Digital Back-Propagation for High Spectral-Efficiency Terabit/s Superchannels

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Abstract: We assess the effectiveness of digital backpropagation algorithm for a 1.2 Tb/s high spectral efficiency superchannel when the input digital bandwidth is varied around the channel of interest. It is shown that the single channel case gives the best performance when 1 sample/s/Hz is used.

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1. Introduction

The never-ending demand for capacity in long-haul fiber transmission systems has pushed research to focus the attention on the generation and transmission of high capacity, high spectral efficiency (SE) channels made up of several optical subcarriers offset at a Nyquist or quasi-Nyquist spacing. In order to improve the performance of these so-called "superchannels" in both spectral efficiency and reach, nonlinear compensation using digital back-propagation (DBP) has been shown to be effective [1]. After detecting the entire superchannel bandwidth it is possible to operate DBP at different digital bandwidths in order to include one or more sub-channels. Recently it has been shown that there are benefits from back-propagating the entire superchannel (full-bandwidth DBP) compared to doing it over a single sub-channel basis [2,3] because of the cancelation of inter-channel nonlinear effects. Nevertheless it is well understood that DBP benefit can be limited by different non-ideal scenarios such as the amount of back-propagated noise at the receiver, polarization mode dispersion (PMD) [4] or limited sampling rate [1]. As a result, arbitrarily increasing the bandwidth may not be optimal in terms of non-linear compensation benefit. In this paper we evaluate the improvement as the DBP bandwidth is varied from the single sub-channel case to the full bandwidth DBP in the specific case where the sampling rate at which DBP is operated is equal to the backpropagated bandwidth. We assess the transmission performance of a PDM-16QAM 1.2 Tbit/s superchannel made up of 5 sub-channels at 32 GBaud each and 33 GHz spacing using Nyquist pulse shaping with 3% roll-off.

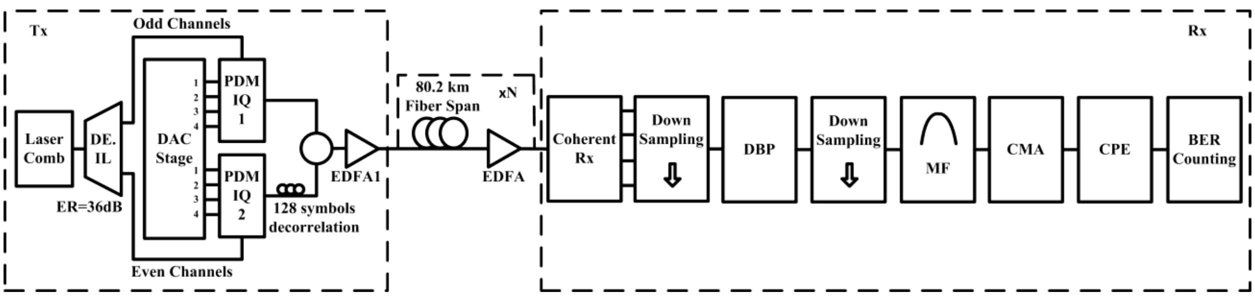
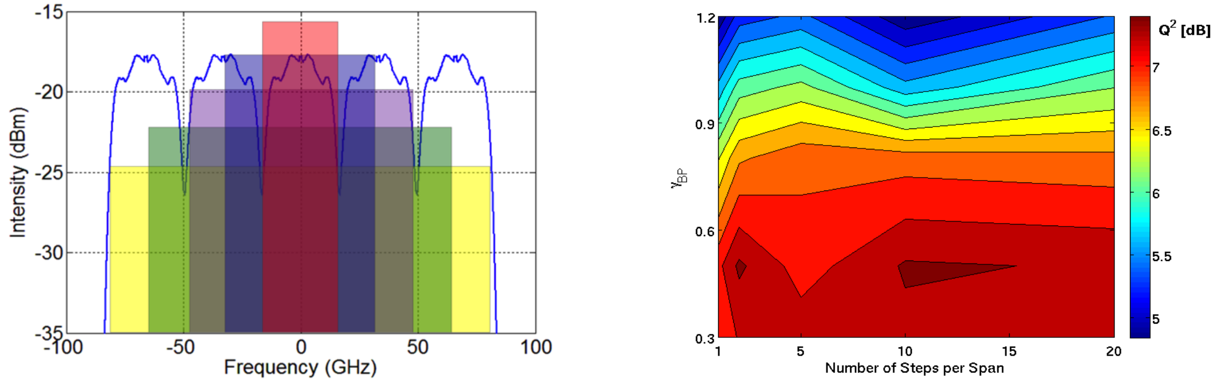


Fig. 1 : Simulation setup for the 5×32 Gbaud/33 GHz spacing PDM-16QAM superchannel transmission performance assessment

