A Delay-Based Multicast Overlay Scheme for WDM Passive Optical Networks With 10-Gb/s Symmetric Two-Way Traffics

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***Abstract*—We propose a delay-based multicast overlay scheme to superimpose a multicast differential phase-shift keying (DPSK) modulated signal on a point-to-point downstream inverse-return-to-zero (IRZ) modulated signal in a wavelength-division-multiplexed passive optical network (WDM-PON). By adjusting the synchronization of the DPSK and the IRZ modulation on the downstream carrier, simple and flexible multicast control could be realized. We have successfully demonstrated the proposed scheme for three different traffics, namely 10-Gb/s IRZ downstream point-to-point data, 10-Gb/s DPSK downstream multicast data, and 10-Gb/s non-return-to-zero (NRZ) upstream re-modulated data, respectively. An error floor of 10^{-4} is observed for the multicast data when it is disabled. The effect of timing misalignment on the downstream DPSK/IRZ orthogonal modulation and the upstream re-modulation is analyzed. We also study the case when the data rates of the multicast and downstream point-to-point data are different.**

***Index Terms*—Differential phase-shift keying (DPSK), inverse return-to-zero (IRZ), orthogonal modulation, multicast, wavelength-division-multiplexed passive optical network (WDM-PON).**

I. INTRODUCTION

THE wavelength-division-multiplexed passive optical net-work (WDM-PON) is a promising technology for the next-generation access networks [1]–[5], due to its large bandwidth and upgrade flexibility compared with the PON systems based on time-division-multiplexing (TDM-PON). With more diverse multimedia and data services available for broadband access, the access network has to be flexible enough to cope with various data or video delivery such as broadcast/multicast services, in addition to the point-to-point traffic. In the wavelength plan for ITU-T TDM-PON standard, the downstream band between 1550 and 1560 nm is assigned to broadcast-video. Broadcast can be easily realized in TDM-PON as it employs power-splitting at the remote node (RN). Whereas it is more challenging for WDM-PON, due to the dedicated connection between the optical line terminal (OLT) and the optical network unit (ONU). To realize more flexible network functions, several studies have been carried out to deliver simultaneously point-to-point data and broadcast/multicast data to subscribers [6]–[11].

Multicast is more attractive, compared to broadcast, as it allows selective control of the connection for each subscriber individually. There are two key issues to transmit both point-to-point and multicast data simultaneously in WDM-PON: (1) how to multiplex the point-to-point and multicast traffic and (2) how to enable/disable the multicast traffic flexibly. An additional wavelength together with a specially designed arrayed waveguide grating (AWG) could be used to realize the broadcast capability in WDM-PONs [6], but it will increase system complexity and cost. Subcarrier multiplexing could be employed to superimpose the multicast data on the point-to-point data and less than 1.5 Gb/s was demonstrated [7]–[9]. However, broadband modulators and oscillators, with bandwidth several times larger than the signal bit rate, are needed at the OLT and/or ONU sides. Recently, two schemes were proposed to superimpose a 10-Gb/s multicast data stream on conventional 10-Gb/s downstream point-to-point data [10], [11]. The multicast control is achieved, respectively, by adjusting the extinction ratio of the downstream point-to-point NRZ data [10], or switching the modulation format of the downstream point-to-point data between non-return-to-zero-on-off-keying (NRZ-OOK) and inverse-return-to-zero-on-off-keying (IRZ-OOK) [11]. However, when the multicast service is disabled, as the upstream transmission is realized by remodulating part of the downstream non-return-to-zero (NRZ) signal with a high extinction ratio (ER), it results in a limited upstream bit rate. Less than 2.5 Gb/s is demonstrated. However, with the surge of peer-to-peer applications, symmetric bit rates in both upstream and downstream signals are highly desirable for future-proof PON systems.

Recently, we proposed a novel scheme to realize 10-Gb/s symmetric uplink and downlink bit rates and 10-Gb/s multicast overlay with simple centralized control for multicast service [12]. The multicast data, encoded in differential phase-shift keying (DPSK) format, are superimposed on all point-to-point data channels, modulated in IRZ format. By adjusting the synchronization of the DPSK/IRZ orthogonal modulation, simple and flexible multicast control could be realized. It should be noted that such synchronization control is also required in [9]–[11]. Compared with prior schemes [7], [9]–[11], additional ER adjustment or modulation format switching is not required when the multicast service is switched from one operation mode (enabled/disabled) to the other, thus reducing

Manuscript received February 10, 2010; revised May 28, 2010; accepted July 07, 2010. Date of publication July 23, 2010; date of current version August 24, 2010. This work was supported in part by the Hong Kong Research Grants Council under Project CUHK4110/07 and Project CUHK4105/08E.

