On the Performance of Digital Resolution Enhancement and Waterfilling in Digital Subcarrier Multiplexing Systems with Low-Resolution DACs

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Abstract: Digital resolution enhancement is experimentally demonstrated for 800G 107 Gbaud 8-carrier PCS-256QAM employing waterfilling. 1.4 dB SNR and 1 dB Q^2-factor gains are obtained with a 4-bit DAC at 1.125 samples/symbol.

1. Introduction

The digital resolution enhancer (DRE) has been studied extensively as a means of improving the signal-to-quantization noise ratio (SQNR) of low-resolution DACs. Experimental demonstrations have shown significant performance gains over uniform quantization, for both coherent and direct-detection applications: e.g. for 4 bits of resolution, the DRE enabled 8 dB of quantization noise reduction at 2 samples/symbols with dual-polarization (DP) 64QAM 400G in [1], while a 2 dB reduction in required OSNR for 56 Gbaud PAM-4 transmission was achieved in [2]. The gains, however, are only obtainable at low resolutions, near or below the effective number of bits (ENOB) of the DAC. For state-of-the-art quantizers with 8-bit physical resolution and ∼5-6 ENOB, there is little advantage of DRE when operating at ≥6 bits. Moreover, its efficacy is highly dependent on the ratio of sampling rate over channel bandwidth: Since it operates by displacing quantization noise, it follows that the more out-of-band frequencies available, the better the SQNR improvement will be. Thus, the DRE can be considered as a method of relaxing DAC requirements, rather than increasing absolute performance of current transmission systems. It has been estimated that 20% power reduction can be obtained when lowering the resolution from 8 to 4 bits [3].

In this work we explore the performance gains of the DRE with 800G coherent digital subcarrier multiplexing (DSCM) in a high-baudrate, low sampling rate scenario. We operate at 107 Gbaud with a 120 Gsample/s DAC, for an oversampling ratio of 1.125. Our choice is motivated by the fact that we want to operate close to the capacity-maximizing symbol rate of the specific transceiver, while also reducing the oversampling rate for better power-efficiency [4]. Though our channel is bandwidth-limited and that represents a good use case for DRE, there is very little out-of-band frequency for noise displacement. As a result, we find that after applying DRE at a DAC resolution of 4 bits, a significant portion of the transferred quantization noise remains in-band (at high frequencies), resulting in a heavily colored SNR channel. We exploit these conditions by waterfilling the digital subcarriers to squeeze even more performance out of the channel, compared to DRE alone. With this approach, we show that DSCM results in an extra ∼0.4 dB in TRx SNR over single-carrier with DRE, enabling BER performance below the FEC limit at ∼30 dB OSNR.

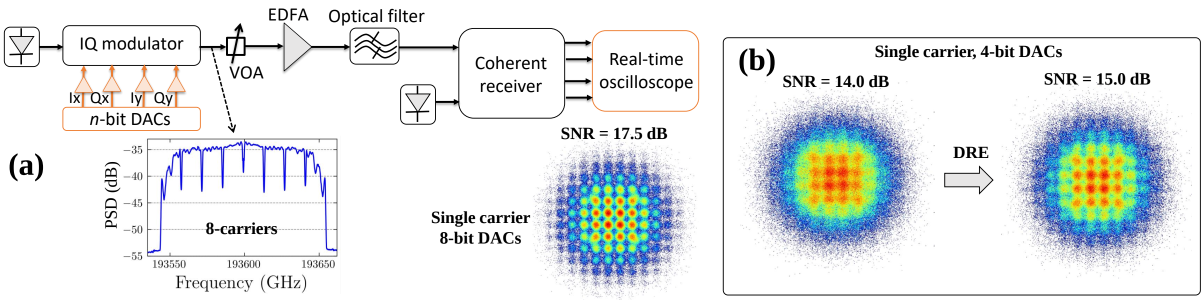

Fig. 1. (a) Experimental setup, insets show an example 8-carrier spectrum and PCS-256QAM constellation using 8-bit DAC; (b) Constellations using 4-bit DAC without and with DRE.

1.1. *Digital Resolution Enhancer Principle*

The DRE shapes the quantization noise power spectral density (PSD) by pushing noise outside the channel bandwidth. This is possible through an appropriate selection of the quantization levels, aiming at minimizing the mean squared error, $MSE = \frac{1}{N}\sum_{n=0}^{N-1}|q[n]*h[n]|^2$, where $q[n]$ is the quantization error at sample time n, and $h[n]$ is the equivalent channel filter. A trellis is used that selects the lowest MSE at the output of N samples. To keep complexity reasonable while still reaping the benefits of the scheme, we used a 5-tap FIR filter to emulate $h[n]$.

1.2. *Waterfilling and Global-SNR Metric*

Waterfilling aims to optimally adjust the power and entropy loading of the subcarriers, in order to maximize the channel capacity or system margin. We use the Global-SNR as a metric, which, just like the conventional SNR for single-carrier, is a proxy for the achievable capacity of the system. It therefore allows for direct comparison between signals with any number of carriers (including single). For an M-carrier system, it is given by: Global-SNR $= \prod_{m=1}^{M}[1+SNR_m]^{1/M} - 1$ [5].

