Effects of Upstream Bit Rate on a Wavelength-Remodulated WDM-PON Based on Manchester or Inverse-Return-to-Zero Coding

Hwan Seok Chung, Bong Kyu Kim, and Kwangjoon Kim

We compare the performance of a wavelength remodulated wavelength-division-multiplexed passive optical network implemented using Manchester-coded or inverse-return-to-zero (IRZ)-coded signal downstream and non-return-to-zero remodulated signal upstream. We investigate the effects of varying differences between downstream and upstream bit rates on the two coding schemes. When the bit rate ratio of upstream to downstream is less than or equal to 50%, the performance of Manchester coding is better than that of IRZ coding. However, when the bit rate ratio of upstream to downstream is higher than 50%, Manchester code requires appropriate time delay between upstream and downstream signals, whereas IRZ code needs reduced extinction ratio in the downstream signal.

Keywords: WDM-PON, access network, wavelength remodulation, centralized light source IRZ, NRZ.

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I. Introduction

Wavelength-division-multiplexed passive optical network (WDM-PON) is a promising technology to implement next generation fiber-to-the-home networks because it provides wide bandwidth and virtual point-to-point connection to end-users [1]-[10]. However, the need for wavelength-specific light sources for every subscriber leads to an inventory problem, which is one of the biggest concerns for wide deployment of WDM-PON. Centralized light source or wavelength remodulation technology is an attractive scheme to solve this problem. In this scheme, all light sources are located at the optical line terminal (OLT) in the central office (CO), and the optical network unit (ONU) on the subscriber side reuses the light that carries the downstream data for the upstream signal. This eliminates light sources and related control units outside the plant. Recently, there has been substantial effort to develop wavelength-remodulated WDM-PON technology including non-return-to-zero (NRZ) coding with reflective semiconductor optical amplifier (RSOA) [1]-[3], inverse-return-to-zero (IRZ) coding [4], and Manchester coding [5]. The NRZ coding requires amplitude compression of downstream signal with gain saturated RSOA. The degree of amplitude compression is seriously affected by the downstream bit rate [6], [7], the extinction ratio (ER) [1], and the optical power injected into the RSOA [1]. It is believed that amplitude suppression is not necessarily required for Manchester and IRZ coding. Previously, the feasibility of an IRZ- or Manchester-coding-based remodulation scheme was demonstrated by assuming that the upstream bit rate was much lower than the downstream bit rate [4], [5]. A symmetrical bit rate would be required for a future upgrade, while asymmetric downstream/upstream bit rates are widely adopted in access networks. In addition, to reduce the network operation cost, a centralized light-source, namely, wavelength remodulation, is a good candidate for other network applications that require high-speed upstream transmission and no light-source outside the plant.

In this paper, we evaluate and compare the performance of wavelength-remodulated WDM-PON, in which data is Manchester- or IRZ-coded downstream and NRZ-remodulated upstream. We investigate the effects of various downstream and upstream bit rates on the two coding schemes, and we evaluate the conditions to support high-speed upstream transmission. The results show that the performance of Manchester coding is better than that of IRZ coding when the upstream bit rate is less than or equal to half the downstream bit rate. We find that both formats require appropriate extinction ratio or synchronization to ensure high-speed upstream transmission. These results will be useful in designing a wavelength-remodulated WDM-PON for cost-effective deployment of optical access networks.

II. Comparison Setup

Figure 1 shows a schematic diagram of a wavelength-remodulated WDM-PON based on Manchester or IRZ coding. Laser output at a wavelength of 1552.52 nm was modulated by a 5 Gb/s pseudo-random bit sequence with Manchester or IRZ code. The electrical Manchester signal was generated by a logic exclusive OR (XOR) operation between NRZ and clock, whereas the electrical IRZ signal was generated by a logic invert operation of the RZ signal. As a result, both codes always include optical power within one bit period regardless of mark or space level, as shown in Fig. 1(b).

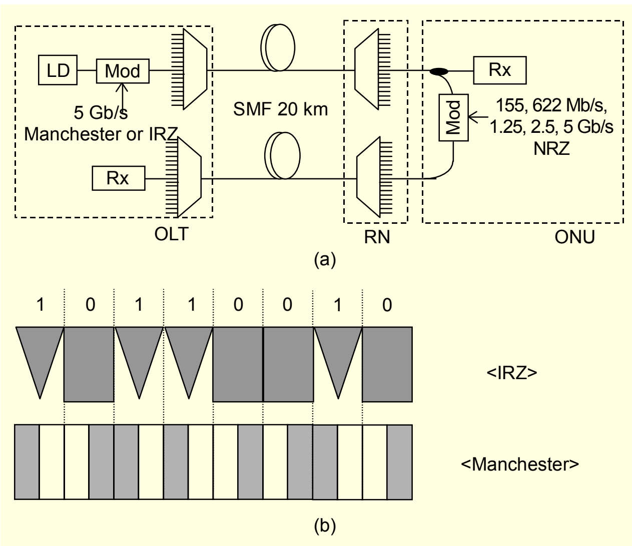

Fig. 1. Schematic diagram of wavelength re-modulated WDM-PON based on Manchester- or IRZ-coded downstream and NRZ-remodulated upstream: (a) comparison setup and (b) IRZ and Manchester formats.

