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Research Article

Signal Processing Algorithms for Down-Stream Traffic in Next Generation 10 Gbit/s Fixed-Grid Passive Optical Networks

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We have analyzed the impact of digital and optical signal processing algorithms, that is, Volterra equalization (VE), digital backpropagation (BP), and optical phase conjugation with nonlinearity module (OPC-NM), in next generation 10 Gbit/s (also referred to as XG) DP-QPSK long haul WDM (fixed-grid) passive optical network (PON) without midspan repeaters over 120 km standard single mode fiber (SMF) link for downstream signals. Due to the compensation of optical Kerr effects, the sensitivity penalty is improved by 2 dB by implementing BP algorithm, 1.5 dB by VE algorithm, and 2.69 dB by OPC-NM. Moreover, with the implementation of NL equalization technique, we are able to get the transmission distance of 126.6 km SMF for the 1 : 1024 split ratio at 5 GHz channel spacing in the nonlinear region.

1. Introduction

Due to the increasing demand of bandwidth and capacity requirements from enterprises and households, the data rates of broadband access network will be required over 10 Gbit/s for each customer. Several passive optical network (PON) architectures have been proposed, that is, G-PON, E-PON, TDM-PON, and so forth, in order to remove the capacity bottleneck. Recently, the 10 Gbit/s long haul wavelength-division multiplexed- (WDM-) PON system has been demonstrated with coherent detection; this configuration represents a significant improvement with a receiver sensitivity of −45 dBm (25 photons/bit) [1].

With the implementation of advanced modulation formats, that is, QPSK, QAM, and so forth, and multiplexing techniques, that is, dual-polarization and so forth, the system performance is limited due to fiber linear and nonlinear effects [2]. These effects are very much dominant at higher signal launch powers and in WDM systems with narrow channel spacing [3]. Rosenkranz and von Hoyningen-Huene presented the results of nonlinearity compensation in access networks; however, the results are limited to the transmitters where optical field is derived from the modulation current with the directly modulated laser (DML) rate equations; thus modulation nonlinearity and chirp are included [4] and are detected by direct detection method. In this paper, we have numerically analysed the transmission characteristics and the nonlinear equalization techniques by employing BP, VE, and OPC-NM in 10 Gbit/s DP-QPSK long haul WDM-PON transmission with coherent receivers, for downstream signals. Furthermore; the impact of nonlinear equalization algorithm on the transmission distance and split ratio factor is investigated.

2. Nonlinear Equalization Methods

In this section, we will briefly discuss the nonlinear equalization techniques implemented in this paper.

2.1. Digital Backpropagation (BP). The joint compensation of linear and nonlinear transmission impairments is implemented by inversely solving the nonlinear Schrodinger equation (NLSE), as in (1). This method is termed as digital backpropagation (BP) [2, 5–12], and it is a topic of high interest in recent years. We have implemented BP algorithm by using the simplest symmetric split-step Fourier method (SSFM) with constant step-size method [7], as in (2). Consider

$$\frac{\partial E}{\partial z} = \left(-\widehat{N} - \widehat{D}\right) E, \quad (1)$$

$$E(z+h,t) = \exp\left(\frac{h\widehat{D}}{2}\right)\exp\left(h\widehat{N}\right)\exp\left(\frac{h\widehat{D}}{2}\right)\cdot E(z,t), \quad (2)$$

whereas $\widehat{D}$ and $\widehat{N}$ are the linear and nonlinear operators, respectively, to solve the inverse NLSE.

2.2. Volterra Equalization (VE). Another alternative approach for joint compensation of linear and nonlinear effects is the Volterra equalization (VE) method [4, 13], as in Figure 1. This method is an expansion of a linear feed forward equalizer (FFE) and decision feedback equalizer (DFE) of higher-order combinations of the delayed signal. The joint FFE-DFE algorithm is applied in order to process the I- and Q-tributaries to avoid intersymbol-interference (ISI). The optimal coefficients are calculated for the equalizer according to the minimum mean squared error (MMSE) criterion and are given by the well-known Wiener solution for the joint FFE-DFE algorithm [14].

