Feed-Forward Control of Transient Gain Dynamics of an EDFA for Optical Burst Networks

Jeong-Sik Cho, Min-Jae Cho, and Yong-Hyub Won

ABSTRACT—In this letter, we demonstrate a technique for suppression of transients in output bursts of an erbium-doped fiber amplifier (EDFA) in an optical burst network. To suppress the transients, the EDFA is forward-fed by non-fluctuating input utilizing a power-modulated burst control packet channel. Using the technique, we obtained a maximum 1.7 dB reduction in gain transient in the EDFA output, and we transmitted 9.953 Gbps data bursts and 2.488 Gbps burst control packets stably.

Keywords—OBS, EDFA, transient gain control, feed-forward control, burst control packet.

I. Introduction

Optical burst switching (OBS) has been studied as a practical alternative to direct migration from optical circuit switching networks into eventual high-speed optical packet switching networks [1]. In the OBS network, data packets are assembled into bursts of a few microseconds to hundreds of microseconds and transported through a core network. The bursts are generated as the occasion demands; therefore, a stream of data bursts (DBs) can have idle intervals. The idle periods cause abrupt power changes in the input of an erbium-doped fiber amplifier (EDFA) deployed in the core optical link. In this case, slow gain dynamics of the EDFA results in transient output. Inter- and intra-burst power variations induced by the transient cause power penalties in optical receivers. To overcome the transient, previously proposed techniques utilized an all-optical feedback method [2], a constant-wave channel [3], and a packet envelope detection technique [4]. However, these suffered from relaxation oscillation [2] and resulted in waste of wavelength resources [3], [4].

In this paper, we experimentally demonstrate a technique for suppression of transients in the output of an EDFA. It uses a burst control packet (BCP) channel whose optical power is modulated to compensate power deficiencies in DB channels. The EDFA fed by the non-fluctuating input can show little transient in the power of an output. In forward feeding a control signal, namely, the BCP channel, this technique differs from previous feed-back approaches [2], [4]. In addition, this feed-forward gain control (FFGC) technique does not require a dummy channel or wavelength; rather, it exploits the existing BCP channel so that it can increase the utilization of wavelength resources.

II. Transient Control Technique

To control transients, abrupt changes in the optical power of an input for the EDFA must be suppressed. To meet this requirement, we reduce the fluctuation of the input power by adding an optical data channel whose power envelope is the same as the inverted envelope of total DBs as shown in Fig. 1. To obtain the inverted envelope, envelope signals of each DB generated by a BCP processor based on information in BCPs are summed and inverted by a signal adder. In the OBS network, information, such as the length of a DB, is delivered by a BCP ahead of the DB as the offset time, and the BCP processor use the information [1]. The inverted envelope signal from the BCP processor is used to modulate the optical power of a BCP channel. The modulated BCP channel is combined with the DB channels before an EDFA. Thus, the fluctuation of the optical power of the EDFA input is reduced. As a result, transients in outputs of the EDFA are suppressed effectively.

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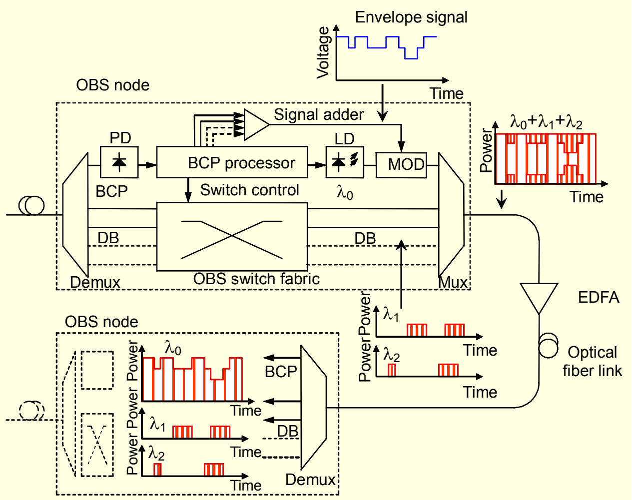

Fig. 1. A schematic diagram of the transient gain control technique (PD: photodetector, LD: laser diode, MOD: optical intensity modulator, Mux: multiplexer, and Demux: demultiplexer).