The modulated Manchester or IRZ signal was combined by an AWG and then transmitted over 20 km of conventional single-mode fiber (SMF) at 17 ps/nm/km. At the ONU, the incident Manchester or IRZ coded signal was split into two paths by an optical coupler. One output of the coupler was connected to a receiver to recover the downstream signal, and the other output was fed into an external modulator for upstream data transmission. The upstream signal was generated by remodulating the downstream signal with NRZ format. We used an RSOA or an electro-absorption modulator for upstream transmission to avoid problems that are caused by the fluctuation of the polarization state in downstream signal. It should be noted that the degree of amplitude compression due to the RSOA is very low when the speed of downstream transmission is higher than several Gb/s [6], [7]. The modulation speed of upstream transmission was 155 Mb/s, 622 Mb/s, 1.25 Gb/s, 2.5 Gb/s, or 5 Gb/s. The remodulated upstream signal was transmitted back along another 20 km-long SMF and then detected by a receiver. In this analysis, we used typical direct detection receivers for downstream and upstream signals, except for the Manchester-coded downstream (that is, the electrical bandwidth is 1.4 times the bit rate). The extinction ratio was 10 dB for both downstream and upstream signals.

III. Results and Discussions

Figure 2(a) shows the bit-error-rate (BER) curves of 5 Gb/s downstream signals modulated with Manchester code and IRZ code, respectively. The receiver sensitivities for Manchester-coded signal and IRZ-coded signal measured at a BER of 10^{-9} were -18.4 and -19.7 dBm, respectively. The sensitivity of Manchester-coded downstream signal was 1.3 dB better than that of IRZ-coded downstream signal. Since the remodulation scheme utilizes the light that carries the downstream data for upstream transmission, even if the spectral component at high frequency is suppressed by the electrical low-pass filter at the OLT, the received upstream data inherently includes spectral components induced by the downstream signal, which causes crosstalk. Thus, decoupling of the spectral overlapping between upstream and downstream signals is critically important to increase the performance of upstream signal. Figure 2(b) shows the RF power spectra of the downstream signals. In the frequency range of less than 1.1 GHz, the amplitude of frequency components for the

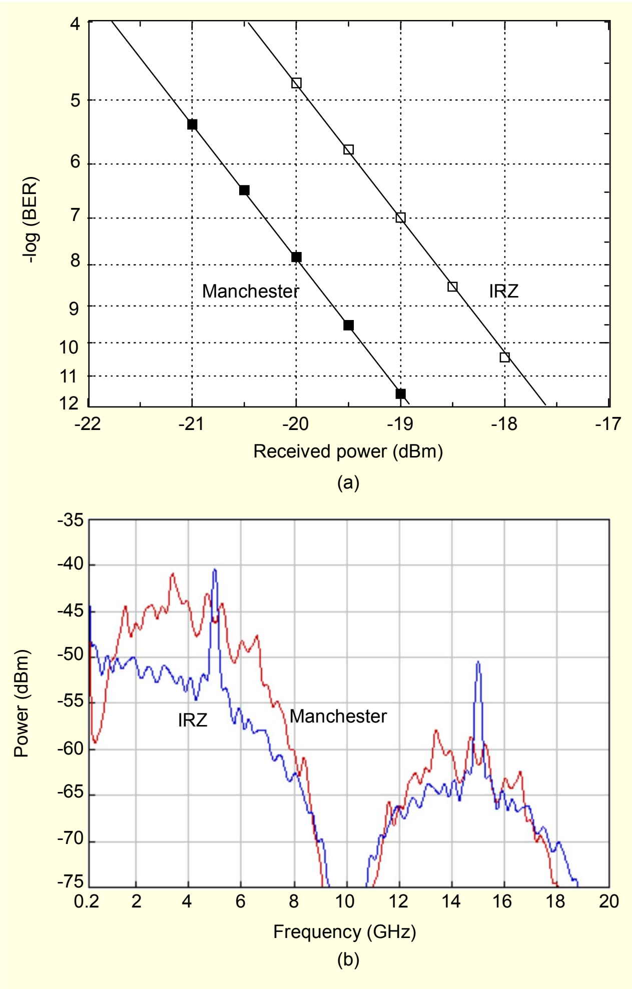

Fig. 2. Performance of 5 Gb/s downstream: (a) BER curves and (b) RF power spectra.