2. Experimental Results and Discussion

The experimental setup is shown in Fig. 1, along with an example spectrum and constellations. For both single- and multi-carrier cases, DP PCS-256QAM was used with average entropy of 5.83, which yields 800 Gbit/s net throughput (with overhead included to account for FEC, pilots and framing). We emulated the DAC's reduced bit-resolution numerically and applied either uniform quantization or DRE. We used an optical back-to-back (B2B) setup with noise loading provided by an EDFA. The signal was coherently detected and the output electrical signals were captured by a 256 Gsample/s 8-bit real-time scope. Offline processing with Python-based DSP included synchronization, pilot-aided equalization and carrier recovery.

2.1. *Gain of DRE with Uniform-Entropy DSCM*

Fig. 2 shows the Global-SNR and Q^2-factor of single-carrier and DSCM as a function of DAC resolution, with and without DRE, at the highest OSNR. The gains in Global-SNR are only significant below 6 bits, i.e., when reducing the DAC resolution close to the original ENOB level. The insets show the signal and noise PSDs of the 8-DSCM signals with 4-bit resolution, with uniform quantization (left) and DRE (right). Clearly, the DRE noise shaping results in a much more colored SNR response. Without entropy-loading, this leads to more BER degradation at the side carriers and worse Q^2-factor compared to single-carrier.

2.2. *Exploiting DRE-induced Noise Coloring with Waterfilling*

In light of the above results, we explore the benefit of adding waterfilling, again at the highest OSNR value. Fig. 3(a) shows Global-SNR gains of single-carrier with DRE, as well as 8-carrier with and without DRE, over single-carrier with uniform quantization. Since the Global-SNR is independent of the modulation format and the use or not of waterfilling, for clarity we are not showing the curve of 8-carrier with entropy-loading. At 4-bit resolution, DRE gives ~1 dB and ~1.4 dB gains for single-carrier and 8-carrier cases respectively.

The uniformly quantized 8-carrier also shows gain w.r.t. single-carrier without DRE, owing to the noise coloring of the channel [5,6]. We note that at <6 bits the gain is smaller, since the noise PSDs are flatter at low resolutions with uniform quantization (see inset of Fig. 2(a)); in this case the performance of DSCM and single-carrier tends to be closer. This is also reflected in the corresponding line (solid blue) in Fig. 3(b), which shows the Q^2-factor gains versus the number of DAC bits: at 4 bits, 8-carrier without DRE and waterfilling shows similar performance with single-carrier. At higher DAC resolution, noise coloring causes more severe degradation on the side subcarriers for

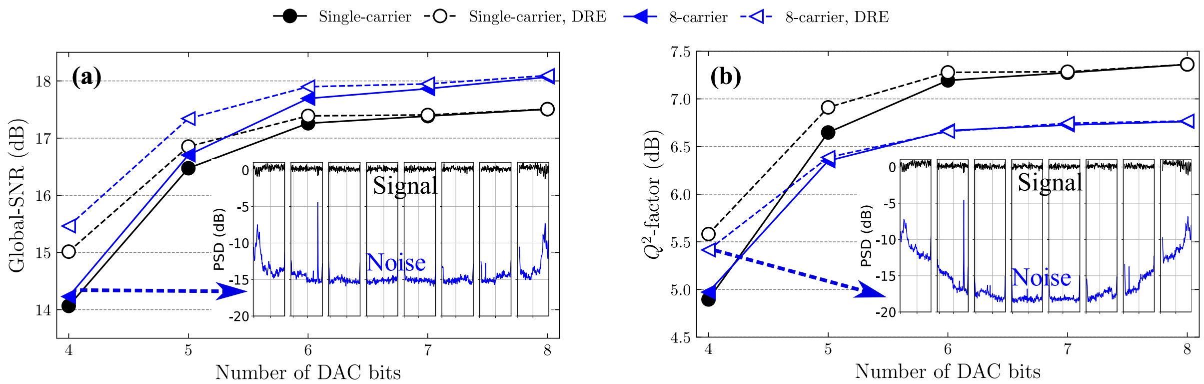

Fig. 2. (a) Global-SNR and (b) Q^2-factor versus the number of DAC bits, without and with DRE.

