# Video-Service-Overlaid Wavelength-Division-Multiplexed Passive Optical Network

Lei Cai, Zhixin Liu, Shilin Xiao, Min Zhu, Rongyu Li, and Weisheng Hu

*Abstract*—We propose and demonstrate a novel wavelength-division-multiplexed passive optical network (WDM-PON) with multicast overlay. By superimposing an inverse return-to-zero multicast signal onto a nonreturn-to-zero point-to-point signal, simultaneous transmission is realized for both services. At the optical network unit (ONU), only one photodiode is required to detect both signals. No complex receiver is demanded. Multicast control is realized through a switch for each wavelength at the optical line terminal. We successfully demonstrate the proposed WDM-PON.

*Index Terms*—Inverse return-to-zero (IRZ), multicast, passive optical network (PON), wavelength-division multiplexing (WDM).

## I. INTRODUCTION

THE wavelength-division-multiplexed passive optical network (WDM-PON) is an attractive solution for broadband access taking its advantages of large capacity, easy management, and network security [1]. The waveguide grating router (WGR) is utilized for virtual point-to-point transmission link. Because of the wavelength-dependence feature of WGR, WDM-PON is not suitable for delivery of broadcast signals. Recently, many efforts were made to solve this problem by slicing the broadcast signal [2] or by utilizing the broadband source [3].

However, in these schemes, all subscribers can receive broadcast signals regardless of their service subscription. In reality, some customers may not subscribe to the video services. Therefore, it is a requirement for WDM-PON to realize selective-broadcasting. The solution in [4] is based on subcarrier multiplexing, which requires high-frequency electronic components. The technique in [5] demands a Mach–Zehnder delay interferometer for recovery of the phase-shift keying signal at the optical network unit (ONU) side, which makes it costly. In practical applications, it is desirable to design a more cost-effective scheme to deliver multicast signals to subscribers.

Recently, we proposed a novel WDM-PON architecture where the broadcast signal is superimposed on the conventional point-to-point signals [6]. In this letter, we improve the multicast control to realize better selective-video service. In addition, we further design a new receiver, which requires only one photodiode for detection of both signals, which reduces the cost further. Compared with [4] and [5], only intensity modulation is introduced, which eliminates the complex receiver at the
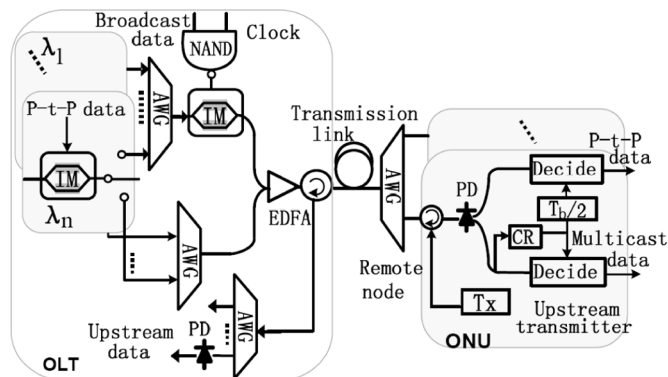
Fig. 1. System architecture. P-t-P data: point-to-point data; IM: intensity modulator; AWG: arrayed waveguide grating; NAND: logic not AND gate; PD: photodiode; CR: clock recovery.

ONU. Thus, this system is cost-effective compared to previous selective-broadcast schemes. We experimentally validate the designed WDM-PON architecture.

