Reduced State DRE for Clipping and Quantization Noise Elimination in Optical Interconnection with Low-resolution DAC

Mingzhu Yin(1), Weihao Ni(1), Fan Li(1), Xingwen Yi(1), Zhaohui Li(1), Chao Lu(1)
(1) School of Electronics and Information Technology, Guangdong Provincial Key Laboratory of Opto-Electronic Information Processing Chips and Systems, Sun Yat-Sen University, Guangzhou 510275, China and Southern Marine Science and Engineering Guangdong Laboratory (Zhuhai), Zhuhai 519000, China, lifan39@mail.sysu.edu.cn.

Abstract *Reduced state DRE for clipping-and-quantization noise elimination is studied with 3-bit DAC. Experiment-results indicate that 99.2% computational complexity reduction can be achieved for 40Gbaud PAM-8 signal, maintaining below 0.2dB ROP penalty at the 1×10^{-2} threshold, using 5-taps CIR-supported DRE with 5 soft-quantization possibilities.*

Introduction

High-order modulation format and transmitter digital signal processing (DSP) techniques, such as pre-equalization, pulse shaping, and look-up table, have been enabled by the high-resolution digital-to-analog converter (DAC) to improve the system capacity [1-4]. However, the adaption of high-resolution DAC will increase the whole system cost, including power consumption, footprint, and hardware cost [5, 6]. Reducing the DAC resolution appears to be a viable solution, while large quantization noise will be induced.

To address this issue, quantization noise elimination techniques, including noise shaping (NS), and digital resolution enhancer (DRE), have been investigated in high-speed optical communication [7-13]. Both techniques mitigate the quantization noise influence by redistributing the quantization noise between the signal band and the unused band. The required computational complexity of NS is low, while due to its feedback architecture, it will meet the problem of DAC overload, especially for the DAC resolution lower than 4 [8]. In contrast, the DRE can avoid the DAC overload and exhibits better noise shaping capability when the DAC resolution is lower than 4. However, the required computational complexity is much higher, especially when the length of the utilized channel impulse response (CIR) L and soft-quantization possibilities N exceed 3 [11-13]. The required high computational complexity of DRE makes it impractical for hardware implementation.

In this paper, a simplified DRE realized by reducing the survived state is studied. And both clipping and quantization noise are considered for the branch metric calculation for DAC output level selection to further improve the system performance that utilizes low-resolution DAC. To validate the effectiveness of this approach, simulation demonstrations have been conducted for 40Gbaud and 50Gbaud PAM-4 signals, and the measured signal-to-noise ratio (SNR) is observed. Simulation results show that DRE exhibits additional signal-to-noise ratio (SNR) improvement when the clipping noise is considered for branch metric calculation, particularly, the clipping ratio is large. The simplified DRE is effective for signal with and without clipping, and it can achieve over 95% computational complexity reduction with only 0.2 dB SNR penalty when the 5-taps CIR-supported DRE with 5 soft-quantization possibilities is utilized. Based on the simplified DRE for clipping and quantization noise elimination, 40Gbaud PAM-8 is experimentally studied and the experimental results show that 99.2 % computational complexity can be compressed, when 5-taps CIR-supported DRE with 5 soft-quantization possibilities is utilized, with below 0.2dB receiver optical power (ROP) penalty at the 1×10^{-2} threshold.

Reduced State Digital Resolution Enhancer

DRE can reduce the influence of quantization noise by reshaping the quantization noise corresponding to the combined inversely channel response and match filter (MF) [8-13]. In addition to DRE, clipping is also an effective solution to reduce the distortion resulting from quantization noise by directly reducing the signal peak-to-average power ratio (PAPR). They can work together to improve the system performance [12, 13]. To further improve the distortion elimination capability, a combined approach of clipping and DRE is studied, and the architecture is depicted

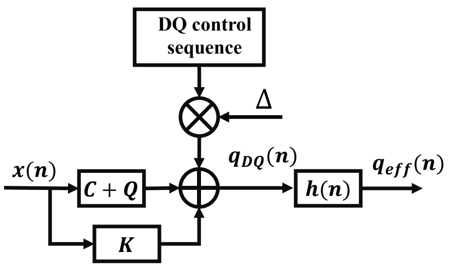

Fig. 1: The architecture of DRE for clipping and quantization noise elimination.