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Digital Object Identifier 10.1109/JLT.2010.2060471

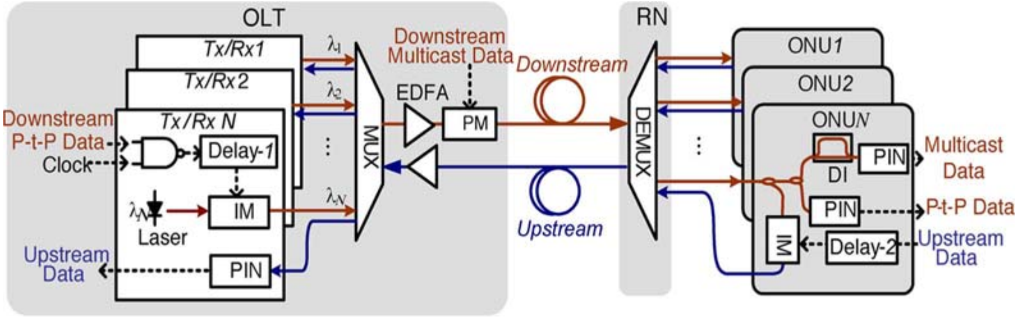

Fig. 1. The proposed WDM-PON architecture with symmetric bit-rates and multicast overlay. Tx/R: transceiver, P-t-P Data: point-to-point data, IM: intensity modulator, OLT: optical line terminal, EDFA: Erbium Doped Fiber Amplifier, DI: delay interferometer, PIN: p-i-n photodetector, PM: phase modulator, RN: remote node, ONU: optical network unit.

system complexity and cost. The upstream transmission can be realized by remodulating part of the downstream IRZ signal which carries optical power in each bit. In this paper, we further investigate different issues for the proposed scheme. First, the effects and tradeoff for different ERs of the IRZ signal are studied. It is shown that the error floor of the multicast disabled data is enhanced from previous 10^{-7} to higher than 10^{-4} when the ER of the downstream IRZ signal is increased from 4.5 dB to 6 dB. The effect of timing misalignment on downstream orthogonal modulation and upstream re-modulation is quantitatively analyzed. We also investigate the applicability of the scheme for systems with different downstream and multicast data rates.

The paper is organized as follows. In Chapter II, we discuss the proposed system architecture and multicast control scheme. Chapter III describes the experimental setup to investigate the proposed scheme and the experimental results. Discussions on the narrow filtering effect of AWGs, the dispersion compensation tolerance and the feasibility of the proposed multicast control scheme for dissimilar multicast data are given in Chapter IV. Finally, conclusion is given in Chapter V.

II. PROPOSED SYSTEM ARCHITECTURE AND MULTICAST CONTROL

A. System Architecture

Fig. 1 shows the proposed WDM-PON architecture with symmetric bit rates and multicast overlay. For each downstream wavelength at the OLT, IRZ-shaped data signal is first generated, via a logic NAND gate, and is used to drive an optical intensity modulator (IM) to generate the downstream point-to-point IRZ signal. All the downstream wavelengths at the OLT are multiplexed by an AWG. The multiplexed signals are first amplified by a shared Erbium Doped Fiber Amplifier (EDFA) and then fed into an optical phase modulator (PM), which is driven by the pre-coded multicast data. Through this orthogonal modulation, the multicast DPSK data are superimposed on all point-to-point data channels in IRZ format. As at least half of a bit period in each downstream point-to-point IRZ bit is in high-power state, it can readily enable the orthogonal modulation. At the ONU, the received downstream signal power is divided into three portions by two 3-dB optical power splitters. One quarter of the received downstream signal power is fed into a photodiode for the direct detection of the downstream point-to-point IRZ data. Another quarter is demodulated by a delay interferometer (DI) before the direct detection of the multicast DPSK data. The remaining power is fed into an optical IM for upstream data remodulation. The high-power portion in each bit of the downstream point-to-point IRZ data also facilitates the upstream data remodulation. Proper synchronization between the downstream and upstream data is needed to assure that the upstream data can be imprinted on the high-power portion of each bit in the downstream IRZ data during remodulation.

B. Multicast Control

By properly aligning the IRZ data temporally through an electronic delay circuit (Delay-1) such that the multicast DPSK data rest in the middle of two adjacent IRZ pulses at the PM, the multicast DPSK data can be properly demodulated and detected at ONUs. In contrast, if the DPSK bits coincide with the IRZ data dips, the multicast DPSK will suffer from excessive intensity fluctuation and cannot be properly demodulated at the ONU. Thus, multicast control can be achieved by centralized electrical delay adjustment of the downstream IRZ signal.

