPC in Scenario 1 and 1-7 Gbps lower than NPC in Scenario 2. The achievable data rate using a fixed DPD-55 exceeded 50 Gbps in Scenarios 1 and 2 regardless of the testing distance. The capacity using DPD-55 was comparable to that using PD self-training at distances exceeding 55 km. Fig. 6 summarizes the maximum achievable data rates under Scenarios 2 at various transmission distances based on DPD trained using training signals over various transmission distances. The red frame indicates data rates exceeding 50 Gbps. Unsurprisingly, DPD performed better when similar transmission distances were used for training and testing (e.g., DPD-self-training). For instance, over a long distance (60-70 km), DPD-60, -65, and -70 achieved the highest data rates of 52 Gbps under Scenarios 2. When the distance used for NLE training was significantly different from that used for testing (e.g., using PD-70 for 30-km transmission), the achievable data rate was notably lower. As indicated by the red frame in Fig. 6, DPD-55 would be the best candidates for an LR-PON at 25 GS/s, as this would enable data rates of >50 Gbps over the largest range (30-70 km).

The total number of multiplications indicates the computational complexity. For a 3rd-order Volterra series without 3rd-order cross terms, the number of multiplications is M^2+5M [8], where M is the memory length. The number of multiplications in Scenario 1 was 986, while the number in Scenario 2 was as low as 126, corresponding to the reduction of 87.2%. Note however that when using DPD-55, the difference in data rates between Scenarios 1 and 2 was only <9.6% over the SMF of 30-70 km, as shown by comparing the results in Fig. 5(a) and (b).

4. Conclusion

This paper experimentally demonstrates the use of DSP-simplified DPD to mitigate the impact of nonlinear distortion in a high-launch-power 10G-class IMDD LR-PON. The Volterra-based DPD enabled the data rates of >50 Gbps with a loss budget of up to 30 dB and the transmission distances over 30 to 70 km without the need for pre- or inline-amplification. Reducing the sampling rate from 50 GS/s to 25 GS/s reduced the complexity by >87% with only a 9.6% decrease in the achievable data rate.

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