A WDM Passive Optical Network With Polarization-Assisted Multicast Overlay Control

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***Abstract*—We propose a novel wavelength-division-multiplexed passive optical network which supports simultaneous delivery of 10-Gb/s point-to-point downstream and upstream data as well as 10-Gb/s downstream multicast data. The multicast overlay control is achieved by a polarization-assisted scheme at the optical line terminal (OLT). A separate lightpath is provided for the downstream multicast differential phase-shift keying (DPSK) data without additional light sources. The upstream amplitude-shift keying signal at the optical network unit is superimposed onto the received multicast DPSK signal before being transmitted back to the OLT.**

***Index Terms*—Amplitude-shift keying (ASK), differential phase-shift keying (DPSK), multicast, orthogonal modulation, passive optical network (PON), wavelength-division multiplexing (WDM).**

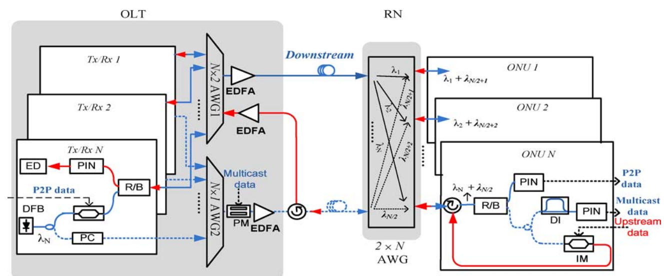

Fig. 1. Proposed WDM-PON with multicast overlay. DFB: distributed-feedback laser. APD: avalanche photodiode. EDFA: erbium-doped fiber amplifier. OC: optical circulator. ED: error detector. MUX/DEMUX: wavelength multiplexer/demultiplexer. PIN: p-i-n photodiode.

I. Introduction

THE wavelength-division-multiplexed passive optical network (WDM-PON) is a promising approach to deliver high-speed services to business and residential subscribers. In order to enable more flexible data delivery, a robust network architecture which can support simultaneous point-to-point (P2P) data as well as multicast data transmissions is highly desirable. Thus, the same data or video service can be delivered to a designated subset of subscribers, which can also be flexibly reconfigured at the optical line terminal (OLT). Recently, several interesting schemes [1]–[3] have been proposed to overlay the multicast data onto a typical WDM-PON. The multicast data in either differential phase-shift keying (DPSK) format [1], [2], or subcarrier-multiplexed form [3], were modulated onto all of the downstream P2P data wavelengths. At the OLT, for each downstream wavelength carrying amplitude-shift keying (ASK) P2P data, the superimposed multicast data can be enabled or disabled by adjusting the extinction ratio [1], [3] of the P2P data, or switching the P2P data format between inverse-return-to-zero and nonreturn-to-zero (NRZ) [2]. However, the P2P ASK data may suffer from system penalty due to its reduced extinction ratio.

In this letter, we propose a WDM-PON architecture which can simultaneously support both P2P and multicast data transmissions. Instead of superimposing the multicast data onto the P2P data on each downstream wavelength, the multicast data is modulated onto part of the unmodulated power from each transmitter at the OLT. In this way, the downstream P2P ASK data and the multicast DPSK data for each optical network unit (ONU) are carried on different wavelength carriers, thus, the system performance can be greatly improved. No additional dedicated light source for the multicast data is needed. The control of the multicast transmission is achieved by controlling the input polarization state of the unmodulated power from each transmitter to the common optical phase modulator (PM) for multicast data modulation at the OLT. We have experimentally demonstrated 10-Gb/s transmissions for the downstream P2P and multicast data, as well as the upstream data in a WDM-PON.

II. Proposed WDM-PON Architecture With Multicast Overlay

Fig. 1 depicts the proposed WDM-PON multicast overlay architecture with N ONUs. At the OLT, the continuous-wave (CW) optical power at λ_k (for $k = 1, 2, \ldots, N$) from the downstream transmitter $\#k$ is split into two parts. The first part is modulated with the respective downstream P2P ASK data, via the optical intensity modulator (IM), before being combined with the other modulated downstream P2P wavelengths, via a commercially available $N \times 2$ arrayed waveguide grating (AWG1) for delivery to the remote node (RN) over the first fiber feeder. The AWG1 is also used to route the upstream wavelengths received from the second fiber feeder to their destined upstream receivers at the OLT. Note that $\lambda_1, \ldots, \lambda_{N/2}$ are assigned in blue band; while $\lambda_{N/2+1}, \ldots, \lambda_N$ are assigned in red band. A red/blue (R/B) filter is employed at each transceiver to separate the received upstream wavelength and the transmitted downstream P2P wavelength, which are operated in counterpropagating directions. The second part of the CW optical power from each downstream transmitter is fed into a polarization control (PC) unit before being combined with

