A WDM Passive Optical Network With Centralized Light Sources and Multicast Overlay

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***Abstract*—We propose a novel wavelength-division-multiplexed passive optical network (WDM-PON) architecture to provide a downstream multicast overlay on the conventional point-to-point data service. The differential-phase-shift-keying multicast data is modulated on the same optical downstream carrier with the inverse return-to-zero point-to-point data signal, thus additional light sources are saved. Broadcast or multicast control is realized at the optical line terminal. For each WDM channel, part of the downstream power is re-used as the upstream data carrier, and thus realizes a colorless optical network unit. We successfully demonstrate the proposed WDM-PON with 10-Gb/s downstream point-to-point signals, 10-Gb/s downstream multicast signals, and 2.5-Gb/s upstream signals.**

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

I. Introduction

THE wavelength-division-multiplexed passive optical network (WDM-PON) is a promising technology to deliver high-capacity data to business and residential subscribers. To realize more flexible network functions, some efforts have been paid to provide both point-to-point data service and broadcast video/data service [1]–[4]. These two kinds of services could be transmitted via time-division multiplexing; however, complicated timing control was required and the downstream bandwidth had to be shared. Another common approach was to use one or more additional light sources [1], [2], which led to significant increase in cost and complexity. Some recent work proposed broadcast overlay on the same optical downstream by means of subcarrier multiplexing [3], [4]. However, such a technique required high-frequency electronic components at both the transmitter and receiver sides.

In conventional WDM-PON, a light source is deployed at each optical network unit (ONU) for each upstream wavelength channel. However, employing centralized light sources at the optical line terminal (OLT) is an attractive approach for low-cost implementation [5], [6]. Since no wavelength registered light source is incorporated at the ONU, wavelength management at the ONU is unnecessary and thus greatly eases the network maintenance. At the ONU, the upstream data transmitter is realized by remodulating part of the received downstream signal power.

Recently, we proposed a novel WDM-PON architecture to superimpose a downstream broadcast overlay on the conventional downstream point-to-point data service [6]. In this letter, we further improve the broadcast control to realize more powerful multicast service. The proposed network offers both downstream services and upstream carrier provision with centralized light sources. With simple control in the OLT transmitters, the broadcast data can be selectively multicast to specific subscribers. We experimentally demonstrate the proposed WDM-PON with multicast overlay at 10 Gb/s and investigate its feasibility and system performance.

II. Proposed WDM-PON Architecture

Fig. 1 depicts the proposed WDM-PON architecture with centralized light sources and multicast overlay. At the OLT, the downstream point-to-point data of every wavelength channel is generated from an inverse return-to-zero (IRZ) transmitter. A commercial logic NAND gate is used to produce an IRZ-shaped data signal, which is then used to drive an optical intensity modulator (IM) to generate an IRZ signal. The downstream signals from all transceiver at the OLT are wavelength-multiplexed, via an arrayed waveguide grating or equivalent. The multiplexed signals are then amplified and fed into an optical phase modulator (PM), driven by the precoded digital broadcast or multicast data. Since an IRZ signal consists of a period of high-power levels at both “1” and “0” bits, the differential phase-shift keying (DPSK) broadcast or multicast data can be successfully superimposed onto all the optical IRZ signals, without any loss of bit information. In this way, every downstream wavelength carries both the IRZ downstream point-to-point data and the DPSK multicast data.

While all the downstream point-to-point transmitters generate the IRZ signals, the superimposed DPSK signal is broadcast to all the ONUs. To realize multicast, a simple electronic control circuit can be added in each IRZ transmitter at the OLT. To disable the DPSK data distribution for a specific subscriber, the control circuit of the respective transceiver at the OLT triggers the point-to-point data signal to bypass the electronic logic NAND gate and directly drive the IM. Therefore, an optical non-return-to-zero (NRZ) signal, instead of IRZ signal, is generated to carry the downstream point-to-point data. In this way, the DPSK broadcast data can be still modulated on the NRZ point-to-point signal, but it cannot be recovered at the ONU, unless the NRZ signal has an extinction ratio lower than 4.7 dB [7]. The large intensity variation of the NRZ signal hinders correct demodulation of the superimposed DPSK signal, via a delay interferometer (DI), at the ONU. Therefore, by properly setting

Manuscript received August 10, 2007; revised October 27, 2007. This work was supported in part by a research grant from the Research Grants Council of Hong Kong.