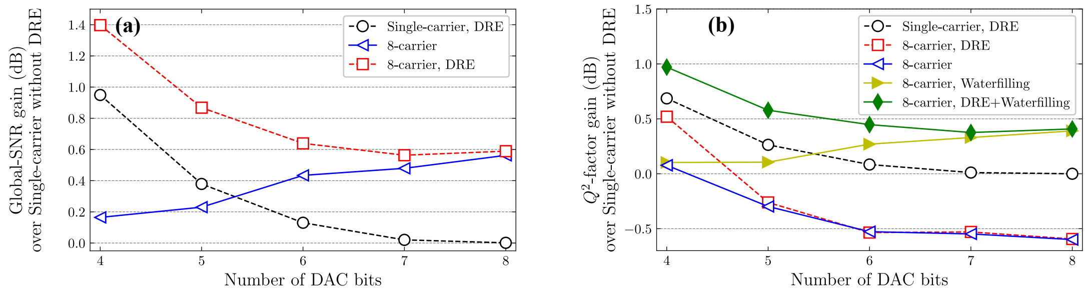

Fig. 3. (a) Global-SNR and (b) Q^2-factor gains (over single-carrier) versus the number of DAC bits, without and with DRE.

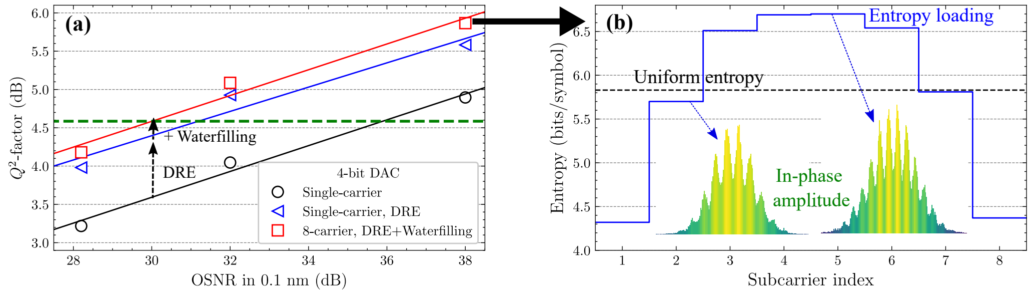

Fig. 4. (a) Q^2-factor versus OSNR using a 4-bit DAC, showing the benefits of DRE and waterfilling; (b) Entropy loading values mapped to subcarriers at highest OSNR.

the uniform-entropy 8-carrier signal, and thus there is performance loss. This loss is only reversed by the DRE at 4 bit resolution (red dotted line). By applying waterfilling, gain can still be achieved even without DRE, although it is insignificant at 4 and 5 bits (yellow line). Finally, the best performance is obtained when combining both DRE and waterfilling at 4 bit resolution (green line), achieving up to 1 dB Q^2-factor gain; the gain then reduces at higher number of bits.

So far the results for highest B2B OSNR were analyzed, indicating the TRx SNR improvement arising from the colored noise PSD. To investigate what happens after transmission-equivalent OSNR degradation, we introduced noise loading: Fig. 4(a) presents the Q^2-factor at different OSNR values, for 4-bit resolution. The performance of uniformly quantized single-carrier is plotted as a benchmark (black circles). The blue triangles correspond to single-carrier with DRE, showing a significant improvement, as expected. Further gain is obtained by applying waterfilling, this time with DSCM (red squares). We conclude that the bulk of the gain is derived from application of the DRE, while the addition of waterfilling further reduces the required (R)OSNR to achieve the FEC limit of $4.5 \cdot 10^{-2}$ by $\sim$1 dB (a $\sim$17% transmission reach increase). The achieved OSNR of 30 dB means we are able to transmit 800G over $\sim$600 km [5]. Fig. 4(b) illustrates the entropy loading values applied to each carrier of the 8-DSCM signal at the highest OSNR.

3. Conclusion

We have investigated the performance gains that can be achieved by combining DRE with waterfilled DSCM for an 800G transceiver. We found that the DRE is clearly beneficial only for low resolutions, while it also introduces colored noise in the TRx; by applying waterfilling over 8-DSCM, we achieved further performance improvement, enabling 1 dB ROSNR reduction vs single-carrier when both cases operate with 4-bit resolution enhanced by DRE.

References

1. Y. Yoffe *et al.*, “Low-Resolution Digital Pre-Compensation Enabled by Digital Resolution Enhancer,” *J. Light. Technol.*, vol. 37, no. 6, 2019.
2. L. Shu *et al.*, “Application analysis of clipping and digital resolution enhancer in high-speed direct-detection PAM4 transmission,” *Opt. Express*, vol. 28, no. 12, Jun 2020.
3. S. Almonacil, F. Boitier, and P. Layec, “Performance Model and Design Rules for Optical Systems Employing Low-Resolution DAC/ADC,” *J. Light. Technol.*, vol. 38, no. 11, 2020.
4. Z. Zhang *et al.*, “Coherent transceiver operating at 61-Gbaud/s,” *Opt. Express*, vol. 23, no. 15, Jul 2015.
5. T.-H. Nguyen *et al.*, “Quantifying the Gain of Entropy-Loaded Digital Multicarrier for Beyond 100 Gbaud Transmission Systems,” in *2021 Optical Fiber Communications Conference and Exhibition (OFC)*, 2021, p. F4D.1.
6. D. Che and W. Shieh, “Approaching the Capacity of Colored-SNR Optical Channels by Multicarrier Entropy Loading,” *J. Light. Technol.*, vol. 36, no. 1, 2018.