IEEE Access
Multidisciplinary | Rapid Review | Open Access Journal

Received June 18, 2020, accepted June 29, 2020, date of publication July 3, 2020, date of current version July 20, 2020.

Digital Object Identifier 10.1109/ACCESS.2020.3007030

Artificial Neural-Network-Based Pre-Distortion for High Loss-Budget 60-km Long-Reach Passive Optical Network

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ABSTRACT High launch optical power can compensate for severe fading and power loss in long-reach passive optical networks (LR-PONs); however, it also aggravates nonlinear degradation, which necessitates the use of complex DSP-based nonlinear compensation techniques at optical network users (ONUs). DSP-related techniques also necessitate the use of additional hardware/software components by the receiver, which can greatly increase implementation costs and energy consumption, particularly when dealing with large-scale ONU deployment. This is the first study to propose artificial neural network (ANN)-based pre-distortion to eliminate the need for complex DSP at ONUs in a high-launch-power LR-PON, thereby permitting the use of a simplified architecture at the user end. In the first phase of the study, the proposed ANN-based pre-distortion scheme was implemented in a single-channel IMDD OFDM LR-PON, which achieved a data rate of >55 Gbps over 60-km transmission with a loss budget of 30 dB without the need for optical inline- or pre-amplification. In the second phase of experiments, the same scheme was applied to a 4-channel wavelength division multiplexing (WDM) OFDM LR-PON. Here, the proposed scheme achieved data rates of >200 Gbps using launch power of 18 dBm per lane, resulting in a loss budget of roughly 29 dB over 60-km single mode fiber transmission.

INDEX TERMS Intensity modulation, OFDM, optical fiber communication, predistortion, neural networks, nonlinear distortion, wavelength division multiplexing.

I. INTRODUCTION

Explosive growth in internet traffic for big-data applications, mobile cloud computing, the Internet-of-Things, and services based on artificial intelligence is severely taxing the capacity of access networks. Researchers have developed a wide variety of transmission systems to address bandwidth bottlenecks, improve data rates, and extend coverage [1]–[3]. Long-reach (LR) passive optical networks (PONs) provide broadband access, wide coverage, and cost-effective configurations. Taken together, these benefits make LR-PONs a promising candidate for next-generation optical access networks [4]–[6]. Coherent detection is the optical transmission technology with the highest capacity [3], [7]; however, the transceivers are expensive and cumbersome. One practical approach to establishing affordable network access in metro areas involves combining intensity modulation and direct detection (IMDD) [8] with orthogonal frequency-division multiplexing (OFDM), which provides high spectral efficiency with robust resistance to inter-symbol interference (ISI). In [9], the authors reported a 100 Gb/s short-reach transmission system using three different signal formats: OFDM, PAM-4 (pulse amplitude modulation) and CAP (carrier-less amplitude and phase modulation). The OFDM format outperformed PAM-4 and CAP-16 in terms of received optical power and computational complexity. The OFDM transmission system in [10] was shown to outperform single carrier systems in terms of linear impairment compensation and bit rate scalability (particularly in high-speed systems) as well as tolerance to non-flat response characteristics resulting from power fading. Overall, OFDM appears to be a promising candidate for next-generation PON, particular in long-reach systems in which dispersion-induced nonlinear distortion and power fading are more severe. Despite the fact that

The associate editor coordinating the review of this manuscript and approving it for publication was Donatella Darsena.

LR-PONs have yet not been implemented commercially, their vast potential makes them worthy of research [11]–[13]. Note that wavelength division multiplexing (WDM) is a robust alternative to PONs for bandwidth-hungry applications [3], [14], [15].

It is important to keep in mind that the capacity of IMDD LR-PONs is limited by severe power fading and high transmission loss. Power fading reduces data rates under the effects of low signal-to-noise ratio (SNR) around fading dips, and a high transmission loss limits transmission distances and/or the number of optical network users (ONUs), due to the limited sensitivity of their photo-detectors. In previous works, we demonstrated that these issues can be mitigated using high optical launch power. Essentially, high launch power directly increases the loss budget and indirectly reduces power fading via strong self-phase modulation (SPM) [16], [17]. Unfortunately, SPM tends to aggravate dispersion-induced nonlinear distortion. Numerous DSP-based methods have been developed to deal with this type of distortion at the receiver end, including digital backpropagation [18], [19] and the well-known Volterra filter [20], [21]. Recently, researchers have begun applying machine learning (ML), a branch of artificial intelligence, to optical communications and networking, particularly for nonlinearity compensation in optical communication systems [22]–[24]. However, the high computational complexity of these schemes limits the scope of applicability. Various research groups have recently developed optical fiber transmission systems that are more cost effective, by simplifying DSPs on the receiver side or eliminating them entirely [25], [26]. There is little doubt that the development of cost-effective LR-PONs would benefit considerably from inexpensive DSP-free ONUs and low-cost optics. It is possible to eliminate nonlinear distortion through the use of pre-distortion at the transmitter [27], [28]; however, the efficacy of this approach has not been investigated in IMDD LR-PONs with a high optical launch power.

