Optics Communications 460 (2020) 125123

Contents lists available at ScienceDirect

Optics Communications

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

Experimental demonstration of direct re-modulation for an IM/DD OFDM-WDM-PON with symmetrical bi-directional transmission

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ARTICLE INFO

Keywords:
Direct re-modulation
OFDM-WDM-PON
Symmetrical
Bi-directional
IM/DD

ABSTRACT

In this paper, we propose and experimentally demonstrate a direct re-modulation scheme for an IM/DD OFDM-WDM-PON. By adjusting the modulation index of the downstream OFDM data via its peak-to-peak laser driving voltage (Vpp), the proposed scheme directly modulates the upstream OFDM data onto the received wavelength at the optical network unit without employing any downstream data erasing technique or using any reflective semiconductor optical amplifier. Thanks to the reduced modulation index of the downstream data, the upstream data can be detected at the optical line terminal by simply regarding the residual downstream signal in the uplink as noise. And a 10-Gb/s symmetrical bi-directional transmission with the BER performance below 3.8×10^{-3} is experimentally demonstrated.

1. Introduction

With the rapid increase in bandwidth demand from various ultra-high resolution multimedia applications, high speed data transmissions are required to be accommodated efficiently not only at the core but also over the access networks, which induces an urgent need for broadband network access [1]. By delivering the data between the optical line terminal (OLT) and different subscribers, via a set of designated wavelengths, wavelength division multiplexing passive optical network (WDM-PON) technique provides a promising solution for broadband access networks [2,3]. However, traditional WDM-PONs [4], which employ conventional modulation formats, such as differential phase shift keying (DPSK) and on-off keying (OOK), usually suffer from fiber's chromatic dispersion in data transmissions with limited spectral efficiency.

In order to overcome the above-mentioned limitations in traditional WDM-PONs, orthogonal frequency division multiplexing (OFDM) modulation technique, which has high immunity to chromatic dispersion and high spectral efficiency, was introduced into these PON systems with the maturity of coherent-detection and intensity-modulation/direct-detection (IM/DD) technologies [5–11]. In these OFDM-based WDM-PON systems, which are also known as OFDM-WDM-PONs, easy implementation and cost effectiveness are essential for their applications in optical access networks. In particular, signal re-modulation technique, which reuses the downstream optical carriers for upstream transmission without additional light sources resided at the ONUs, is highly desirable in OFDM-WDM-PONs, since this realizes colorless ONU [12], which simplifies the ONU implementation. Several signal re-modulation schemes have been reported for OFDM-WDM-PONs [12–17]. In [12–14], low-rate OOK upstream data were superimposed onto the high-rate OFDM downstream data, via a reflective semiconductor optical amplifier (RSOA) or a Fabry–Perot laser diode (FP-LD) at the ONUs. Although these schemes realized bi-directional data delivery, the data-rate of the upstream signals was always limited by the adopted modulation format and the modulators at the ONUs. In [15,16], OFDM re-modulation schemes based on single-sideband modulation technique were proposed for OFDM-WDM-PON systems, in which OFDM modulation format was adopted for bi-directional data transmission over a single feeder fiber. However, additional optical filters were needed, either at the OLT or the ONUs, to generate the single-sideband modulated signals. Besides, the RSOA employed in these schemes might also suffer from severe intensity noise and restricted modulation bandwidth. In [17], another signal re-modulation scheme was proposed for OFDM-WDM-PONs. By employing different frequency bands for the downstream and the upstream data (e.g. up-shifted band for the downstream OFDM modulated data and baseband for the upstream OFDM modulated data), duplex transmission was realized without downstream data erasure, but two dedicated feeder fibers were needed to realize the data delivery in both directions. In addition, the directly-modulated colorless laser diode (e.g. injection-locked FP-LD) employed in [17] might suffer from inadequate modulation bandwidth and required the modulation format to have relatively high spectral efficiency. However, the modulation format with relatively high spectral efficiency always has limitation in the transmission span.