III. EXPERIMENT DEMONSTRATION

A. Experimental Setup

We have performed a proof-of-concept experiment for the proposed delay-based multicast overlay scheme based on the architecture shown in Fig. 1. At the OLT, the IRZ-shaped data signal was first generated by the logic NAND operation of a NRZ 10-Gb/s 2^{31}-1 pseudorandom binary sequence (PRBS) and a 10-GHz clock, via a commercial NAND gate. A continuous-wave light source at 1547.8 nm was then modulated with an IM driven by the obtained IRZ-shaped data. The resultant output with a dark pulse width of 55 ps was amplified by an EDFA. An optical bandpass filter with a 3-dB bandwidth of $\sim$0.8 nm and an insertion loss of 2.1 dB was used to suppress the amplified spontaneous emission (ASE) noise. After power amplification and filtering, the IRZ signals with an ER of $\sim$4.5 dB were fed into a PM driven by a 10-Gb/s PRBS as the pre-coded multicast data. Then the orthogonally modulated signal (DPSK/IRZ) with an average power of 5 dBm was coupled into a 20-km dispersion-shifted fiber to emulate the dispersion-compensated transmission between the OLT and the RN. At the ONU, one quarter of the received downstream signal power was fed into

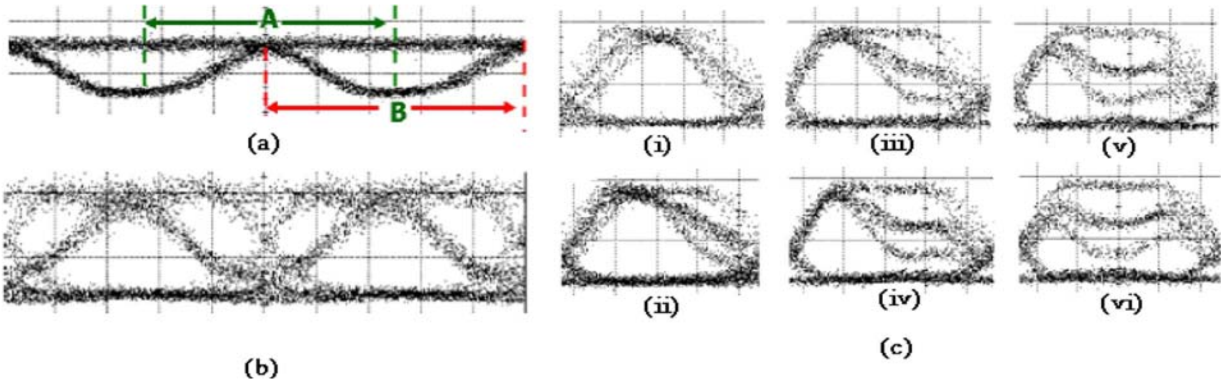

Fig. 2. Eye diagrams of (a) the detected 10-Gb/s downstream point-to-point data in IRZ format, (b) the detected upstream data with proper delay at the Delay-2, (c) (i)–(vi) the 10-Gb/s demodulated DPSK multicast signal with timing misalignment adjusted from 0 to 50 ps with a 10-ps step. Time scale: 20 ps/div.

a p-i-n photodiode for IRZ detection. Another quarter was demodulated by a DI with a relative delay of 94.3 ps for DPSK detection. The remaining power was fed into an optical IM, driven by a properly aligned 10-Gb/s 2^{31}-1 PRBS as the upstream data, before being transmitted back to the OLT via another piece of 20-km dispersion-shifted fiber. A commercially available $LiNbO_3$ IM was used in this experiment. For practical implementation it can be replaced by an electro-absorption modulator integrated with semiconductor optical amplifiers (SOA-EA-SOA) for 10-Gb/s polarization-insensitive operation [13].