Our objective in the current study was to resolve the severe fading, insufficient loss budget, and need for complex DSPs at ONUs. This was achieved by implementing a system that uses high launch power in conjunction with artificial neural network (ANN)-based pre-distortion. In the first phase of the study, the proposed ANN-based pre-distortion scheme was implemented in a single-channel IMDD LR-PON, which achieved a data rate of >55 Gbps over a 60-km dispersion-uncompensated single-mode fiber (SMF) with a loss budget of 30 dB without the need for optical inline amplification or pre-amplification. In the second phase, the same ANN-based pre-distortion scheme was applied to a 4-channel WDM transmission system, which achieved a data rate of >200 Gbps over 60-km SMF. Note that nonlinear distortion was resolved using pre-distortion at the central office (CO), thereby eliminating the need to equip cost-sensitive ONUs with a complex compensation scheme to deal with nonlinear distortion. In experiments, the proposed ANN-based pre-distortion scheme improved data rates by 46% in a 60-km single-channel transmission scheme and 36-40% over the same distance using the 4-channel WDM network. Even without inline amplification, pre-amplification, or digital nonlinear post-compensation, the proposed 60-km LR-PON supported a loss budget of 30 dB for single-channel 55-Gbps LR-PON and 29 dB for the 4-channel 200-Gbps system.

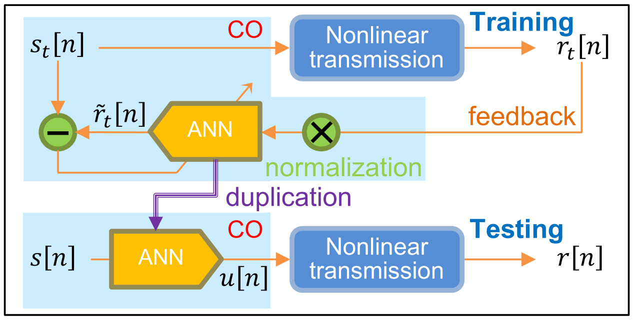

FIGURE 1. Pre-distortion architecture.

The remainder of this study is organized as follows. Section 2 introduces the principles underlying the proposed nonlinearity compensation scheme. Section 3 presents the experiment setup and analysis of the ANN-based pre-distortion scheme in single-channel transmission. Section 4 presents the experiment results using the proposed ANN-based pre-distortion scheme in a 4-channel WDM transmission system. A brief summary is presented in Section 5.

II. PRINCIPLES UNDERLYING PROPOSED ANN-BASED PRE-DISTORTION SCHEME

In an IMDD LR-PON, dispersion can lead to severe power fading, and SMF-related loss can deplete the power budget; however, both of these issues can be eliminated through the use of high launch power [16]. Unfortunately, high launch power inevitably induces severe nonlinear distortion. The effects of this distortion can largely be overcome through the use of digital nonlinear post-compensation at ONUs; however, those methods are of high computational complexity, and could increase the costs due to additional hardware/software for DSP implementation. In this study, we developed a novel scheme in which pre-distortion is applied to the signal to compensate for nonlinear distortion. Note that this is done prior to transmission at the CO, with the aim of reducing computational complexity at the user end. Theoretically, the pth-order inverse pre-distortion and post-compensation are identical [29], such that training of pre-distortion is identical to the training of post-compensation. Fig. 1 presents a schematic illustration of the proposed pre-distortion CO architecture aimed at mitigating unwanted nonlinearities in LR-PON systems. In the first phase, the received waveform $r_t[n]$ is fed back to the CO to optimize the ANN compensator by minimizing the mean square error (MSE) between the output $\tilde{r}_t[n]$ and the transmitted waveform $s_t[n]$. In the second phase, the trained ANN is tasked with applying the pre-distortion, while the transmitted OFDM waveform $s[n]$ is processed using the pre-distortion module to generate a pre-distorted signal $u[n]$ prior to transmission. Note that the input power of the post-compensators must be normalized during training to ensure that the pre-distorters and post-compensators provide unit gain. A failure to do so would see the nonlinear characteristics of the system altered by pre-distorted signals at different power levels.

The proposed scheme was based on an ANN with the optimized hyper-parameters of 51 features and two hidden layers (respectively using 70 and 50 neurons) to eliminate nonlinearities in single-channel and 4-channel WDM transmission. The input features included consecutive OFDM samples obtained at a sampling rate of 50 GS/s. The rectified linear unit (ReLU) was used as an activation function in the application of the ANN. A training sequence of 104,000 samples (i.e., 10% that of testing) was used to train the proposed model. Note that overestimating equalization ability can have a negative impact on the reliability of ANN-based applications in optical networks. This can be attributed to the fact that the ANN recognizes patterns instead of compensating for channel characteristics [30]–[32]. Researchers have shown that ANN-based equalizers are able to learn the rules for the generation of pseudo-random bit sequences (PRBSs), resulting in overestimates pertaining to equalization performance. The issue of PRBS pattern recognition issue can be avoided by ensuring that the memory used in the ANN is equal to or less than the word width in a training sequence (e.g., 15 symbols for PRBS 15). Mersenne Twister pseudo-random number sequences, which are very long, have been recommended as an alternative sequence to prevent the problem of overestimation. In our experiment, OFDM training and testing signals were generated using a Mersenne Twister pseudo-random number sequence to prevent the ANN from the learning the rules for sequence generation rule of the sequence. Fig. 2 presents the MSE plotted logarithmically as a function of the number of epochs. Note that the MSE between the input and target signals prior to the ANN was used as a reference in order to calculate the MSE in terms of dB. The MSE presented a rapid drop for a few epochs and then dropped slightly until approximately 15 epochs, at which point it leveled off. The high degree of similarity between the training and testing curves up to 30 epochs demonstrates that the ANN model did not suffer from fitting problems.