## II. PROPOSED WDM-PON SYSTEM

The architecture of the proposed WDM-PON is depicted in Fig. 1. At the optical line terminal (OLT) side, all the channel wavelengths are first nonreturn-to-zero (NRZ) modulated with their respective downstream point-to-point data. The low modulation depth of about 0.1 to 0.2 is employed. For broadcast-enabled channels, the point-to-point signals are multiplexed and then fed into the inverse return-to-zero (IRZ) transmitter, driven by the broadcast data. The modulation depth of IRZ is about 0.5. Thus, the broadcast signal is superimposed onto the NRZ point-to-point signals for all broadcast-enabled channels. As for broadcast-disabled channels, the point-to-point signals are multiplexed and bypass the IRZ transmitter. Thus, no broadcast signal is covered in these channels. A switch is employed in each channel so that the point-to-point signal is either directed into the IRZ transmitter or directed into another path so that the signal bypasses the IRZ transmitter. In this way, selective-broadcast is realized. Both signals in the broadcast-enabled channels and broadcast-disabled channels are fed into the optical amplifier, and then directed into the downstream link. In [6], the NRZ point-to-point signals have different modulation depths between broadcast-enabled channels and broadcast-disabled channels. Thus all the channels do not have the same quality of service of point-to-point delivery. The technique proposed in this letter successfully solves this problem. At the ONU side, the optical signal is first converted to an electric signal and then split and fed into two different paths for recovery of point-to-point and multicast data, respectively. Thus, the receiver requires only one photodetector, which saves
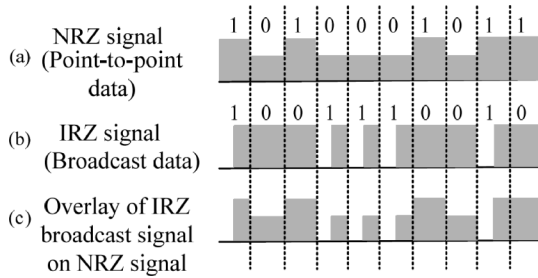
Fig. 2. Data sequence to explain how the IRZ signal is successfully superimposed on the NRZ signal and how both data can be recovered.



Fig. 3. Eye diagrams of (a) the NRZ signal, (b) the IRZ signal, and (c) the overlay of IRZ signal on NRZ signal.

the cost of ONU. The upstream transmission can take the form of any previous works [2], [4]. In this letter, the scheme in [4] is introduced for upstream transmission. The upstream transmitter consists of a laser diode (LD), which is directly modulated with upstream data. Upstream signals are WDM at the remote node and delivered to OLT via transmission fiber, where signals are wavelength-division demultiplexed and the upstream data are recovered for each channel. To avoid Rayleigh backscattering, different wavelengths are allocated for downstream and upstream transmissions.

Fig. 2 provides the data sequences for explanation of the overlay of the IRZ signal onto the NRZ signal. The duty cycle of the IRZ signal is 50%. Fig. 2(a)–(c) shows the NRZ point-to-point signal, the IRZ broadcast signal, and the superimposed signal, respectively. Since the modulation depth of the NRZ signal is low, there is certain power at both "1" and "0" bits. Thus the broadcast data can be superimposed onto the NRZ point-to-point data. In the following, we describe how both broadcast and point-to-point data can be recovered respectively. For broadcast data "1", the superimposed signal consists of almost no power at the first half-bit. As for data "0", the signal consists of certain power at the first half-bit [see Fig. 2(c)]. Thus, the broadcast data can be recovered by sampling at the first half-bit of the superimposed signal. Meanwhile, the power in the second half-bit of the IRZ signal is high for both "1" and "0" bits. Thus during the second half-bit, the superimposed signal is the same compared to the NRZ signal that is not superimposed by the IRZ signal [see Fig. 2(c)]. Therefore, the point-to-point data can also be recovered by sampling at the second half-bit of the superimposed signal. There is a $T_b/2$ delay between the clocks used for recovery of point-to-point and multicast data.

## III. EXPERIMENT AND DISCUSSION

According to the system architecture described in Fig. 1, the proposed scheme is experimentally demonstrated. Continuous-wave lights at 1553.6 and 1555.2 nm are NRZ modulated by Mach–Zehnder modulators, driven by a 2.5-Gb/s $2^{31-1}$ pseudorandom binary sequence (PRBS). The modulation depth is 0.115. The point-to-point signals are wavelength-multiplexed, and are then fed into the IRZ transmitter, also driven by a 2.5-Gb/s PRBS as the broadcast data. The modulation depth of IRZ is 0.5. The IRZ transmitter comprises an intensity modulator driven by an IRZ-shaped radio-frequency (RF) signal, which is generated by a logic NAND operation between an RF clock signal and an NRZ RF data signal. After amplification by an erbium-doped fiber amplifier (EDFA), the signals are fed
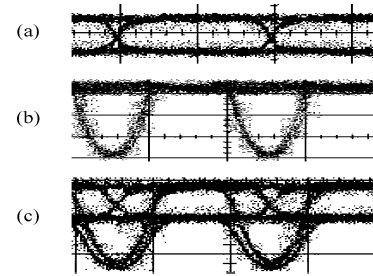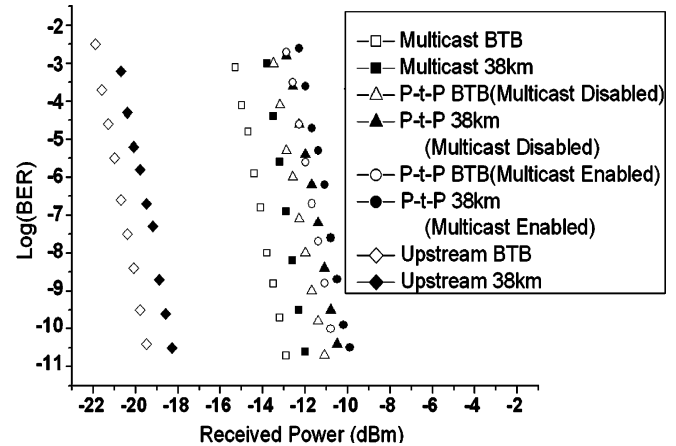