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Digital Object Identifier 10.1109/LPT.2007.912549

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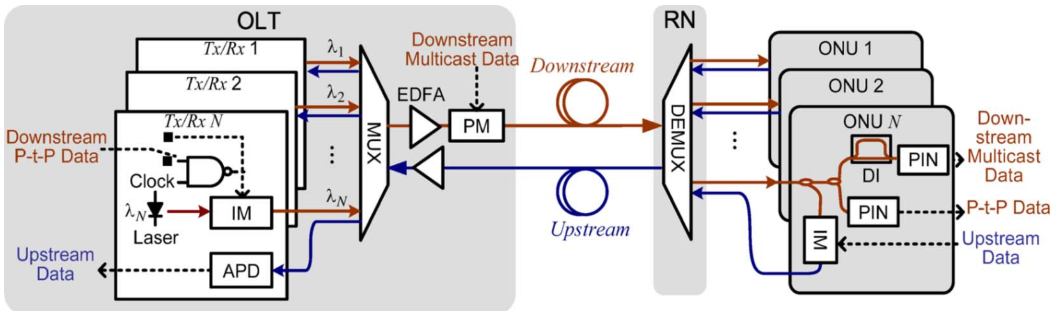

Fig. 1. Proposed WDM-PON architecture with centralized light sources and multicast overlay. EDFA: erbium-doped fiber amplifier; P-t-P Data: point-to-point data.

the control circuits at individual tranceivers at the OLT, only the selected ONUs can demodulate the DPSK multicast data, thus downstream multicasting is realized. It is noteworthy that the multicast operation is centrally controlled at the OLT, and is transparent to all ONUs. At an ONU, a portion of the received downstream signal power is tapped off for reception. The remaining downstream power is fed into an optical IM for upstream data remodulation. As the downstream signal has a finite extinction ratio, the optical power in each bit can provide the light source for the upstream data in every bit slot. As the upstream bit rate (say 2.5 Gb/s) is usually lower than the downstream bit rate (say 10 Gb/s), no bit synchronization is required at the ONU.

III. Experimental Demonstration

We have experimentally demonstrated downstream multicast and upstream remodulation of the proposed WDM-PON. Continuous-wave lights at 1546.9 and 1547.7 nm were IRZ (or NRZ) modulated by a 10-Gb/s $2^{31} - 1$ pseudorandom binary sequence (PRBS) and its complementary data, respectively, with an extinction ratio of around 8 dB. After wavelength multiplexing and power amplification, the WDM point-to-point signals were fed into a PM, driven by the decorrelated 10-Gb/s PRBS as the precoded broadcast data. In this experiment, the point-to-point and the broadcast signals at the same bit rate were bit synchronized to assure the best signal performance, which could be simply realized by applying a common clock signal at the OLT. The requirement on synchronization may be relaxed if the two signals have different bit rates. Then the composite signal was coupled into a 20-km dispersion-shifted fiber to emulate the downstream transmission link with dispersion compensation. In practice, one common broadband dispersion-compensating module could be placed at the OLT to compensate all the downstream channels. At the ONU, a portion of the received downstream signal power was tapped off by a 3-dB optical power splitter, in which a half was fed into a photodiode for IRZ detection and the rest was demodulated by a DI with a relative delay of 94.3 ps for DPSK detection. Temperature control was used for stable operation of the DI and it could be saved by using athermal DI. The other portion of the received downstream signal was fed into an optical IM, driven by a 2.5-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 reflective semiconductor optical amplifier could be alternatively used to achieve polarization-insensitive operation [8]. A pair of feeder fibers

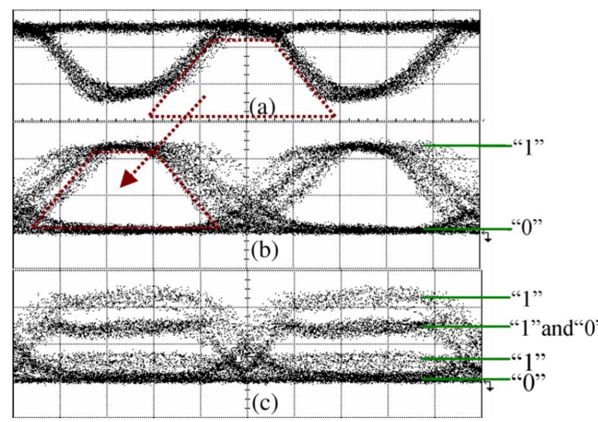

Fig. 2. Eye diagrams of (a) the 10-Gb/s downstream point-to-point data signal while in IRZ format (the high level of each bit in the trapezoid provided power for DPSK modulation), (b) the 10-Gb/s demodulated DPSK multicast signal when multicast was enabled, and (c) the demodulated DPSK signal when multicast was disabled. Time scale: 20 ps/div.

was used to separate the downstream and the upstream signals [5] so as to avoid the possible Rayleigh-backscattering-induced performance degradation.

When the multicast was enabled, that is, when the downstream point-to-point signal was in IRZ format, the superimposed DPSK multicast data could be detected at the ONU. As every bit of an IRZ signal provided a period of high level as shown in Fig. 2(a), the demodulated DPSK signal showed a clear eye diagram as Fig. 2(b), though the horizontal width of the eye was narrowed and appeared to have multiple levels. On the contrary, when the multicast was disabled, the demodulated DPSK signal on the point-to-point NRZ signal had a multiple-level eye as Fig. 2(c), agreeing with the theory [7]. Since the point-to-point signal had a relatively high extinction ratio of 8 dB, some "0" bits of the demodulated DPSK signal had a higher level than some "1" bits, causing significant detection errors. We have measured the bit-error rate (BER) of the demodulated DPSK signal when the multicast was enabled, as shown in Fig. 3. As the two WDM channels had very similar performance, only the BER for the 1546.9-nm channel was shown. The performance of both the downstream DPSK and IRZ signals depended on the duty cycle of the IRZ signal, which was around 50% in the experiment. The receiver sensitivity for the multicast data was less than -19 dBm (measured after DPSK demodulation) when multicast was triggered, while the BER could not be measured when multicast was disabled.

