Analysis of back-propagation and RF pilot-tone based nonlinearity compensation for a 9x224Gb/s POLMUX-16QAM system

Alberto Diaz,[1] Antonio Napoli,[2] Susmita Adhikari,[3] Zied Maalej,[4] Adriana Lobato,[5] Maxim Kuschnerov[2] and Josep Prat[1]

[1] *Polytechnic University of Catalonia, Jordi Girona, 1-3, 08034 Barcelona, Spain, adiaz.souto@gmail.com*
[2] *Nokia Siemens Networks, St.-Martin-Str. 76, D-81541 Munich, Germany*
[3] *Chair for Communications, Christian-Albrechts-Universität zu Kiel, Kiel, Germany*
[4] *Federal Armed Forces University Munich, D-85577 Neubiberg, Germany*
[5] *Department Munich University of Technology, Arcisstraße. 21 80333 Munich, Germany*

Abstract: We investigate the joint implementation of back-propagation and RF-pilot tone for fiber nonlinear compensation in POLMUX-16QAM and show that the nonlinear tolerance is drastically improved when compared to OFDM system.
OCIS codes: (060.4510) Optical communications; (060.1660) Coherent communications.

1. Introduction

Coherent optical communications in conjunction with digital signal processing (DSP) has emerged as an efficient method to attain data rates as high as 100 Gbit/s [1]. The main advantage of the usage of a DSP-based coherent detection is its capability to mitigate transmission impairments. This advantage acquires more importance in long-haul transmission where fiber propagation effects, linear and nonlinear, are the signal limiting factors. Although the linear effects are no longer considered to be an issue anymore, the nonlinear effects such as Kerr effects (e.g self-phase modulation (SPM) and cross-phase modulation (XPM)) are becoming a bottleneck for long-haul transmission. Recently, some researches have aggressively faced this topic, and different techniques have been proposed over the last years in order to mitigate them. In particular, back-propagation (BP) and RF pilot-tone (RFP) based compensation for SPM and XPM mitigation respectively have received considerable attention. In [2], the authors showed that BP can efficiently compensate for SPM. However, in a WDM scenario with dispersion managed long-haul link, XPM plays an important role and only SPM compensation is not enough. Similar to our work, [3] implemented RFP for XPM mitigation while 1 step per span BP compensated for SPM. Nowadays, the increase in data demand has lead to a massive research for the next generation of advanced modulation formats. For these reasons, OFDM and 16-QAM have both been proposed as a solution for next 200 Gb/s systems updates. Since nonlinearity is the major limiting factor for long-haul transmission, in this paper the joint usage of RFP and BP has been proposed to mitigate the nonlinearities of a 200 Gb/s POLMUX 16-QAM single carrier (SC) system. Finally, the performance of this system is also compared with its equivalent OFDM such as the one reported in [4], resulting in an improvement of 8% for the SC in terms of maximum reached distance.

2. RFP for Single Carrier and simulation setup

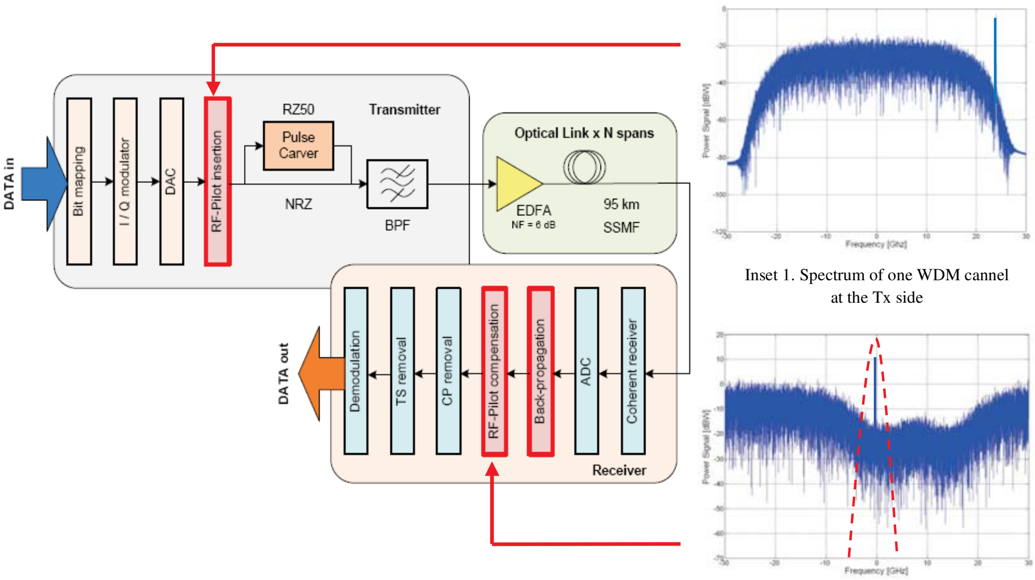
The principle of the idea proposed in this paper is similar to the one presented in [5]. Hereafter, the RFP is inserted at the transmitter, with a specific offset respect to the central channel. After the pilot addition, the entire spectrum is transmitted over the fiber channel as depicted in Inset 1 of Fig. 1. As a result of channel propagation, the pilot tone will experience a phase shift. As shown in Inset 2 of Fig. 1, if this information is properly filtered and used, the recovery of the transmitted data signal can be easily carried out. This operation is possible provided that we have the knowledge of the pilot transmitted phase from which we can easily correct the phase induced into data symbols.

