Novel optical packet with non-return-to-zero label and duobinary carrier-suppressed return-to-zero payload

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A novel packet format with non-return-to-zero (NRZ) label and duobinary carrier-suppressed return-to-zero (DCS-RZ) payload is proposed for optical packet switching networks. NRZ label is followed by DCS-RZ payload with a certain guard time. The spectra of the low-rate NRZ label locate around the optical carrier frequency where some parts of the corresponding spectra of the high-rate DCS-RZ payload have been suppressed due to DCS-RZ modulation. At the switching node, the label or payload extraction can be realized simply through an optical bandpass or notch filter respectively. The feasibility of the scheme is verified by the simulation on the famous photonic design platform designed by Virtual Photonics Inc. (VPI). The effects of optical filter bandwidth on the received signal quality are discussed by analyzing bit error rate (BER) and contrast ratio performances.

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Optical packet switching, which provides the smallest switching granularity and avoids the electronic bottleneck, has been one of the hottest research areas on the next-generation optical networks[1]. For the convenience of separating optical label and payload signals which will be sent to control unit and optical switch matrix respectively, several optical packet formats have been proposed, including bit-serial label[2−4], subcarrier multiplexing (SCM) label[5,6], optical code (OC) label[7], orthogonal-modulated label[8] and so on. For separating the label and payload, bit-serial label or OC label requires accurate timing to control optical gate or 1×2 optical switch. Orthogonal-modulated label, such as differential phase-shift keying (DPSK) label and amplitude-shift-keying (ASK) payload, requires to decrease the extinction ratio of payload to guarantee the correct detection of DPSK label. In addition, a wavelength conversion module is adopted to suppress the old DPSK label. The scheme of SCM label is the easiest method to realize the separation of label and payload by using optical filter, compared with other schemes. But the linear modulation of high-frequency subcarrrier imposes many great difficulties and the highest bit-rate of payload is limited by the subcarrier frequency. In this paper, a novel packet format with non-return-to-zero (NRZ) label and duobinary carrier-suppressed return-to-zero (DCS-RZ) payload will be introduced and the separation of label and payload can be realized by using optical filters.

DCS-RZ modulation suppresses the optical carrier frequency completely and reduces the signal bandwidth to the same as the NRZ modulation. DCS-RZ signal can enhance the nonlinearity and chromatic dispersion tolerance in the fiber transmission[9]. So the high bit-rate payload with DCS-RZ modulation can enhance the fiber transmission length. Another important characteristic of DCS-RZ payload is the notch-shaped spectrum around the optical carrier frequency. If the low bit-rate label is modulated with NRZ format on the same optical wavelength, the spectra of NRZ label will locate around the optical carrier frequency. NRZ modulation of the label guarantees the smallest bandwidth and decreases the interference between the label and payload caused by their spectral overlap. The spectral separation of NRZ label and DCS-RZ payload makes it possible to extract the label or payload by using an optical filter.

According to the introduction of the packet format with NRZ label and DCS-RZ payload, the module of optical packet generation consists of NRZ label generation and DCS-RZ payload generation. Figure 1 shows

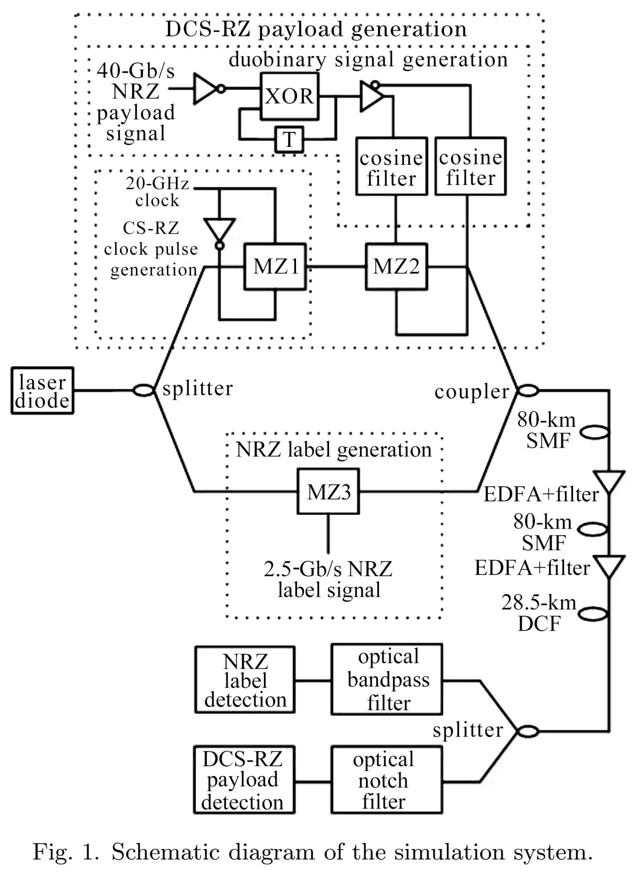

Fig. 1. Schematic diagram of the simulation system.