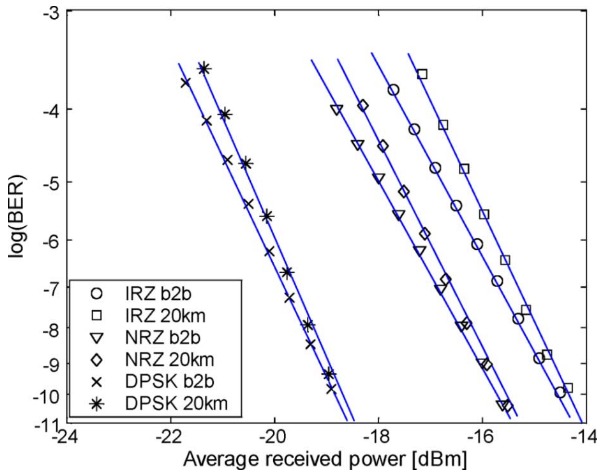

Fig. 3. BER measurements of the downstream point-to-point IRZ (○, □) or NRZ (◇, ▽) signals, and BER of the downstream multicast DPSK signal (×, ∗) superimposed on the IRZ point-to-point signal, respectively.

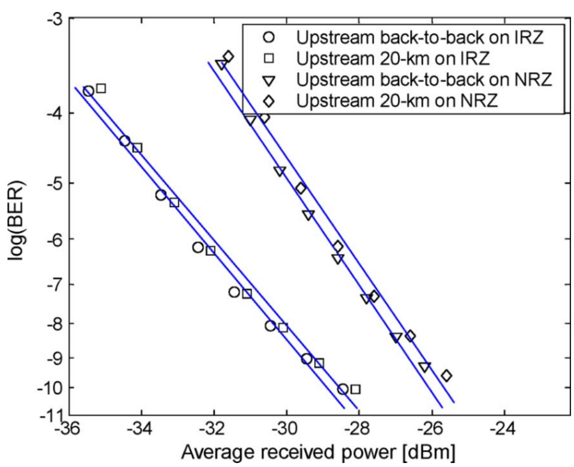

Fig. 4. BER measurements of the upstream remodulated signals.

Fig. 3 also shows BER of the downstream point-to-point IRZ or NRZ signal. Negligible penalty was observed for both signals after transmission. For the upstream 2.5-Gb/s remodulated signal, an avalanche photodiode was employed at the OLT for detection, followed by an electrical low-pass filter with a 3-dB bandwidth of 1.87 GHz. It could effectively alleviate the degradation caused by the crosstalk from the downstream 10-Gb/s IRZ or NRZ signal. As seen from Fig. 4, the remodulated upstream signal had better performance when the downstream point-to-point signal was in IRZ format. This was attributed to the fact that the intensity variation of “0” and “1” bits of an IRZ signal was smaller than that of an NRZ signal. Such difference of the receiver sensitivities does not influence the normal operation of the system, as sufficient system margin has been designed for both cases.

In the demonstration, the signal power of each channel fed into the downstream transmission link was around 3 dBm. The downstream loss caused by transmission and demultiplexing was around 10 dB, thus the downstream power arrived at the ONU was −7 dBm. For 50/50 power splitting, the respective received power for DPSK demodulation and for IRZ or NRZ detection was −13 dBm, implying around 2-dB system margin for the downstream point-to-point signal and at least 3-dB system margin for the broadcast signal. Another portion of −10-dBm downstream light was remodulated by the upstream data, via an IM (∼6-dB loss). The optical power received at the receiver in the OLT for a channel would be around −30 dBm without amplification. However, by using an optical amplifier before the wavelength multiplexer at the OLT, at least 6-dB system margin could be provided for each upstream signal. The detailed power budget is shown in Table I.

TABLE I
POWER BUDGET FOR THE WDM-PON WITH MULTICAST OVERLAY

	Modulation format	Received power	Receiver sensitivity	System margin
Downstream point-to-point	IRZ	−13 dBm	−15 dBm	2 dB
	NRZ	−13 dBm	−16 dBm	
Downstream multicast	DPSK	−16 dBm	−19 dBm	3 dB
Upstream Signal	Remodulated on IRZ	−20 dBm	−29 dBm	6 dB
	Remodulated on NRZ	−20 dBm	−26 dBm	

IV. SUMMARY

We have proposed and demonstrated a novel WDM-PON architecture to provide both downstream point-to-point data service and digital multicast service on the same light carrier. The multicast overlay adds only a little complexity to the existing WDM-PON structure, but offers better network flexibility and capacity by providing another downstream service. The multicast control is simple and centralized at the OLT. Experimental demonstration with 10-Gb/s downstream signals and 2.5-Gb/s upstream remodulated signals confirmed the feasibility of the proposed scheme.

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