Manchester code is smaller than that for the IRZ code. When the frequency is higher than 1.1 GHz, however, the amplitude of frequency components for the Manchester code gradually increases and is larger than that for the IRZ code. Thus, as the bit rate ratio of downstream to upstream becomes larger, the performance of remodulated upstream transmission based on the Manchester code downstream is better than that based on the IRZ code downstream.

Figure 3 shows the BER curves and eye diagrams of upstream signals measured at the OLT. The speed of downstream transmission was fixed at 5 Gb/s, whereas the speed of upstream transmission was varied from 155 Mb/s to 2.5 Gb/s. The closed and open symbols represent the results obtained with NRZ remodulation on Manchester code and IRZ code downstream, respectively. The results show that the difference in receiver sensitivity between Manchester code and IRZ code increases as the bit rate of upstream transmission increases. In the case of a 155 Mb/s upstream, for example, the

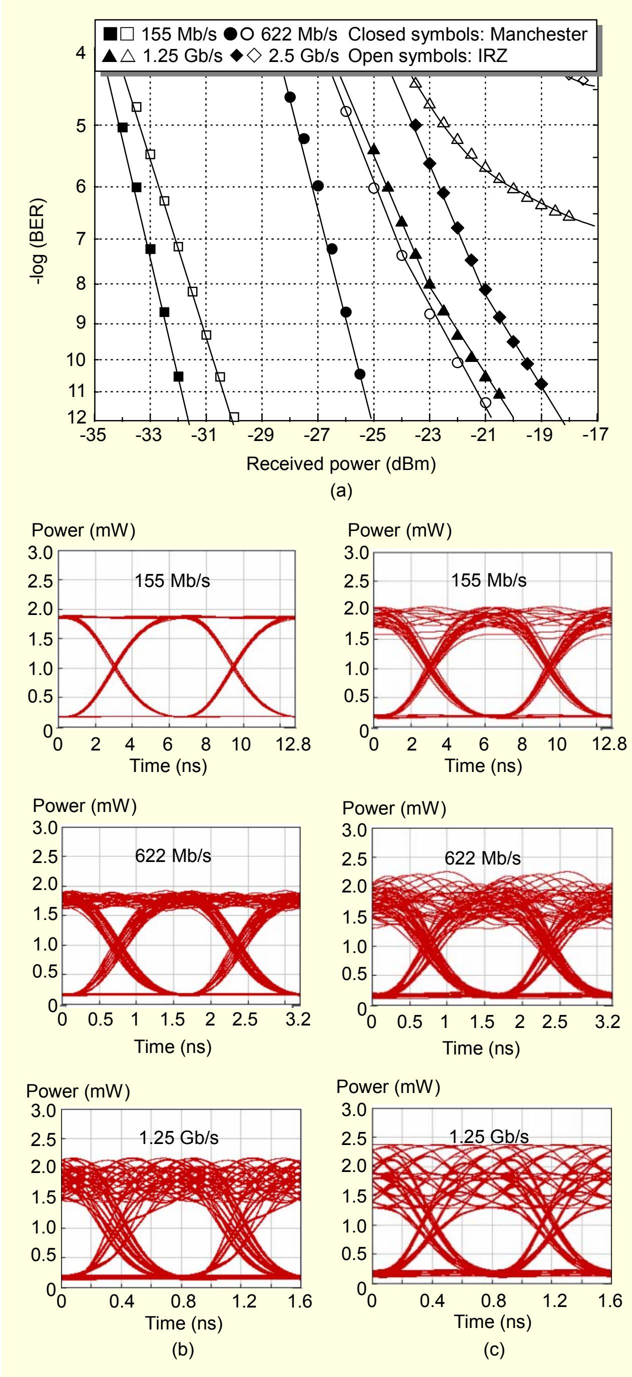

Fig. 3. Effects of bit-rate difference between downstream and upstream transmission: (a) BER curves for upstream, (b) received upstream eye diagrams when downstream is modulated with Manchester code, and (c) received upstream eye diagrams when downstream is modulated with IRZ code.

sensitivity of the remodulated upstream based on Manchester code is -32.4 dBm (■), while the sensitivity of the remodulated upstream based on IRZ code is -31.2 dBm (□). In the case of 622 Mb/s, the difference increases to 3.3 dB.

