Time-Interleaved Phase Remodulation to Enable Broadcast Transmission in Bidirectional WDM-PONs without Additional Light Sources

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Abstract: Time-interleaved phase remodulation is proposed to realize broadcast transmission for WDM-PONs. Simultaneous transmission of 5-Gb/s bidirectional unicast data and broadcast data is demonstrated at the same carrier wavelength over a 20-km SMF.
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1. Introduction

Broadcast is an efficient way to provide information accessibility to a large number of users. For time-division-multiplexed passive optical network (TDM-PON), broadcast can be easily realized as power-splitting is employed at the remote node (RN). In the wavelength plan for ITU-T TDM-PON standard, the downstream band between 1550 and 1560 nm is assigned to broadcast-video. TDM-PONs such as Ethemet PON (EPON) and Gigabit PON (GPON) are being widely deployed in current fiber-based access networks, offering broadband triple-play services including video, data and voice. Wavelength-division-multiplexed passive optical network (WDM-PON) can be the enabler of the next-generation optical broadband access that requires large dedicated bandwidth and upgrade flexibility. However, the dedicated connection between the optical line terminal (OLT) and the optical network unit (ONU) also imposes a technical challenge to the broadcast services provisioning in WDM-PONs. To realize more flexible network functions, intensive studies have been carried out to deliver simultaneously unicast and broadcast data to subscribers [1]-[7]. The broadcast capability in WDM-PONs can be realized via an additional wavelength together with a specially designed arrayed waveguide grating (AWG) [1], at the expense of increased system complexity and cost. Subcarrier multiplexing could be employed to superimpose the multicast data on the unicast data [2]-[4]. However, broadband modulators and oscillators, with bandwidth several times larger than the signal bit rate, are needed at the OLT and/or ONUs. These schemes are demonstrated at bit rate lower than 1.5 Gb/s. Cascaded Inverse-RZ-duobinary modulation can also be used to multiplex the unicast and broadcast traffics [5]. However, in addition to the downstream laser sources, extra laser diodes have to be installed at the OLT to remotely provide optical carrier to each ONU for the upstream data, resulting in higher system cost. One scheme that uses the cyclic wavelength routing property of an AWG has been proposed, however, dual feeder fibers are needed [6]. Several orthogonal-modulation based schemes are also demonstrated over dual feeder fibers [7].

In this paper, we propose a novel time-interleaved phase remodulation scheme to multiplex the broadcast traffic with the conventional bidirectional unicast traffics in a WDM-PON. The broadcast data encoded in DPSK format is superimposed onto all downstream unicast data channels that are also encoded in DPSK format. At ONU, the unicast and broadcast data can be simultaneously obtained from a DI's destructive port. By properly reducing the modulation depth of the broadcast and unicast DPSK signals at OLT, optical carrier can be recovered from the constructive port of the DI at ONU and used as the source for upstream transmission, without compromising the downstream extinction ratio (ER) [8]. Additional light sources as in [1, 5] are not needed in the proposed scheme.

2. Proposed system architecture and operation principles

Fig. 1 shows the proposed WDM-PON architecture with symmetric unicast bit rates and broadcast overlay. For each downstream wavelength at the OLT, differentially precoded data is used to drive an optical phase modulator (PM) to generate the downstream unicast DPSK signal. All downstream wavelengths at the OLT are multiplexed by an AWG before feeding into a shared optical phase modulator (PM), which is driven by the pre-coded broadcast data. The broadcast and unicast DPSK signals with the same bit rate are temporally offset by *T/2*, with *T* being the bit period. At an ONU, the downstream broadcast and unicast DPSK signals are demodulated simultaneously by the destructive port of a DI with half-bit delay, before direct detection by a single photo-detector with two decision modules. Light from the DI's constructive port is fed into an optical intensity modulator (IM) for upstream data re-modulation. The modulation depths of both the broadcast and unicast DPSK signals are properly reduced to assure acceptable optical carrier recovery from the constructive port of DI [8]. Compared with the ONU structure in [7],

