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# Performance enhanced down-stream signalling for next generation long-reach 10 Gbit/s passive optical networks

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ABSTRACT

In this paper, we have analyzed the signal processing methods both in digital and optical domain to enhance the transmission performance of downstream signalling in long reach passive optical networks (LR-PONs). The impact of non-linear (NL) equalization through signal processing, i.e. Volterra Equalization (VE), Digital Backpropagation (BP) and Optical Phase Conjugation with Non-linearity Module (OPC-NM) is investigated, in 10 Gbit/s (XG) DP-QPSK long-reach wavelength division multiplexed (WDM) PONs without midspan repeaters over 120 km standard single mode fibre (SMF) link for down-stream signals. Due to the compensation of optical Kerr effects, the sensitivity penalty is reduced to 2 dB by 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 non-linear region. Furthermore, the concept of super passive optical network (S-PON) is also evaluated, which involves a repeater stage consisting of optical amplifiers, to study the feasibility for receiver side signal processing and simplification.



## 1. Introduction

Due to increasing demand of bandwidth and capacity requirements from enterprises and households, the data rates of broadband access network, as in Fig. 1, will be required over 1 Gbit/s for each customer. Several passive optical network (PON) architectures have been proposed, i.e. G-PON, E-PON, TDM-PON, etc., in order to remove the capacity bottleneck. Moreover, next generation passive optical networks (NG-PONs) need enhanced spectral bandwidth in-order to accommodate video and digital media. As in Fig. 2, the wavelength required for upstream (US) traffic is 1310 nm ± 50 nm, for downstream (DS) traffic it is 1530 nm ± 50 nm, for high definition video it is 1550–1560 nm (Ref: ITU-T J.185/J.186) and for digital media transmission it is 1539–1565 nm. However, a lot of research has been done in-order to increase the transmission distance as well as to increase the split ratio. Recently, the 10 Gbit/s long reach wavelength-division multiplexed (WDM) PON system have 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, i.e. QPSK, QAM, etc., and multiplexing techniques, i.e. dual-polarization, etc., the system performance is limited due to fibre linear and non-linear effects [2]. These effects are very much dominant at higher signal launch powers and in WDM systems with narrow channel spacing [3]. W. Rosenkranz et al. presented the results of non-linearity 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 non-linearity and chirp are included [4] and is detected by direct detection method. In this paper, for the first time at access network level, we have analyzed the transmission characteristics and the non-linear equalization techniques by employing BP, VE and OPC-NM in 10 Gbit/s DP-QPSK long reach WDM-PON transmission with coherent receivers, for down-stream signals. Furthermore; the impact of non-linear equalization algorithm on the transmission distance and split-ratio factor is investigated.

## 2. Non-linear equalization methods

In this section, we will briefly discuss about the non-linear equalization techniques implemented in this letter. The joint compensation of linear and non-linear transmission impairments is implemented by inversely solving the non-linear Schrödinger

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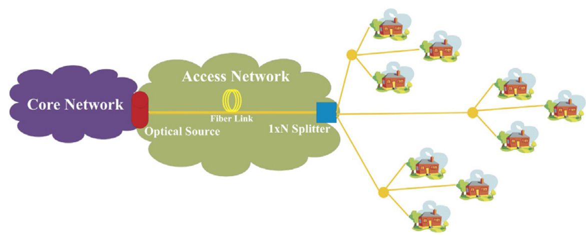


**Fig. 1.** Model for core (long haul transmission) and passive optical networks from telecommunication system perspective.

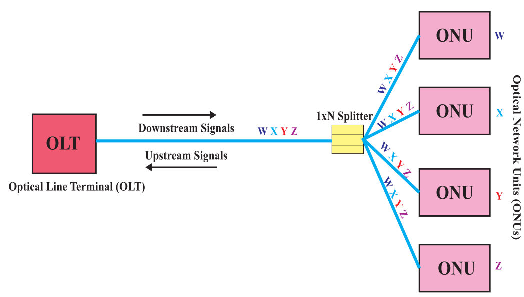


**Fig. 2.** Downstream and upstream traffic model for passive optical networks.

equation (NLSE), as in Eq. (1). This method is termed as Digital Backpropagation (BP) [5,6] 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 [6], as in Eq. (2).

$$\frac{\partial E}{\partial z} = (-\hat{N} - \hat{D})E \tag{1}$$

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

whereas $\hat{D}$ and $\hat{N}$ are the linear and non-linear operators respectively, to solve the inverse NLSE. Another alternative approach for joint compensation of linear and non-linear effects is the Volterra equalization (VE) method [4,8], as in Fig. 3. 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 inter-symbol-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 [9].