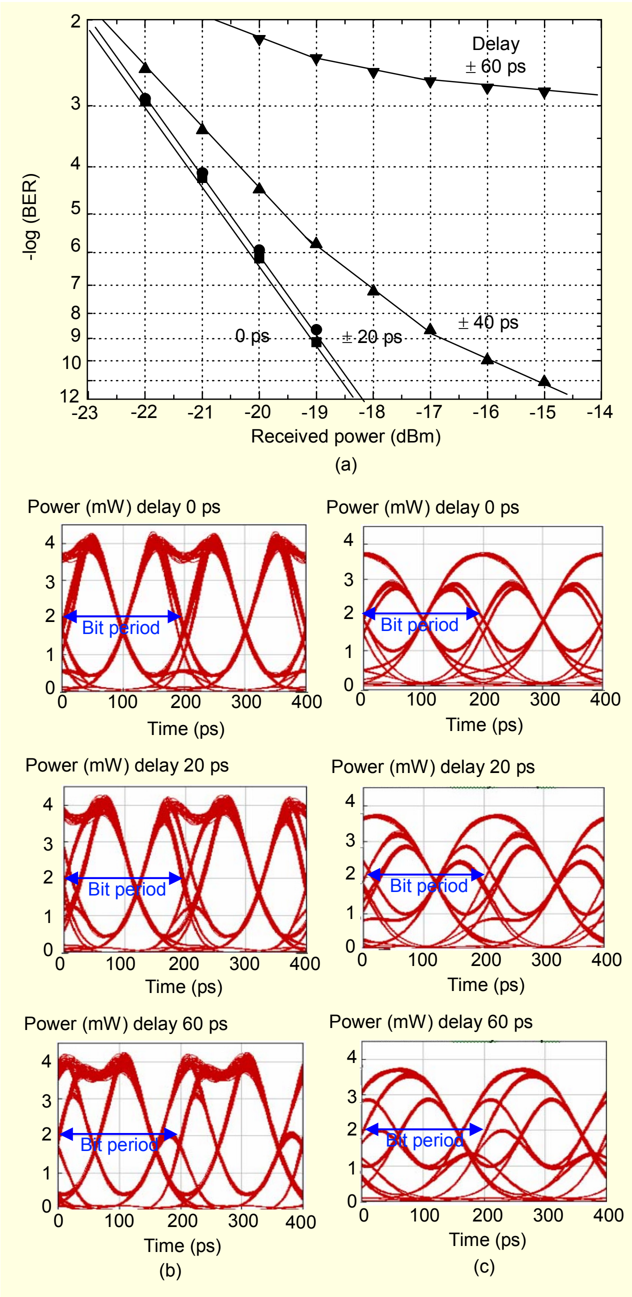

Fig. 4. Performance of Manchester code case when bit-rate ratio of upstream to downstream is 100% (upstream and downstream: 5 Gb/s): (a) upstream BER curves with various time delays, (b) measured eye diagrams before electrical low-pass filter, and (c) measured eye diagrams after electrical low-pass filter.

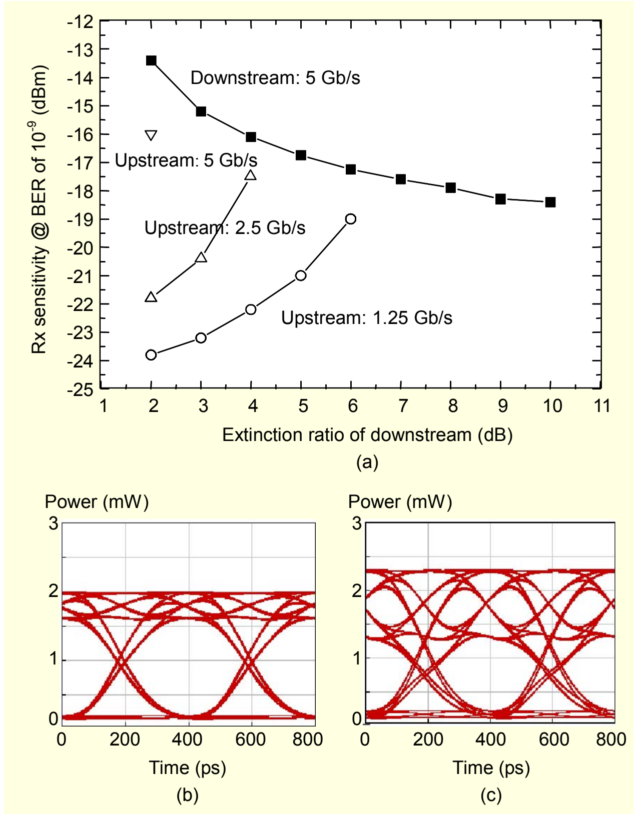

Fig. 5. Performance of IRZ code: (a) effect of downstream extinction ratio, (b) received upstream eye diagram when downstream bit rate is 2.5 Gb/s and extinction ratio is 2 dB, and (c) received upstream eye diagram when downstream bit rate is 2.5 Gb/s and extinction ratio is 10 dB.