Fig. 4. BER measurements of point-to-point data and multicast data. The modulation depth of the NRZ signal is 0.115.

into the 38-km single-mode fiber. For upstream transmission, the LDs at 1523.9 and 1525.5 nm are directly modulated with a modulation depth of 0.43, driven by the 2.5-Gb/s PRBS as upstream data. To emulate the case when the multicast is enabled, the switch is placed at the upper branch so that the point-to-point signals are directed to the IRZ transmitter, where they are superimposed by the multicast IRZ signal. To emulate the case when the multicast is disabled, the switch is triggered so that the point-to-point signals bypass the IRZ transmitter. Thus no broadcast information is covered in the signals.

The eye diagrams of the NRZ signal, the IRZ signal, and the overlay of them are provided in Fig. 3. Clear and open eyes can be obtained for both point-to-point and multicast services. The bit-error-rate (BER) results of both services are shown in Fig. 4. The BER performances of two channels are almost the same. Thus only the BER results for 1553.6 nm are provided. The receiver sensitivities (at the BER of $10^{-9}$) for multicast and point-to-point data are $-12.4$ and $-10.3$ dBm, respectively. Compared to back-to-back cases, power penalties of 1.0 and 0.7 dB are observed, respectively. The superimposed signal has a wider spectrum. In addition, since half-bit of time-slot is used to detect both point-to-point and multicast signals, the signal is less tolerant to time jittering. Thus both services suffer high power penalties. The relatively higher penalty for multicast may be caused by the imperfectness of the sampling and decision circuits for multicast data recovery. Further work need to be carried out to verify this hypothesis. The low modulation depth leads to low $Q$-factor, which is responsible for the relatively lower receiver sensitivity of point-to-point data. Enhancing the
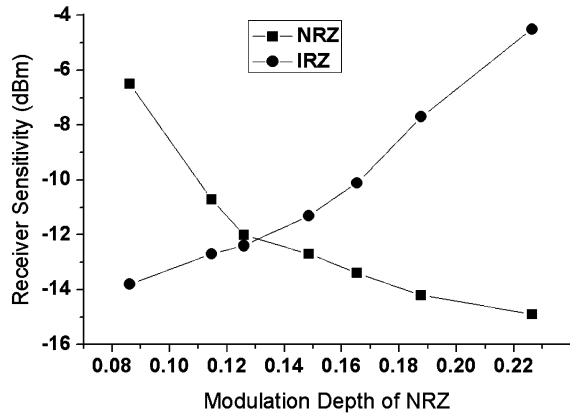
Fig. 5. Receiver sensitivities of downstream point-to-point and multicast signals versus modulation depth of NRZ.

TABLE I
POWER BUDGET ANALYSIS

| | | Downstream | Upstream |
|---|---|---|---|
| Power@Tx | | 2 dBm | 0 dBm |
| Power loss | Loss in fiber | 7.5 dB | 9.0 dB |
| | Loss in AWG | 3 dB | 6 dB |
| | Other loss | 0.5 dB | 0.5 dB |
| | Total loss | 11.0 dB | 15.5 dB |
| Power at ONU | | -9.0 dBm | -15.5 dBm |
| Receiver sensitivity | | -11.9 dBm | -18.8 dBm |
| Power margin | | 2.9 dB | 3.3 dB |

modulation depth leads to lower receiver sensitivity for multicast data and higher receiver sensitivity for point-to-point data. The low receiver sensitivities are also limited by the photodiodes utilized in our experiment. Nevertheless, since the optical power of the signal arrives at the receiver is high, enough power margin is observed, as discussed later. There are two reasons for the high signal power. First no 50/50 coupler is required to direct the optical signal into two photodetectors, and thus the optical power does not suffer a 3-dB loss. Another reason is that no power slicing is required at the remote node (see Fig. 1). For upstream transmission, the BER result of 1523.9 nm is provided. The receiver sensitivity is −18.8 dBm and the power penalty is 1.2 dB. The relatively high power penalty is explained by the direct modulation induced chirp.