B. Experimental Results

To enable multicast, the synchronization of the DPSK/IRZ orthogonal modulation was carefully adjusted via a commercially available digital phase shifter (Delay-1) at OLT as shown in Fig. 1, such that each bit of the DPSK data could be superimposed right in the middle of two adjacent IRZ pulses, as denoted by 'A' in Fig. 2(a), in which the longest period of high intensity level resides. The DPSK data was detected at the ONU, showing a clear eye diagram as depicted in Fig. 2(c)(i). The uplink data was measured, with the eye-diagram shown in Fig. 2(b). To show the effect of timing misalignment on multicast control using electronic delay circuit (Delay-1), the eye diagrams for different timing misalignments are depicted in Fig. 2(c)(i)–(vi), and the increasing degradation by the increasing timing misalignment is shown clearly. When the synchronization of the DPSK was detuned by 50 ps, corresponding to the period 'B' in Fig. 2(a), the superimposed DPSK multicast data could not be detected correctly at the ONU. Its degraded eye diagram is depicted in Fig. 2(c)(vi). The BER measurement results for both downlink and uplink signals are shown as the solid lines in Figs. 3 and 4, respectively.

The performance of the downstream point-to-point signal, the downstream multicast signal, and the upstream signal depends on the ER of the IRZ signal. We then adjusted the ER of the IRZ signal to 6 dB for BER measurements to investigate the tradeoff for different ER's. The corresponding results for all the three types of data are depicted by the dashed lines in Figs. 3 and 4.

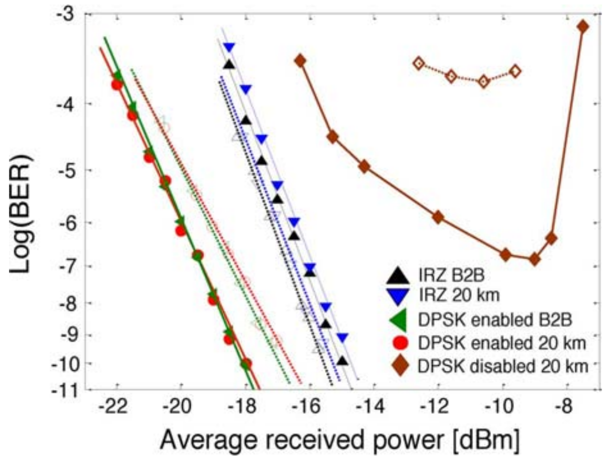

Fig. 3. BER measurements of downstream IRZ point-to-point signals and multicast DPSK signals with multicast enabled (0-ps time misalignment) and disabled (50-ps time misalignment) cases. The solid and dashed lines correspond to the cases that the ERs of the IRZ signal are ~ 4.5 dB and ~ 6 dB, respectively.

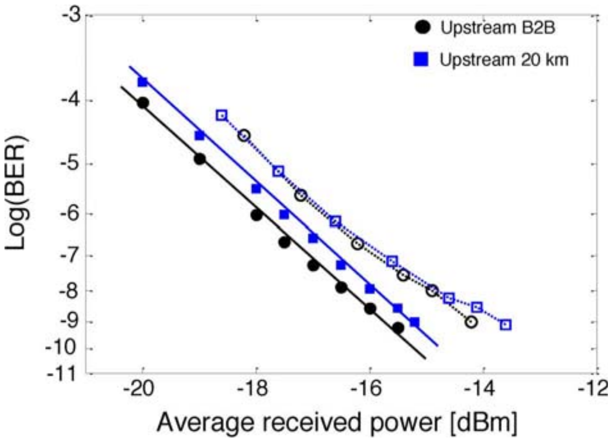

Fig. 4. BER measurements of upstream signals. The solid and dashed lines correspond to the cases that the ERs of the IRZ signal are ~ 4.5 dB and ~ 6 dB, respectively.

For both ER values, negligible power penalty is observed after 20-km transmission for the downstream point-to-point and multicast enabled signals. For the upstream signal, less than 0.5-dB power penalty at the BER of 10^{-9}, mainly due to the degraded waveform, is shown. When multicast is disabled, the multicast DPSK signal exhibits an error floor. The error floor is enhanced from 10^{-7} to higher than 10^{-4} when the ER of the downstream IRZ signal is increased from 4.5 dB to 6 dB. Thus

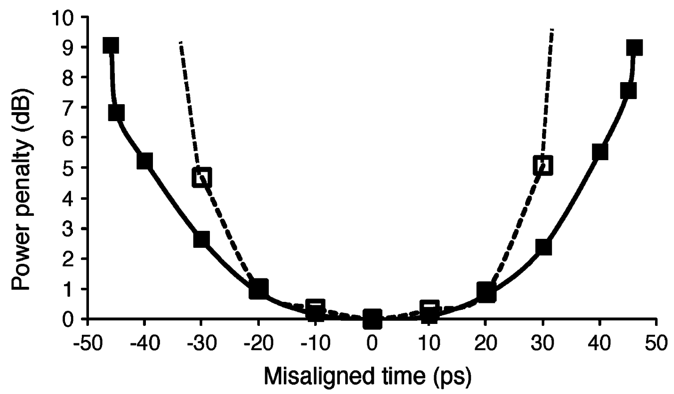

Fig. 5. Power penalty versus misaligned time between the downstream IRZ signals and the multicast DPSK signals. The solid and dashed lines correspond to the cases that the ERs of the IRZ signal are ~4.5 dB and ~6 dB, respectively.