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the schematic diagram of the simulation system including optical packet generation, transmission, separation, and detection. As shown in Fig. 1, the continuous wave (CW) signal generated by the laser diode is split into the NRZ label generation module and the DCS-RZ payload generation module. NRZ label generation has no special to the normal intensity modulation. DCS-RZ payload generation consists of CS-RZ clock pulse generation and duobinary signal generation[9,10]. In the CS-RZ clock pulse generation section, the dual-drive Mach-Zehnder (MZ) optical modulator is driven by half-line-rate clock signal of payload with pull-push operation at the transmission null point. After the first MZ modulator (MZ1 in Fig. 1), a two-beat mode pulse train with alternate π phase flip is generated. In the duobinary signal generation section, the input NRZ payload signal is inverted and performs exclusive OR (XOR) operation with one bit delay feedback signal. The XOR output binary signal is converted into two parts of complementary three-level electrical duobinary signal by the cosine filters (also called duobinary filter). The transfer function $H(\omega)$ of cosine filter is given by

$$\begin{cases} H(\omega) = 2T\cos(\frac{T}{2}\omega) & |\omega| \leq \frac{\pi}{T} \\ H(\omega) = 0 & |\omega| > \frac{\pi}{T} \end{cases}, \quad (1)$$

where T is the payload bit duration. The second dual-drive MZ optical modulator (MZ2 in Fig. 1) is driven by the synchronized electrical duobinary signal with pull-push operation at the transmission null point.

In the long-haul fiber transmission, the fiber nonlinearity and chromatic dispersion are the two important factors of degrading the high bit-rate optical signal quality. In the proposed packet format, the payload with DCS-RZ format can tolerate the effects of fiber nonlinearity and chromatic dispersion. On the other hand, the low bit-rate of the NRZ label can alleviate the nonlinearity and dispersion effects. So the proposed packet format can guarantee the long-haul fiber transmission.

Because the NRZ label spectra are separated from the DCS-RZ payload spectra, the label or payload is easily extracted from the optical packet signal by using optical filter. The difference is that the label extraction is to use optical bandpass filter and the payload extraction is to use optical notch filter. The bandwidth of optical filter determines the extracted spectral ingredient and affects the contrast ratio of the required signal to suppress signal. The extracted NRZ label signal or DCS-RZ payload signal can be directly detected according to the pulse intensity. In the switching node, the extracted label will be fed into control unit to decide the output port and new label. The extracted payload will be sent to optical switch matrix and the contention resolution unit, and then be inserted with new label and transmitted to next node.

For verifying the feasibility of the proposed scheme, the simulation is performed on the famous photonic design platform designed by Virtual Photonics Inc. (VPI). The system diagram is shown in Fig. 1. The optical packets consist of 2.5-Gb/s label with NRZ modulation and 40-Gb/s payload with DCS-RZ modulation. The optical packets transmit through two spans of 80-km single-mode fiber (SMF), erbium-doped fiber amplifier (EDFA), and the corresponding amplifier noise filter. 28.5-km dispersion-compensation fiber (DCF) is used to decrease the total dispersion to zero before the label and payload detection. The wavelength of laser diode is 1552.52 nm. The dispersion values of SMF and DCF are 1.6 and −9 ps/(nm·km), respectively. The attenuation values of SMF and DCF are 0.2 and 0.5 dB/km, respectively. The fiber nonlinearity is also included in the fiber module according to the nonlinear Schrödinger equation. The optical filter used to extract NRZ label or DCS-RZ payload has Gaussian shape. In the simulation, the control unit, optical switch matrix, and other scheduling and switching modules in optical packet switching are excluded. The extracted label and payload are directly detected by the PIN receivers which have taken beat noise and thermal noise into account.