Like the DB, the BCP is generated randomly, that is, the BCP channel can have an idle period between two BCPs. However, in the proposed technique, the BCP channel operates in continuous mode by using a technique that multiplexes meaningful BCPs and dummy BCPs as demonstrated in [5].

In this technique, the number of DB channels accommodated by one BCP channel must be considered carefully. If one BCP channel covers a number of DB channels, then the probability of congestion in the BCP channel could increase [6]. Moreover, the BCP channel fluctuation for the suppression of transients degrades the performance of the BCP channel. BCP channel power variation can be described by the modulation index δ, defined by $\delta = (V_{\max} - V_{\min}) / (V_{\max} + V_{\min})$, where the $V_{\max}$ and $V_{\min}$ are maximum and minimum values of BCP channel power detected in voltage unit, respectively. Accommodating a number of DB channels leads to the requirement of an increase in δ and a small power ratio of the DB channel to the BCP channel. Increasing the δ requires a receiver with a high dynamic range to deal with the fluctuating signal. The small power ratio results in a low optical signal to noise ratio (OSNR) of the DB channel after amplification. Assuming that a BCP channel covers N DB channels and a duty ratio of a DB channel is ρ_i for a selected time span, the power ratio of the k-th DB channel is given by

$$\left\{\frac{2\delta}{N(1+\delta)}\rho_k\right\} \Bigg/ \left\{1+\frac{2\delta}{1+\delta}\left[\sum_{i=1}^{N}\frac{(1-\rho_i)}{N}-1\right]\right\}, \qquad (1)$$

where $0 \leq \rho_i < 1$. When $N = 2$, $\delta = 0.4$ and $\rho_i = 0.5$, the ratio is –6.99 dB. This value increases up to –13.98 dB when N becomes 10. This means that the OSNR of the DB channel is at least 13.98 dB less than that of the BCP channel, and the BCP channel consumes most of the amplification energy of an EDFA.

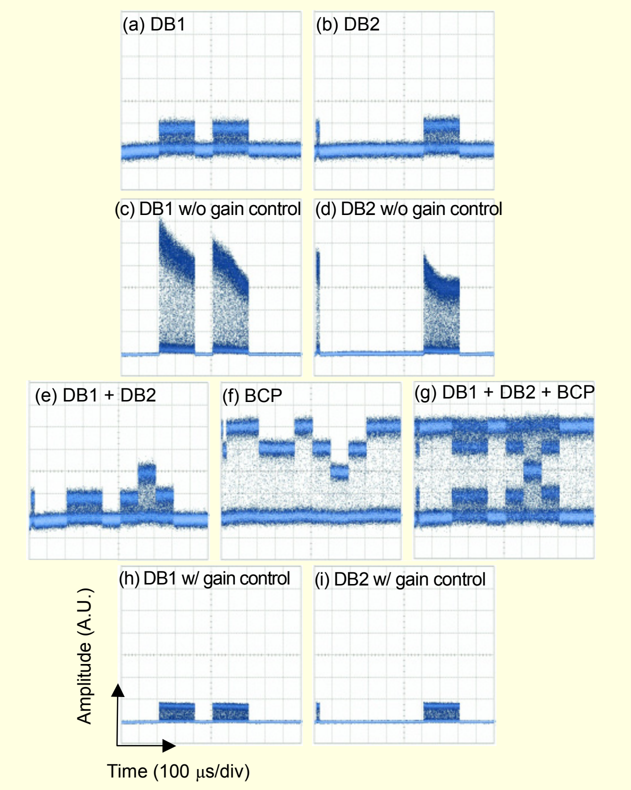

Fig. 2. Timing diagrams for (a), (b) DB channels before amplification, (c), (d) DB channels after amplification without gain control, (e) combined DB channels, (f) power-modulated BCP channel, (g) combination of the DB channels and the BCP channel, and (h), (i) transient-suppressed outputs of the EDFA.