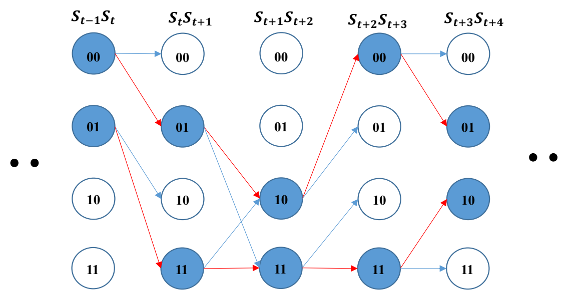

Fig.2: The principle of reduced state DRE for DAC output level section.

in Fig. 1, where the "C" and "Q" represent the clip and quantization processes. The "K" is the attenuation factor of signal after clipping and the attenuation factor can be calculated by: $K = E(x_c x) / E(x^2)$, where the x and x_c represent the signal before and after clipping. Both the clipping and quantization noise are considered for the branch metrics calculation, which is used for the DRE output quantization levels selection. Therefore, a performance improvement can be achieved compared to using either method independently.

The required computational complexity of DRE is high, as it is realized by the Viterbi algorithm [8-13]. To reduce the implementation complexity, a simplified DRE is studied and the principle is described in Fig. 2 with a simple example. In this example, the length of CIR *L* is 3 and the soft-quantization possibilities *N* is 2, which indicates that the survived state of DRE directly using Viterbi algorithm is *4* (N^{L-1}) [11]. In this simplified DRE algorithm, a state of *M* ($M<N^{L-1}$) is reserved. As shown in the example, *M=2* states are reserved. According to *M* surviving states in the current stage, states in the next stage can be generated. For each state in the next stage, single or multi-path will arrive. For the state with multi-path, only one path needs to be reserved. Then, *M* survived state with the only survived path can be found with the principle of minizine MSE. Repeating these processes, until the end of trellis is arrived.

Simulations

In this simulation, we emulate the performance of DRE technique for 40Gbaud and 50Gbaud PAM signal with the fixed 80Gsa/s 3-bit DAC without considering channel noise. Since the SNR of signal after DRE is high, we utilize PAM-4 signal to calculate the SNR to reflect DRE performance. The simulation results are shown in Fig. 3. Figs. 3(a) and 3(b) exhibit the simulation results of signals with various clipping ratios. Since the clipping can reduce the signal PAPR, obvious SNR improvement can be realized when the clipping is utilized. For the DRE shaping both

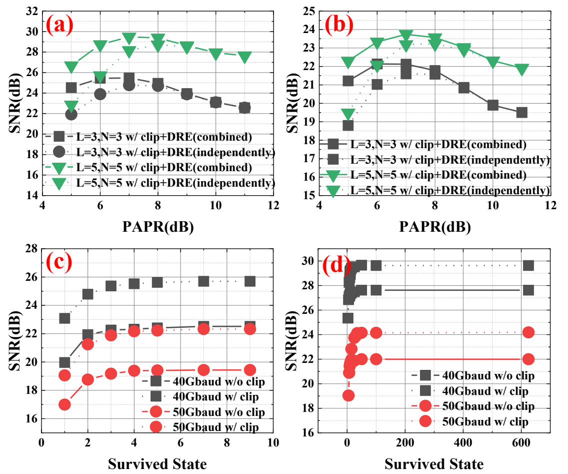

Fig.3: Simulation results of (a) 40Gbaud and (b) 50Gbaud PAM-4 signal with various clipping ratio. Simulation results of signal with simplified (c) 3-taps CIR-supported DRE with 3 soft-quantization possibilities and (d) 5-taps CIR-supported DRE with 5 soft-quantization possibilities.

Tab. 1: The required survived state for the simplified DRE with only 0.2 dB SNR penalty.

	40 Gbaud	50 Gbaud	Ratio
L=3,N=3, w/o clip	4	4	55%
L=3,N=3, w/ clip	4	4	55%
L=5,N=5, w/o clip	12	12	98.08%
L=5,N=5, w/ clip	15	25	96.8%

clipping and quantization noise, additional SNR improvement can be achieved compared with the signal that clipping and DRE work independently, especially for the signal with a serious clipping ratio. It is noted that there is an obvious SNR improvement, increasing the CIR length *L* and soft-quantization possibilities *N* as shown in Figs. 3(a) and (b). The increased CIR length *L* and soft-quantization possibilities *N* will lead to a significant computational complexity increase, as the required computational complexity of DRE is linearly related to the number of branch metrics of Viterbi algorithm (N^L). Increasing the CIR length *L* and soft-quantization possibilities *N* is uneconomic for optical interconnection. To cope

