First 100Gb/s Fine-Granularity Flexible-Rate PON Based on Discrete Multi-Tone and PAPR Optimization

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Abstract: We propose the first 100Gb/s fine-granularity flexible-rate PON based on discrete multi-tone and PAPR optimization. The proposed flexible-rate PON can achieve the widest-range rate adjustment from 25Gb/s to 100Gb/s with a granularity of $\sim$ 50Mbit/s under the optical power budget from 36dB to 26dB.

1. Introduction

To meet rapidly growing customer-traffic demands, 50Gb/s passive optical networks (50G-PONs) have been standardized as the pivot of the next-generation optical access [1]. Although digital signal processing (DSP) is applied in the PONs for the first time, the optical power budget of 50G-PONs is still on the brink of requirement [2]. Besides, one common imperfection for the commercially deployed PONs is that the rate to all optical network units (ONU) is uniform. In this case, the maximum rate is limited by the optical power budget of the worst-case ONU. Flexible-rate PONs have been proposed for delivering the flexible-rate data to match the optical path losses and the channel responses of the ONUs thanks to DSP, which can increase the overall throughput [3].

The first 100Gb/s flexible-rate PON was implemented by using the on-off keying (OOK) and four-level pulse amplitude modulation (PAM4) with flexible code rate [4]. However, the granularity of the rate adjustment is larger than 1Gb/s, which is quite coarse and cannot achieve the continuous adjustment from 100Gb/s to 50Gb/s. The probabilistic shaping can be applied to further decrease the granularity of the rate adjustment [5]. The floor of the rate adjustment is limited to the 35Gb/s by using probabilistic shaping with flexible code rate [6]. Discrete multi-tone (DMT) is a natural flexible modulation scheme [7], which is able to continuously adjust the rate by using bit allocation depending on the optical path losses and the channel responses. Unfortunately, high peak-to-average power ratio (PAPR) limits the performance of DMT in the peak-power-constrained optical systems, especially PONs [8]. How to reduce the PAPR of the DMT signal is crucial for its practical applications in PONs.

In this paper, we propose the first 100Gb/s fine-granularity flexible-rate PON and report on the experimental results using 10G direct-modulated laser (DML), semiconductor optical amplifier (SOA), and 20G PIN. The main contributions of this paper are: (1) using DMT to achieve a finer granularity for rate adjustment; (2) proposing PAPR optimization to improve the optical power budget; (3) demonstrating a rate adjustment of wide range up to 75Gb/s, i.e. 25Gb/s-100Gb/s.

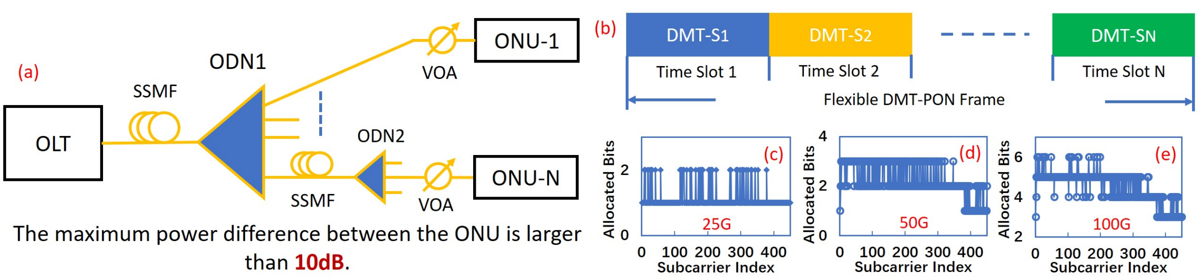

Fig. 1. (a) Schematic diagram of PON; (b) Flexible-rate DMT-PON frame; (c)-(e) Allocated bits for 25Gb/s, 50Gb/s, and 100Gb/s ONUs.

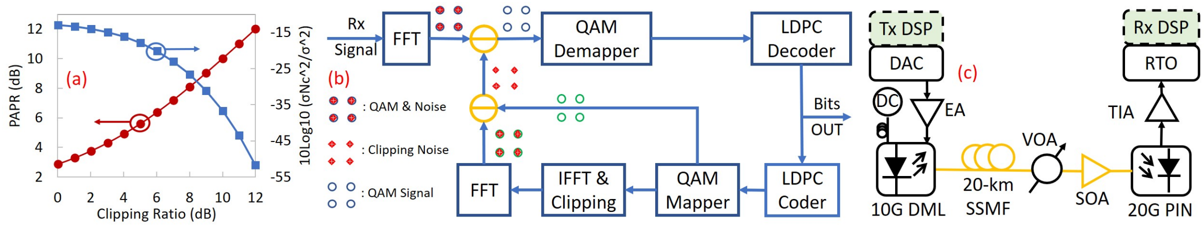

Fig. 2. (a) The PAPR (red circle) and clipping noise (blue square) versus clipping ratio for the DMT; (b) Schematic diagram of the clipping-noise cancellation (CNC) algorithms for the DMT with clipping operation; (c) Experimental setups of 100Gb/s flexible-rate DMT-PON.