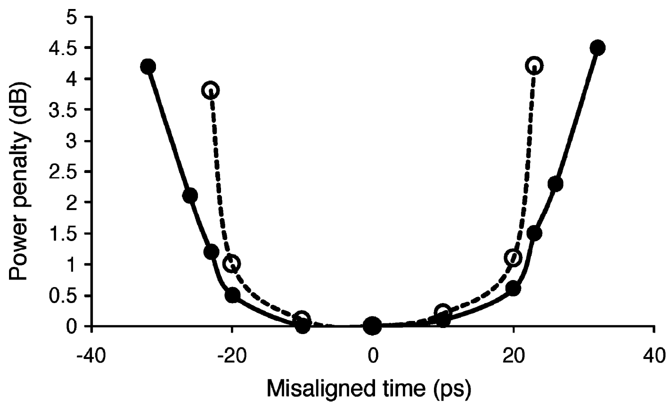

Fig. 6. Power penalty versus misaligned time between the downstream IRZ signals and the upstream signals. The solid and dashed lines correspond to the cases that the ERs of the IRZ signal are ~4.5 dB and ~6 dB, respectively.

the multicast disabled signal can be suppressed more effectively. However, the trade-off is that the upstream signal has an error floor below 10^{-9} when the ER of the IRZ signal is 6 dB. For the upstream BER, if more stringent BER (better than the conventional 10^{-9}) is required, the ER of the IRZ signal should be limited to a lower value.

To quantitatively analyze the effectiveness of the proposed multicast control scheme to suppress the multicast disabled signal, we also measured the power penalty of the multicast DPSK signals at the BER of 10^{-9}, for different timing misalignments as depicted in Fig. 5. In the multicast enabled case, Fig. 5 shows that the multicast data can tolerate up to ±20-ps time misalignment for less than 1-dB power penalty, for both ER values. When the time misalignment is larger than ±20-ps, the corresponding power penalty of the multicast DPSK signals increases sharply, especially for the case with a larger ER, thus the multicast DPSK signals can be effectively disabled via increasing the timing misalignment.

It should be noted that the uplink performance was measured under the best remodulation synchronization such that each bit of the upstream data could be superimposed right in the middle of two adjacent IRZ pulses as denoted by ‘A’ in Fig. 2(a). The remodulation synchronization was realized via carefully adjusting a digital phase shifter (Delay-2) at ONU as shown in Fig. 1. For practical implementation, the recovered clock from the downstream point-to-point data could be used for remodulation synchronization. To investigate the tolerance to re-modulation misalignment we had deliberately adjusted the re-modulation synchronization through the Delay-2. We measured the power penalty of the upstream signals at the BER of 10^{-9}, for different timing misalignments as shown in Fig. 6. For less than 1-dB power penalty, the upstream data can tolerate up to ±20-ps re-modulation misalignment when the ER of the IRZ signal is ~6 dB, and can further tolerate up to ±23-ps re-modulation misalignment when the ER is ~4.5 dB.

In the demonstration, the signal power fed into the transmission link was 5 dBm after the PM. For both ER values of 4.5 and 6 dB, the receiver sensitivity at the BER of 10^{-9} for the downstream IRZ signals was higher than -15 dBm, and for the downstream multicast enabled DPSK signals was higher than -17 dBm, while that for the upstream NRZ signals was higher than -13.8 dBm. The loss caused by the transmission link and the optical demultiplexing at the remote node was around 10 dB, and the insertion loss of a 3-dB optical power splitter or a DI (when the destructive port of the DI is used) was around 3.5 dB. Thus, the received powers for the IRZ and DPSK detection were -12 dBm and -15.5 dBm, respectively, implying around 3-dB and 1.5-dB system margin for the downstream point-to-point and multicast enabled signals, respectively. Via an IM (~6-dB insertion loss), a portion of the downstream light (at -8.5 dBm) was re-modulated by upstream data. The optical power arrived at the OLT was around -24.5 dBm without amplification. An EDFA with a gain of around 20 dB was used as the upstream pre-amplifier at the OLT, thus around 3-dB system margin could be obtained for each upstream channel. Standard EDFAs can support more than 23-dBm saturation output power. They can satisfy the requirement of the two shared EDFAs at the OLT for 32 channels, to have an output power of 5-dBm/ch for the downstream signals or to have a 20-dB small signal gain for the upstream signals. In the analysis of power margin, we assume the insertion loss of one AWG is 6 dB, based on our current available device (with a channel spacing of 0.8 nm and a 3-dB bandwidth of 0.35 nm). This is a conservative estimate, as the AWG with an insertion loss of 3 dB or less is commercially available. By using the integrated SOA-EA-SOA module as the upstream modulator [13], the upstream power budget can be further improved and the upstream EDFA can possibly be eliminated.