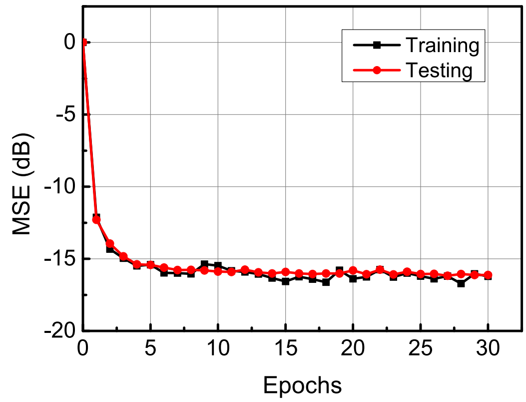

FIGURE 2. MSE against the number of epochs.

III. SINGLE-CHANNEL TRANSMISSION

A. EXPERIMENT SETUP

Fig. 3 illustrates the experiment setup of the 60-km transmission system in this study. OFDM signals (with or without pre-distortion) were generated offline in the Matlab environment. The parameters of the OFDM signal included 216 subcarriers, an FFT size of 1024, a cyclic prefix (CP) of 16, and a signal bandwidth of ∼10.5 GHz. The modulation format for training signals was set at 16 QAM, and the modulation format for testing signals was adaptively adjusted in accordance with the signal performance using the bit- and power-loading (BPL) algorithm [33]. The baseband signal was loaded into an arbitrary waveform generator (AWG; Tektronix AWG70001A) with a sampling rate of 50 GS/s. The light source was a DFB laser (Thorlabs WDM8000) operated at a wavelength of 1540.50 nm and modulated using an electro-absorption modulator (EAM; CIP 10G-LR-EAM-1550). An Erbium-doped fiber amplifier (EDFA) was used with a variable optical attenuator (VOA) to achieve a launch power of 18 dBm. Following transmission over standard SMF for a distance of 60 km without inline- or pre- amplification, the received signal was detected using a 10G-PIN and then captured using a digital oscilloscope (Tektronix DPO 71254) with a sampling rate of 50 GS/s and bandwidth of 12 GHz. All necessary DSP procedures were implemented offline to demodulate the OFDM signals using a sampling rate of 50 GS/s with or without nonlinear post-compensation. This also made it possible to evaluate the system performance, including SNR, bit-error-rate (BER), and achievable data rate based on the BPL algorithm.

The subsets in Figs. 3(a) and (b) respectively present the transmitted spectra of the original OFDM signal and our ANN-based pre-distorted signal. Fig. 3(c) presents the spectra after smoothing. The original OFDM signal produced a flat power curve for all subcarriers within a bandwidth of 10.5 GHz; however, the pre-distorted OFDM signal clearly indicated the allocation of power to different subcarriers. Obviously, not all subcarriers have equal power, as more power is assigned to subcarriers above 9 GHz and less power is assigned to subcarriers in the 3 to 8 GHz frequency range. This can be attributed to the fact that the post-compensator in the training procedure compensates for nonlinear distortion and seeks to equalize the power of the various subcarriers, even though the total gain is maintained at roughly 0 dB through the normalization of $r_t[n]$, as shown in Fig. 1. Unfortunately, the ANN-based pre-distorted signal imposes a slightly wider bandwidth; i.e., the spectral edge is expanded to ∼12 GHz with relatively low spectral roll-off outside the signal band.

