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Effect of forward error correction on spectral sliced WDM/TDMA-PON system

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Abstract: A simple and scalable wavelength division multiplexing/time division multiple access passive optical network (WDM/TDMA-PON) system is demonstrated that uses spectral slicing and forward error correction (FEC) with a Reed-Solomon (255, 239) encoder in burst mode upstream transmissions. Receiver sensitivities are improved to −33.5, −34.9 and −35.5 dBm at a sliced bandwidth of 100, 200 and 400 GHz with FEC. Moreover, the dispersion penalties after a 20 km transmission are only about 0.6 and 0.4 dB at a bit error rate (BER) of 10^{-10} at 200 and 400 GHz, respectively.

Keywords: WDM/TDMA-PON, forward error correction, spectral slicing, burst-mode transmission

Classification: Fiber-optic communication

References

[1] M. H. Reeve et al., "LED Spectral Slicing for Single-Mode Local Loop Applications," *Electron. Lett.*, vol. 24, no. 7, pp. 389–390, 1988.

[2] S. Kaneko et al., "Scalability of Spectrum-sliced DWDM transmission and Its Expansion Using Forward Error Correction," *J. Lightwave Technol.*, vol. 24, pp. 1295–1301, 2006.

[3] T. Mitsui et al., "Simple and scalable WDM/TDMA-PON using spectral slicing and forward error correction," *OFC2011*, OTuB5, 2011.

[4] Y. Fukada et al., "Gain-Clamp Light Auto Level Control (GCL-ALC) Technique for Gain-Controllable Burst-Mode PON Amplifying Repeater," *OFC2008*, OThT5, 2008.

[5] G. J. Pendock et al., "Transmission Performance of High Bit Rate Spectrum Sliced WDM Systems," *J. Lightwave Technol.*, vol. 14, pp. 2141–2148, 1996.

[6] Y. Yi et al., "Simulations and Experiments on the Effective Optical Gain of FEC in a GPON Uplink," *IEEE Photon. Technol. Lett.*, vol. 19, no. 2, pp. 82–84, 2007.

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1 Introduction

Passive optical networks (PON) based on time division multiple access (TDMA) are being widely deployed as economical access network systems. In contrast, wavelength division multiplexing (WDM)-PON has been extensively researched to allow each subscriber to use a different wavelength and thus greatly increase the average and total capacities compared with a TDMA-PON. The WDM/TDMA-PON is a hybrid of these two concepts; the average and total capacities can be increased according to the number of assigned wavelengths, and each wavelength can be shared dynamically and effectively through TDMA.

One major issue with WDM-PONs including WDM/TDMA-PONs is how to realize a "colorless" optical network unit (ONU) to avoid the increased cost and complexity that would be incurred by equipping each ONU with a laser that had a unique wavelength. The spectral slicing of a cost effective broadband incoherent light source, such as a light-emitting diode (LED), is a simple way to realize this [1]. Fig. 1 shows the typical architecture of a WDM/TDMA-PON system with spectral slicing. The optical line terminals (OLTs) broadcast downstream data with assigned each wavelength in a continuous mode. On the other hand, upstream traffic from an ONU is managed by using TDMA technology to avoid any overlap between burst mode signals at the same wavelength. While the available bit rate is inherently limited by the slicing bandwidth in the spectral slicing scheme, it has been reported that the use of forward error correction (FEC) can greatly increase the scale of the network in terms of both loss budget and bandwidth efficiency [2]. However, most studies about spectral slicing scheme with FEC are mainly based on theoretical analysis and simulation results, or target a continuous mode transmission. The FEC effect for burst mode transmission in a spectral slicing scheme has not been fully clarified.