Figure 2(a) shows the pre-transmitted packet waveform that consists of 25.6-ns NRZ label, 6.4-ns guard time, and 64-ns DCS-RZ payload. Figure 2(b) shows the eye diagram of the DCS-RZ payload before the 3-dB coupler in Fig. 1. Figure 2(c) shows the spectra of the packet.

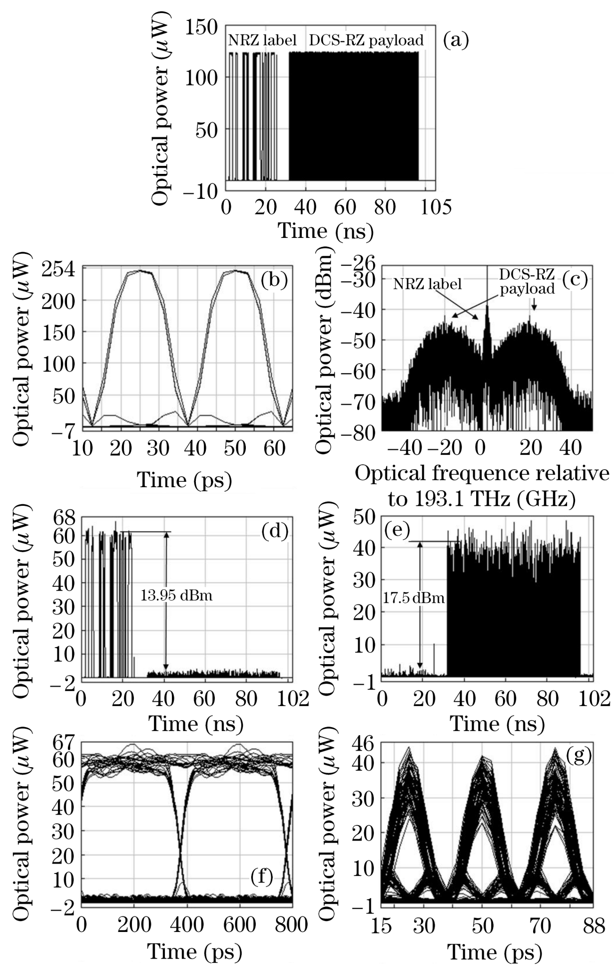

Fig. 2. (a) Packet waveform with 25.6-ns NRZ label, 6.4-ns guard time and 64-ns DCS-RZ payload; (b) eye diagram of DCS-RZ payload generated by the DCS-RZ payload generation; (c) spectra of the packet with 2.5-Gb/s NRZ label and 40-Gb/s DCS-RZ payload; (d) extracted NRZ label waveform by optical bandpass Gaussian filter with 10-GHz 3-dB bandwidth; (e) extracted DCS-RZ payload waveform by optical notch Gaussian filter with 40-GHz 3-dB bandwidth; (f) eye diagram of NRZ label; (g) eye diagram of DCS-RZ payload.

2.5-Gb/s NRZ-label spectra and 40-Gb/s DCS-RZ payload spectra are easily distinguished. Figure 2(d) shows the extracted label waveform by optical bandpass Gaussian filter with 10-GHz 3-dB bandwidth. The contrast ratio of label to payload reaches 13.95 dB. Figure 2(e) shows the extracted payload waveform by optical notch Gaussian filter with 40-GHz 3-dB bandwidth. The contrast ratio of payload to label reaches 17.5 dB. Figures 2(f) and (g) show the eye diagrams of the extracted label and payload respectively. The eye opening indicates that the signal quality is still acceptable after 188.5-km fiber transmission.

As mentioned above, the bandwidth of optical filter before the label or payload detection decides the extinction ratio. Figure 3 shows the relationship between the extinction ratio and optical filter bandwidth. With the increase of notch filter bandwidth, the contrast ratio of payload to label is not improved. With the increase of bandpass filter bandwidth, the contrast ratio of label to payload is degraded severely since more and more spectral ingredient of DCS-RZ payload are passed by the filter.