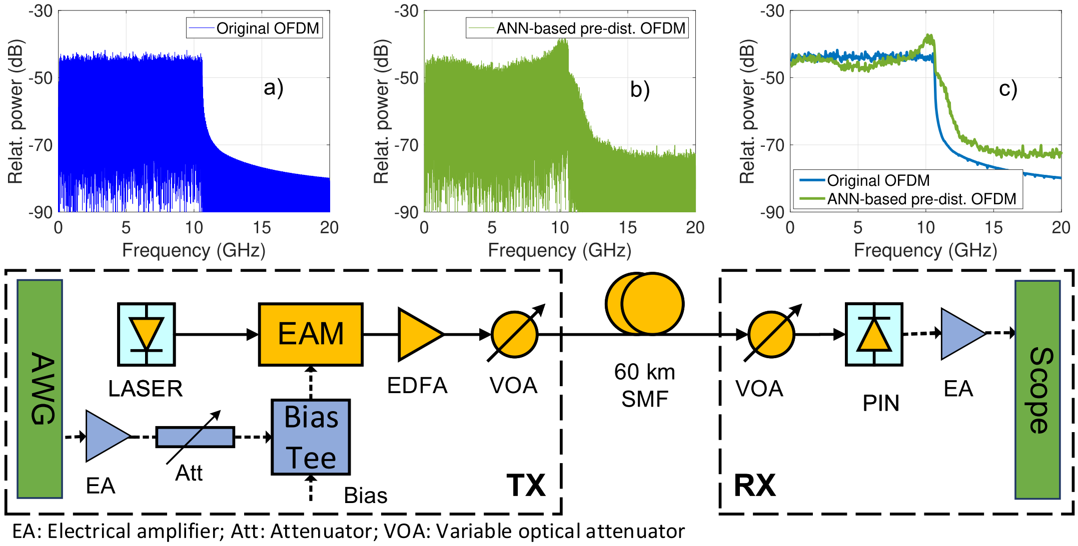

FIGURE 3. Schematic showing single-channel 60-km LR-PON and transmitted spectra of (a) original OFDM, (b) ANN-based pre-distortion OFDM, and (c) results after spectral smoothing.

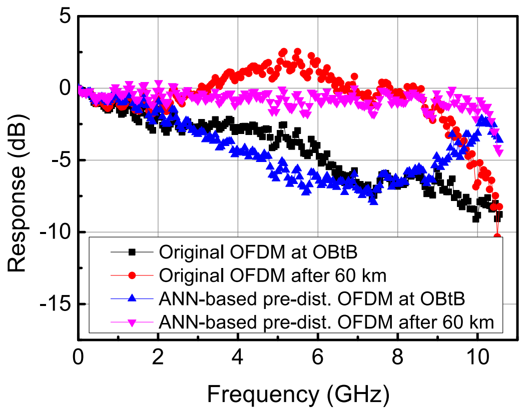

FIGURE 4. Responses before and after transmission with and without ANN-based pre-distortion.

B. SYSTEM PERFORMANCE AND DISCUSSION

Fig. 4 presents the frequency response of the original OFDM signal at optical back-to-back (OBtB) as well as after 60-km SMF transmission. It also lists the frequency responses of the pre-distorted OFDM systems. Note that all responses were normalized in accordance with the responses of their first subcarriers. Overall, the frequency responses tend to diverge, due to the frequency-dependent response of dispersive transmission. Note also that only the pre-distortion scheme produced flat response for all subcarriers over 60-km transmission. Specifically, the response of the original OFDM signal at OBtB presented a gradual decrease from 0 to −9 dB with an increase in frequency, due mainly to the limited bandwidth of the AWG. Meanwhile, the response of the original OFDM signal (i.e., without compensation) over 60-km transmission increased to ∼2.5 dB at 5.5 GHz before declining rapidly due to the interaction between the SPM effect and dispersion in the IMDD system. This is a clear indication that high launch power eliminated power fading at frequencies below 10.5 GHz. Note that without the SPM effect, there would be no power gain but severe fading would occur at ∼8 GHz [16]. The proposed pre-distorter was used to generate nonlinear distortion to eliminate nonlinear degradation associated with dispersive fiber transmission. It was also used to adjust the subcarrier power in advance to adapt to the frequency-dependent gain/loss, which resulted in a flat response at ∼0 dB after 60-km transmission. However, as shown in Fig. 4, the power of the subcarriers near the band edge (i.e., 10.5 GHz) declined dramatically. This can be attributed to the fact that the proposed ANN-based pre-distorter was unable to fully compensate for severe nonlinear distortion in the region near the fading dip. By contrast, equalizing the power of the subcarriers to match the dispersion resulted in a response variation at OBtB that was roughly the reverse of the response of the original OFDM signal after 60-km SMF.

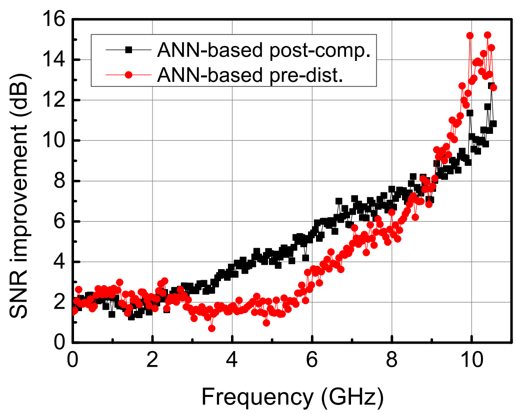

FIGURE 5. Improvements in SNR as a function of frequency using various compensation schemes.

