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Effectiveness of Digital Back-Propagation and Symbol-Rate Optimization in Coherent WDM Optical Systems

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Abstract: We apply DBP to an experimental WDM system where multisubcarrier transmission provides a 12% reach gain vs. single-carrier. DBP provides further gain for both single- and multisubcarrier systems but significantly underperforms ideal theoretical predictions.
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1. Introduction

In recent experiments, maximum-reach gains have been obtained when the system symbol rate was optimized. The technique has therefore been called SRO (symbol rate optimization). Since the optimum rates turned out to be low (typically in the 2 to 4 GBaud range), these experiments were conducted by breaking up each single optical channel into subcarriers, generated digitally through the transmitter DSP and DACs.

Results were not unanimous in the amount of gain achievable. In [1] a 23% reach increase was found when a single-channel was broken up into 8 subcarriers. [2] found quite substantial gain which however could be attributed to other beneficial effects of using subcarriers in that particular set-up. Subsequent WDM experiments [3]-[5] found conflicting results, between 8% gain and no gain at all. On the other hand, a 19-channel PM-QPSK WDM experiment over ultra-long-haul (ULH) distances found a 12% reach increase (from 12,620 km to 14,180 km) when the 32 GBaud channels, spaced 37.5 GHz, were subdivided into 8 subcarriers, operating at 4 GBaud each [6], consistently with a theoretical prediction based on the EGN model [7]. The same model was used to carry out theoretical studies of SRO [8]-[9], that found very good agreement between simulations and model predictions. The reach gains of SRO appear to be due to a smaller amount of non-linear-interference (NLI) being generated at low symbol rates [8]-[9]. Interestingly, the gain increases when going from a few channels to C-band, where it appears [9] to be comparable (for PM-16QAM) or even greater (for PM-QPSK) than what *ideal* digital back-propagation (DBP) can provide. Note that ideal DBP can typically gain 10% --15% of max reach at C-band (see Sect. IX of [12]).

Since NLI mitigation due to SRO and DBP is based on quite different mechanisms, it is possible that their benefit might add up. If so, then max reach gains in the 20% to 30% range might be feasible, depending on how effectively the two techniques combine. To verify to what extent a combination of SRO and DBP could be synergistic, we carried out both a theoretical study up to C-band based on the EGN model, and a re-processing of the PM-QPSK SRO experiment [5] with the addition of DBP.

Regarding the theoretical study, we show that indeed the two techniques combined yield an overall NLI mitigation which is greater than that of each technique alone, and close to the sum of the two. On the other hand the experiment, although it did find benefit from combining DBP and SRO, also showed that the DBP boost was much smaller than the theoretical prediction based on the assumption of *ideal* DBP. This was in contrast with SRO, which experimentally provided a reach gain close to its theoretical prediction. The under-performance of DBP, which we also found when DBP was used with conventional single-carrier per channel, was likely not an implementation impairment, but rather due to the relatively low target operating OSNR of the system (8 dB over 32 GHz). As shown in [10], at low OSNRs the large ASE *fundamentally* degrades DBP performance. Polarization-related effects may also have played a role in diminishing DBP returns.

2. Theoretical analysis of combining SRO and DBP

We carried out a theoretical study of SRO, DBP and SRO+DBP on a test-system configuration consisting of 32 GBaud WDM channels, spaced 33.6 GHz. The modulation format was either PM-QPSK or PM-16QAM. The number of channels was varied from 3 to 133, the latter being full C-band (5 THz). The link consisted of 50 spans of SMF, with span length 100 km. The value of 50 spans was chosen because it is close to the theoretical max-reach for PM-QPSK with EDFA and for PM-16QAM with hybrid Raman/EDFA amplification. SRO consisted of transmitting each channel as 14 subcarriers at 2.3 GBaud, which is the optimum rate for this system, independently of the WDM bandwidth [8], [9]. DBP was assumed *completely ideal*, carried out over the whole receiver bandwidth of 33.6 GHz, whether the channel was subdivided into subcarriers or not. Possible ASE-noise degradation of DBP was neglected. Spectra were raised-cosine with roll-off 0.05, both for single-carrier and multi-subcarrier. Subcarriers did not overlap. In Fig.1 the theoretical NLI mitigation is shown, as found using the EGN model [7]. Note that it is indispensable that the FWM terms reported in [7] are included in the calculations. XPM-only models are completely inadequate for dealing with SRO [8]. Not shown, the predicted SRO mitigation of Fig.1 is in very good agreement with that found through split-step simulation at 500 GHz and 1.5 THz total WDM bandwidths [9].