The simulation setup implemented in the simulation is shown in Fig 1. The performance of a 200 Gbit/s POLMUX-16QAM is evaluated. The signal is generated at the transmitter at a net symbol rate of 25 Gbaud. With an overhead of 20% for FEC and 5% for training symbol sequences the gross symbol rate becomes 31.5 Gbaud. Note that the signal is differentially encoded, in order to avoid catastrophic error propagation due to cycle slips.

Afterwards, the signal is non-return-to-zero (NRZ) pulse shaped and passes through the pre-emphasis stage, where a 2nd order Gaussian optical low-pass filter (LPF) with a 16.5-GHz bandwidth is applied to compensate the transmitter low-pass filtering (LFP) impairments. Digital-to-analog converter (DAC) implements a second LFP with a joint 3-dB bandwidth of 21 GHz. Once the SC signal passes through all the stages described above, the RFP is finally inserted in the analog domain. No zero-padding is forced for the tone insertion because we considered the option of applying only one RFP beside the signal spectrum. The distance between the RFP tone and the central channel was optimized resulting in an optimal frequency offset of 24 GHz. The resulting signal spectrum can be seen in Inset 1 of Fig.1.

In the simulation, the transmission link consists of several spans of 95 km of standard single-mode fiber (SSMF) and Erbium Doped Fiber Amplifier (EDFA) with 6 dB of noise figure (NF). No dispersion-managed (DM) links are considered in our analyses but other DM simulations were carried out in order to explain our final results. Further details of the fiber loss and Kerr nonlinearities used in the simulations can be found in [6].

Finally, the different stages of the DSP receiver are illustrated in Fig. 1. One point to be mentioned is about the analog-to-digital converter (ADC), where the parameters are not the same as in the DAC because of the RFP insertion. For this reason, a larger ADC filter bandwidth of 23.1 GHz is needed, incurring in a less noise filtered efficiency as a consequence of ASE induced in this filtering. At the end, the BP stage is applied in order to mitigate the SPM impairment and another filtering is needed in the carrier phase recovery stage to recover the pilot and compensate the phase noise, shifting the signal constellation with the information extracted from the RFP.



Inset 1. Spectrum of one WDM cannel at the Tx side

Inset 2. Spectrum at the Rx side for pilot recovery

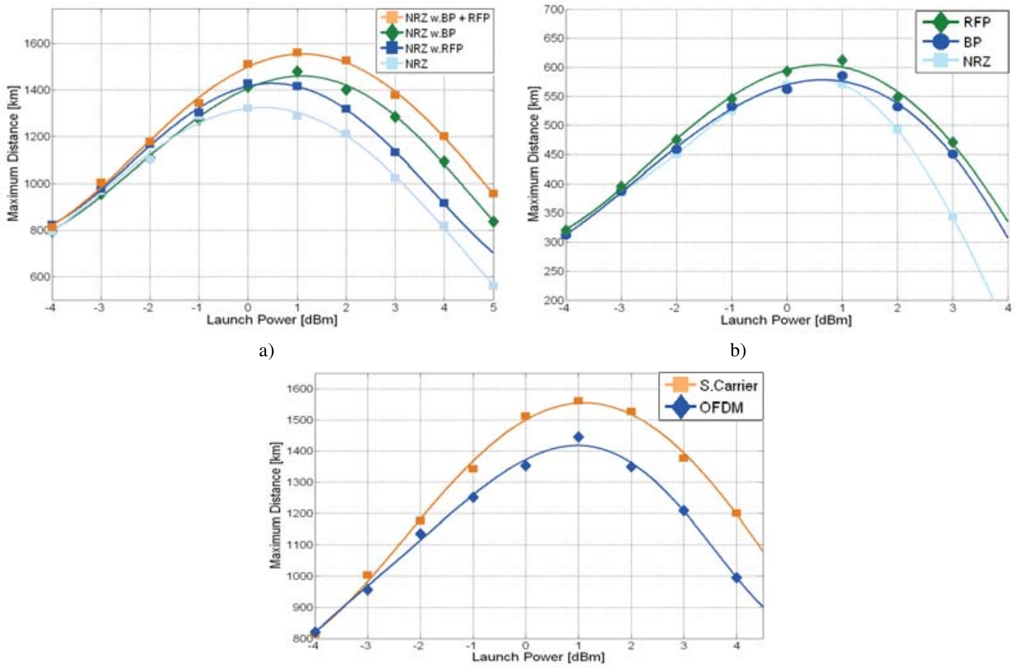
Fig. 1 . Block diagram of the simulation system used in our analysis.