These two methods, i.e. BP and VE, are the post-processing methodologies implemented with coherent receivers. We have also implemented an all-optical signal pre-processing method for non-linear equalization, which is termed as Optical Phase Conjugation with Non-linearity Module (OPC-NM) [10]. The module contains

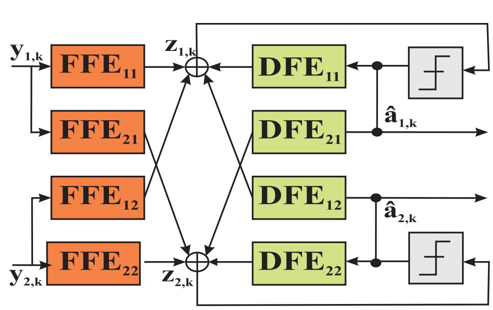


**Fig. 3.** Numerical model of Volterra-based nonlinear FFE-DFE equalizer.

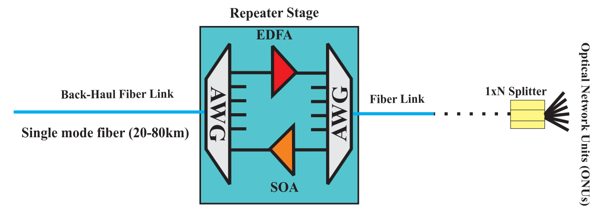


**Fig. 4.** Long reach passive optical network (LR-PON) architecture.

highly non-linear fibre (HNLF) and OPC. The non-linear stage is implemented by 19 km of SMF with input launch power $P_m$ tuned by an erbium doped fibre 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 fibre link. The parameters of this module, i.e. fibre length $L_m$, signal power $P_m$ and non-linear coefficient $\gamma_m$, is adjusted along with OPC module, so that it produces negative non-linear phase shift of $(-\Delta\phi_m)$, cancelling the original $(\Delta\phi_m)$ from fibre transmission link.

## 3. Super passive optical networks (S-PONs)

Super PON is a network structure similar to a PON, but supports a much higher splitting ratio by exploiting repeater stages consisting of optical amplifiers, as in Fig. 4. The downstream direction uses Erbium Doped Fibre Amplifiers (EDFAs/1.5 μm) and the upstream direction Semiconductor Optical Amplifiers (SOAs/1.3 μm). Super PON is not standardized, but it can be adapted to any of the above described PONs. The split ratio of 1:2048 can also be achieved by using this architecture [11]. PON architectures with large split sizes are intended to maximize the number of components shared between all end consumers. Even though optical amplifiers (either EDFA or SOA) must be used to increase the overall power budget, the distribution section closest to the consumer premises still remains passive.

## 4. Numerical model

The architecture, as in Fig. 5, consists of: optical line terminal (OLT) having 3 CW lasers multiplexed together (with 50 GHz, 10 GHz and 5 GHz channel spacing) and 10 Gbit/s WDM DP-QPSK signal per wavelength is produced. The applied pattern was a pseudo-random bit sequence (PRBS) of length $2^{15}-1$. An EDFA at the OLT adjust the signal input launch power into the fibre back-haul, and passive optical splitters are used to distribute the signal to the optical network units (ONU). The standard single mode fibre is used to transmit over a distance of 120 km. The physical parameters of SMF fibre are: $\alpha$ = +0.2 dB, $D$ = +16.75 ps/(nm-km) and $\gamma$ = +1.3(km$^{-1}$ 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 same power budget. The signal is detected with a phase and polarization diverse coherent receiver. At the receiver the channels can be selected through

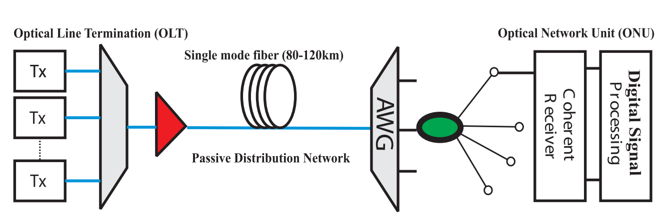


**Fig. 5.** Architecture of coherent 10 Gbit/s long reach WDM-PON employing DP-QPSK downstream signals.