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https://doi.org/10.1016/j.optcom.2019.125123
Received 21 August 2019; Received in revised form 27 November 2019; Accepted 16 December 2019
Available online 18 December 2019

In this paper, we propose and experimentally demonstrate a direct re-modulation scheme for an IM/DD OFDM-WDM-PON without using any data erasing technique or any colorless laser diode. By adjusting the modulation index of the downstream OFDM data via its Vpp, the proposed scheme directly superimposes the upstream OFDM data onto the downstream wavelength via an intensity modulator at the ONU, and delivers the upstream signals to the OLT via the same feeder fiber that the downstream signals traverse. Due to the reduced modulation index of the downstream data, the upstream data can be correctly recovered at the OLT with the residual downstream signal in the upstream transmission being regarded as noise. In this way, bi-directional transmission on a single feeder fiber is realized by the proposed scheme. In addition, since no RSOAs or FP-LDs are employed, the proposed re-modulation scheme can be released from the insufficient modulation bandwidth for upstream data. In this work, a symmetrical bi-directional 10-Gb/s 4-QAM OFDM modulated data transmission on a single feeder fiber with the BER performance below 3.8×10^{-3} is experimentally demonstrated.

The rest of the paper is organized as follows. Section 2 describes the proposed direct signal re-modulation for an OFDM-WDM-PON with symmetric bi-directional transmission. Section 3 presents the experimental demonstration for the proposed re-modulation scheme. Section 4 concludes this paper.

2. Direct signal re-modulation for an IM/DD OFDM-WDM-PON with symmetric bi-directional transmission

In this section, we describe the proposed signal re-modulation scheme for an OFDM-WDM-PON system with symmetric bi-directional transmission. As shown in Fig. 1, the OFDM-WDM-PON system employing the proposed re-modulation scheme consists of N ONUs. At the OLT, each downstream wavelength from a continuous-wave light source is first intensity modulated by the downstream OFDM data with its extinction ratio adjusted, via an optical intensity modulator (e.g. Mach–Zehnder modulator). Then, all the modulated downstream wavelengths are combined at the WDM multiplexer before being delivered to the remote node (RN), via a single mode fiber (SMF), which acts as the feeder fiber for both downstream and upstream transmissions. The combined downstream wavelengths are then de-multiplexed at the RN before being sent to individual destined ONUs. At the ONU, half of the downstream optical power is tapped off for direct data detection at the OFDM receiver, while the other half is amplified via an optical amplifier and reused as the upstream wavelength. The amplified wavelength is then intensity modulated by the upstream OFDM data, via another optical intensity modulator, before being delivered back to the OLT over the same feeder SMF. In this way, bi-directional transmission is realized on a single feeder fiber. Noticeably, the optical amplifier employed at the ONU can help improve the performance of the upstream transmission when a single photodetector (PD) is used at each OFDM receiver for the simple and low-cost direct detection. Since the PD can be modeled as a square-law detector, at the receiver, the resulting photo current via direct detection is given as,

$$I(t) \propto |r(t)|^2 = \left|r_s(t) + r_{dc}\right|^2 \tag{1}$$

where r_s(t) is the received signal to be recovered, r_{dc} is the DC component determined by the optical carrier. Eq. (1) can then be expressed as

$$I(t) \propto \left|r_s(t)\right|^2 + \left|2r_s(t)\, r_{dc}\right| + \left|r_{dc}\right|^2 \tag{2}$$

Note that $\left|r_{dc}\right|^2$ is a constant, which can be easily eliminated by a DC blocking filter. The term of $\left|r_s(t)\right|^2$ is called signal-to-signal beating interference (SSBI), which highly deserves the signal recovery. The linear term of $\left|2r_s(t)\, r_{dc}\right|$ is the signal to be retrieved. Therefore, compared to the signal $r_s(t)$, the absolute value of r_{dc}, i.e., the intensity of the optical carrier, should be large enough in order to minimize the penalty from SSBI. On the other hand, in view of the power sensitivity of the PD, we thus need to employ an optical amplifier before the modulator at each ONU. Besides, since no data erasing technique is employed in the scheme, which keeps the simplicity of the proposed scheme in algorithm, conventional off-line algorithm can be used for the data detection in the proposed scheme with regarding the residual downstream signal in uplink as noise by adjusting the Vpp of the downstream OFDM data.