2. Simulation setup

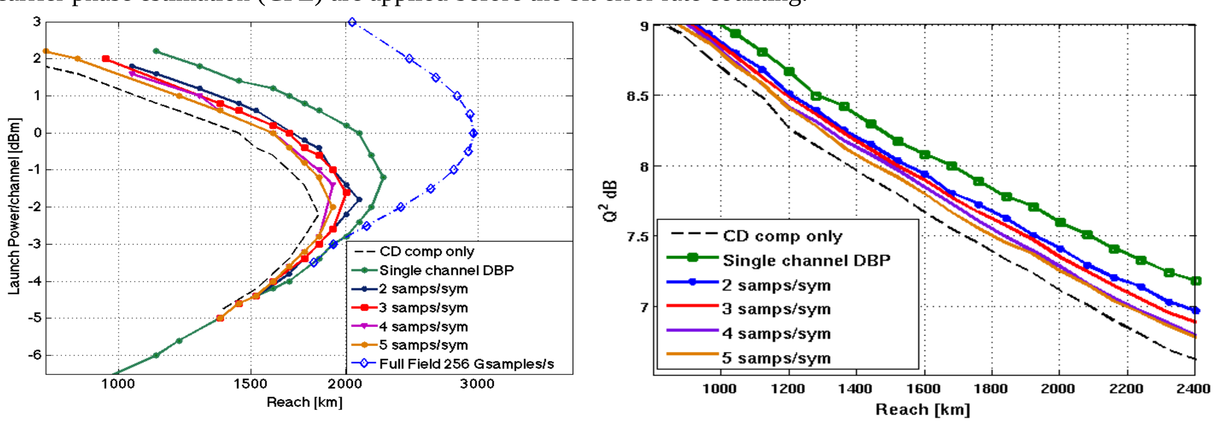
The simulation setup used to assess the transmission quality of the superchannel is shown in Fig. 1. A 5 lines, 33 GHz spacing comb is de-interleaved with a limited extinction ratio (ER) of 36 dB into 2 different sets of sub-channels (odd and even) that are separately modulated by a 8 binary signals encoding 8 uncorrelated pseudorandom binary signals to generate a PDM-16QAM format at 32 GBaud. The behavior of a real digital-to-analog converter has been emulated reproducing a Nyquist 3% roll-off pulse shape at 2 samples/sym and subsequent low-pass filtering to remove the aliases. In order to keep our results as close as possible to real signal generator devices we introduced electrical noise at the transmitter equivalent to a 12% electrical error-vector magnitude (EVM). This translates to approximately 24.5 dB OSNR sensitivity at 3.8×10^{-3} for the single channel case, that we deem to be fitting the current the experimental scenario at this baud-rate. The odd and even channels are decorrelated by 128 symbols and combined before EDFA optical amplification. Fiber transmission was carried out using an 80.1 km SSMF fiber span with non-linear parameter γ=1.2 $(W \cdot km)^{-1}$ and a 4.2 dB noise figure EDFA compensating for the span losses. At the receiver the entire superchannel with 165 GHz of optical bandwidth is detected and digitally sliced using a resampling filter to capture the desired digital bandwidth around the central channel. The down-sampled sequence is then passed to the DBP block that mitigates the non-linear distortions and then again down-sampled to 2 samples/symbol for the following digital signal processing. The digital bandwidth was varied from 2 samples per symbol up to 5 samples per symbol (full bandwidth DBP) and BER is evaluated for the central sub-



(a) (b)

Figure 2: (a) Back-propagated spectral slices of the transmitted superchannel and (b) optimization of DBP in number of steps and nonlinear parameter γ_{BP}

channel to characterize the DBP benefit and a result of a trade-off between the in-band noise and inter-channel nonlinear distortion. In a real system where the bandwidth of each “stitched” receiver roughly fit the bandwidth of a single sub-channel, such an implementation would correspond to stitching by “clusters” of sub-channels before applying DBP, differently from [2] where the superchannel bandwidth is entirely digitally reconstructed. It is a reasonable to predict that the former technique might be less impaired from the non-ideal phase matching between several sub-channels. Moreover if the superchannel is partitioned into non-overlapping slices the DBP algorithm results in a lower overall complexity. A matched filter is used to get the optimum signal-to-noise-ratio (SNR) out of the received signal and finally polarization de-multiplexing (radially-directed equalizer) and decision-directed carrier phase estimation (CPE) are applied before the bit error rate counting.