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TABLE I
EXAMPLE OF WAVELENGTH ASSIGNMENT FOR A WDM-PON WITH EIGHT ONUS

	← Blue Band →				← Red Band →			
	ONU#1	ONU#2	ONU#3	ONU#4	ONU#5	ONU#6	ONU#7	ONU#8
P2P	λ_1	λ_2	λ_3	λ_4	λ_5	λ_6	λ_7	λ_8
Multicast	λ_5	λ_6	λ_7	λ_8	λ_1	λ_2	λ_3	λ_4

that from all other downstream transmitters, via AWG2. The combined signal, which comprises the same set of downstream wavelengths, is then modulated with the multicast data in DPSK format, via the common PM, before being delivered to the RN, over the second fiber feeder. At the RN, a commercially available $2 \times N$ AWG, in which its first and the $(N/2+1)$th input ports are connected to the first and the second fiber feeders, respectively, is employed. Based on its cyclic wavelength routing property [4], it routes λ_i, which carries the downstream P2P data for ONU$\#i$, from the first fiber feeder and λ_j, where $j = \{[(i-1)+N/2]\mathrm{mod}N\}+1$, which carries the multicast data from the second fiber feeder, to ONU$\#i$, via its ith output port. In this way, the downstream P2P wavelength and the multicast wavelength received at the same ONU are always spaced by at least quadruple wavelength spacing and thus can be easily separated by an R/B filter. Part of the power of the received multicast wavelength is remodulated with ASK upstream data and thus serves as the upstream carrier. The upstream wavelengths from all ONUs are sent back to the OLT, via the second fiber feeder, as shown in Fig. 1. Table I shows an example of the wavelength assignment.

The control of the multicast transmission is achieved by a simple polarization-assisted scheme at the OLT. It is based on the property that the PM for multicast data modulation is polarization-dependent with respect to the polarization of the input optical carrier. From the wavelength assignment, $\lambda_j\{j = [(i-1)+N/2]\mathrm{mod}N+1\}$ is the multicast wavelength destined for ONU$\#i$. In order to enable the multicast data for ONU$\#i$, the PC unit at the jth transceiver at the OLT should be set to align the polarization of λ_j with the principal axis of the crystal in the PM, so as to maximize the degree of phase modulation. In contrast, the multicast data can be flexibly disabled by switching the polarization of λ_j to be orthogonal with the principal axis of the crystal in the PM, so as to minimize the degree of phase modulation. The PC unit can be realized by employing a commercially available polarization switch module or dynamic polarization controller to perform the electronic-controlled polarization conversion. A central control module is needed to coordinate all transceivers at the OLT.

III. EXPERIMENT AND RESULTS

Fig. 2 shows the experimental setup. A CW light at 1541.23 nm was intensity-modulated by a 10-Gb/s $2^{31}-1$ pseudorandom binary sequence (PRBS) P2P data, while another CW light at 1547.63 nm was phase-modulated by the 10-Gb/s multicast data. A polarization controller was placed before the PM to serve as the PC unit for multicast control. We have characterized the polarization sensitivity of the PM for DPSK modulation by varying the input polarization. Fig. 3 shows that the performance of the demodulated DPSK signal

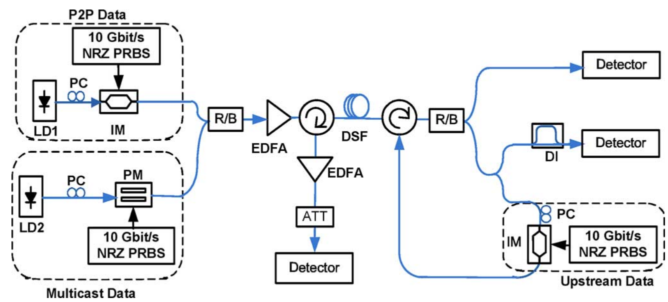

Fig. 2. Experimental setup. ATT: optical attenuator.

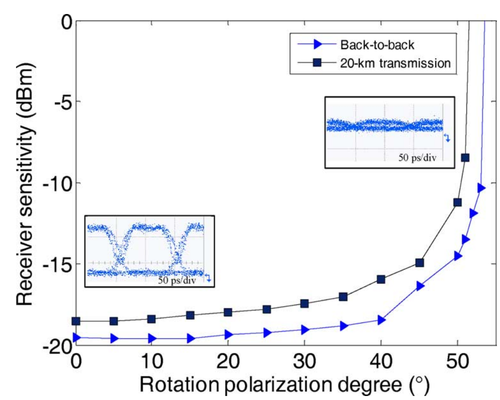

Fig. 3. Measured performance of the demodulated DPSK signal versus the input polarization to the optical PM. Insets show the respective eye diagrams at different input polarizations.