IV. DISCUSSIONS

A. *Narrow Filtering Effect of AWGs*

As the DPSK multicast data are imposed on the IRZ point-to-point signal and the upstream NRZ signal, the channel bandwidth of the AWGs used at the OLT and the RN should be wide enough. Otherwise improper optical filtering will cause phase-to-amplitude conversion, corrupting the IRZ signal and the upstream NRZ signal. AWGs with flat-top passband are preferred to alleviate this degradation. We also investigated such narrow filtering effect via simulation. The relationship between the power penalty (at $\mathrm{BER} = 10^{-9}$) by optical filtering and the AWG channel bandwidth is shown in Fig. 7. For all the three

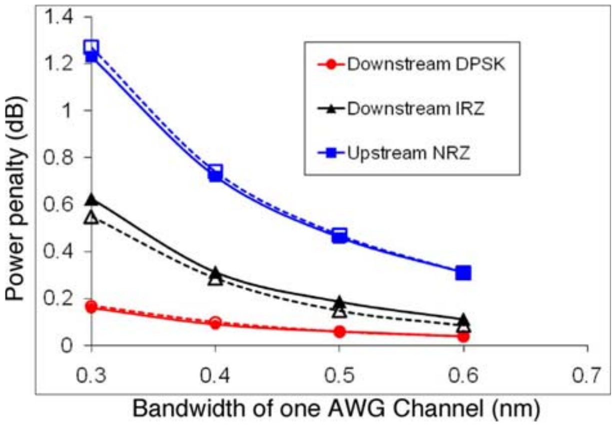

Fig. 7. Power penalty (at $\mathrm{BER} = 10^{-9}$) versus the 3-dB channel bandwidth of AWGs used at the OLT and the RN. The solid and dashed lines correspond to the cases that the ERs of the IRZ signal are $\sim$4.5 dB and $\sim$6 dB, respectively.

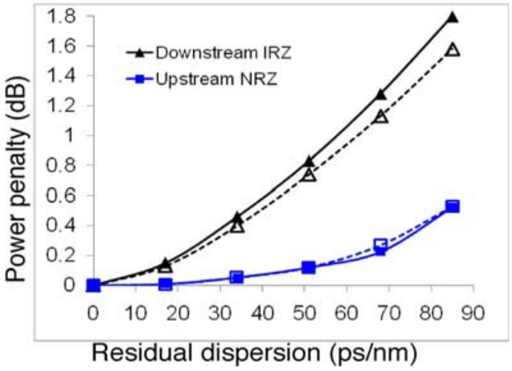

Fig. 8. Power penalty (at $\mathrm{BER} = 10^{-9}$) versus residual dispersion in the distribution fiber. The solid and dashed lines correspond to the cases that the ERs of the IRZ signal are $\sim$4.5 dB and $\sim$6 dB, respectively.

types of data, less than 0.5-dB power penalty is observed when the AWG bandwidth is larger than 0.5 nm.

B. Dispersion Compensation Tolerance

The dispersion-shifted fiber was used in the proof-of-concept experiment, whereas standard single-mode fiber (SSMF) together with a broadband dispersion compensation module (DCM) can be used as the feeder fiber for practical deployment. As the length of the distribution fiber (between the RN and the ONU) may vary in a range of several kilometers, it is necessary to investigate the dispersion compensation tolerance of the proposed scheme, which was studied through simulation. The 3-dB channel bandwidth and insertion loss of AWGs used in the simulation were set to be 0.44 nm and 3 dB, respectively, according to a commercially available AWG. As shown in Fig. 8, for both ER values of 4.5 and 6 dB, the power penalty (at $\mathrm{BER} = 10^{-9}$) induced by 51-ps/nm (corresponding to $\sim$3-km SSMF) residual dispersion in the distribution fiber is less than 0.83 dB and 0.19 dB for the downstream IRZ signal and the upstream NRZ signal, respectively. The downstream multicast DPSK signal is more robust to dispersion, and the power penalty induced by 85-ps/nm residual dispersion in the distribution fiber is less than 0.06 dB (not shown in Fig. 8) for both ER values.