The Manchester code shows error-free operation up to 2.5 Gb/s (◆), while the IRZ code shows an error floor at a BER of 10^{-6} at 1.25 Gb/s (◇). Manchester code downstream data induces relatively less crosstalk than IRZ code downstream. This can be confirmed by measured upstream eye diagrams, as shown in Figs. 3(b) and (c). Manchester code has less amplitude noise at the mark level than IRZ code. All these results demonstrate that Manchester code achieves better performance than IRZ code when the bit rate ratio of upstream to downstream is not more than 50%.

To investigate the possibility of adopting a symmetric bit rate in the wavelength remodulated scheme based on Manchester-coded downstream transmission, we increased the upstream bit rate up to 5 Gb/s, as shown in Fig. 4. In this analysis, we used the same setup as that of the asymmetric bit rate case, except we adjusted the time delay between downstream and upstream. The upstream signal utilized the downstream signal with a period of 200 ps, and the optical power is on and off every 100 ps or 200 ps as shown in Fig. 1(b). It was expected that the remodulated upstream signal quality would be worst when it is delayed with the downstream signal by about 50% of the bit-period. As expected, the best receiver sensitivity value was obtained when the upstream NRZ signal was in phase (0 ps time delay with downstream signal). When the time delay was varied by less than ±20 ps, the receiver sensitivity remained around -19 dBm. The BER rapidly degraded when the time delay deviation exceeded ±40 ps. Since Manchester code always includes amplitude transition within one bit period, when the appropriate time delay was applied, we could achieve eye opening after the electrical low-pass filter, as shown in Figs. 4(b) and (c). The proper adjustment of the time delay could be done by using the clock extracted from the downstream signal as a triggering source of upstream data. The amplitude noise at the mark level shown in Fig. 4(c) could be suppressed by a limiting amplifier. We have experimentally confirmed that an appropriate time delay ensures transmission with a symmetric bit rate based on Manchester coding in [8].

The IRZ-coded downstream could not support the remodulated upstream when the upstream bit rate was higher than 1.25 Gb/s, as shown in Fig. 3(a). To reduce the amplitude noise at the mark level in the upstream signal, we investigated the effects of the downstream extinction ratio (ER). Figure 5(a) represents the upstream sensitivity as a function of the downstream ER. The results show that reduction of the ER in IRZ code improves the sensitivity of the remodulated upstream, allowing high-speed upstream transmission. Low ER induces smaller amplitude noise in the upstream signal than high ER, as shown in Figs. 5 (b) and (c). However, low ER costs downstream sensitivity. As shown in Fig. 5(a), to ensure error-free transmission of upstream signals of 1.25 Gb/s, 2.5 Gb/s, and 5 Gb/s, the ER of the downstream signals should be less than 6 dB, 4 dB, and 2 dB, respectively, causing the degradation of downstream signal sensitivity by 1.2 dB, 2.3 dB, and 5 dB, respectively, in comparison with 10 dB ER. It should be noted that the RSOA would not have amplitude compression when used for data modulation since the degree of amplitude compression is very low when the speed of downstream transmission is higher than several Gb/s [6], [7]. Unlike the Manchester code case, when ERs are maintained at 10 dB, the BER curve of the 5 Gb/s remodulated upstream based on IRZ-coded downstream transmission reaches the floor at BERs in a range from 10^{-3} to 10^{-9}, even when the time delay between downstream and upstream is adjusted.

IV. Summary

We analyzed and compared the performance of Manchester code and that of inverse-RZ code for a wavelength-remodulated WDM-PON. In addition, we investigated the effects of varying difference between downstream and upstream bit rates on the two coding schemes. When the bit rate ratio of upstream to downstream is less than or equal to 50%, which has been widely accommodated in recent access networks, the performance of the remodulated upstream based on Manchester code was better than that based on IRZ code since Manchester code has very little crosstalk induced by downstream signal. We found that, when the bit rate ratio of upstream to downstream is higher than 50%, Manchester code requires an appropriate time delay between the upstream and downstream signals, whereas IRZ code needs a reduced extinction ratio in the downstream signal. These results will be useful in designing wavelength remodulated WDM-PONs for cost-effective deployment of optical access networks.

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