suffered from bit-error-rate (BER) floor when the deviation of the input polarization from its optimal ON-state was beyond 52° and the respective eye diagram almost closed. This can be adopted as the threshold for polarization switching. Then, the P2P and multicast data were combined by an R/B filter before being fed into an erbium-doped fiber amplifier, where they were amplified to 7 dBm. The downstream signals were delivered to the ONU, via a piece of 20-km dispersion-shifted fiber (DSF), which was used to emulate a dispersion-compensated link. At the ONU, the P2P and multicast wavelengths were separated by an R/B filter. The P2P signal was directly detected. On the other hand, the multicast signal was fed into a 50/50 fiber coupler, where half of its power was fed into an optical delay interferometer (DI) for demodulation before direct detection, while the other half was reused as the upstream carrier, which was then intensity modulated with the 10-Gb/s $2^{31}-1$ PRBS ASK upstream data. The upstream signal was then sent back to the OLT, via the 20-km DSF and an optical circulator, before it was separated from the downstream signal and detected.

We have also measured the BER performance of the 10-Gb/s transmissions of the downstream P2P data, the multicast data,

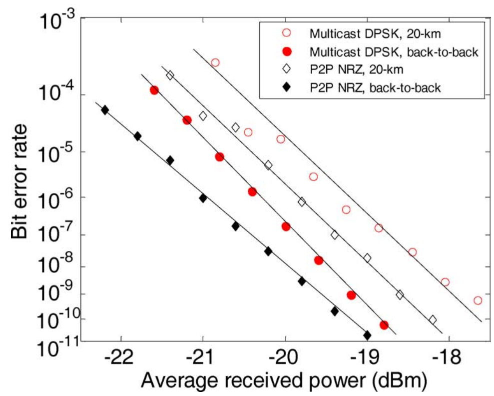

Fig. 4. BER measurements of 10-Gb/s downstream transmissions P2P NRZ data: (♦, ◊); multicast DPSK data (•, ∘).

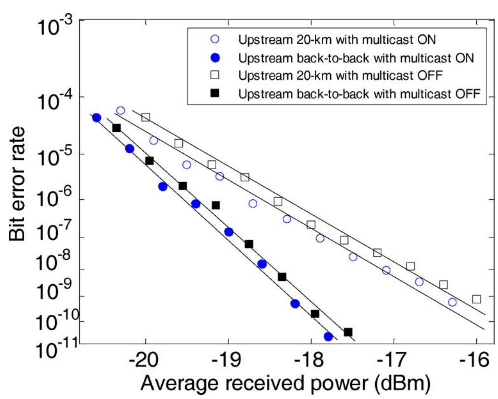

Fig. 5. BER measurements of 10-Gb/s upstream transmission Multicast-enabled (•, ∘); multicast-disabled (■, □).

as well as the upstream data. Fig. 4 shows the BER performance of the downstream P2P ASK and multicast DPSK data for both back-to-back and 20-km transmissions. The P2P ASK data and the multicast DPSK suffered from about 1- and 1.2-dB power penalty after 20-km transmission, respectively, due to possible Rayleigh backscattering, while they showed sensitivity improvement by 7 and 4 dB, respectively, compared with the measurements, as reported in [1], as they were carried on two individual copies of the same downstream optical carrier, instead of using orthogonal modulation. When the multicast transmission was disabled by PC of the multicast wavelength at the OLT, the received DPSK signal suffered from severe eye-closure and thus could not be demodulated properly.

Fig. 5 shows the BER measurements for the upstream transmission. Negligible penalty was observed between ON–OFF states of the multicast operation. Under multicast-enabled and multicast-disabled conditions, about 2.3-dB power penalty was measured after 20-km transmission, due to possible Rayleigh backscattering for bidirectional transmission on single fiber. About 0.3-dB power penalty was observed for multicast-enabled case, compared with the multicast-disabled case, mainly due to possible phase-to-intensity conversion.

In our experiment, the power fed into the transmission link was about 7 dBm. The aggregate downstream loss caused by fiber, optical circulator, and R/B filter was around 7 dB, thus the power after R/B filter was around −3 dBm. The received power for the 10-Gb/s P2P data gave more than 16-dB system margin, while that for the 10-Gb/s multicast data after DI was around −11 dBm, implying around 7-dB system margin. Another portion of the multicast power was remodulated by an IM, which induced about 6-dB loss, so the received power at OLT was around −18 dBm without amplification. A better system margin for the upstream transmission can be realized by employing an optical amplifier at the OLT.

IV. Conclusion

We have proposed and experimentally investigated a WDM-PON with simultaneous 10-Gb/s transmissions of the downstream P2P and multicast data, as well as the upstream data. The downstream P2P data and the multicast data have been shown to have improved system performance. The flexible control of the multicast overlay is achieved by employing a simple polarization-assisted scheme at the OLT.

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