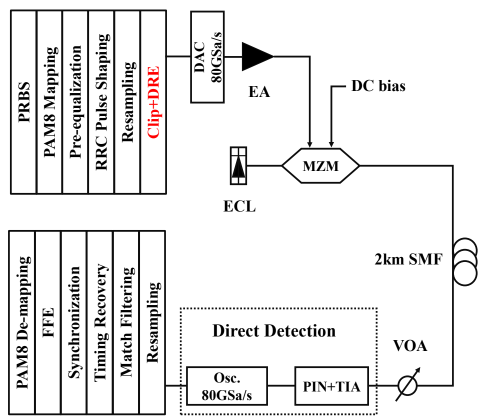

Fig.4: The offline DSPs and experimental setups.

with this problem, a simplified DRE is studied, and the simulation results are given in Figs. 3(c) and 3(d). Table 1 shows the required survived state for the simplified DRE with only 0.2 dB SNR penalty, and the corresponding mean reduced ratio compared to traditional DRE. It is worth noting that the simplified DRE can effectively reduce the required survived state, especially for the 5-taps CIR-supported DRE with 5 soft-quantization possibilities, which can bring beyond 95% computational complexity reduction with only below 0.2 dB SNR penalty. The required computational complexity of the simplified DRE makes it more practical for hardware implementation when the CIR length and soft-quantization possibilities are increased to improve the system performance.

Experimental Setups

To verify the effectiveness, 40Gbaud PAM-8 signals with various schemes are experimentally studied. The offline DSPs and experimental setups are shown in Fig. 4. The pre-equalization is first realized by a 19-taps FIR filter to reduce the influence of bandwidth limitation. After the pre-equalization, a 1/16 roll-off factor RRC filter is utilized to improve the system spectrum efficiency. Then, a 3-bit quantizer combined with DRE technique is used to emulate the quantization of DAC. After quantization, an 8-bit DAC with an 80 Gsa/s sampling rate is used to realize analog signal generation. A fixed 23 dB gains electrical amplifier is utilized to amplify the drive signal. Then, a MZM based on a quadrature point is used to realize the generation of optical signal. The generated optical signal is launched into a 2-km single-mode fiber (SMF). A PD is used to realize optical signal detection and the electric signal is detected by an 80 Gsa/s oscilloscope. For the receiver DSP, a MF implemented by a RRC filter with the same roll-off at the transmitter is used to improve the signal SNR, then synchronization and post-equalization implemented by a 39-taps feed-forward equalizer are used for data recovery.

Experimental Results

The experimental results of 40Gbaud PAM-8 signals with various schemes are shown in Fig. 5. Due to the implementation of pulse shaping and pre-equalization, serious quantization noise appears when 3-bit DAC is utilized for signal generation, as shown in Fig. 5(a). Obvious BER performance improvement can be observed as various DRE techniques are employed. Compared with the signal with the 3-taps CIR-supported DRE with 3 soft-quantization possibilities, obvious receiver sensitivity improvement is achieved at the 1×10^{-2} threshold

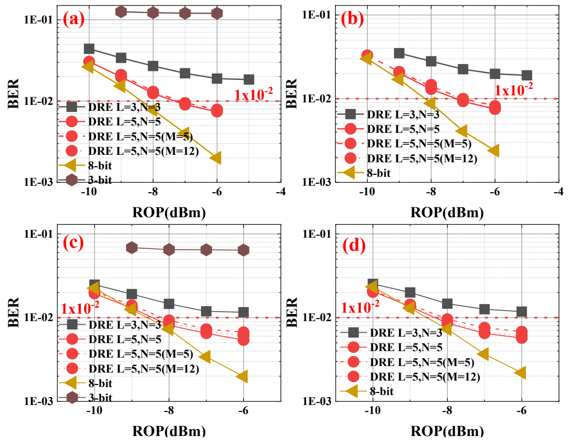

Fig.5: BER versus ROP of 40Gbaud PAM-8 signal over (a) OBTB and (b) 2-km SMF transmission. BER versus ROP of clipped 40Gbaud PAM-8 signal over (c) OBTB and (d) 2-km SMF transmission.

when the 5-taps CIR-supported DRE with 5 soft-quantization possibilities is utilized. For the signal with simplified DRE, even for the survived state *M* is 5 which indicates that 99.2% computational complexity reduction can be achieved compared to the traditional DRE algorithm, below 0.2 dB ROP penalty at the 1×10^{-2} threshold is observed. Based on the DRE for clipping and quantization noise elimination, we experimentally evaluate the effectiveness of the simplified case, and experimental results are shown in Figs. 5(c) and 5(d). We can find that the performance of signal generated by 3-bit DAC with the combined clipping and 5-taps CIR-supported DRE with 5 soft-quantization possibilities approaches the signal generated by the 8-bit DAC at the 1×10^{-2} threshold. And the penalty of the signal using the simplified DRE algorithm is still below 0.2dB.