Fig. 5 illustrates the improvements in SNR attributable to pre-distortion and post-compensation using the ANN approach. Note that this assessment was based on reference values for the case without any compensation for nonlinear distortion at a received optical power (ROP) of −12 dBm. Overall, pre-distortion and post-compensation were both shown to significantly increase the SNR by mitigating nonlinear distortion. In all cases, the improvements in SNR were most pronounced in the high frequency band (i.e., above ∼6 GHz), due to the fact that nonlinear distortion is less pronounced at lower frequencies. Compared to the post-compensation, pre-distortion had a more pronounced effect on SNR at frequencies above ∼9 GHz, due to the allocation of more power to those subcarriers, as indicated by the spectrum of pre-distorted OFDM signals in Fig. 3. However, in the frequency range of 3 to 8 GHz, pre-distortion resulted in relatively poor SNR values (compared to post-compensation), due to the fact that subcarriers in this range were assigned less power.

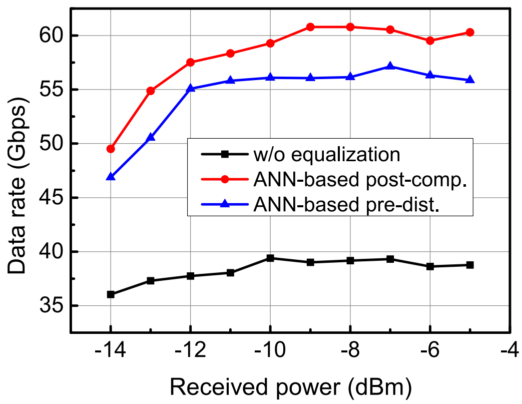

FIGURE 6. **Achievable data rates versus ROP under various compensation schemes.**

We also estimated the maximum achievable data rate as a performance indicator at various ROPs, based on the BPL algorithm with a desired BER target of 3.8×10^{-3}; i.e., below the hard-decision forward error correction (FEC) limit with 7% overhead, as summarized in Fig. 6. Clearly, pre-distortion and post-compensation both contributed to significant improvements in data rates. The case without any compensation for nonlinear distortion was limited to 39.40 Gbps (at an ROP of −10 dBm), which dropped to 36.04 Gbps (at an ROP of −14 dBm). Note that a lower ROP was associated with lower data rates, due to a smaller ratio of received signal power to additive noise at the receiver. Moreover, without compensation, the system was impaired primarily by nonlinear distortion; i.e., data rates were less sensitive to other effects. It is for this reason that the capacity varied less with ROP in the case without nonlinear equalization than in the other two cases in Fig. 6. A similar relationship between data rates and ROP was observed in the cases involving pre-distortion and post-compensation. At an ROP ranging from −10 to −5 dBm, the maximum data rates were as follows: ∼56 Gbps for pre-distortion (44% improvement) and ∼60 Gbps for post-compensation (54% improvement). At an ROP of −14 dBm, these data rates dropped dramatically, as follows: pre-distortion (∼47 Gbps) and post-compensation (∼49 Gbps). The rapid drop in data rates at an ROP of less than −12 dBm proved that system performance was more sensitive to additive noise. At an ROP of −12 dBm, the proposed ANN pre-distortion scheme achieved a data rate of 55 Gbps (see Fig. 6). Note that post-compensation outperformed pre-distortion by no more than ∼3 to ∼5 Gbps.

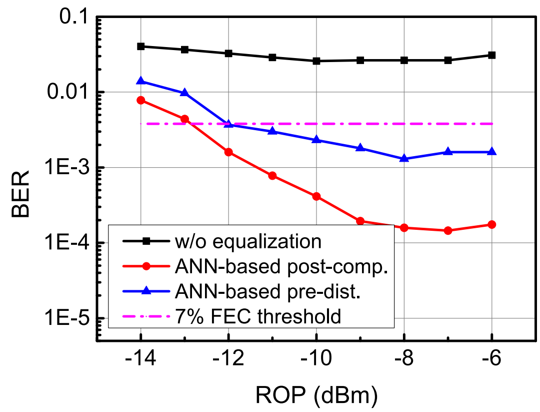

FIGURE 7. **BER performance when using fixed 55-Gbps signal over 60-km LR-PON with/without compensation.**

Fig. 7 presents the estimated BERs of a signal fixed at 55 Gbps as a function of ROP using various compensation schemes. As shown in Fig. 7, the two ANN schemes achieved lower BER values for any given ROP. In fact, without compensation, it was not possible to achieve the target transmission of 55 Gbps. ANN-based pre-distortion made it possible to attain the FEC limit with sensitivity of −12 dBm. As shown in Fig. 7, ANN-based post-compensation achieved the lowest BER (close to 10^{-4}) at ROP values exceeding −9 dBm, thereby outperforming the pre-distortion approach by an order of magnitude.