C. Feasibility for Multicast Overlay of Lower Bit Rate

We have demonstrated the effectiveness of the proposed multicast control scheme in the case when both multicast and downstream point-to-point data are 10 Gb/s. We should point out that when the bit rate of the multicast data is lower than that of the downstream point-to-point data, the proposed multicast control scheme may not function properly. We first investigated the feasibility of the proposed multicast control scheme by simulation for 5-Gb/s multicast data, which are superimposed on the 10-Gb/s downstream point-to-point data. In the simulation, the ER of the 10-Gb/s downstream point-to-point data was set at a higher value of 10 dB, which shall provide a stronger suppression for the multicast disabled signals. The optical eye diagrams of the 5-Gb/s multicast data for timing misalignment of 50 ps and 0 ps are shown in Figs. 9(a) and (b), respectively. The 50-ps timing misalignment corresponds to the multicast disabled case. In this case, the 5-Gb/s DPSK bits coincide with the 10-Gb/s IRZ data dips, leading to large intensity fluctuation in the optical eye diagram of the detected 5-Gb/s multicast data. Nevertheless, such intensity fluctuation is significantly suppressed in the detected electrical eye diagram of the 5-Gb/s multicast data, as shown in Fig. 9(c), due to the low-pass filtering effect of the electronic filter used in the receiver. In the simulation, a 4-GHz electronic filter was used in the receiver. Compared to the electrical eye diagram with 0-ps timing misalignment in Fig. 9(d), which corresponds to the multicast enabled case, no obvious degradation is observed for the multicast disabled mode. The electrical eye diagram of the multicast disabled case is even a little more open than that of the multicast enabled case. It is different from the previous case when both the multicast and the downstream point-to-point data are with the same data rate of 10 Gb/s, for which obvious degradation is observed for the multicast disabled data. The proposed scheme is not applicable to this case with 10-Gb/s downstream point-to-point data and 5-Gb/s multicast data, as the multicast data cannot be effectively disabled even when the IRZ signal has a higher ER value of 10 dB.

We then further investigated the feasibility of the proposed multicast control scheme for 2.5-Gb/s multicast overlay. Prior to the 10-Gb/s systems, 2.5-Gb/s systems are widely used. In the simulation, the ER of the 10-Gb/s downstream point-to-point data was also 10 dB and a 2-GHz electronic filter was used in the receiver. The BER measurement results for the 2.5-Gb/s multicast data with timing misalignment of 50 ps and 0 ps were shown in Fig. 10. At the BER of 10^{-9}, compared with the multicast data with 0-ps timing misalignment, a negative power penalty of around 0.4-dB was observed for the multicast data with 50-ps timing misalignment. It is consistent with the previous case of 5-Gb/s multicast overlay in that the multicast disabled mode has slightly better performance than the multicast enabled mode and the multicast data cannot be disabled through timing misalignment adjustment.

As discussed above, the proposed multicast control scheme may not function properly when the bit rate of the multicast data is lower than that of the downstream point-to-point data. In a real system deployment, it will be a limiting factor for the proposed scheme if the multicast bit rate is lower than the point-to-point bit rate at the initial stage of the deployment.

