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ABSTRACT

Orthogonal modulation superimposes non-amplitude-modulated signals on Manchester coded or pulse position modulated amplitude shift keying (ASK) signals, allowing two traffic flows with different bit rates to be modulated on the same wavelength channel, and hence improving spectrum efficiency. Inspired by the orthogonal modulation, this paper proposes a novel modulation format, i.e., mark ratio modulation over pulse position modulation (PPM), which utilizes the mark ratio difference between the PPM symbols and the inverse PPM symbols to deliver an overlaid signal. Better than traditional orthogonal modulation, in the mark ratio modulation over PPM, both low-speed and high-speed traffic flows are modulated by ASK with no need to sacrifice the extinction ratio, while keeping the reception simple and easy. According to theoretical analysis and test, we found 4PPM is a good option, which can balance the trade-off between the PPM signal's effective bit rate and the mark ratio modulated signal's quality.

1. Introduction

Different from the traditional electrical packet switching, in which the low-speed label for control and the payload for data are framed together (for example, Internet protocol IP), the label in optical label switching (OLS) [1–3] is usually superimposed onto the optical payload packet for routing and forwarding. Often, the label and the payload are separated into two wavelength channels, making the intermediate nodes read the label easily and route/forward the packet without detecting the payload signal. The packets can be carried directly over the wavelength division multiplexing (WDM) layer without the need to be handled over any other layers, minimizing the overhead and thus simplifying network control and management. The efficiency, scalability and throughput of the network are all improved, especially in the case with a large number of intermediate nodes [2].

In the recent years, many types of OLS have been proposed, which are summarized and compared in [3]. Among these OLS methods, orthogonal modulation is widely applied [4–13]. Orthogonal modulation means superimposing a non-amplitude-modulated signal on an amplitude shift keying (ASK) signal. The non-amplitude modulation includes frequency shift keying (FSK) [4–5], phase shift keying (PSK) [6–12] and polarization shift keying (PolSK) [13]. As the label and the payload apply the orthogonal modulations, the combination of them could be superimposition without extra bandwidth resource, e.g., extra time slots or wavelength channels. Meanwhile, the separation of them could be easily achieved at the corresponding receivers.

During the orthogonal modulation, the amplitude fluctuation of the ASK signal induces unneglectable crosstalk to the superimposed non-amplitude-modulated signal. There are two methods to reduce such crosstalk. One way is to reduce the extinction ratio (ER) of the ASK signal at the cost of its performance degradation. The other way is to apply certain code formats to equalize the power of the ASK signal. The preferred candidates include Manchester code [4,7] and pulse position modulation (PPM) [9]. Besides the crosstalk reduction, the PPM also provides high tolerance to dispersion [14].

On the other hand, there are several drawbacks of the orthogonal modulation. Firstly, it requires double modulation, which increases the cost and the loss. Secondly, all non-amplitude-modulated signals require ASK-conversion before photodetectors. A Mach-Zehnder delay interferometer (MZDI), an optical filter and a polarization splitter perform as a convertor for differential PSK (DPSK), FSK and PolSK, respectively. For the PSK, the conversion is more complicated as an oscillator is needed to generate a reference optical carrier. Thirdly, compared with the ASK, the non-amplitude modulation brings some problems. The DPSK requires pre-coding as the received data after the MZDI is differentially encoded, and the MZDI is not transparent to the bit rate. The PolSK signal suffers from polarization mode dispersion and polarization rotation. The FSK requires two wavelengths, causing more

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dispersion. Finally, non-amplitude signals could be regarded as multiplexing with two opposite ASK signals. As a result, a non-amplitude modulated signal occupies two channels, which might be two orthogonal phases, two polarization states or two wavelengths.