3. Experimental demonstration

In this section, we perform a proof-of-concept experiment for our proposed signal re-modulation scheme. Fig. 2 depicts the setup of the experiment. As shown in Fig. 2, a continuous-wave light at 1560 nm was first fed into an optical intensity modulator (SUMITOMO T.MEH1.5-40PD-ADC-S-FA), which was driven by the downstream 10-Gbit/s 4-QAM OFDM data generated from an arbitrary waveform generator (Tektronix AWG7122C) via digital signal processing offline. As for the downstream OFDM data, its subcarrier number was set as 256 with 127 of them effectively carrying 4-QAM symbols due to Hermitian symmetry, while the length of cyclic prefix (CP) was set to 1/16 of one OFDM symbol. To increase power efficiency, the peak-to-average power ratio (PAPR) was set to be 11 dB by clipping for all the generated OFDM signals. Then the modulated downstream wavelength was delivered to the ONU, via a 20-km SMF. At the ONU, 10% of the downstream optical power was used for data detection by employing a photodiode (PD) (XPDV 2020R) and a real-time oscilloscope (Tektronix DSA72004B), while the other 90% was amplified by an Erbium-doped fiber amplifier (EDFA) before being modulated by the upstream 10-Gbit/s 4-QAM OFDM data (with the same parameters as the downstream data) at another intensity modulator (SDL 10AP-MOD9140-f-f-0). The optical power of the output of EDFA was fixed at ∼5.6 dBm. For the case of back-to-back (B2B), the input optical power to EDFA was ∼5.6 dBm (no EDFA required). Meanwhile, after employing an additional SMF link, the input optical power to EDFA was reduced to ∼0.6 dBm due to the attenuation after 20-km SMF transmission. The re-modulated wavelength was directly reused for upstream transmission, and sent back to the OLT via the above-mentioned 20-km SMF. At the OLT, the upstream data was also directly detected as we did for downstream data.

In the experiment, adjusting the extinction ratio of the downstream OFDM data is essential to realize the direct re-modulation of the upstream OFDM data onto the reused downstream wavelength without erasing the downstream data. Therefore, we investigate the effect of the variation of the modulating amplitude (Vpp) at the intensity modulator of the downstream signal on both the downstream and the upstream transmission performances during the bi-directional transmission with the assumption that the Vpp of the upstream signal is already set at its optimum value. Fig. 3 shows the bit-error-rate (BER) performances of both the received upstream and the received downstream data after 20-km transmission with different Vpp value of the downstream signal, while the Vpp of the upstream signal is always set at its optimum value (i.e., 6 V in the experiment) and the received optical power (ROP) is set as −12 dBm. As shown in Fig. 3, the BER performance of the received downstream data increases with the increase of the Vpp of the downstream signal, while the BER performance of the received upstream data decreases with the increase of the downstream signal's Vpp. This indicates that higher Vpp of the downstream signal can improve the performance of the downstream transmission, but cause more severe interference to the upstream transmission. It is worth to note that the downstream and the upstream have the closest BER performance below the FEC threshold (i.e., 3.8×10^{-3}) when the Vpp of the downstream signal is set at 0.6 V, which implies that both the downstream and the upstream transmission performances can be guaranteed in this case. Thus, we set the Vpp of the downstream signal as 0.6 V in the experiment. It should be noted that the optimal Vpp of the downstream signal is different for different modulators used in the practical bi-directional transmission. Moreover, we can observe from