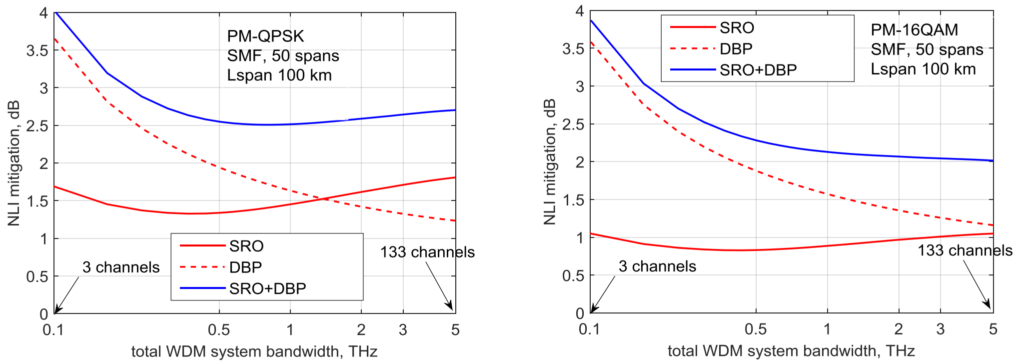

Fig.1: NLI mitigation in dB obtained through either SRO, DBP, or SRO+DBP, vs. total system WDM bandwidth. The channel spacing was 33.6 GHz in all cases. DBP is assumed completely ideal and applied over the 33.6 GHz receiver bandwidth. SRO consists of transmitting each channel as 14 subcarriers at 2.3 GBaud.

Fig.1 clearly confirms the well-known decrease of effectiveness of DBP vs. WDM bandwidth [12]. SRO, on the contrary, shows a C-band value that is comparable to the 3-channel value. SRO effectiveness actually has a dip at about 400 GHz of WDM bandwidth. Both the dip and the subsequent increase of mitigation were confirmed by simulations, up to the maximum achieved simulation bandwidth of 1.5 THz.

At C-band, SRO outperforms ideal DBP with PM-QPSK, whereas SRO and ideal DBP are almost equivalent with PM-16QAM. In both cases their combined use appears to be potentially *synergistic*, with a total mitigation that almost adds up the individual mitigations (in dB). Note that the relationship between NLI mitigation and potential max-reach gain amounts to about 8% max-reach increase per dB of NLI mitigation [12]. So the projected max-reach gains at C-band in Fig.1 for combined SRO+DBP are about 16% and 22% for PM-16QAM and PM-QPSK, respectively, assuming that both DBP and SRO deliver *ideal gains*.

2. Experiment

To find out whether indeed SRO and DBP can be effectively combined, we re-processed the raw data obtained in the SRO experiment [5]. More details of the set-up can be found in [5]. The system consisted of 19 channels, spaced 37.5 GHz. Transmission was PM-QPSK, either single-carrier per channel at 32 GBaud, or 8 digital subcarriers (8-SC) per channel, at 4 GBaud per subcarrier. Independent PRBSs were used for each subcarrier, and different for the channel under test (the center one), odd and even channels. All spectra, either single-carrier or subcarrier, were raised-cosine with roll-off 0.05. The subcarrier frequency spacing was set to 1.05·4GHz, so they did not overlap. The back-to-back sensitivity of the single-carrier and 8-SC system were identical. The transmission link was implemented as a re-circulating loop consisting of 4 spans of PSCF, with average length and loss of 108.2 km and 18.75 dB, respectively. The non-linearity coefficient was 0.65 1/(W· km). The loop made use of EDFA-only amplification and included a gain equalizer and a loop-synchronous polarization scrambler. At the receiver, either conventional CD compensation or DBP, with 5 steps per span, was performed, at the sample rate of 64 Gsamples/s. The DBP steps in a span were generated using a logarithmic law. The DBP-applied phase-shift coefficient was optimized for each launch power and number of loop re-circulations. Then, in the case of multi-subcarrier signals, a frequency down-shift stage converted each separate subcarrier to baseband, which were then independently received. BER estimation was obtained as the average of all subcarriers of the center WDM channel. Interpolation from one recirculation to the next was used to estimate the maximum reach at BER=10^{-2}. For more details on Rx DSP see [5].