Fig. 8 compares ANN-based pre-distortion versus the case without nonlinear equalization after 60-km transmission, in terms of SNR at an ROP of −12 dBm before and after the BPL algorithm. Under these conditions, ANN-based pre-distortion achieved a data rate of 55 Gbps, compared to 37.7 Gbps without nonlinear equalization. High SNRs permitted the application of higher order QAM and vice versa. As shown in Fig. 8, higher order QAM can be utilized in the low frequency band due to higher SNR. Meanwhile, relatively low SNRs at high frequencies allowed for lower order QAM implementation. Without nonlinear equalization, the SNR was insufficient to support any bits at frequencies around 10 GHz. The proposed pre-distortion scheme boosted the SNR to >10 dB, which supported 8-QAM or higher after the BPL algorithm. Fig. 9 compares the constellations of the 55-Gbps ANN-based pre-distortion signal at OBtB and after 60-km transmission. The proposed pre-distortion scheme intentionally introduces nonlinear distortion to cancel out nonlinear degradation associated with dispersive transmission. This results in signals with worse constellations

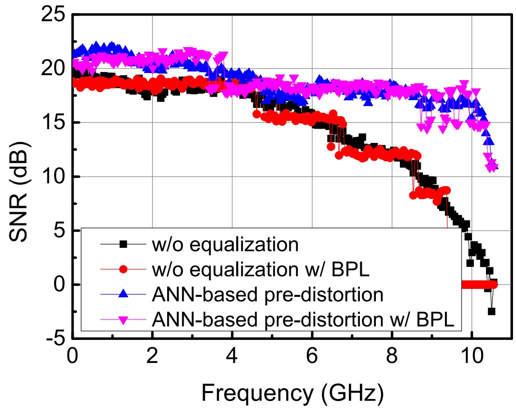

FIGURE 8. SNR values with and without ANN-based pre-distortion OFDM before and after BPL algorithm over 60 km.

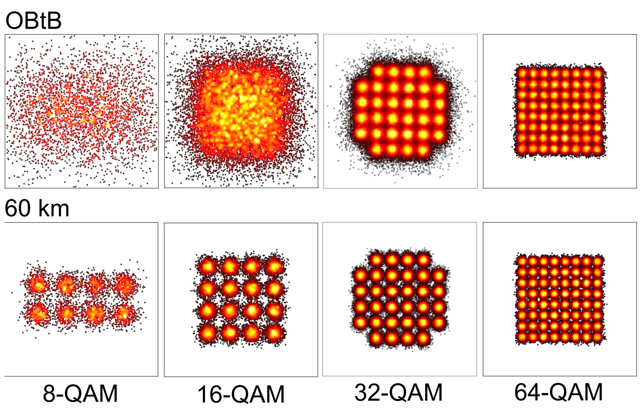

FIGURE 9. Constellations of 55-Gbps ANN-based pre-distorted OFDM signal at OBtB and over 60 km.

under the OBtB configuration, particularly at high frequencies close to the band edge (e.g., 8-QAM and 16-QAM).

IV. 4-CHANNEL WDM TRANSMISSION

A. EXPERIMENT SETUP

4-channel WDM transmission was achieved using four DFB lasers (Thorlabs WDM8000) with wavelengths of 1540.50, 1542.80, 1544.65, and 1546.90 nm. As shown in Fig. 10, we employed a polarization-interleaved configuration with unequal channel spacing to reduce the effects of inter-channel nonlinearities and cross-talk in WDM transmission. The polarization-interleaved configuration was achieved by establishing orthogonal polarization between the odd channel (λ_1 and λ_3) and even channel (λ_2 and λ_4), which were modulated using two separate modulators. To compensate for the fact that we had only one EAM for this experiment, we used an additional Mach-Zehnder modulator (MZM) for the emulation of optical signals. Note that the channels being tested were always modulated by the EAM. Following combination of the even and odd channels using a polarization beam combiner (PBC), EDFA and VOA were used to achieve a total launch power of 24 dBm. Following transmission over a distance of 60 km without an inline amplifier or dispersion compensator, we used an optical tunable bandpass filter to emulate WDM multiplexing, as shown in Fig. 10. The subset in Fig. 10 plots the optical spectrum recorded prior to transmission using an optical spectrum analyzer with resolution of 0.01 nm. Note that the same ANN architecture was used to compensate for nonlinear degradation in this WDM OFDM system.

B. RESULTS AND DISCUSSION

Fig. 11 plots the SNR values in channel 2 under the various compensation schemes at an ROP of −10 dBm. Similar to the results obtained for single-channel transmission (Fig. 5), the application of nonlinear compensation enabled a significant improvement in SNR values, particularly at frequencies exceeding 6 GHz (i.e., where nonlinear degradation was far more severe). The allocation of more power to subcarriers at high frequencies (i.e., above 9 GHz) enabled the pre-distortion scheme to surpass post-compensation in terms of SNR. The SNR values obtained using pre-distortion were comparable to those obtained using post-compensation at frequencies below 3 GHz, where the gain provided by pre-distortion was close to 0 dB (as shown in Figs. 3 and 4) and nonlinear distortion was less pronounced. Note that the SPM effects were sufficient to compensate for dispersion-induced power fading, which dramatically increased the transmission bandwidth to beyond 10 GHz; however, the SNR without nonlinear compensation remained relatively low at higher frequencies.