Next, we investigate the impact of modulation depth of NRZ signal on the performances of both services. Fig. 5 shows the receiver sensitivities of both signals versus modulation depths of NRZ signal. There is a tradeoff for the modulation depth. A low modulation depth is required to guarantee satisfactory performance of multicast. The low modulation depth imposes certain restriction on sensitivity. Thus the transmission distance is limited. However, in the access network, the transmission distance is not long. Thus it is allowed in the access network. The experimental result for the access network with 38-km transmission length, which is long for a typical access network, proves the feasibility of this system with low modulation depth. The network designer may decide the modulation depth according to the qualities of service of both services. Generally, a modulation depth between 0.115 and 0.165 is required to guarantee enough power margins for both services. If the same receiver sensitivity is required, the modulation depth should be 0.13.

In the final remark, we analyze the power budget. The output power from the EDFA is 2 dBm for each channel. The saturated output power of the EDFA is 16 dBm. For output power of 2 dBm for each channel, the number of channels is limited within 25. The signal is then fed into the downstream transmission link and suffers an 11.0-dB loss. The downstream power

which arrives at the ONU side is thus −9.0 dBm. As demonstrated before, when the modulation depth of NRZ is 0.13, the same receiver sensitivity of −11.9 dBm is achieved for both services. Thus, the power margin for both point-to-point and multicast is 2.9 dB. A power margin of 3.3 dB is achieved for upstream transmission. Since optical signals at different wavelength bands suffer different fiber losses, the losses in fiber are different between downstream and upstream. Table I shows the details of the power budget.

## IV. CONCLUSION

We propose a novel WDM-PON architecture with selective-video service overlay. This system requires only one photodetector for detection of both point-to-point and multicast signals. Only intensity modulation is introduced, and thus no complex receiver is required at the ONU side. We have made the investigation of the impact of modulation depth on the performances of point-to-point and multicast services, and the results show that a modulation depth of 0.13 is required to achieve the same receiver sensitivity for both services.

REFERENCES

[1] R. D. Feldman, E. E. Harstead, S. Jiang, T. H. Wood, and M. Zirngibl, "An evaluation of architectures incorporating wavelength division multiplexing for broad-band fiber access," *J. Lightw. Technol.*, vol. 16, no. 9, pp. 1546–1559, Sep. 1998.
[2] E. S. Son, K. H. Han, J. K. Kim, and Y. C. Chung, "Bidirectional WDM passive optical network for simultaneous transmission of data and digital broadcast video service," *J. Lightw. Technol.*, vol. 21, no. 8, pp. 1723–1725, Aug. 2003.
[3] J. Cho, J. Kim, D. Gutierrez, and L. G. Kazovsky, "Broadcast transmission in WDM-PON using a broadband light source," in *Proc. OFC/NFOEC 2006*, Anaheim, CA, Paper OWS7.
[4] M. Khanal, C. J. Chae, and R. S. Tucker, "Selective broadcasting of digital video signals over a WDM passive optical network," *IEEE Photon. Technol. Lett.*, vol. 17, no. 9, pp. 1992–1994, Sep. 2005.
[5] N. Deng, C. K. Chan, L. K. Chen, and C. Lin, "A WDM passive optical network with centralized light sources and multicast overlay," *IEEE Photon. Technol. Lett.*, vol. 20, no. 2, pp. 114–116, Jan. 15, 2008.
[6] L. Cai, S. Xiao, Z. Liu, R. Li, M. Zhu, and W. Hu, "Cost-effective WDM-PON for simultaneously transmitting unicast and broadcast/multicast data by superimposing IRZ signal onto NRZ signal," in *Proc. ECOC 2008*, Brussels, Belgium, Paper Th.1.F.4.