Optical filter not only decides the passed spectral ingredient but also changes the spectral shape of the extracted label or payload. The adjustment of spectral shape will affect the signal quality. For studying these affections, the bit error rate (BER) performance of the extracted label and payload is tested under different optical filter bandwidths. In these BER tests, only label or payload is considered. The tests neglect the error caused by the interference between label and payload due to insufficient contract ratio. Figure 4(a) shows the BER performance of the extracted NRZ label under the bandwidths of optical bandpass filter of 10, 20, 40 and 60 GHz. With the increase of the bandwidth, the BER performance is degraded slightly since the noise included in the optical bandpass filter increases. Figure 4(b) shows the BER performance of the extracted DCS-RZ payload under different bandwidths of optical notch filter. The BER performance is degraded when the bandwidth is changed from 10 to 20 GHz. But it is interesting that the BER performance is improved when the bandwidth is changed from 20 to 40 GHz or from 40 to 60 GHz. Especially, the BER performance of 60-GHz bandwidth is better than that of 10-GHz bandwidth. For distinguishing the performance changes caused by the transmission noise or by the spectral shape, the BER tests are performed before the fiber transmission. Figure 4 (c) shows the

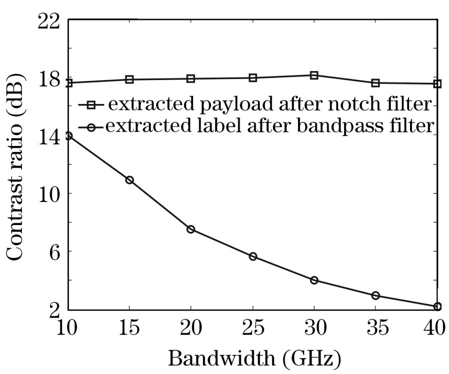

Fig. 3. Relationship between contrast ratio and optical filter bandwidth.

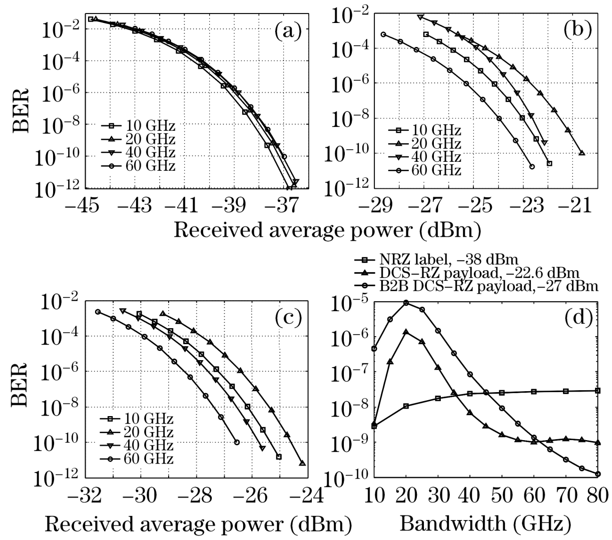

Fig. 4. (a) BER of NRZ label under the different bandwidths B of optical notch Gaussian filter; (b) BER of DCS-RZ payload under the different bandwidths B; (c) BER of back-to-back DCS-RZ payload under the different bandwidths B; (d) relationship between BER and optical filter bandwidth under the different average received optical power.

back-to-back BER performance of DCS-RZ payload. The similar results are obtained in Fig. 4(c) and 20-GHz BER performance is worse than 10, 40 and 60-GHz performance. It means that the change of spectral shape by optical notch filter is the main factor to affect the signal quality of the extracted payload. Figure 4(d) shows the relationship between BER and bandwidth in detail. It means that the signal quality of the extracted DCS-RZ can be improved by increasing the bandwidth of optical notch filter and adjusting the spectral shape. It is seen that the back-to-back BER curve is above the transmitted BER curve since the values of their average received power are different.

In all of the simulation systems, the most stringent requirement is 10-GHz 3-dB bandwidth optical bandpass filter although FP filter is the most potential candidate. The optical bandpass filter with narrow bandwidth can be replaced by electrical low-pass filter (LPF) after the detection of the whole packet signal. The NRZ label extraction by electrical low-pass filter (LPF) and the DCS-RZ payload extraction by optical notch filter will make the scheme more realizable.

The proposed optical packet format with NRZ label and DCS-RZ payload has high spectral efficiency by locating NRZ label spectra on the notch position of DCS-RZ spectra. The optical or electrical filter can separate the label and payload easily. The packet format has the ability of long-haul fiber transmission by tolerating the effects of the fiber nonlinearity and chromatic dispersion. The bandwidth design of optical or electrical filter is the key process of the proposed scheme. The extinction ratio of the extracted label or payload is determined by the filter bandwidth. The signal quality can be improved by using optical or electrical filter to shape the extracted signal spectra.

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