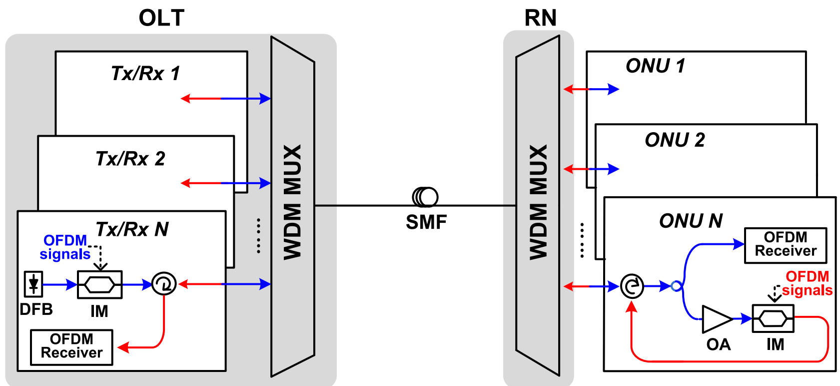

Fig. 1. The OFDM-WDM-PON architecture employing the proposed re-modulation scheme. IM: optical intensity modulator, SMF: single mode fiber, OA: optical amplifier.

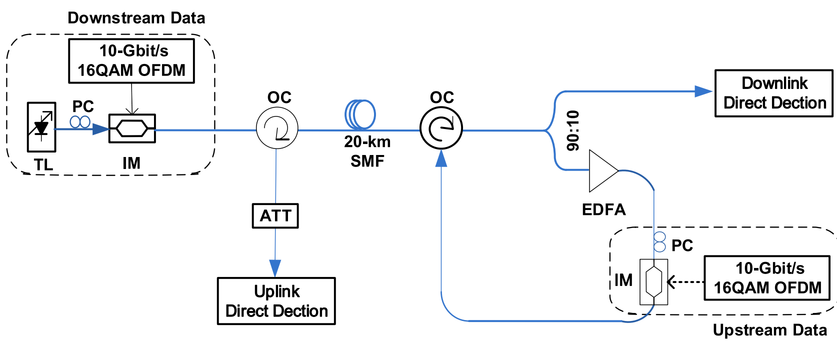

Fig. 2. Experimental setup. PC: polarization controller, TL: tunable laser, OC: optical circulator, EDFA: Erbium-doped fiber amplifier.

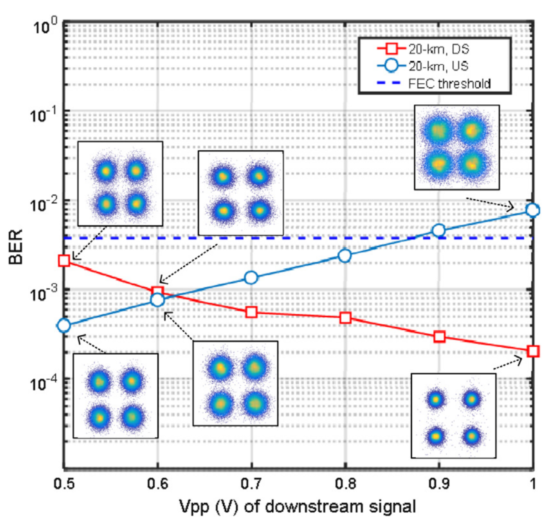

Fig. 3. BER performances of both US and DS transmissions vs. Vpp of downstream signal. DS: downstream, US: upstream.

Fig. 3 that there is a voltage margin for the optimal Vpp of ∼0.3 V (0.5 V–0.8 V), ensuring BER below HD-FEC threshold for both signals. Therefore, the stability of this scheme can also be guaranteed.

We have also investigated the transmission performance of the proposed OFDM-WDM-PON system in both the B2B and the 20-km transmission cases. Fig. 4(a) shows the BER performance of the system with different values of ROP in the back-to-back transmission case. As shown in Fig. 4(a), when the Vpp of the downstream signal is set at 0.6 V, upstream transmission causes negligible power penalty to the downstream transmission during the bi-directional data delivery in the case of B2B. This can be understood by the fact that the Rayleigh Backscattering (RB) effect is almost negligible in the B2B transmission case, when the transmission length is too short for the accumulation of the RB effect. However, adjusting the Vpp of the downstream signal (i.e., set at 0.6 V) will induce about 4.4 dBm power penalty (at the BER of 3.8×10^{-3}) to the downstream transmission, compared to the occasion when the Vpp of the downstream signal is set at its optimum value (i.e., 2.5 V). As for the upstream transmission, the received upstream data suffers about 1.1 dB power penalty at the BER of 3.8×10^{-3} with the OFDM data modulated onto the downstream wavelength, compared to the case when no OFDM data is modulated onto the downstream wavelength. This power penalty mainly comes from the residual downstream signal in the upstream transmission, which may introduce interference to the direct detection of the upstream signal.

