Optics Communications 403 (2017) 252–256

Contents lists available at ScienceDirect

Optics Communications

journal homepage: www.elsevier.com/locate/optcom

Orthogonal modulation application to achieve flexible migration and colorless ONUs for next generation PON

Yang Lu [a,b,*], Meihua Bi [a], Miao Hu [a], Yizhen Wei [a], Guowei Yang [a], Xuefang Zhou [a], Qiliang Li [a]

[a] College of Communication Engineering, Hangzhou Dianzi University, Hangzhou 310018, China
[b] KTH Royal Institute of Technology, Electrum 229, Kista 164 40, Sweden

ARTICLE INFO

Keywords:
PON
Migration
Colorless ONU
Orthogonal modulation

ABSTRACT

Flexible migration that reuse the deployed infrastructure and colorless ONUs which avoid inventory problem are two major challenges of next-generation passive optical network (NGPON). In this paper, flexible migration is achieved by the coexistence of legacy PON and NGPON and colorless ONUs is achieved by upstream remodulation. Orthogonal modulation methods such as DPSK, PolSK and WSK are applied for NGPON downstream signal to ensure the constant amplitude. The amplitude-constant NGPON downstream signal induces low crosstalk to the coexisting legacy PON signal and the remodulated upstream signal. The experimental demonstration shows error free transmission and verifies the feasibility of the proposed scheme.

1. Introduction

In recent years, Passive optical networks (PONs) have been widely deployed as the ultimate solution to fiber-to-the-home in many countries [1]. Due to the emergence of bandwidth-hungry applications such as high-definition video services, online gaming and cloud storage, the bandwidth provided by the current PONs will be exhausted. Next generation PONs providing higher bit rate are expected to replace the current PONs [2–8]. The specifications have been proposed for the next generation PONs (NGPONs) which could provide 10 Gb/s bit rate [9,10] and 40 Gb/s bit rate [11].

As access networks, PONs are cost-sensitive. The infrastructure investment is dominant in total expenditure of a PON. In the migration, to avoid high cost from rebuilding a new infrastructure, reusing the deployed infrastructure is expected. NGPON should be added into current optical distribution network (ODN) to share the deployed infrastructure with the legacy PON, which is called as flexible migration. In flexible migration, the coexistence of NGPON and legacy PON is required. As described in [11], the legacy ONU and OLT must remain unchanged and should not require any additional filters to protect them against NGPON signals. In the event that extra filtering is required, this should preferably be at the OLT where access may be easier and not the ONU to avoid truck rolls.

Because the legacy ONUs have no additional filters to protect them against NGPON signals, they will receive NGPON downstream signal, which become the crosstalk to the legacy PON signal. Several upgrade methods have already been proposed to eliminate or reduce such crosstalk [12,13], including subcarrier modulation, sync pulse interleaving, electrically stacked modulation and spectrum shaping line-coding (SSLC). All above methods still use amplitude shift keying (ASK) for NGPON downstream modulation, so the crosstalk from NGPON signal to the legacy PON signal is reduced but not eliminated. Theoretically, if the modulation for NGPON downstream does not change the amplitude, the crosstalk to the ASK modulated legacy PON signal could be eliminated. Such modulations orthogonal to the ASK includes differential phase shift keying (DPSK), wavelength shift keying (WSK) and polarization shift keying (PolSK). We have proposed orthogonal modulation for flexible migration [14]. Thanks to the constant amplitude of orthogonal modulated NGPON signal, the crosstalk induced to the ASK legacy PON signal is very low.

Besides flexible migration, another challenge of NGPON is colorless ONU. NGPON is hybrid time division multiplexing/wavelength division multiplexing (TWDM). WDM in upstream requires ONUs in different wavelength channels to transmit in different wavelengths. That brings in an inventory problem that management of multiple ONU types that scale in number with the number of wavelengths. In order to facilitate flexibility and reduce operational expenditures due to inventory management, deployed ONUs must be 'colorless', i.e., they are not specific to a certain wavelength [11].