Fig. 12 presents the data rates of channel 2 without nonlinear compensation. Fig. 12 also compares the data rates of WDM transmission in channel 2 with those of the single-channel system, as a function of ROP ranging from −12 dBm to −6 dBm. Note that the data rate without nonlinear compensation (37.5 Gbps) was insensitive to ROP, due to the dominant effects of nonlinear distortion. Clearly, single-channel transmission outperformed WDM transmission. The single-channel data rate with ANN-based pre-distortion or post-compensation was 3 or 4 Gbps higher than WDM transmission at an ROP of −10 dBm (see Fig. 12). The poor performance of the WDM configuration can be attributed primarily to nonlinear effects, including cross-phase modulation (XPM) and four-wave mixing (FWM) [34]. Note that system performance deteriorated despite the advantages of unequal channel spacing in modulating the impact of inter-channel nonlinearities [35]. As also shown in Fig. 12, the proposed ANN-based pre-distortion scheme achieved outstanding data throughput: single-channel (>55 Gbps at ROP of −12 dBm) and WDM transmission (>50 Gbps at ROP of −11 dBm). Note that the launch power of each channel was approximately 18 dBm, which permitted a power budget of 30 dB (single channel) and 29 dB (WDM transmission) over 60-km LR-PON.

Table 1 summarizes the performance of the four channels in the WDM LR-PON, where all data rates were the highest values obtained at the FEC limit of 3.8×10^{-3} and at an ROP of −11 dBm. Without nonlinear compensation, all of the

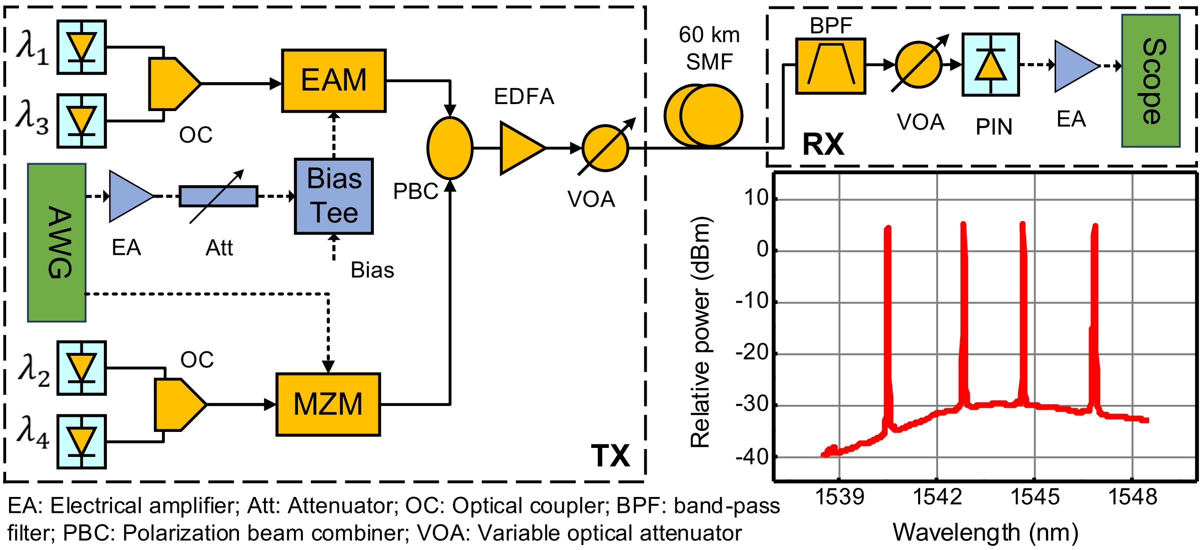

FIGURE 10. Experiment setup of 4-channel WDM LR-PON.

TABLE 1. Data rate and corresponding percent of improvement (Impr.) of 4 channels at ROP of −11 dBm.

Methods	Channel 1		Channel 2		Channel 3		Channel 4	
	Data rate (Gbps)	Impr. (%)	Data rate (Gbps)	Impr. (%)	Data rate (Gbps)	Impr. (%)	Data rate (Gbps)	Impr. (%)
w/o EQ	37.21	0	37.45	0	37.65	0	37.70	0
Post-comp.	55.91	50.26	55.32	47.72	54.98	46.03	56.49	49.84
Pre-dist.	52.05	39.88	51.22	36.77	51.22	36.04	51.95	37.80

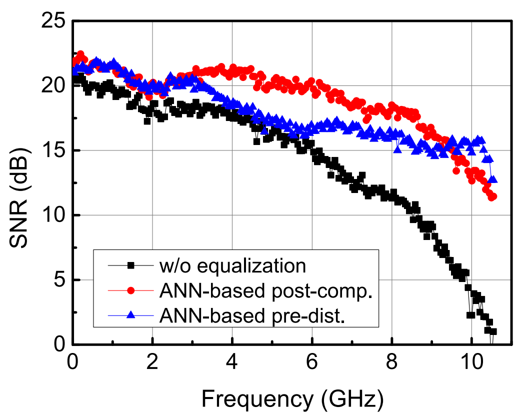

FIGURE 11. SNR performance of channel 2 over 60-km SMF using various compensation schemes at ROP of −10 dBm.