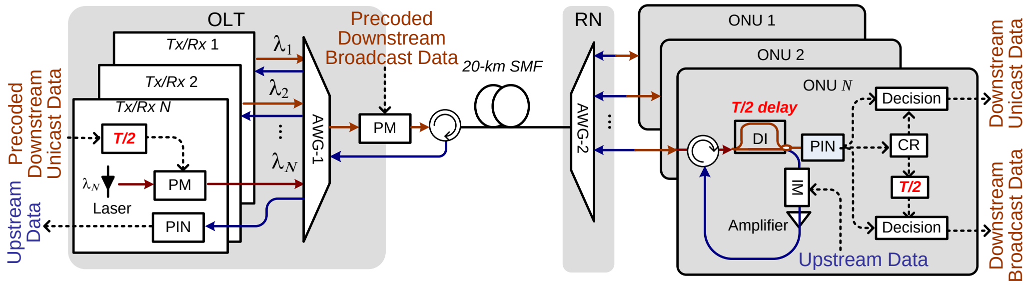

Fig. 1: Proposed WDM-PON architecture with symmetric bit rates and broadcast overlay. CR: clock recovery.

one receiver module and two power splitters for the separation of the downstream signals and the upstream source can be saved in the proposed scheme, leading to cost-effective and simplified implementation of ONU. Athermal DIs, with C+L band coverage by a single device, are commercially available and can be used at ONU [9].

As a half-bit-delay DI, rather than a conventional one-bit-delay DI, is used at ONU, the demodulated DPSK signal is determined by the phase difference between the leading half of a bit in the downstream unicast (or broadcast) DPSK signal and the trailing half of its previous bit. As for the leading half and the trailing half within one bit in the DPSK signal, at DI's destructive port, destructive interference always occurs. Thus RZ-shaped eye diagram can be obtained when the destructive port a half-bit-delay DI is used to demodulated the downstream unicast or broadcast DPSK signal, as shown in Fig. 2(a)(i) and Fig. 2(a)(ii). The uncast and broadcast signals have slightly different waveforms as the two phase modulators have different modulation bandwidths.

By temporally offsetting the broadcast and unicast data by *T/2*, the phase difference between the leading half of a bit in the downstream unicast DPSK signal and the trailing half of its previous bit will not be altered as they will experience the same phase change induced by the phase modulation of the broadcast data. Thus correct demodulation of the unicast DPSK signal via the destructive port of a half-bit-delay DI can be obtained as long as the broadcast and unicast data are temporally offset by *T/2*, as shown in Fig. 2(b). Likewise, correct demodulation of the broadcast DPSK signal can be obtained simultaneously. At the DI's destructive port, the demodulated broadcast and unicast DPSK signals are interleaved, as shown in Fig. 2(a)(iii) and Fig. 2(b). To facilitate the carrier recovery from the DI's constructive port for upstream remodulation, both the broadcast and unicast DPSK signals are with reduced modulation depth (RMD). The output from the constructive port is Inverse-RZ shaped with optical power in each bit as shown in Fig. 2(a)(iv), and can be readily re-modulated by the upstream data [8]. For RMD modulation, the "π" phase in Fig. 2(b) is changed to a smaller value, leading to a "1" bit with smaller level after demodulation. The operation principle of the time-interleaved phase remodulation scheme is still valid.

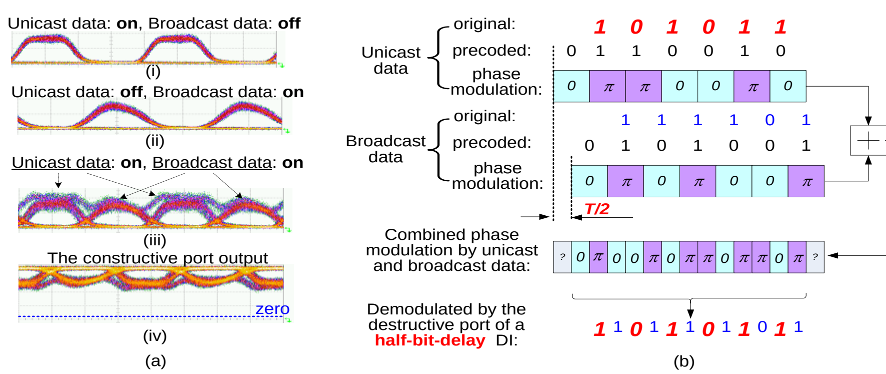

Fig. 2: (a) Eye diagrams of (i) the detected downstream unicast data when the broadcast signal is off, (ii) the detected broadcast data when the unicast signal is off, (iii) the detected downstream unicast and broadcast data, (iv) the constructive port output with optical power in each bit. Time scale: 50 ps/div. (b) Operation principles of time-interleaved phase remodulation.