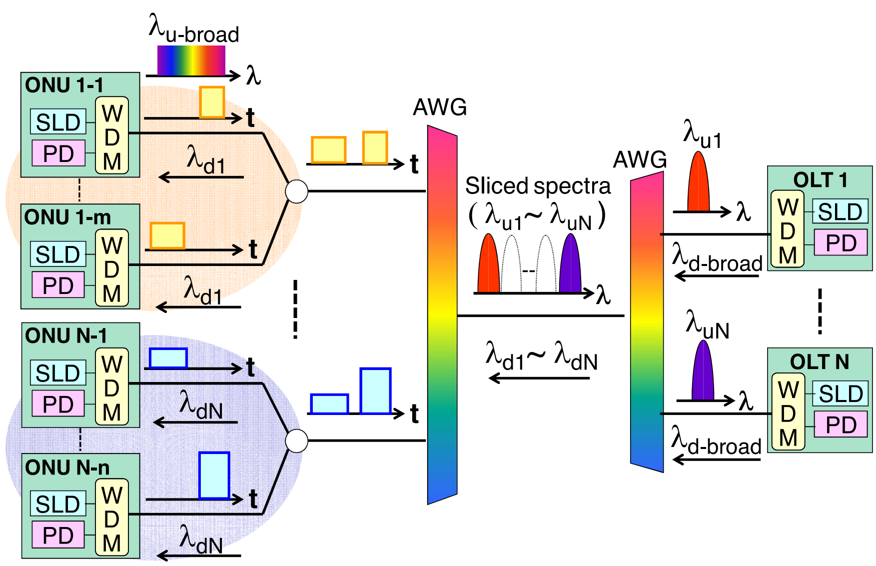

Fig. 1. Architecture of WDM/TDMA-PON system with spectral slicing

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We have previously estimated the effectiveness of combining FEC and spectral slicing in a burst mode upstream transmission, and confirmed that the upstream sensitivity had been improved by FEC [3]. In this paper, we further analyze the FEC effect in the spectral sliced burst mode transmission as well as confirm the dispersion penalty through a 20 km transmission.

2 Experimental setup

Fig. 2 (a) shows the experimental setup we used to evaluate the effectiveness of the Reed-Solomon (255, 239) FEC code with upstream burst mode signals. For a basic evaluation, the experimental system consists of a gigabit Ethernet PON using spectral slicing and an ONU with an amplified spontaneous emission (ASE) light source. An electrical signal from the ONU was input into lithium niobate (LN) modulators via a PON chip that could separate upstream data with 8 B/10 B coding and a Tx_enable signal. Note that the FEC coding was implemented per Ethernet frame as standardized in IEEE Std. 802.3ah.

A continuous lightwave from the ASE light source through an isolator was input into LN modulator #1 and modulated at 1.25 Gbit/s. The polarization of a continuous mode modulated signal was adjusted by using a polarization controller (PC) to obtain maximum output optical power, and