To overcome the drawbacks of the orthogonal modulation, a novel modulation scheme, referred to as mark ratio modulation over PPM, is proposed in this paper, which utilizes the mark ratio difference between the PPM symbols and inverse PPM symbols to deliver an overlaid signal. Different from traditional orthogonal modulations, the proposed mark ratio over PPM modulation modulates two signals only by one conventional ASK modulator. It does not need two modulators or non-amplitude modulation so the operation cost and complexity could be reduced. To the best of our knowledge, it is for the first time to propose mark ratio modulation. To support the OLS, the label (the low-speed traffic flow) and the payload (the high-speed traffic flow) are combined by using an XOR operation and amplitude-modulated into one optical packet without using any extra time slot or wavelength channel. The simulation results verify the feasibility of the proposed mark ratio modulation over PPM.

2. Mark ratio modulation over PPM

Fig. 1 shows how the proposed mark ratio modulation over PPM applied for the OLS. In the source node, the payload is PPM coded and then combined with the label by the XOR operation. The combination (i.e. XOR result) is ASK-modulated onto an optical carrier as an optical packet. There is no ER limitation for the ASK modulation. The bit rate of the label signal is much lower than that of the payload signal. When the optical packet arrives at one node, part of power is split into a label reader. The label reader uses a conventional ASK receiver to detect the label signal. If the label shows that the node is not the destination, the optical packet is forwarded to the next node according to the label information. Once it reaches the destination node, the optical packet is sent to the payload receiver. The payload receiver is followed by a PPM decoder to recover the origin payload data.

To reduce the crosstalk to the overlaid label signal, the PPM is applied for the payload, as the same as the schemes in [4,7,9]. In each PPM symbol, there is only one pulse whose position represents the information this PPM symbol carries. *N*PPM is referred to the case where *N* possible pulse positions in each symbol. Each *N*PPM symbol contains $\log_2 N$ bits and the code efficiency is $(\log_2 N)/N$. Manchester code could be regarded as 2PPM and its code efficiency is 50%. The code efficiency of 4PPM is also 50%. When the *N* becomes larger, the code efficiency of the *N*PPM decreases. As a result, in this paper we consider the payload employs 4PPM, representing the highest code efficiency that *N*PPM can achieve.

Fig. 2(a) shows one way of mark ratio modulation over 4PPM. The payload applies 4PPM. One 4PPM signal maps two bits into a symbol with one pulse, which may appear in four possible positions. The first bit is combined with clock signal 1, which has the doubled frequency of the final 4PPM signal, by XOR operation to generate a double-frequency Manchester coded signal. The second bit is combined with clock signal 2 with the same frequency as the final 4PPM signal by XOR operation to generate a Manchester coded signal. Then the two generated Manchester coded signals are combined by AND operation to generate a 4PPM signal, which is further combined with the label data by XOR operation. As the bit rate of the label is typically much lower than that of the payload, each label bit covers multiple 4PPM symbols. If the label data is “0″, the final signal remains a 4PPM signal. Otherwise, the final signal is changed to an inverse 4PPM signal. The position of the pulse or the hollow depends on the payload data, so the payload data is modulated in 4PPM (or inverse 4PPM) format. The mark ratio of the 4PPM is 25% and the mark ratio of the inverse 4PPM is 75%. The final format (4PPM or inverse 4PPM) depends on the label data, which is referred to as mark ratio modulation. Obviously, the inverse 4PPM symbols have a higher mark ratio and hence have higher power compared with the 4PPM symbols. Such a power difference results into an amplitude difference when the signal passes through a low-pass filter. The low-pass filter acts as an integrator which smooths the pulses and the hollows (i.e., removes the position information). As a result, the overlaid mark ratio modulated (MRM) signal, carrying the label