Fig. 4(b) shows the BER performance of the system with different values of ROP after 20-km transmission. As shown in Fig. 4(b), when the Vpp of the downstream signal is set at 0.6 V, upstream transmission causes negligible power penalty to the downstream transmission during the bi-directional data delivering on the single fiber when the ROP is less than −13 dBm. However, different from the B2B case, the additional upstream transmission results in an error floor in the downstream transmission during the bi-directional data delivery, which can be attributed to the accumulated RB effect after 20-km SMF transmission. Similar to that shown in Fig. 4(a), decreasing the Vpp of the downstream signal (i.e., set at 0.6 V) introduces about 4.4 dBm power penalty (at the BER of 3.8×10^{-3}) to the received downstream data after 20-km transmission, compared to the occasion when the Vpp of the downstream signal is set at its optimum value. As for the upstream transmission, the received upstream data after 20-km transmission suffers about 1 dB power penalty at the BER of 3.8×10^{-3} with the OFDM data modulated onto the downstream wavelength, compared to the case when no OFDM data is modulated onto the downstream wavelength. Noticeably, different from what shown in Fig. 4(a), the received upstream data after 20-km transmission suffers from an obvious error floor below the FEC threshold either with or without

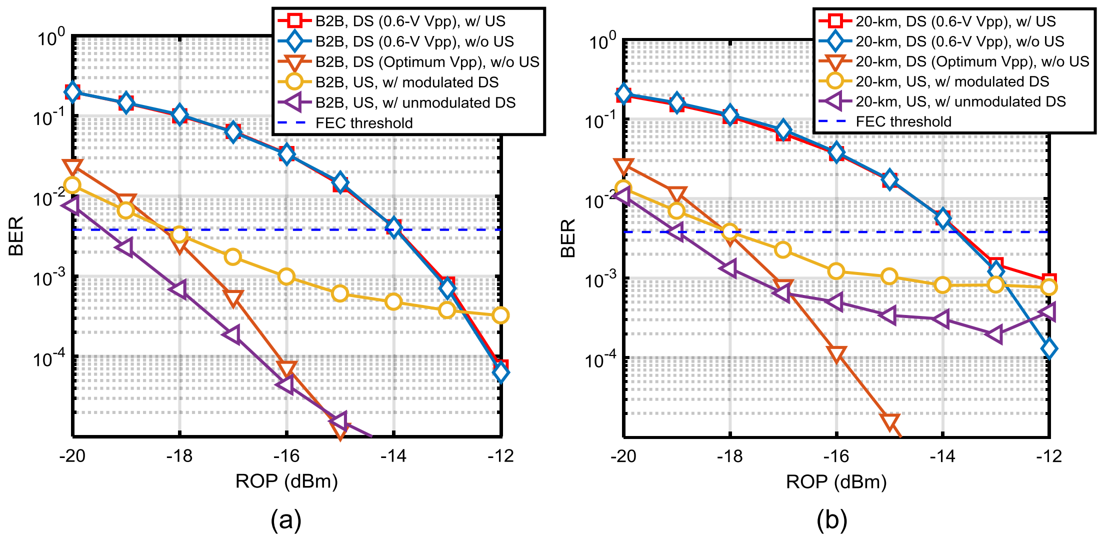

Fig. 4. BER performance vs. ROP. (a) back-to-back, (b) after 20-km transmission, DS: downstream, US: upstream.