3. Experimental demonstration

We have experimentally demonstrated the proposed scheme based on the architecture shown in Fig. 1. At the OLT, continuous-wave (CW) light at 1552.7 nm was coupled into a PM driven by a 5-Gb/s 2^{31}-1 pseudorandom binary sequence (PRBS) with a driving voltage of ~0.4 Vπ. The obtained RMD-DPSK signals were fed into another PM also driven by a 5-Gb/s PRBS as the pre-coded multicast data. Then through a circulator, the phase remodulated signal with an average power of 5 dBm was coupled into a 20-km SMF. After propagating through a 100-GHz AWG (insertion loss= 4 dB, 3-dB bandwidth= 0.6 nm) at the RN and a circulator, -3.6-dBm optical power was fed

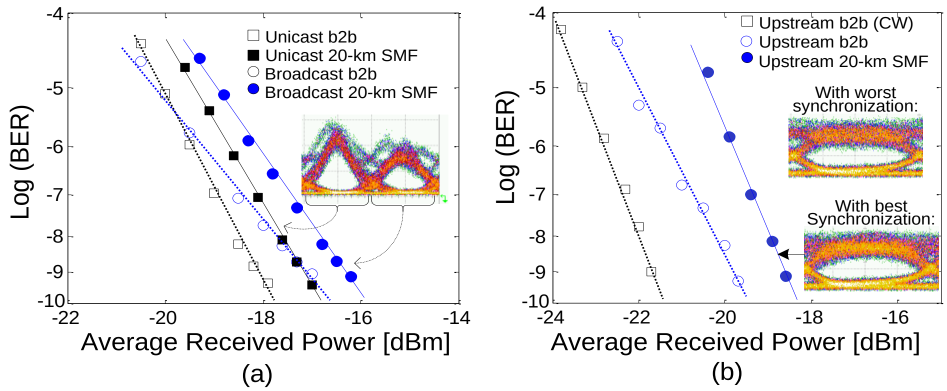

Fig. 3: BER results of (a) the downstream unicast and broadcast signals. (b) the upstream signal. Inset: the corresponding eye diagrams for different cases. Time scale: 50ps/div.

into a 94-ps DI at ONU. The destructive port of the DI was used to simultaneously demodulate the downstream unicast and broadcast RMD-DPSK signals. The output power from the DI's destructive port was -13.9 dBm. The demodulated unicast and broadcast RMD-DPSK signals could attain a high ER [8]. After demodulation, the interleaved RZ-shaped unicast and broadcast signals were detected by a 10-Gb/s p-i-n receiver followed by a 12.5-GHz bit-error-rate (BER) tester. The clock delay of the BER tester was manually adjusted correspondingly when measuring the BERs of the unicast and broadcast RMD-DPSK signals, to emulate the two decision modules of the receiver shown in Fig. 1. Optical power of -6.3-dBm from the constructive port was fed into an intensity modulator (IM), driven by a 5-Gb/s 2^{31}-1 PRBS as the upstream data. The upstream signal with a power of -15 dBm from the IM was amplified to 5 dBm, and then transmitted back to the OLT. The amplification increased the power ratio of the upstream signal to the Rayleigh backscattered signal. The BER measurement results for downstream and upstream signals are shown in Fig. 3(a) and Fig. 3(b), respectively. After 20-km transmission in SMF, around 1-dB power penalty is observed for the unicast and broadcast signals, due to dispersion. The insets in Fig. 3(a) show the wide-open eye diagrams of the downstream unicast and broadcast signals. In the back-to-back case, compared with that using CW light as the upstream source, around 2-dB power penalty (at BER=10^{-9}) is observed for the upstream signal modulated on the DI's constructive port output, as shown in Fig. 3(b). After 20-km transmission in SMF, around 1.5 dB power penalty is observed for the upstream signal due to dispersion and Rayleigh backscattering. To investigate the tolerance to remodulation timing misalignment we have deliberately adjusted the remodulation synchronization through an electronic delay within one bit period. Only less than 0.9-dB power penalty was observed. The eye diagram corresponding to the worst remodulation synchronization is shown in the inset of Fig. 3(a), with only slight distortion compared with the eye with optimal re-modulation synchronization.

4. Conclusions

We propose a novel time-interleaved phase remodulation scheme to multiplex the broadcast traffic with the conventional bidirectional unicast traffics in a WDM-PON without any additional light sources. Error-free transmission of 5-Gb/s bidirectional unicast data and 5-Gb/s broadcast data is experimentally demonstrated at the same carrier wavelength over a 20-km SMF. The project is supported in part by RGC GRF CUHK411007.

5. References

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