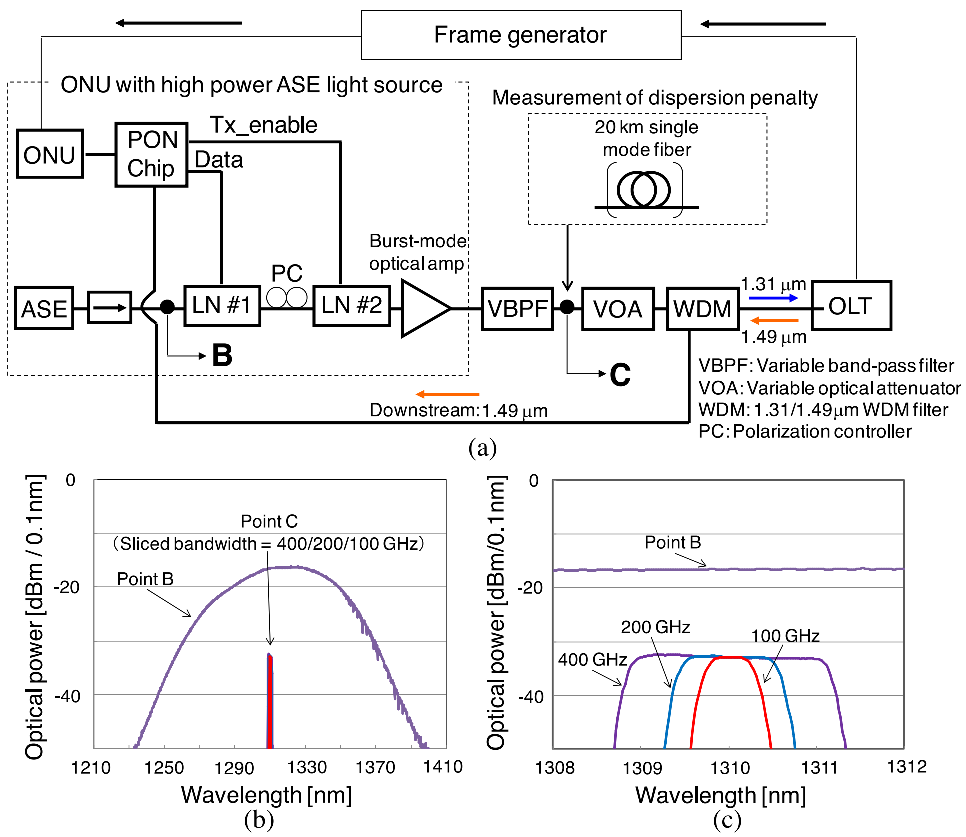

Fig. 2. (a) Experimental setup, (b) spectra at measurement points "B" and "C", (c) expanded view of spectra

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gated with LN modulator #2 to generate a burst mode signal by using the Tx_enable signal. The optical burst signals were input into a burst mode optical amplifier, whose optical gain and noise figure (NF) were 10 dB and 6.8 dB, respectively [4], to compensate for the loss of the LN modulators. The ASE spectrum of the optical signals was sliced with a variable optical band-pass filter (VBPF) at a central wavelength of 1310 nm, and then the optical signals were received via a variable optical attenuator (VOA) and a WDM filter by the commercial burst mode transceiver module in the OLT. Here, receiver sensitivity, dynamic range, and response time of this burst mode transceiver when using a direct modulation laser were −30 dBm at a bit error rate (BER) of 10^{-12}, 24 dB, and 250 ns, respectively.

Fig. 2 (b) shows the spectra obtained at measurement points "B" and "C" in Fig. 2 (a). Point "B" is the spectrum from the ASE light source, and point "C" indicates the spectra of the output from the VBPF for sliced bandwidths of 100, 200 and 400 GHz. Fig. 2 (c) shows the expanded spectra around 1310 nm of the wavelength in Fig. 2 (b).

We used a higher power ASE light source than that in our previous report [3], whose total optical power, central wavelength and 3-dB optical bandwidth were +12 dBm, 1310 nm and 52 nm, respectively. We used a 20 km single mode fiber in the last experiment to confirm the dispersion tolerance against spectral slicing.

3 Experimental results

We measured the upstream packet error rate (PER) with and without FEC against the input optical power and the sliced bandwidth when the bandwidth was varied to 100, 200 and 400 GHz by the VBPF. The upstream frame was transmitted by a frame generator. The frame length was fixed at 64 bytes, and the received frame count was about 20,000,000 frames to obtain a BER of 10^{-10}.

Fig. 3 (a) shows the BER performance, which is based on the measured upstream PER results. Here, PER is the number of incorrectly transferred data packets divided by the number of transferred packets. A packet is assumed to be incorrect if at least one bit is incorrect in a frame. Therefore, the relationship between the PER and BER for a frame length of N bits can be expressed as:

$$PER = 1 - (1 - BER)^N \tag{1}$$

The open/closed circles, triangles, and squares correspond to sliced bandwidths of 100, 200 and 400 GHz with/without FEC, respectively. The BER characteristic was degraded as the sliced bandwidth became narrower as the result of a reduction in the signal part of the signal to noise ratio (S/N). Without FEC, the BER characteristic of each sliced bandwidth indicated an error floor because of the "mark" level noise added by using the incoherent light source. This means that the optimum threshold point is typically not the cross-point of the eye-pattern, and we could not adjust the threshold level because we used a commercially available burst mode transceiver module in