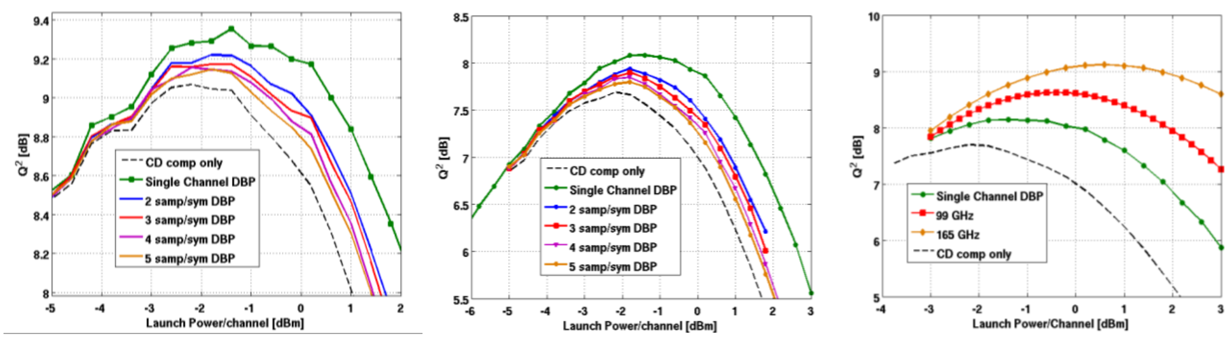


(a) (b)

Figure 3: (a) Central channel reach curves and (b) variation of Q^2 factor vs. distance at the optimal launch power of -1.8 dBm as a function of DBP bandwidth

3. 1.2 Tb/s Superchannel Transmission Results

For a fair performance comparison among the different bandwidths at which DBP was operated we first optimized the algorithm in terms of two key parameters: the nonlinear coefficient γ_{BP} used to undo the nonlinear phase shift at each step and the number of steps per span. We found that the optimal values are different for different digital bandwidths and, consistent with [2], varying for different distances and launch powers. Therefore, we selected optimal values for which the longest transmission distance (reach) was achieved at the BER threshold of 10^{-2} (Q^2=7.33 dB), which represents a conservative threshold for 20% or higher redundancy soft-decision FEC schemes. In fig. 2b it is shown that when DBP was operated with an input bandwidth corresponding to resampling at 3 samples per symbol the detected superchannel spectrum, the Q^2 factor can dramatically decrease as the DBP parameters are varied way from the optimal values. A fine tuning of the algorithm at each bandwidth is then required in order to obtain optimal results. After undergoing this optimization we found the optimal γ_{BP} values to be equal to 0.1 $(W \cdot km)^{-1}$ for DBP operated at 2 samples/symbol, 0.2 $(W \cdot km)^{-1}$ for 3 samples/symbol, 0.3 $(W \cdot km)^{-1}$ for 4 samples/symbol and 0.4 $(W \cdot km)^{-1}$ for 5 samples/symbol. We didn't notice any significant improvement in using more than 10 steps/span (up to 40 steps/span) for each of these γ_{BP} values. Figure 3a shows the resultant reach curves for the central sub-channel as a function of different backpropagation bandwidths. The results show a marked improvement (~22%) in reach using single channel backpropagation while, unexpectedly, increasing the DBP spectral window leads to a decrease in reach from 2245 km to 2084 km. This is also observed if the bandwidth is increased to 5 samples/symbol (full-field DBP) where a small (5%) increase in maximum reach with respect to chromatic dispersion compensation only was achieved. We also show the full-field DBP reach curve when a sampling rate of 8 samples/symbol (256 Gsamples/sym) was used. In this case we do observe a gain in reach of 60% with respect to CD only and 53% to the full-field at 1 sample/s/Hz. This result shows that limiting the sampling rate to 1 sample/s/Hz can incur in a significant penalty, which turns out to impact more as the DBP bandwidth increases. Examining fig. 3b we can also see that, as we increase the reach, the lower OSNR values impact too on the performance increasing the Q^2 factor gap between the different bandwidths. Finally in figure 4 we analyze the Q^2 factor as a function of launch power at different distances. The comparison shows that at short distances (10 spans) (a) where the signal-noise nonlinear interaction is lower the difference in the optimal Q^2 factors between the best case (single sub-channel DBP) and the worst case (full-field DBP) is just around 0.2 dB and this gap remains quite constant even at high launch powers. At longer distance (20 spans - 1600 km) (b) increasing DBP bandwidth results in a higher deterioration and the Q^2 gap between single sub-channel DBP and full-field DBP increases with launch power. Fig. 4c instead shows how this trend can be inverted using a fixed sampling rate of 256 Gsamples/s for all the different bandwidths. In this case a maximum gain of 1.4 dB in Q factor can be achieved using full-field DBP.



(a) (b) (c)

Fig. 4: Q^2 factor vs. launch power at (a) 10 spans, (b) 20 spans and (c) 20 spans with DBP at 256 Gsamples/s

4. Conclusions

We report on the effectiveness of the digital backpropagation as a function of different backpropagated bandwidths when applied to a 1.2 Tb/s superchannel made up of 5 quasi-Nyquist spaced subcarriers at 32 GBaud and PDM-16QAM modulation format. When the algorithm is operated with realistic complexity, that is 1 sample/s/Hz sampling rate and relatively limited number of steps per span, it is shown that single channel DBP outperforms all other cases where the suboptimal equalization outbalances the benefit given by the increased bandwidth. As a result, depending on the system constraints, partial or full field reconstruction may not be indicated for optimum performance.

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5. References

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