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and equally-spaced levels are generated. Then, the DSP is included with the purpose to apply the Nyquist filter (NyFil) that properly shapes the spectrum and the pre-emphasis filter (PEFil) compensating for the DAC sample-and-hold (S/H) and low-pass filtering (LPF). After the DSP, signals are analog-converted to obtain voltages driving the I/Q modulators. One of the modulated signals is polarization rotated and then a polarization-beam combiner generates the field $E_{tx}(t)$ with power P_{tx} launched in the link.

Fig. 1b shows details of the DSP. It is supposed to operate with resolution and rate much higher than the DAC ones to avoid DSP implementation limits. The DSP algorithms implement the NyFil, the *ArcSin* operation and the PEFil. The NyFil gives a square-root raised-cosine (*rcos*) shape to the spectrum of the input squared pulses (*sinc* spectra), hence the NyFil transfer function is:

$$H_{NyFil}(f) = \sqrt{\mathrm{rcos}_{\beta}(f)}\ \mathrm{sinc}^{-1}\left(\pi \tfrac{f}{R_s}\right) \quad (1)$$

where β is the *rcos* roll-off. We choose β=0.05 to limit the length of FIR filters in Rx equalizer. The other DSP filter is the PEFil compensating for the DAC S/H (the inverse of *sinc*) and for bandwidth limitation. Its shape is:

$$H_{PEFil}(f) = H_{LPF}^{-1}(f)\,\mathrm{sinc}^{-1}\left(\pi \tfrac{f}{R_{DAC}\cdot R_s}\right) \quad (2)$$

where $H_{LPF}(f)$ is the electrical transfer function of the DAC and R_{DAC} is the DAC rate in samples per symbol (SpS). Between the two filters, the DSP may include an *ArcSin* operation to compensate for the MZM sinusoidal trans-characteristics (see Fig. 1d). In case the *ArcSin* is ON, the DSP must implement separately the two filters, while, with *ArcSin* OFF, the DSP complexity can be limited implementing a single filter $H_{DSP}(f)=H_{NyFil}(f)\cdot H_{PEFil}(f)$. Therefore, in evaluating possible benefits of using *ArcSin*, drawbacks regarding DSP complexity must be taken into account. DSP includes also gains G_1 and G_2 setting *ArcSin* input range and controlling the DSP output range $\Delta V_{out,DSP}$, respectively.

Fig. 1c displays the model for the DAC. First, the signal at the DSP output is sub-sampled at the DAC working rate R_{DAC}=2 SpS[4,5]. Different values (4,5,6,8) are considered for the DAC resolution in number of bits (N_{bit}). The quantization operation implies some amount of signal clipping. We define the clipping percentage defined:

$$CP = 100 \cdot \frac{\Delta V_{out,DSP} - \Delta V_{DAC}}{\Delta V_{out,DSP}} \quad (3)$$

where $\Delta V_{out,DSP}$ is the range of $V_{out,DSP}$ and ΔV_{DAC} is the voltage interval over which the DAC operates. After the digital-to-analog conversion, we emulate the DAC electrical bandwidth limitation with a Bessel-5 LPF with BW_{DAC}=‰•R_s=16 GHz. The DAC output driver G_3 adjusts signal levels in order to set the *MD* of the following nested MZMs.

Tab. 1: Optimal CP (average on Δf) for different DAC resolutions with DSP *ArcSin* turned OFF/ON

N_{bit}	4	5	6	8
ArcSin OFF	29%	20%	14%	12%
ArcSin ON	36%	26%	20%	20%

Fig 1d describes the input/output trans-characteristics of each MZM composing the I/Q modulators. The *MD* is defined as shown in Fig. 1d insert. The considered model for MZMs includes also a finite extinction ratio (*ER*).

In the described Tx structure, gain G_1 is chosen in order to avoid any signal clipping in the DSP, even when the *ArcSin* operation is ON. The gain G_2 at the output of the DSP is used to tune the DAC *CP*, while the DAC driver G_3 defines $\Delta V_{out,DAC}$, hence controls the MZM *MD*.

Note that, when DSP *ArcSin* is turned ON, a perfect compensation of MZM sinusoidal electro-optics trans-characteristics can be obtained only when *CP*=0%, or when *CP*>0% in the absence of PEFil. In general, we change *CP*, and *MD* looking for the best system performance.

Tx optimization analysis

In order to optimize the DSP algorithm and DAC characteristics, we simulated the back-to-back setup displayed in Fig. 1e. We considered 5 Nyquist-WDM channels with Tx structures defined in the previous section. The system parameters were: R_s=32 Gbaud, R_{DAC}=2 SpS and BW_{DAC}=16 GHz[4,5], while the channel spacing Δf was varied in the range [32;50] GHz. We optimized *CP* and *MD* with *ArcSin* ON/OFF, for N_{bit}=4,5,6,8.

ASE noise was added at the Rx input in order to set the OSNR value. The target BER was 10^{-3}.

We used a standard receiver based on 90° hybrids and balanced photodetectors with electric bandwidth ‰•R_s=16 GHz and ideal local oscillator. The Rx DSP operated at 2 SpS and implemented a least mean squares (LMS) butterfly equalizer based on 51-tap FIR filters. Simulation results were obtained by error counting on 2^{16} symbols (2^{19} bits).