3. Simulations results and comparisons

In this section, we report the results obtained for the aforementioned 200 Gb/s DPOLMUX-16QAM system. In Fig. 2, we present one after the other, the performance of this system with and without BP, applying RFP and finally for the case where both techniques are simultaneously implemented. The results are reported for the case where all RFP parameters are optimal. Among them, we would like to mention: the pilot-to-signal ratio (PSR) and the RFP filter bandwidth.

The comparison between four different mitigation schemes are presented in terms of maximum reachable distance as a function of launch power for NRZ pulse shaping where the target bit error rate assumed in our system is 10^{-2}. As is reported in [4], no significant improvement can be seen for power values below -1 dBm since the signal is only limited by ASE. For launched power values higher than 0 dBm the signal experiences the effects of nonlinearities and the three compensation scenarios mentioned before show different tolerance against these nonlinearities. Compared to the case where no compensation is applied, all techniques provide a clear benefit. Directly from Fig. 2a, we can draw the following conclusions: the compensation provided by single RFP is less performing that the one obtained by using a standard BP module. Moreover, the joint use of BP and RFP mitigation provide the absolute best performance, and the maximum improvement achieved is of about 18% compared to the NRZ case where nonlinear compensation was not implemented.

The same simulation setup is used for the case of DM links. In Fig. 2b, the implementation of only BP or RFP is depicted in order to justify the reliance of these techniques for SPM and XPM compensation. It is known that XPM effect plays an important role in DM links [7], for this reason RFP gives us a better performance compensating most of the XPM effects. In the case of BP, the performance is nearly the same as NRZ case below a launch power value of 1 dBm. For higher power values, the mitigation of SPM gives better improvement but we can conclude that no XPM compensation is done applying only BP for the DM link case.



a) b)

c)

Fig. 2 . Maximum reach distance versus launch power for 9 WDM channels transmission for: a) NRZ Single Carrier, b) NRZ Single Carrier for DM links and c) Comparison between NRZ and OFDM case

The performance achieved for SC is compared to OFDM from [4] in Fig. 2c. The system setup is kept the same for a reliable comparison. In addition, only the case where RFP and BP are applied together is considered. It can be seen that in the usage of both techniques, the optimal launched power value is shifted to 1 dBm, giving better performance in the case of SC.

4. Conclusions

A joint usage of BP and RFP is proposed for a SC system for SPM and XPM mitigation. Better performance is obtained in the case of applying both techniques because as explained in the last section of this paper, BP can severally remove SPM from the signal, while RFP can compensate for the remaining SPM and for a significant part of XPM. We conclude that the combination of the two techniques is necessary to enable a significant improvement in terms of maximum reachable distance for long-haul optical communications.

5. References

[1] X. Liu et al., "Transmission of a 448-Gb/s reduced-guard-interval CO-OFDM signal with a 60-GHz bandwidth," OFC, 2010

[2] D.S. Millar et al., "Mitigation of fiber nonlinearity using a digital coherent receiver," JoST QE. 16 (5), 1217-1226, 2010

[3] L.B. Du and A.J. Lowery, "Pilot-based cross-phase modulation compensation for coherent optical orthogonal frequency division multiplexing long-haul optical communications systems," Optics Letters, Vol.36, No.9, 1647-1649, 2011

[4] A. Diaz et al., "Comparison of single carrier and OFDM with back-propagatino and RF pilot tone for a 9x224Gb/s POLMUX-16QAM system," in IEEE Photonics conference, 2011

[5] T.Kobayashi et al., "45.2Tb/s C-band WDM transmission over 240km using 538Gb/s PDM-64QAM single carrier FDM signal with digital pilot tone," in ECOC, 2011

[6] A.J.Lowery, "Fiber nonlinearity pre- and post-compensation for long-haul optical links using OFDM" in Optical Express 15, 12965, 2007

[7] A.Bononi et al., "Which is the Dominant Nonlinearity in Long-haul PDM-QPSK Coherent Transmissions?," in ECOC, 2010.