These two methods, that is, BP and VE, are the postprocessing methodologies implemented with coherent receivers. We have also implemented an all-optical signal preprocessing method for nonlinear equalization, which is termed as optical phase conjugation with nonlinearity module (OPC-NM) [15].

2.3. All-Optical Signal Preprocessing. This module, as in Figure 2, contains highly nonlinear fiber (HNLF) and optical phase conjugation (OPC) module [15, 16]. The nonlinear stage is implemented by 19 km of SMF with input launch power P_m tuned by an erbium doped fiber amplifier (EDFA). The OPC stage uses the four-wave mixing of the signal with a CW laser as the pump in a 120 m long HNLF. The generated signal is passed through band-pass filter, amplified, and launched into the passive fiber link. The parameters of this module, that is, fiber length L_m, signal power P_m, and nonlinear coefficient γ_m, are adjusted along with OPC module so that it produces negative nonlinear phase shift of $(-\Delta\phi_m)$, canceling the original $(\Delta\phi_m)$ from fiber transmission link.

3. Numerical Model

The architecture, as in Figure 3, consists of optical line terminal (OLT) having 3 CW lasers, which are individually modulated with DP-QPSK signal and multiplexed together (with 50 GHz, 10 GHz, and 5 GHz channel spacing) resulting in 10 Gbit/s WDM DP-QPSK signal per wavelength. The applied pattern was a pseudorandom bit sequence (PRBS) of length 2^{15}-1 and RZ pulse shaping is used. An EDFA at the OLT adjusts the signal input launch power into the fiber backhaul and passive optical splitters are used to distribute the signal to the optical network units (ONUs). Moreover, narrow optical filtering is used at the transmitter to compensate the spectral overlapping. The standard single mode fiber is used to transmit over a distance of 120 km. The physical parameters of SMF fiber are attenuation $\alpha = +0.2$ dB/km, dispersion $D = +16.75$ ps/(nm-km), and nonlinear coefficient $\gamma = +1.3(\text{km}^{-1}\cdot\text{W}^{-1})$. No midspan repeaters are used in the transmission link. For our investigations, all the ONUs are considered at the same transmission distance and having the same power budget.

The signal is detected with a phase and polarization diverse coherent receiver. At the receiver, the channels can be selected through the tunable local oscillator (LO) laser source. The transmission performance of the middle channel of the WDM grid is monitored and is quantified by the bit-error-ratio (BER). The FEC threshold limit corresponds to the BER level of 3.8×10^{-3} (as indicated by the dashed line in graphs). As we are investigating the deterministic impairments (linear and nonlinear effects) of fiber transmission, we have considered the effect of polarization mode dispersion (PMD) and laser line width negligible in these numerical analyses [8]. The model is implemented by using OptiSystem v.12 and DSP modules are implemented in Matlab.

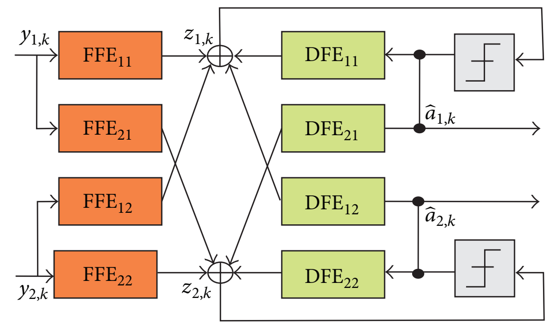

Figure 1: Numerical model of Volterra-based nonlinear FFE-DFE equalizer.

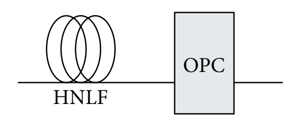

Figure 2: Basic architecture of optical phase conjugation with nonlinearity module (OPC-NM).