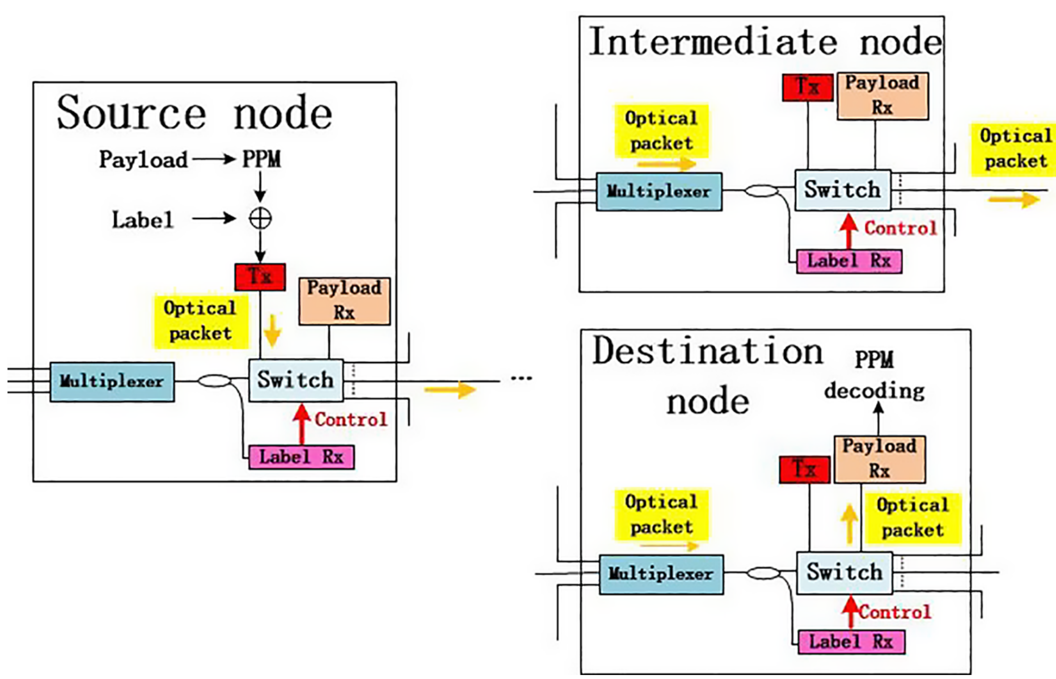

Fig. 1. The proposed mark ratio modulation over PPM for optical label switching. Tx: Transmitter; Rx: Receiver; PPM: Pulse position modulation.