III. Experimental Findings

For a BCP channel, a laser diode operating at a wavelength of 1549.32 nm (λ_0) was modulated by a 2^{31}–1 pseudo-random signal at 2.488 Gbps using an optical intensity modulator. This BCP channel was modulated further by the inverted envelope signal using the second modulator. For DB channels, two laser diodes with wavelengths of 1550.92 nm (λ_1) and 1552.52 nm (λ_2), respectively, were turned on and off to obtain bursts with an envelope but no data. The two beams were modulated by 2^{31}–1 pseudo-random signals at 9.953 Gb/s. Then, the BCP and DB channels were combined optically and input to an EDFA with 15 dB gain. Total input power was –8 dBm. For the first DB channel, DB1, two 200 μs length bursts were generated. For the second DB channel, DB2, 20 μs and 200 μs length bursts were generated. To examine coexistence effects, two bursts of each channel were allocated to partially overlap.

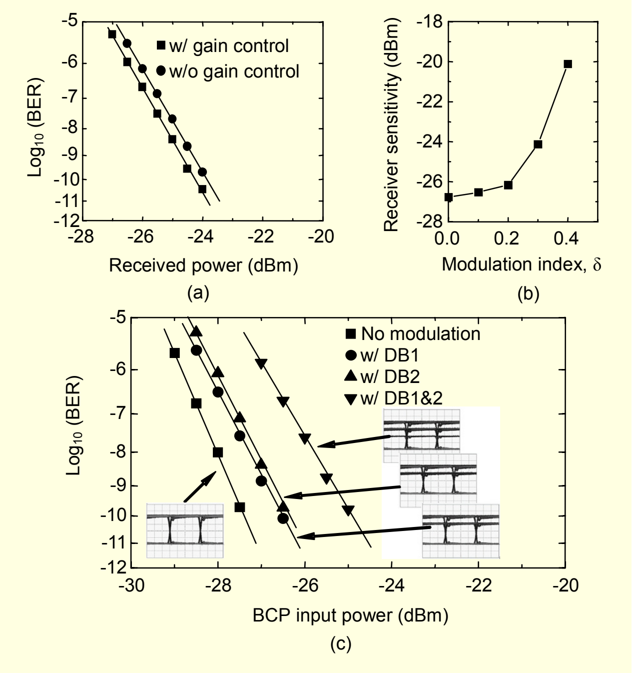

Fig. 3. (a) BER curves for the DB1, (b) sensitivity of an AC-coupled receiver at a BER of 10^{-9} for several δ, and (c) BER curves of the BCP channel for supporting no DB channel, one DB channel, and two DB channels.

Figure 2 shows input and output streams of the EDFA. Without the FFGC technique, power excursion by gain transient and burst-by-burst power fluctuation were maximally 2.0 dB and 2.6 dB, respectively. When the FFGC technique was applied, the transients were suppressed effectively and were less than 0.3 dB as shown in Figs. 2(h) and (i).

Figure 3(a) shows two BER curves of DB1 with and without the FFGC technique. Without the technique, a 0.4 dB power penalty was observed. When the input power was increased, transient increased, and, eventually, the penalty increased further.

In the FFGC technique, performance of the BCP channel was degraded because optical power fluctuates depending on the existence of bursts in neighboring channels. For a conventional direct current (DC) coupled receiver at 2.5 Gbps, the maximum δ was measured to be about 0.3 in our preliminary experiments. For an alternating current (AC) coupled receiver, this value was further improved up to 0.4 as shown in Fig. 3(b). But, further increase in the δ was not achieved. A higher δ is more advantageous because it means that more DB channels can be controlled by one BCP channel. However, limitations on the number of DB channels covered by one BCP channel cannot be avoided.

Figure 3(c) shows BER curves of the BCP channel and eye diagrams under selected conditions. Even for simultaneous operation of DB1 and DB2, the power penalty was 2.3 dB, and it was in the dynamic range of the AC-coupled receiver (–27 dBm to –10 dBm). The insets in Fig. 3(c) show unfamiliar eye diagrams. As the number of DB channels increases, the δ increases and the eyes close. In the case of simultaneous operation of two DB channels, the δ was 0.33.

IV. Conclusion

We experimentally demonstrated a technique to control the EDFA gain transient in optical burst networks. Optical power of the BCP channel was adjusted based on information in the BCP, and the BCP channel compensated deficiencies in power between two bursts. Based on the FFGC technique, the gain transient was suppressed from 2.0 dB to 0.3 dB. The BCP channel did not show a severe power penalty even for the 0.33 modulation index. The FFGC method could be applied to an OBS network to control the gain transients without introducing additional light sources; however, the number of the DB channels handled by one BCP channel must be considered carefully.

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