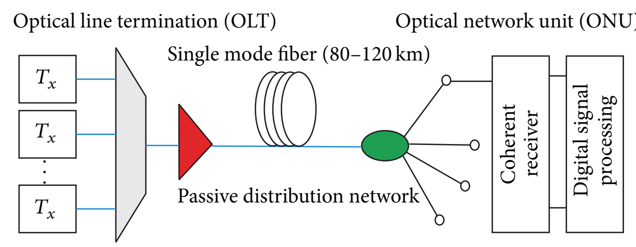

Figure 3: Architecture of coherent 10 Gbit/s long haul WDM-PON employing DP-QPSK downstream signals.

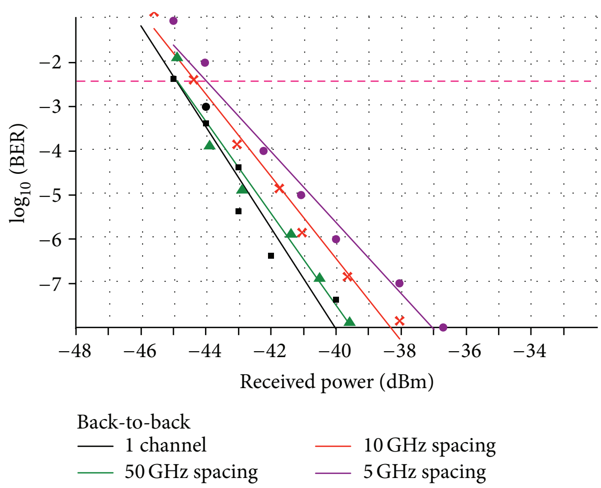

FIGURE 4: Back-to-back sensitivity measurements for single channel and WDM transmission with different channel spacings.

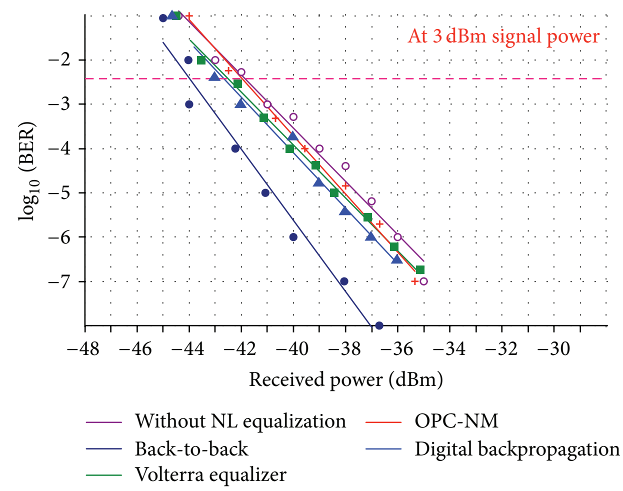

FIGURE 5: Performance analysis at 5 GHz channel spacing for 3 dBm signal launch power using BP, VE, and OPC-NM.

4. Results and Discussion

Figure 4 shows the back-to-back receiver sensitivity and the impact of channel spacing on WDM-PON. At 50 GHz channel spacing, there is no significant nonlinear penalty observed at the FEC threshold limit. As the narrow channel spacing is used, that is, 10 GHz and 5 GHz, we have observed a penalty of 0.75 dB and 1.1 dB, respectively, at a BER level of 3.8×10^{-3}. The results depict that, for long haul transmission in PONs, nonlinearities are the major degrading factors with narrow channel spacing. We have further investigated the impact of nonlinearities and their compensation on the receiver sensitivity. As narrow channel spacing, that is, 5 GHz channel spaced transmission, has dominant multichannel nonlinear impairments, that is, cross-phase modulation (XPM), we have investigated this scenario for different signal launch powers and resultant impact of using NL equalization techniques.

Figure 5 shows the performance of 5 GHz channel spaced WDM-PON transmission over 120 km SMF link. At 3 dBm signal launch power, the incurred penalty is less than 2 dB. The NL equalization methods, that is, BP and VE, show efficient and improved transmission performance. The incurred penalty is reduced to 1.51 dB with the postprocessing of data by BP and VE. While we have not observed any prominent improvement in system performance by employing OPC-NM around the region of 3.8×10^{-3} BER, at higher launch power, that is, 6 dBm, nonlinear impairments dominate and the system performance is degraded, as in Figure 6. We have observed a penalty of 4 dB with respect to back-to-back transmission. The results of NL equalization show significant improvement in performance reducing the penalty to 2 dB by BP algorithm, 1.5 dB by VE algorithm, and 2.69 dB by OPC-NM technique. By virtue of this performance, the system can be operated at higher transmission powers and physical transmission distance for the ONUs can be increased.