The actual results are shown in Fig. 2. The black solid curves are reach predictions using the EGN model for the non-DBP case. They were drawn taking into account the effect of co-propagating ASE noise and channel power depletion as proposed in [11]. The loop-equivalent EDFA noise figure (5.2 dB) was estimated by best-fitting the performance of the single-carrier system (without DBP) when operating in the linear regime (at -3 to -1 dBm launch power). No further fitting was performed to generate any other analytical reach prediction curve.

The dashed-dotted curves represent the *ideal DBP* expected reach (not taking into account the effect of ASE noise on DBP). They predict large gains for this experiment, in fact much larger (25%-30%) than SRO (12%-13%). This is because the SRO gain actually has a minimum (see Fig.1) at total WDM bandwidths close to that of the experiment, which was 700 GHz, whereas DBP is favored by the limited experiment WDM bandwidth. Also, the optimum SRO rate would have been about 1.3 GBaud, whereas the implemented 8-SC system operated at 4 GBaud.

At any rate, the experimental curves show DBP gains which were *much less than predicted* by the ideal DBP reach curves. An actual DBP reach gain of only 10% is found for the single-carrier system and only 8% for the 8-SC system. Going up from 5 to 10 steps per span did not change the result. According to the analysis in [10], most of the gap between ideal and actual DBP gains could be ascribed to the detrimental effect of ASE noise on the DBP algorithm. ASE was substantial since the target BER was 10^{-2}, corresponding to 8 dB OSNR over 32 GHz. To try to verify this, in Fig.2 we also plotted an approximate correction for the impact of ASE on DBP, similar to [11].

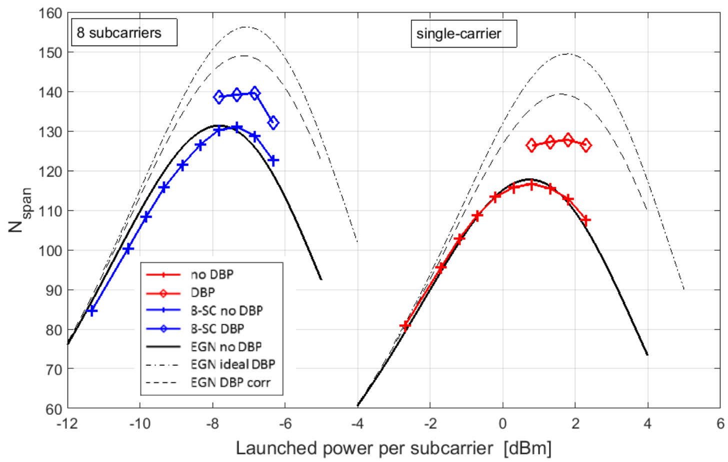

Fig.2: Markers: experimental reach curves, at a target BER=10^{-2}, for a 19-channel PM-QPSK experiment with spacing 37.5 GHz. The channels were sent either single-carrier at 32 GBaud or 8 digital subcarriers at 4 GBaud each. The btb performance was identical for the two systems. Diamond markers include DBP. Curves with no markers are theoretical (see legend).

A gap remains which may be partly due to polarization-related effects, which are known to impair DBP especially over ULH links. Also, penalty may come from back-propagating the NLI noise due to *inter-channel non-linearity*, which might have a similar detrimental effect to that of ASE. The underperformance of DBP is in contrast with the SRO experimental curve, which shows that the 8-SC system gain vs. the single-carrier system is essentially coincident with its *ideal* analytical prediction. This suggests that SRO insensitive to low OSNR conditions. At any rate, a substantial max-reach increase from the combined SRO+DBP of 20% was experimentally found vs. single-carrier with no DBP, raising it from 12,620 to 15,040 km, the addition of DBP contributing about 8% of such gain.

3. Conclusion

Our theoretical analysis, combining SRO and DBP in realistic-parameter WDM systems up to full C-band, shows that the two techniques are potentially synergistic, i.e., their gains almost add up. This is an interesting finding because, taken alone, the individual gains are limited, but their combination may achieve substantial max-reach gains, on the order of 15% to 25% in our theoretical test-case, for PM-16QAM and PM-QPSK, respectively.

Our ULH experiment confirms the advantage of combining the two techniques. However, it clearly shows that DBP may substantially underperform vs. its expected benefit. This is due to the fundamental vulnerability of DBP vs. low operating OSNRs and possibly vs. polarization effects. Yet, a further 8% max-reach gain was obtained through DBP on top of the 12% due to SRO, achieving a total of about 20% vs. single-carrier, no-DBP. In higher-OSNR systems, such as PM-16QAM, DBP may be expected to be less impaired and provide more synergy gain with SRO.

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