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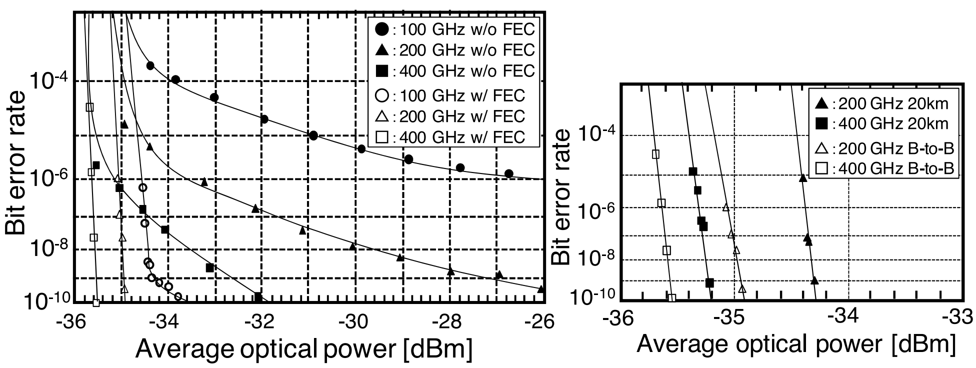
this experiment. When adjusting the threshold level of the burst mode receiver or an error detector at a physical layer, the BER characteristics will be improved as drawing not floor but straight line [5]. Thus, we considered that the error floor was induced at each sliced bandwidth without FEC.

On the other hand, as regards the BER characteristics with FEC, it should be noted that the error floor was improved by FEC. The BERs for sliced bandwidths of 100, 200 and 400 GHz showed error free operation when the input optical powers exceeded about −33.5, −34.9 and −35.5 dBm, respectively.

The FEC gains were more than 3.5 dB against each sliced bandwidth and this increased as the sliced bandwidth decreased. These results mean that we demonstrated the effect of FEC on a burst mode upstream transmission with a spectral slicing technique. However, an error floor was confirmed at a sliced bandwidth of 100 GHz even when using FEC. We consider this to be because the errors, which exceeded the FEC error correcting capability, have occurred intensively and the FEC could not correct all errors, because Reed-Solomon (255, 239) cannot correct errors longer than 8 byte in a code word. Moreover, it is reported that the burst mode transmission is more likely to have burst errors compared with continuous mode transmission [6]. Therefore, such burst errors longer than 8 byte are likely to be occurred in burst mode transmission, and it occurred at 100 GHz sliced bandwidth in our experiment.

From these results, we concluded that the optimum sliced bandwidth in WDM/TDMA-PON systems was more than 200 GHz.

We then performed a 20 km transmission experiment to estimate the dispersion penalty in an uplink. A 20 km single mode fiber was placed between the VBPF and the VOA shown in Fig. 2 (a). The sliced bandwidths were 200 and 400 GHz in consideration of error free operation without a noise floor. Fig. 3 (b) compares the back-to-back BER performance shown in Fig. 3 (a), and that for the 20 km transmission with FEC. As shown in Fig. 3 (b), the power penalties of 20 km transmissions at 200 and 400 GHz were about 0.6



(a) (b)

Fig. 3. BER performance, (a) with/without FEC at back to back, (b) with FEC at back to back and 20 km transmission

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and 0.4 dB at a BER of 10^{-10}, respectively. Therefore, the dispersion penalty hardly influenced the 20 km transmission. We consider that this is because the modulation speed was 1.25 Gbit/s and the wavelength dispersion was almost zero as the result of employing a wavelength of 1.3 μm in the single mode fiber.

Consequently, sufficient performance was achieved with FEC even for 20 km transmissions at sliced bandwidths of 200 and 400 GHz.

4 Conclusion

We demonstrated a simple and scalable WDM/TDMA PON system that uses spectral slicing and FEC for burst mode upstream transmissions. When using FEC, the sensitivity was improved by −33.5, −34.9 and −35.5 dBm at sliced bandwidths of 100, 200 and 400 GHz, respectively. We also showed that the dispersion penalty hardly influenced the 20 km transmission at sliced bandwidths of 200 and 400 GHz. From these results, we concluded that FEC-assisted spectral slicing allowed us to realize a feasible WDM/TDMA-PON system at sliced bandwidths of 200 and 400 GHz.

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