Furthermore, we have investigated the number of ONUs (network subscribers) for maximum split ratio, that is, 1 : 1024, with respect to obtainable transmission distance, as in Figure 7. As we are emphasizing on the nonlinear compensation, we plotted the graph for the system with 5 GHz channel spacing at 6 dBm signal launch power. The maximum transmission distance for 5 GHz channel spaced system after a 1 : 1024 split ratio is found to be 92.06 km, whereas, by employing VE algorithm, we are able to get the transmission distance of 126.6 km for the same split ratio.

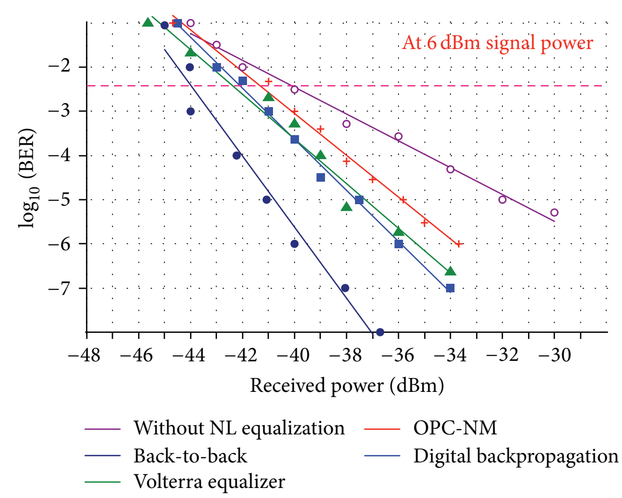

FIGURE 6: Performance analysis at 5 GHz channel spacing for 6 dBm signal launch power using BP, VE, and OPC-NM.

5. Conclusion

To summarize, special focus is given to compensate fiber nonlinear transmission impairments and their interplay between transmission distance and split ratio. We have numerically evaluated the nonlinear equalization algorithms in 10 Gbit/s DP-QPSK long haul WDM-PON over 120 km fiber link without midspan repeaters. The results of NL equalization,

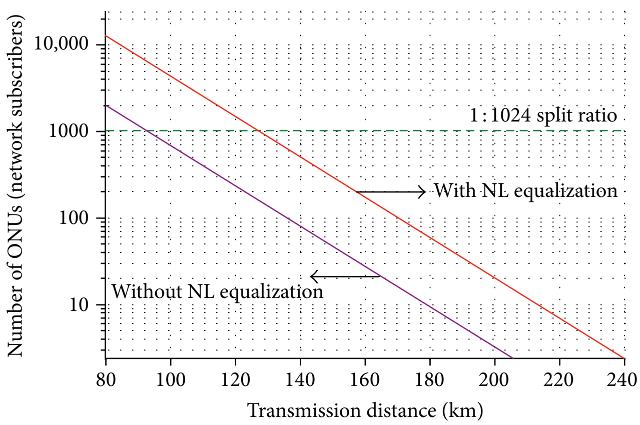

FIGURE 7: Performance analysis for number of ONUs (network subscribers) versus maximum transmission distance.

with 5 GHz channel spacing and at 6 dBm signal launch power, show significant improvement in system performance reducing the penalty to 2 dB by BP algorithm, 1.5 dB by VE algorithm, and 2.69 dB by OPC-NM technique at the BER level of 3.8×10^{-3}.

Moreover, the maximum transmission distance after a 1 : 1024 split ratio is improved by 35.4 km by VE algorithm, which is the optimal NL equalization technique. From the over-all results, we conclude that NL equalization techniques are beneficial for PONs. They compensate the impairments to a considerable extent and will be helpful in the next generation networks where higher-order modulation formats, that is, m-ary QAM, will be implemented at access network level.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

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