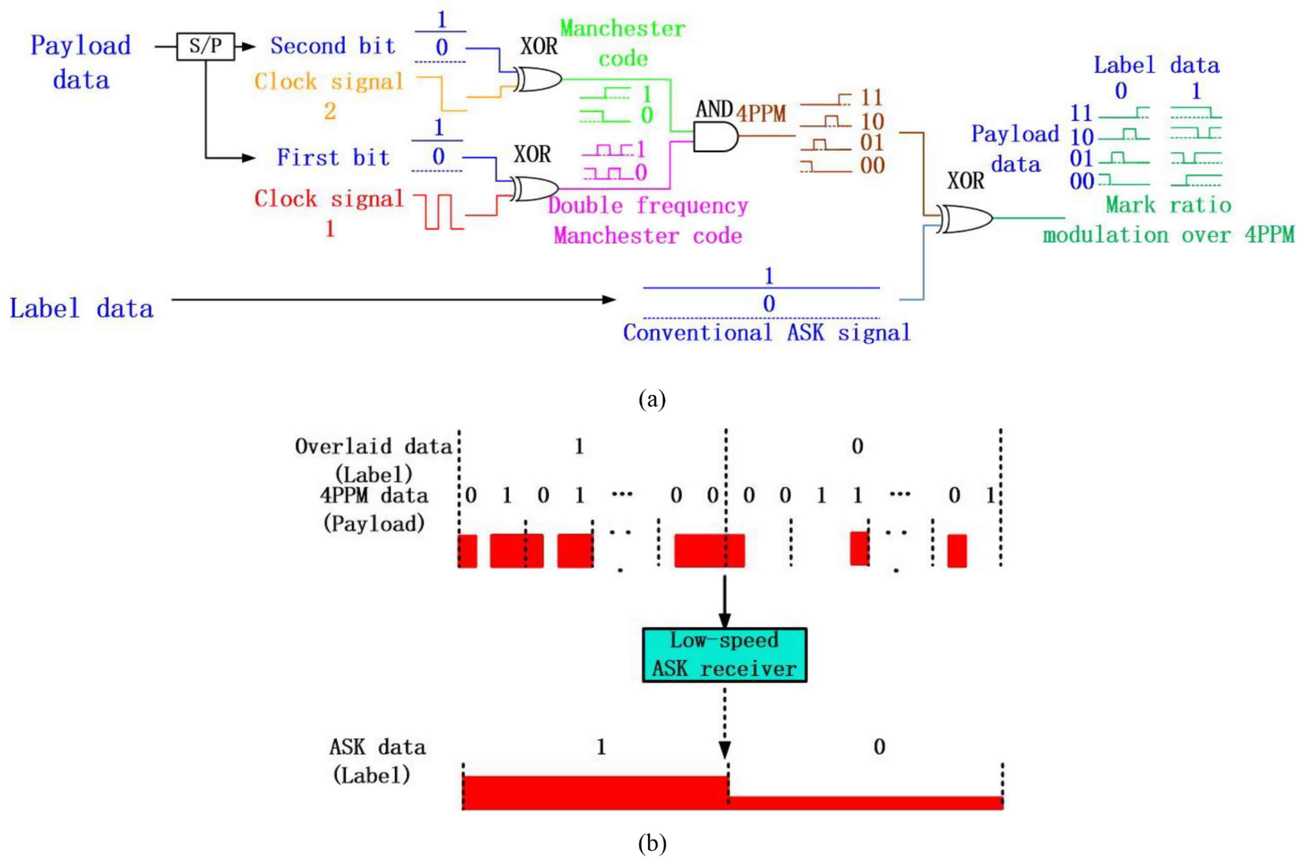

Fig. 2. (a) The generation reception of mark ratio modulation over 4PPM and (b) the reception for the overlaid mark ratio modulated signal (label signal).

information, becomes ASK modulated after passing the low-pass filter and can be received directly by an ASK receiver, as shown in Fig. 2(b). The PPM symbols and the inverse PPM symbols are converted to low-level and high-level square waves, respectively.

The *N*PPM uses pulse positions to express the information. When *N* is larger than 2, no confusion is induced even some PPM symbols are changed to inverse ones. However, it does not work for 2PPM (i.e., Manchester code). The mark ratio difference between the PPM symbols and the inverse PPM symbols can be used to deliver an overlaid signal. The mark ratio modulation induces very low crosstalk to the PPM signal. The ER of the PPM signal is determined by the index of the intensity modulation. The ER of the overlaid signal relates to both the ER and the mark raito of the PPM signal as its modulation is from the mark difference. The mark ratio is $1/N$ of the *N*PPM and $(N\text{-}1)/N$ of the inverse *N*PPM, so the maximum ER of the overlaid signal is theoretically equal to $10\log_{10}(N\text{-}1)$ dB when the ER of the PPM signal is ideally infinite. Assuming the power of mark is P_1 and the power of space is P_0, the ER of the PPM signal equals to $10\log_{10}(P_1/P_0)$ and the ER of the overlaid mark ratio modulated signal equals to $10\log_{10}[(N\text{-}1)\ P_1 + P_0]/[(N-1)\ P_0 + P_1]$. The PPM signal's ER is not affected by the value of *N*. It should be kept as high as possible which is good for both the overlaid mark ratio modulated signal and PPM signal.

3. Performance evaluation

To show the feasibility, the proposed mark ratio modulation over PPM is tested by simulation carried out by Optisystem and the setup is shown in Fig. 3. One pseudo random binary sequence (PRBS) is coded in 4PPM (payload). Then it is combined with another PRBS, which is used as the overlaid MRM signal (label), by XOR operation. The two signals are of different bit rates and the bit rate ratio of the overlaid MRM signal to the PPM signal is a key parameter for the proposed mark ratio modulation over PPM. In the test, such a bit rate ratio is set as 1:8, 1:4 and 1:2, respectively. The binary sequence generated by the XOR operation is a 4PPM signal with an overlaid MRM signal, which is loaded into a pattern generator in the Optisystem. The pattern generator outputs a PPM signal (with an overlaid MRM signal) whose bit rate is set as 10 Gb/s, 20 Gb/s, and 40 Gb/s, respectively. The signal is then externally modulated onto an optical carrier by a Mach-Zehnder modulator (MZM). The rising time and falling time are 10% of the bit period and the ER of the signal is set as 14 dB. A variable optical attenuator is used after the MZM to adjust the optical power for testing. The optical signal finally arrives at a photodetector for detection. The detected electrical signal is divided into two branches. One is the 4PPM signal (payload) and the other is sent to a low-pass filter for label receiving. The cutoff frequency of the low-pass filter is set to 75% of the corresponding bit rate.