* Corresponding author at: College of Communication Engineering, Hangzhou Dianzi University, Hangzhou 310018, China.
E-mail address: luyangcoer@gmail.com (Y. Lu).

http://dx.doi.org/10.1016/j.optcom.2017.07.060
Received 23 March 2017; Received in revised form 19 July 2017; Accepted 21 July 2017
Available online 2 August 2017

Upstream remodulation, which reuses part of the downstream as the upstream carrier, is proposed to achieve colorless ONUs [15–21]. The carrier has already carried downstream signal, which results into crosstalk to the remodulated upstream signal. To reduce or eliminate the crosstalk from remodulation, some operations are proposed for downstream, including low extinction ratio [17], SSLC [19–21] and orthogonal modulation [15,16,18]. The downstream signal of low extinction enhances the quality of upstream signal at the cost of its own degradation. SSLC could reduce but not eliminate the crosstalk. The crosstalk will increase rapidly when the bit rate of upstream signal becomes close to the downstream signal. The orthogonal modulated downstream signal provides an amplitude-constant carrier for upstream remodulation. As the upstream signal is ASK, it suffers low crosstalk from the amplitude-constant downstream signal.

Orthogonal modulation has been applied in upstream remodulation to achieve colorless ONUs [18,19,21] and in coexistence to achieve flexible migration [14]. However, to the best of our knowledge, previous schemes only focus on remodulation or coexistence individually. In this paper, it is the first time to apply orthogonal modulation to achieve flexible migration and colorless ONU at the same time. The NGPON links are added into the deployed ODN to coexist with the legacy PON link and apply remodulation. The NGPON downstream signal is orthogonal modulated, so it is of constant amplitude. The amplitude-constant NGPON downstream signal induces very low crosstalk to both the coexisting legacy PON signal and the remodulated NGPON upstream signal. The coexistence and remodulation are simultaneously achieved with NGPON downstream signal modulated in DPSK, PolSK or WSK respectively.

2. Orthogonal modulation based scheme

Our proposed scheme is shown in Fig. 1. The NGPON OLTs and ONUs are added into the deployed ODN. NGPON links share the existing infrastructure with the legacy PON links. The legacy PON applies ASK modulation while the NGPON applies orthogonal modulation in downstream and ASK modulation in upstream. The wavelengths assigned to NGPON links are in a different band from that occupied by legacy PON link. The downstream signals of NGPON and legacy PON are combined by a coarse wavelength division multiplexer and then fed into the feeder fiber. The legacy ONUs receive both the legacy PON signal and NGPON signals due to the absence of wavelength division multiplexers or filters. As the NGPON signals are orthogonal modulated, resulting in constant amplitude, the induced crosstalk to the ASK modulated legacy PON signal is very low. Each NGPON ONU receives the corresponding wavelength with the help of wavelength division multiplexer. The received downstream signal is divided into two branches for downstream signal receiving and upstream remodulation, respectively. As the photo diode (PD) only responds to ASK signal, the orthogonal modulated signal should be converted into ASK signal before injected into the receiver. The conversion from DPSK, WSK and PolSK signal could be achieved by a delay interferometer (DI), interleaver (IL) or polarization beam splitter (PBS), respectively. DI, IL and PBS output two opposite converted ASK signals, so balance detection could be applied to improve 3 dB receiving sensitivity. The modulator for upstream remodulation is an intense modulator (IM). It could be a Mach–Zehnder modulator (MZM) or an electrical absorption modulator (EAM). As the IM is employed in each NGPON ONU, it should be of low cost. MZMs are not preferred due to the high cost and polarization dependent. Semiconductor optical amplifier (SOA) or injected Fabry–Perot laser (FP-LD) are good candidates if the power budget is tight. As the downstream signal is orthogonal modulated, it seems a blank carrier for ASK modulation. The crosstalk in the remodulation is low.