Conclusions

In this paper, simplified DRE is studied for clipping and quantization noise elimination. Simulation results demonstrate that further SNR improvement can be observed for DRE when the clipping noise is considered for branch metric calculation, particularly the clipping ratio is serious. Based on the simplified DRE for clipping and quantization noise elimination, 40Gbaud PAM-8 is experimentally investigated. The experimental results prove that with the use of 5-taps CIR-supported DRE with 5 soft-quantization possibilities, computational complexity can be curtailed by 99.2%, with ROP penalty less than 0.2dB at the 1×10^{-2} threshold.

Acknowledgements

This work is partly supported by the National Key R&D Program of China (2018YFB1800704); National Natural Science Foundation of China (U2001601, 62271517, 62035018); Guangdong Basic and Applied Basic Research Foundation (2023B1515020003), Local Innovation and Research Teams Project of Guangdong Pearl River Talents Program (2017BT01X121).

References

[1] K. Zhong, X. Zhou, T. Gui, L. Tao, Y. Gao, W. Chen, J. Man, L. Zeng, A. P. T. Lau, and C. Lu, "Experimental study of PAM-4, CAP-16, and DMT for 100 Gb/s short reach optical transmission systems," Optics express 23, 1176-1189 (2015).

[2] L. Tao, Y. Ji, J. Liu, A. P. T. Lau, N. Chi, and C. Lu, "Advanced modulation formats for short reach optical communication systems," IEEE network 27, 6-13 (2013).

[3] F. Li, D. Zou, L. Ding, Y. Sun, J. Li, Q. Sui, L. Li, X. Yi, and Z. Li, "100 Gbit/s PAM4 signal transmission and reception for 2-km interconnect with adaptive notch filter for narrowband interference," Optics express 26, 24066-24074 (2018).

[4] D. Zou, F. Li, Z. Li, W. Wang, Q. Sui, Z. Cao, and Z. Li, "100G PAM-6 and PAM-8 signal transmission enabled by pre-chirping for 10-km intra-DCI utilizing MZM in C-band," Journal of Lightwave Technology 38, 3445-3453 (2020).

[5] S. Almonacil, F. Boitier, and P. Layec, "Performance model and design rules for optical systems employing low-resolution DAC/ADC," Journal of Lightwave Technology 38, 3007-3014 (2020).

[6] M. Kilic, and Y. Leblebici, "A DAC assisted speed enhancement technique for high resolution SAR ADC," in 2017 13th Conference on Ph. D. Research in Microelectronics and Electronics (PRIME)(IEEE2017), pp. 253-256.

[7] W. A. Ling, "Shaping quantization noise and clipping distortion in direct-detection discrete multitone," Journal of Lightwave technology 32, 1750-1758 (2014).

[8] L. Shu, Z. Yu, K. Sun, H. Huang, Z. Wan, and K. Xu, "Performance Investigation of Error-Feedback Noise Shaping in Low-Resolution High-Speed IM/DD and Coherent Transmission Systems," Journal of Lightwave Technology 40, 3669-3680 (2022).

[9] M. Yin, X. Wang, D. Zou, W. Wang, Q. Sui, and F. Li, "Low cost O-band inter-datacenter interconnect utilizing a 4-bit resolution digital-to-analog converter for PAM-4 signal generation," Optics Express 29, 31527-31536 (2021).

[10] C. Huang, H. Jin, M. Cheng, Q. Yang, D. Liu, M. Tang, and L. Deng, "Virtual-Carrier-Assisted 64QAM Millimetre-Wave Signal Generation Using Low-Resolution Digital-to-Analog Converter," in European Conference and Exhibition on Optical Communication(Optica Publishing Group2022), p. Tu5. 56.

[11] Y. Yoffe, G. Khanna, E. Wohlgemuth, E. De Man, B. Spinnler, N. Hanik, A. Napoli, and D. Sadot, "Low-resolution digital pre-compensation enabled by digital resolution enhancer," Journal of Lightwave Technology 37, 1543-1551 (2018).

[12] L. Shu, Z. Yu, Z. Wan, and K. Xu, "Application analysis of clipping and digital resolution enhancer in high-speed direct-detection PAM4 transmission," Optics Express 28, 17841-17852 (2020).

[13] M. van den Hout, S. van der Heide, and C. Okonkwo, "Digital resolution enhancer employing clipping for high-speed optical transmission," Journal of Lightwave Technology 38, 2897-2904 (2020).