2. Flexible-Rate PON and PAPR Optimization

The schematic diagram of PON is depicted in the Fig. 1 (a). In the actual situation, the optical signals for the different ONUs pass different number of optical distribution networks (ODNs) and different length of SSMF, leading to different optical path losses. Based on the on-hand statistic of the existing PONs, the maximum difference of optical path losses between the ONUs is usually larger than 10dB. The rate of current deployed PONs is limited by the worst-case optical path loss, for that each ONU works at the same pre-defined rate, which implies an insufficiently exploitation of the power and bandwidth resources. Fig. 1 (b) shows the flexible-rate DMT-PON frame, which can achieve the higher overall throughput. DMT-PON frame is an extension of the TDM frame where the DMT subframe with maximum spectral efficiency S_i is assigned to i-th time slot depending on its optical path loss and channel response. The calculated bit allocation for 25Gb/s, 50Gb/s, and 100Gb/s ONUs are demonstrated in the Fig. 1(c), Fig. 1(d), and Fig. 1(e). In the 100Gb/s flexible-rate DMT-PON, the sample rate is set to 50GSa/s for all the ONUs. When the size of fast-Fourier transform (FFT) is set to N, the total target bits per DMT symbol is equal to target average bits per sample times N, which are $2N$ bits, N bits, and $N/2$ bits for 100Gb/s, 50Gb/s, and 25Gb/s ONUs. The rate of the ONU can be adjusted by changing the target total bits with a granularity of one bit. As a result, the granularity of the rate adjustment can be calculated by $(50/N)$Gb/s.

To reduce the PAPR, symmetric clipping operation is a straightforward and practical method. Fig. 2 (a) shows the PAPR (red circle) and clipping noise (blue square) versus clipping ratio for the DMT, which offers the clear evidence of the effective reduction of PAPR via symmetric clipping operation, whereas the increase of the clipping noise at the same time. To improve the performance, we propose a clipping-noise-cancellation (CNC) algorithm to mitigate the clipping noise, as shown in Fig. 2 (b). In the proposed CNC algorithm, the clipping noise is accurately estimated and removed. Firstly, the received clipping DMT signal is sent into the FFT to obtain the recovered symbols $\boldsymbol{X}$, which contain the quadrature-amplitude modulation (QAM) symbols and the clipping noise. After the QAM demapper, the recovered bits are sent into the LDPC decoder to correct the error bits. Then, the corrected bits are used to regenerate the clipping DMT signal by the low-density-parity-check (LDPC) coder, QAM mapper, inverse FFT (IFFT) and clipping operation. After the FFT, the QAM signal with clipping noise subtracts the QAM signal to estimate the clipping noise. Obviously, the BER of the corrected bits determines the accuracy of the estimated clipping noise. Finally, the recovered symbols $\boldsymbol{X}$ subtract the estimated clipping noise to extract more-clear QAM. As a result, the symmetric clipping operation and the CNC algorithm can jointly mitigate the drawback of high PAPR in the flexible-rate DMT-PON.

3. Experimental Setups and Results

Fig. 2(c) depicts the experimental setups of 100Gb/s flexible-rate DMT-PON. At the transmitter end, the digital DMT signal was generated by offline Tx DSP using MATLAB. The random bit sequence was firstly encoded by the LDPC with 20% overhead. After interleaving operation, bit allocation and power allocation were implemented based on the estimated signal-to-noise ratios (SNRs) for generating the QAM symbols. Then, the generated QAM symbols were fed into IFFT with size of 1024 to generate the digital DMT signal. The indices of the valid subcarriers are from 1 to 450 for avoiding the serious high-frequency distortions. Finally, the peaks of the digital DMT signal were clipped for reducing the PAPR. Digital-to-analog converter (DAC) converted the digital DMT signal into an analogue electrical signal, which has a maximum sampling rate of 90GSa/s and a 3dB bandwidth of 16GHz. After resampling operation, the sample rate of the analogue electrical signal is 50GSa/s. The link rate of DMT signal can be adjusted from 100Gb/s to 25Gb/s with a granularity of approximately $(50/1024)$Gb/s $\approx$ 50Mbit/s. An electrical amplifier was used to amplify the analogue electrical signal. Then, the amplified electrical signal was modulated on 1310nm optical carrier to generate an optical DMT signal using the 10G DML. The optical DMT signal was launched into 20km standard single-mode fiber (SSMF) with launch optical power of 9dBm. At the receiver end, we used a variable optical attenuator (VOA) to change the received optical power (ROP). An