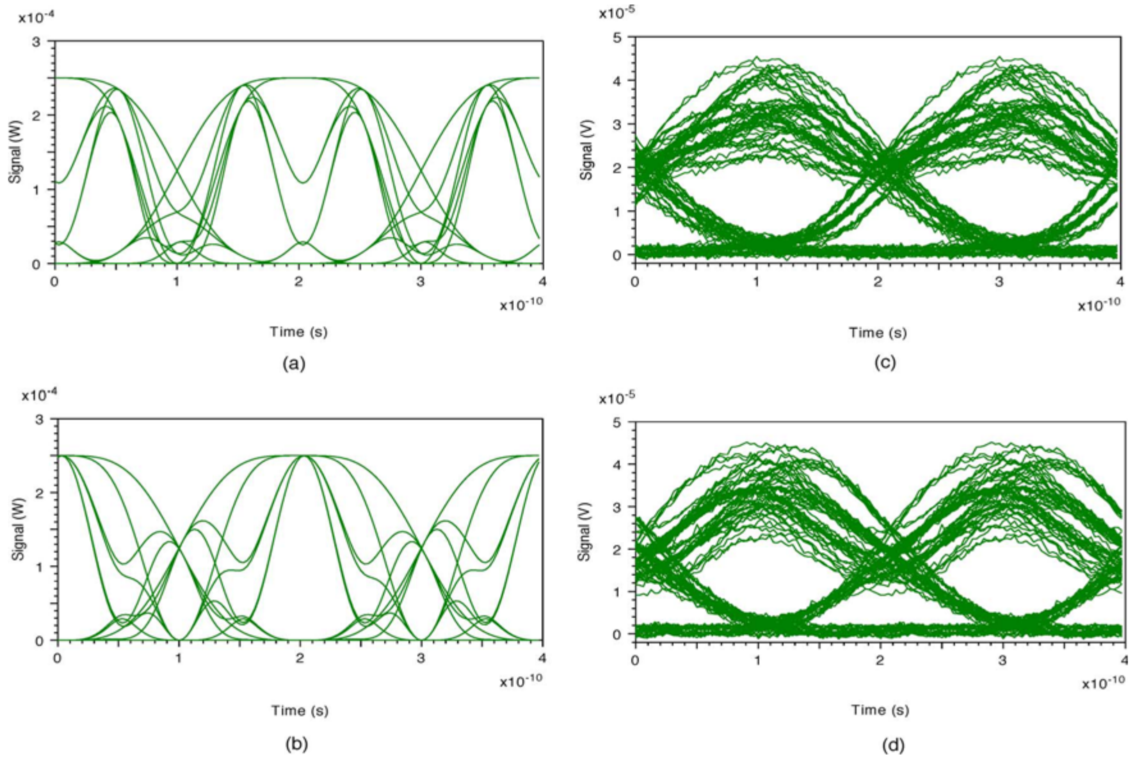

Fig. 9. (a) Optical eye diagram of the detected 5-Gb/s multicast data with timing misalignment of 50 ps. (b) Optical eye diagram of the detected 5-Gb/s multicast data with timing misalignment of 0 ps. (c) Detected electrical eye diagram of the 5-Gb/s multicast data with 50-ps timing misalignment using a 4-GHz receiver. (d) Detected electrical eye diagram of the 5-Gb/s multicast data with 0-ps timing misalignment using a 4-GHz receiver.

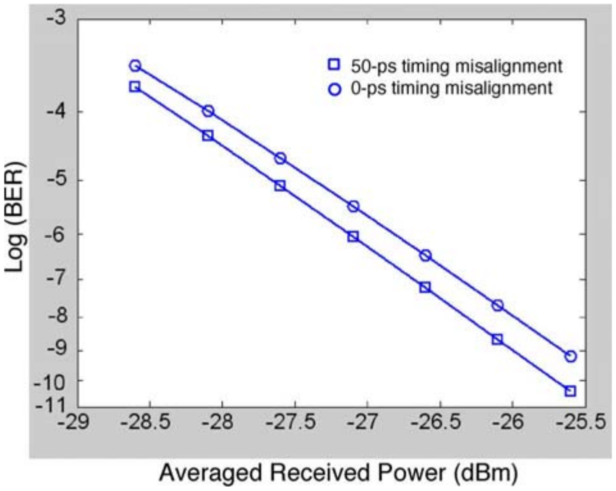

Fig. 10. BER measurements of the 2.5-Gb/s multicast data for timing misalignment of 50 ps and 0 ps. The ER of the 10-Gb/s downstream point-to-point data is 10 dB.

V. CONCLUSION

We propose a novel WDM-PON architecture to provide symmetric bit rates and multicast overlay based on DPSK/IRZ orthogonal modulation and synchronization control. Simple and flexible multicast control could be realized at the OLT. Experimental demonstration of downstream point-to-point signals, downstream multicast signals, and upstream signals, all at 10 Gb/s, are achieved with power penalties less than 0.5 dB for all signals after 20-km dispersion-shifted fiber. The error floor of the multicast disabled data is enhanced from 10^{-7} to higher than 10^{-4} when the ER of the downstream IRZ signal is increased from 4.5 dB to 6 dB. The effect of timing misalignment on downstream orthogonal modulation and upstream re-modulation is quantitatively analyzed. For less than 1-dB power penalty, both the multicast enabled data and the upstream data can tolerate 20-ps or above timing misalignment. We also investigate the feasibility of the proposed multicast control scheme for 2.5-Gb/s and 5-Gb/s multicast overlay. For 10-Gb/s downstream point-to-point data, the 2.5-Gb/s or 5-Gb/s DPSK overlay cannot work in multicast mode, whereas it can still operate in broadcast mode.

ACKNOWLEDGMENT

The authors would like to thank Dr. N. Deng and K.-H. Tse for valuable discussions.

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