3. Experiment and results

The proposed scheme is experimental demonstrated, as shown in Fig. 2. The bit rate of NGPON is 2.5 Gb/s or 10 Gb/s per wavelength [11]. The bit rate of legacy PON is not higher than 2.5 Gb/s. The bit rates of the legacy PON downstream signal, NGPON downstream signal and upstream signal are all set as 2.5 Gb/s. A 1530 nm DFB laser is external modulated by a LiNO3 MZM as the transmitter of legacy PON. NGPON transmitter is an orthogonal modulation transmitter. The orthogonal modulation methods in the experiment are shown in Fig. 2(b). DPSK or PolSK modulation is achieved by a $LiNO_3$ phase modulator (PM) with the injected optical carrier's polarization accordance with or 45° off from the PM's modulation axis, respectively. In practical application, pre-coding is required for DPSK modulation, but it is not necessary in the experiment as the data used is pseudo random bit sequence (PRBS). WSK modulation is achieved by combining two optical carriers of 1549.32 nm and 1550.52 nm. The two optical carriers are polarization division multiplexed with their polarization states orthogonal. The polarization division multiplexed carriers are PolSK modulated with their polarization states 45° and −45° off from the PM modulation axis. After modulation, two complimentary WSK signals are generated in two orthogonal polarizations and one of them is selected by a PBS. The power of the ASK legacy PON signal and orthogonal modulated NGPON signal are adjusted the same. Then they are combined and fed into a 25 km standard single mode fiber (SSMF), followed by one variable attenuator for bit error rate (BER) testing. After transmission, the combined signals are split into two branches. One is directly detected as legacy PON signal. The other is through an optical filter (OF) to filter out the legacy PON signal and split again into another two branches for NGPON downstream receiving and upstream remodulation. The ASK convertor in the experiment is DI, PBS and OF for DPSK, PolSK and WSK signal, respectively. To simplify the demonstration, directly detection is used for NGPON downstream signal instead of balance detection. The modulator for upstream remodulation is a MZM. The remodulated signal travels back for upstream signal receiving. The photo detectors used are PINs. The maximum modulation index of the used MZMs is about 14 dB. MZMs are used just for experimental demonstration. In practical use, as mentioned before, MZMs are too expensive to be applied in PONs. In practical schemes, the downstream modulators are usually low-cost directly modulated lasers or integrated EAM lasers and upstream modulators could be injected FP-LDs or other low-cost intense modulators.

The eye-diagrams of the signals are measured and shown in Fig. 3. The back to back (b2b) cases are in the upper rows and the transmission cases are in the lower rows. The orthogonal modulated NGPON downstream signals are of constant amplitude in b2b cases (the second eye-diagrams in the upper rows). When combined with an orthogonal modulated NGPON signal, the eye-diagram pattern of legacy ASK signal stays the same expect for a rise (the first and the third eye-diagrams in the upper rows). Such rise is a direct current (DC) component and will be filter out if the receivers in legacy ONUs are alternating current (AC) coupled. If the receivers are not AC coupled, the additional operation is to adjust the decision level. After 25 km transmission, the orthogonal modulated signal is no longer constant due to the dispersion induced fluctuation (the second eye-diagrams in the lower rows). The fluctuation is also "added" to the ASK signal after combination. The eye-diagrams show the fluctuation is slight after 25 km transmission. Among the three orthogonal modulated signals, the WSK signal suffers most dispersion induced degradation because it consists of two carriers of different wavelengths. If the two used wavelengths become closer, the dispersion induced crosstalk will be less.

Bit error rates (BERs) of the signals after 25 km transmission are tested and shown in Fig. 4. Error free (BER $< 10^{-9}$) operation is achieved for all signals. Fig. 4(a) shows the BERs of legacy PON signals with and without NGPON orthogonal modulated signals. The receiving sensitivity of ASK signal is −19.7 dBm and the power penalty from