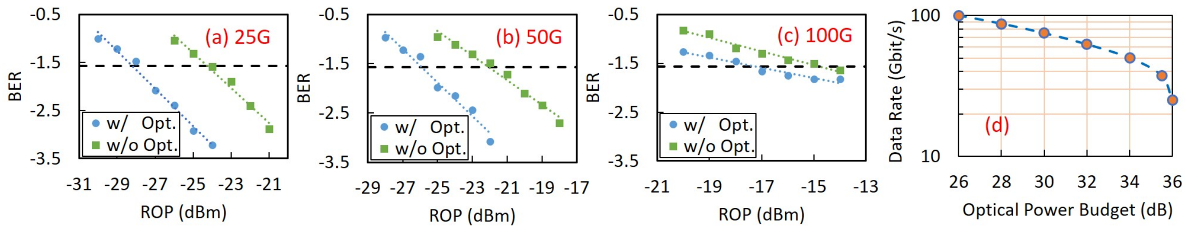

Fig. 3. (a)-(c) The BER versus ROP for the ONUs with the rate of 25Gb/s, 50Gb/s, and 100Gb/s in the flexible-rate DMT-PON; (d) The rate versus optical power budget at the 20% SD-FEC limit for the ONUs in the flexible-rate DMT-PON. The dashed black lines denote the 20% SD-FEC limit.

SOA was used to amplify the optical signal. A 20G PIN with transimpedance amplifier was used to convert the optical signal into an electrical signal. Then, the electrical signal was digitized by an 80GSa/s real-time oscilloscope (RTO) with a cutoff frequency of 36GHz. Finally, the offline Rx DSP at the receiver end was used to recover the digital signal into the transmitted bits. The Rx DSP should obtain the parameters of bit allocation, power allocation, and clipping ratio from the Tx DSP. The offline Rx DSP mainly consists of a time-domain equalizer for compensating the linear and nonlinear distortions, and the CNC algorithm for eliminating the clipping noise.

Fig. 3(a)-Fig. 3(c) show the BER versus ROP for ONUs with the rate of 25Gb/s, 50Gb/s, and 100Gb/s in the flexible-rate DMT-PON. For optimizing the PAPR, the optimized clipping ratios are set to 5dB, 5dB, and 7dB for 25Gb/s, 50Gb/s, and 100Gb/s DMT, respectively. With optimized PAPR, the ROP of the 25Gb/s, 50Gb/s, and 100Gb/s ONUs can achieve the approximately −27dB, −25dB, and −17dB under the 20% soft-decision forward-error correction (SD-FEC) limit. Therefore, the 25Gb/s, 50Gb/s, and 100Gb/s ONUs with the optimized PAPR achieve approximately 4dB, 4dB, and 2dB higher optical power budget than those without optimized PAPR. Fig. 3(d) shows the rate versus optical power budget at the 20% SD-FEC limit for the ONUs in the flexible-rate DMT-PON. The rate of ONUs can be adjusted from 100Gb/s to 25Gb/s in the flexible-rate DMT-PON, which demonstrates the fine-granularity and continuous rate adjustment. The maximum optical power budget is 36dB for the 25Gb/s ONUs, which have the maximum optical path loss, whereas the minimum optical power budget is 26dB for the 100Gb/s ONUs. The difference of optical power budget between the 25Gb/s and 100Gb/s ONUs is approximately 10dB, which meets the requirement of the existing PONs .

4. Conclusions

In this paper, we report the first 100Gb/s fine-granularity flexible-rate DMT-PON, which allows the continuous rate adjustment from 25Gb/s to 100Gb/s with the granularity of 50Mb/s. Meanwhile, we integrate the symmetric clipping operation and CNC algorithm to improve the PAPR of the DMT signal, and thus to earn at least 2dB gain of optical power budget.

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