The tested mark ratio modulation over 20 Gb/s 4PPM signals are shown in Fig. 4, where the spectrum is shown in the left column. For mark ratio modulation over PPM, the spectrum has two peaks. The peak in the high-frequency domain corresponds to the 4PPM signal as the PPM suppresses the low- frequency component. The peak in the low-frequency domain corresponds to the overlaid MRM signal. The overlaid MRM signal can be recovered by picking up the low-frequency peak with a low-pass filter. When the bit rate of the overlaid MRM signal increases, the two peaks become closer and the signal separation becomes more difficult as the overlaid MRM signal overlaps with more

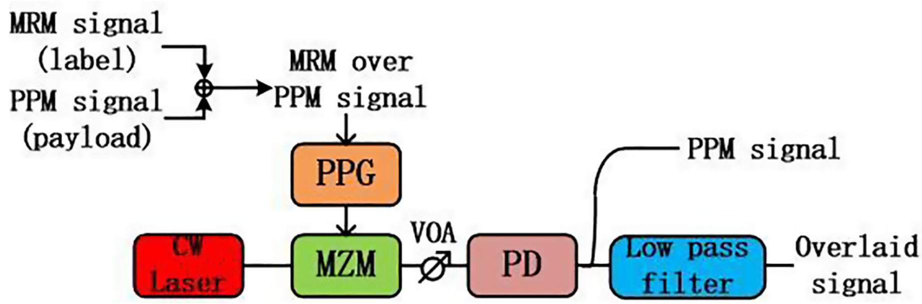

Fig. 3. Simulation setup. PPG: programmable pattern generator; CW laser: continuous wave laser; MZM: Mach-Zehnder mdoulator; VOA: variable optical attenuator; PD: photodetector.

low-frequency components of the 4PPM signal. As a result, the overlaid MRM signal with the higher bit rate shows worse performance, as shown in the upper part of the right column of each subfigure in Fig. 4. According to the eye-diagrams shown in the lower part of the right column of each subfigure in Fig. 4, the 4PPM signal shows the same performance no matter which bit rate of the overlaid MRM signal is. The impact of the crosstalk from the overlaid MRM signal on the 4PPM can be ignored.

Fig. 5 depicts the simulated bit error rate (BER) results for 10 Gb/s, 20 Gb/s and 40 Gb/s mark ratio modulation over 4PPM signals. The performance of the overlaid MRM signals relates mainly with the bit rate ratio of the MRM signals to the 4PPM signals. When the bit rate ratio is 1:8, the MRM signals show better performance than the 4PPM signals. When the bit rate ratio is increased, the MRM signals suffer obvious degradation and even cause BER floors. In each subfigure, the 4PPM signals under different bit rate ratios show almost the same performance. That is because the mark ratio modulation induces little crosstalk to the 4PPM signals.

In summary, the PPM signal does not suffer from the mark ratio modulation, but the overlaid MRM signal does. The MRM signal's degradation attributes to two key factors.

The first factor is N, which is the number of the possible positions in each NPPM symbol. N determines the maximum ER of the overlaid MRM signal as $10\log_{10}(N\text{-}1)$ dB. Increasing N could increase the ER of the overlaid MRM signal but at the cost of reducing the code efficiency of the NPPM signal to $(\log_2 N)/N$, which reflects the effective bit rate. The performance of the MRM signals could be improved if 4PPM is changed to 8PPM because the maximum ER is increased from 4.77 dB to 8.45 dB. However, as shown in the results, the MRM signal over 4PPM is able to achieve a lower sensitivity compared with the PPM signal. The main factor that limits the power budget is PPM signal transmission, so it might not be worth sacrificing the PPM signal's effective bit rate for the further improvement of the overlaid MRM signal. $N = 4$ is a good option which balances the NPPM signal's effective bit rate and the overlaid MRM signal's quality. The code efficiency of 4PPM reaches 50%, which is the same as widely applied Manchester code (equivalent to 2PPM).