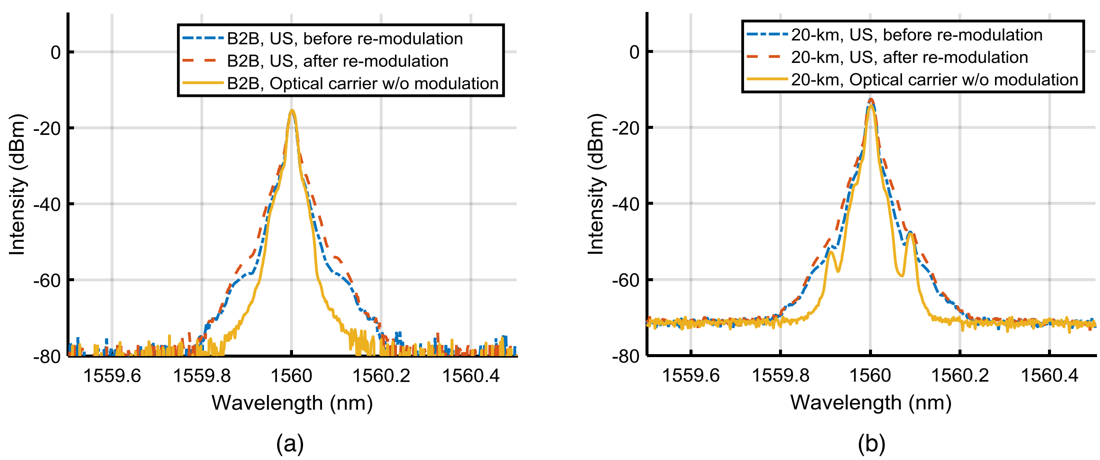

Fig. 5. Optical spectra of upstream signals after (a) B2B and (b) 20-km SMF transmission.

OFDM data modulated onto the downstream wavelength, which mainly results from the RB effect in the bi-directional data delivery.

Fig. 5 presents the optical spectra of upstream signals in different scenarios. We can see that the re-modulation of the upstream signals broadens the spectrum band of the optical carrier without any central-wavelength-shifting. This indicates that upstream signals need higher modulation index to suppress the interference from downstream signals. Besides, this may also imply that the downstream signals may induce RB effect to the upstream ones during their bi-directional transmission along a single fiber [18,19]. Noticeably, two side lobes, i.e., Brillouin peaks, are observed when the optical carrier is transmitted after 20-km SMF without any signal modulation as shown in Fig. 5(b).

In this work, since we have not yet applied any interference cancellation techniques to the upstream signal, the modulation formats used in both downstream and upstream are limited to 4-QAM. However, we should note that the purposely-induced interference (downstream signal) is deterministic. Therefore, higher-order modulation formats could be supported if we also employ some advanced interference cancellation techniques in our future work. Although its scalability and data rate were limited in the current demonstration, we believe that it is a potential re-modulation scheme with the advantages of low complexity and low cost.

4. Summary

In this paper, we have proposed and experimentally demonstrated a direct signal re-modulation scheme to realize symmetric bi-directional transmission in an IM/DD OFDM-WDM-PON with low cost and implementation complexity by modifying the modulation index of the downstream OFDM signal, via its Vpp. Due to the reduced modulation index, the residual downstream data on the reused wavelength can be regarded as noise to upstream OFDM signal in the uplink, and thus the upstream data can be detected at the OLT. Besides, no RSOA or FP-LD is required in the scheme, which guarantees the transmission capacity of the system. A 10-Gb/s symmetrical bi-directional transmission of OFDM signals with the BER performance below 3.8×10^{-3} is experimentally demonstrated to verify the feasibility of the scheme.

CRediT authorship contribution statement

Zhouyi Hu: Writing - original draft, Software. **Yang Qiu:** Conceptualization, Methodology, Supervision, Funding acquisition. **Wentong Li:** Resources, Data curation. **Chun-Kit Chan:** Conceptualization, Writing - review & editing.

Acknowledgments

This work was partly supported by National Natural Science Foundation of China (No. 61705190), and the Fundamental Research Funds for the Central Universities, Southwest Minzu University, China (No. 2018HQZZ26). We appreciate the reviewers' suggestions on the paper.

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