The *ER* was set to 20 dB. We varied the other parameters with the purpose to obtain the optimal *CP* for each Δf and N_{bit}. Results vs. Δf showed limited variation, therefore we were able to average on Δf obtaining a unique optimal *CP* for each N_{bit} with *ArcSin* ON and OFF. Results are presented in Tab. 1. With the decreasing of

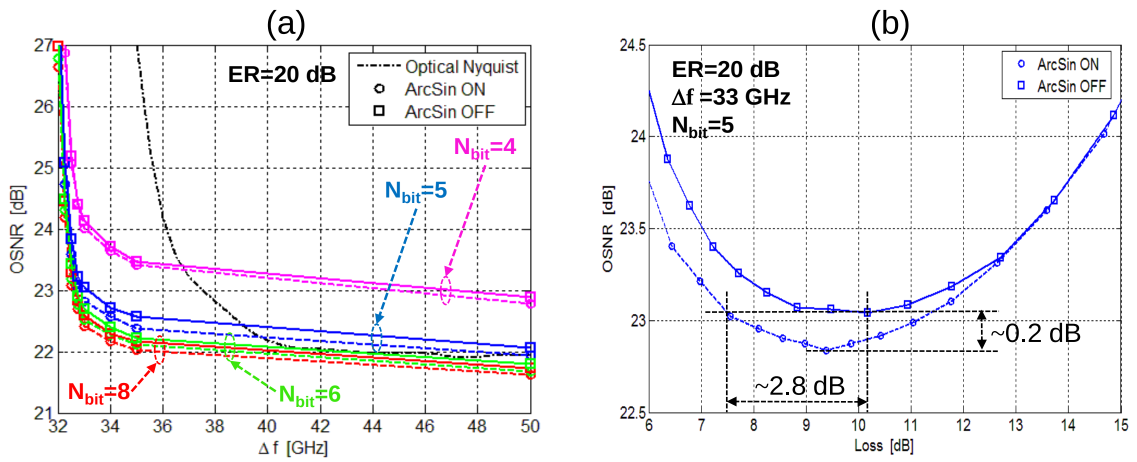

Fig. 2: Optimal OSNR@BER=10^{-3} vs. channel spacing (Δf) for different DAC resolutions and DSP *ArcSin* turned OFF/ON. Simulation results for optically shaped Nyquist WDM are plotted as a reference (a). OSNR@BER=10^{-3} vs. *Loss* at the Tx output for the case Δf=33 GHz and N_{bit}=5 and DSP *ArcSin* turned OFF/ON (b).

DAC resolution, the trade-off with quantization noise induces an enlargement of optimal *CP*. With the use of *ArcSin*, such a behavior is further emphasized because of MZM linearization. Moreover, for N_{bit}≥6 the optimal *CP* is stable because, as shown in the following, performances do no improve anymore.

The second step of Tx optimization analysis was aimed to derive the required OSNR@BER=10^{-3} vs. Δf for all the considered DAC resolutions. For each N_{bit}, we set the *CP* to the previously obtained optimal values (see Tab. 1) and varied *MD*, for Δf in [32;50] GHz. The results are plotted in Fig. 2a. First, it can be observed that for N_{bit}=6 improvements due to an increase in DAC resolution are almost negligible, and already N_{bit}=5 gives limited impairments. Second, the use of *ArcSin* in DSP gives almost negligible improvements to OSNR requirements that do not justify to afford the increasing in DSP complexity. Behaviors vs. Δf show a limited penalty for Δf ≥1.1·R_s that can be assumed as lower limit in channel spacing. It is a large improvement with respect to the optically-shaped pulses using 4th-order Super-Gaussian optical filters, whose performances are plotted in Fig. 2a as a comparison. Penalties with smaller Δf could be reduced decreasing the NyFil roll-off and increasing N_{taps} of the Rx equalizer.

We performed the same investigations for different values of *ER*. We observed that behaviors of OSNR vs. Δf are similar to the 20 dB ones for all *ER* values, as well as the hierarchy between the considered scenarios (different N_{bit} and *ArcSin* ON/OFF). We observed a penalty that is 0 dB for *ER*≥28 dB, is about 1 dB for *ER*=20 dB and is 4 dB for *ER*=12 dB.

The last analysis we carried out was the evaluation of Tx power P_{tx} at the output of the I/Q modulators with respect to the CW case: for each scenario we evaluated *Loss* as the ratio of P_{tx}/P_{CW}, where $P_{CW}=P_{tx}$ w/o modulation. For each Δf, N_{bit} and *ER* it was possible to plot OSNR@BER=10^{-3} vs. *Loss* with *ArcSin* ON/OFF. Fig. 2b shows an example of results for Δf=33 GHz, N_{bit}=5 and *ER*=20 dB. Qualitatively, these plots are similar for all the analyzed scenarios. From this analysis we can say that *ArcSin* ON in DSP gives OSNR advantages that are always below 0.5 dB (0.2 dB in plot of Fig. 2b). On the other hand, a more relevant improvement, always between 2 to 3 dB (2.8 dB in Fig. 2b), can be estimated in terms of reduced *Loss*. Therefore, the use of *ArcSin* in DSP is not justified by the sensitivity improvement, but can be considered in cases when the power at the Tx output is a relevant issue for the system.

Conclusions

We analyzed the Tx characteristics for Nyquist-WDM PM-16QAM based on DSP and DAC. We showed that with roll-off=0.05 in the shaping filter we can pack channels down to 1.1•R_s with penalty below 0.5 dB. The requirement in the DAC resolution is N_{bit}≥5 with a clipping percentage of 20%. The use of *ArcSin* operation in the DSP ensures OSNR advantages below 0.5 dB, but gives more than 2 dB of Tx power improvement.

Acknowledgements

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