The second factor is the bit rate ratio of the overlaid MRM signal to the PPM signal. The lower bit rate ratio means less overlap of two signals in the spectrum and thus less crosstalk to the overlaid MRM signal. In label switching, the label signal usually has a much lower bit rate compared to the payload signal. In asynchronous transfer mode (ATM) and synchronous optical network (SONET), the bit rate ratio of the label to the payload in one frame is 5/48 and 3/87, respectively. In the Ethernet and IP over Ethernet, the minimum bit rate ratio is 14/1500 and 20/1480, respectively. The simulation and results have shown that the acceptable level of the BER can be achieved for the MRM signals when the bit rate ratio is up to 1:4. The BER performance is expected to be further improved when the bit rate ratio is reduced.

4. Conclusion

A novel scheme, mark ratio modulation over PPM is proposed for the OLS, where the PPM signal is used for the payload and the overlaid mark ratio modulated signal is for the low-speed label. The main idea of the proposal modulation is to utilize a mark ratio difference of the PPM symbol and the inverse PPM symbol to deliver an overlaid signal. Through the mark ratio modulation over PPM, two signals can be modulated by only one ASK modulator, without the need of extra modulator or non-amplitude modulation, which has a great potential to reduce the operation cost and complexity. The performance of the mark ratio modulation over PPM is theoretically analyzed and then tested by simulation. The results have shown that the PPM signal for the payload does not suffer any degradation from the overlaid mark ratio modulation, while the overlaid mark ratio modulated signal could be degraded due to the limited ER and the crosstalk from the PPM signal. Considering a trade-off between the PPM signal's effective bit rate and the overlaid signal's quality, 4PPM can be a good option for the OLS applications. For future work, we plan to carry out proof-of-concept demonstration to experimentally verify the proposed mark ratio modulation over PPM.

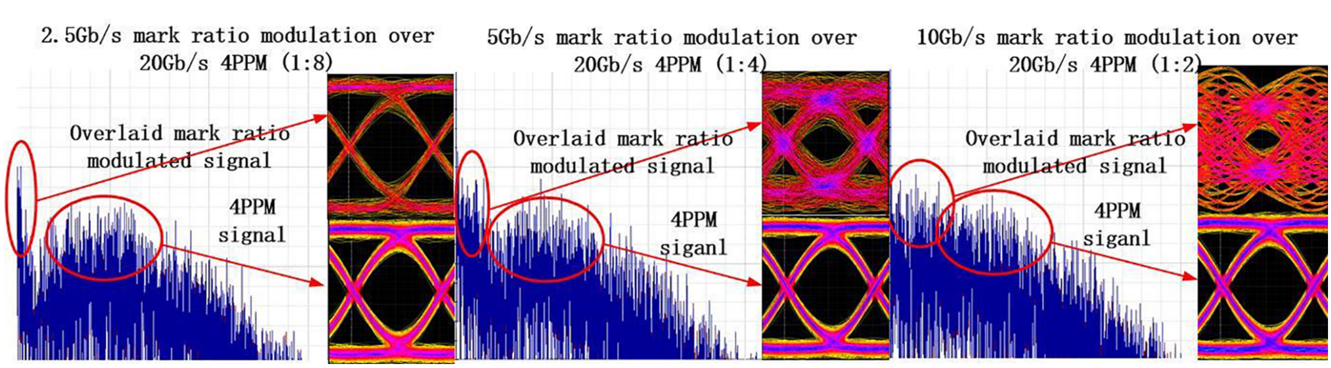

Fig. 4. Mark ratio modulation over 20 Gb/s 4PPM.