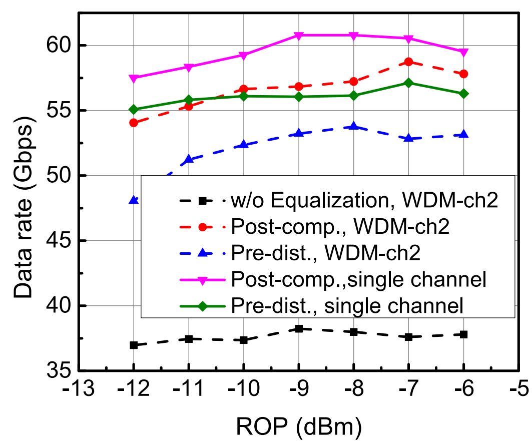

FIGURE 12. Comparison of single-channel and channel 2 of WDM transmission in terms of data rates over 60-km SMF using ANN-based compensation.

channels achieved data rates of approximate 37 Gbps. Implementing post-compensation increased the maximum capacity to 55-56 Gbps, which represents an improvement of 46-50%. Implementing pre-distortion increased the maximum capacity to 51-52 Gbps, which represents an improvement of 36-40%.

Fig. 13 presents a comparison of data rates among the various channels in WDM transmission using ANN-based pre-distortion. Overall, the four channels were similar in terms of capacity, which increased with an increase in ROP. The proposed scheme achieved the following data rates as a function of ROP: ∼46 Gbps (at −13 dBm), ∼52 Gbps (at −10 dBm), and ∼53 Gbps (at −6 dBm). All channels achieved data rates exceeding 50 Gbps at an ROP of −11 dBm, which resulted in a total transmission rate of > 200 Gbps over 60-km 4-channel WDM LR-PON. Fig. 14 presents the BER performance of the 4-channel WDM configuration after transmitting a 50-Gbps ANN-based pre-distorted signal over a distance of 60 km. When the ROP exceeded −11 dBm, the estimated BERs dropped to below the FEC limit. The BER performance in the first and the fourth channels achieved the FEC limit at an ROP of −12 dBm. Our experiment results demonstrated that the total capacity of 4-channel WDM LR-PON could exceed 200 Gbps over a distance of 60 km with a loss budget

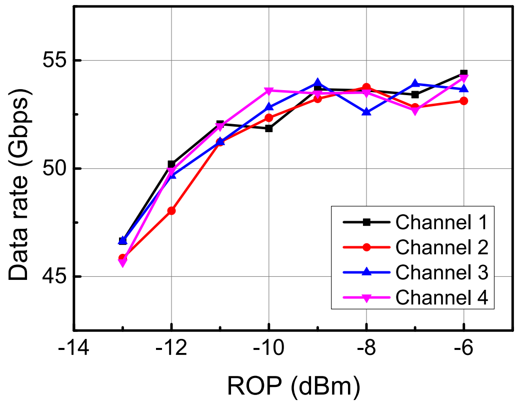

FIGURE 13. **Capacity comparison of various channels using ANN-based pre-distortion.**

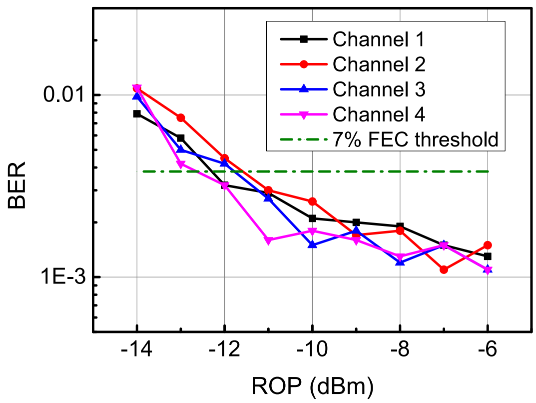

FIGURE 14. **BER performance of various channels sending fixed 50-Gbps signal with ANN-based pre-distortion.**

of 29 dB without the need for dispersion compensation, inline amplification, or nonlinear DSP compensation at ONUs.

V. CONCLUSION

This paper presents the first ANN-based pre-distortion scheme to mitigate nonlinear distortion in a 60-km OFDM LR-PON. Experiments were based on a low-cost IMDD using 10G-class devices. The use of high launch power made it possible to overcome severe power fading and deficiencies in the power budget, whereas the proposed pre-distortion system helped to alleviate the effects of nonlinear distortion to enhance data rates and allow the use of simple (i.e., cost-effective) receivers at ONUs. The performance of the proposed pre-distortion scheme did not match post-compensation in terms of data rates improvement; however, it greatly reduced computational complexity at ONUs. In experiments using ANN-based pre-distortion with a launch power of 18 dBm per channel, single-channel LR-PON achieved a data rate of >55 Gbps with a loss budget of 30 dB, whereas 4-channel WDM LR-PON achieved a data rate of >200 Gbps with a loss budget of 29 dB. ANN-based post-compensation improved data rates by 46-50%, whereas ANN-based pre-distortion compensation improved data rates by 36-40%.

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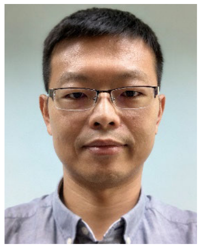

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