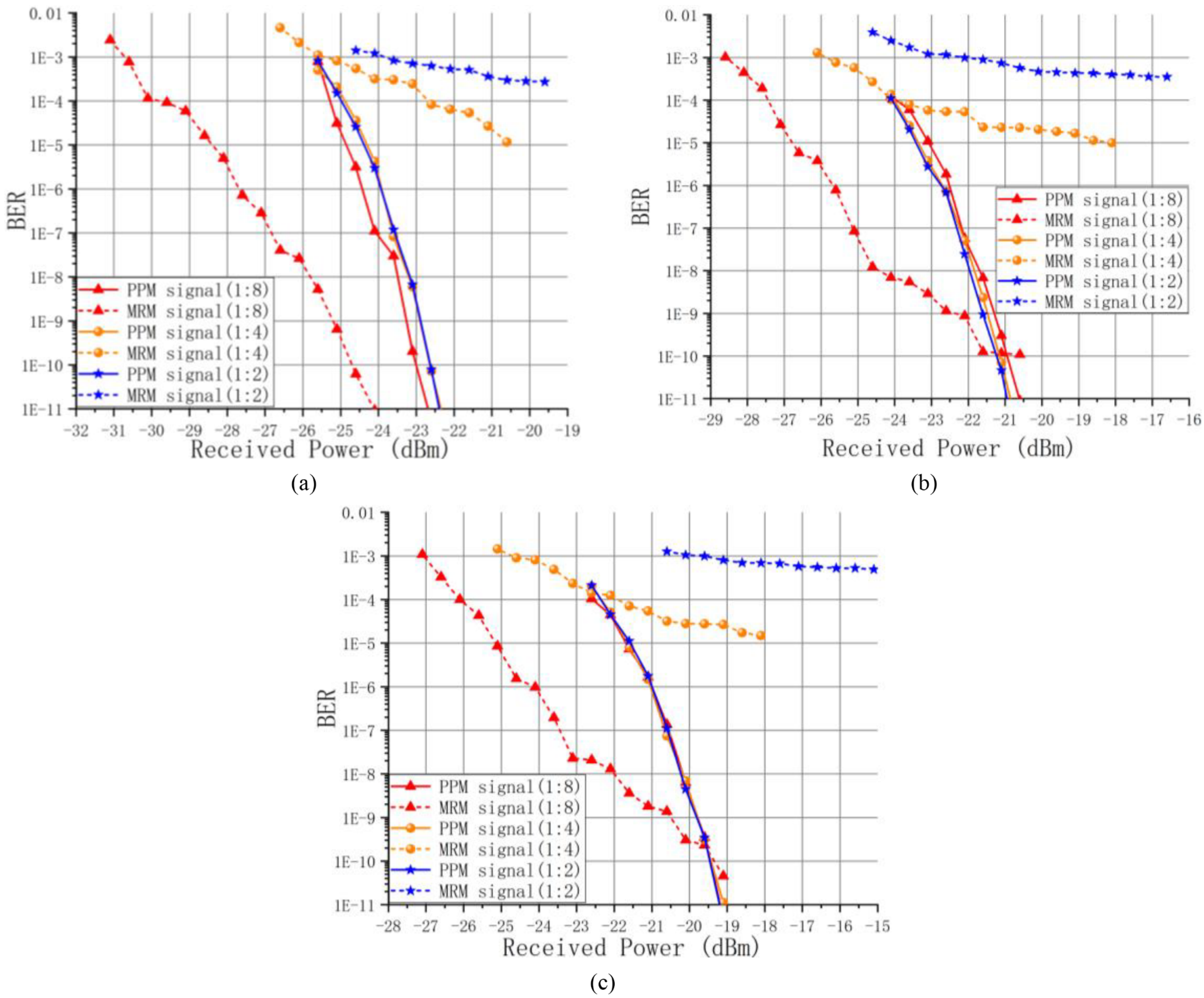

Fig. 5. The BER of (a) 10 Gb/s, (b) 20 Gb/s and (c) 40 Gb/s mark ratio modulation over 4PPM signals measured in the simulation.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.yofte.2020.102201.

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