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# Experimental Analysis of Non Linear Tolerance Dependency of Multicarrier Modulations versus Bandwidth Efficiency

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**Abstract** We report on the experimental comparison of the non linear tolerance of multicarrier and single-carrier modulations in WDM scenarios while varying the bandwidth efficiency. Non linear tolerance improvement of multicarrier approach decreases with bandwidth efficiency.

## Introduction

Although linear effects in coherent receivers can be compensated using digital signal processing (DSP), the mitigation of nonlinear impairments remains a major issue in optical fiber transmission systems<sup>1</sup>. Some techniques have been proposed in order to combat these impairments, such as digital back propagation<sup>2,3</sup>, perturbative non linear compensation<sup>4,5</sup>, but requiring high computational complexity. Another technique, based on dividing high baud rate signals into several lower baud rate subcarriers, has been investigated to increase the tolerance to nonlinearities in uncompensated optical transmission systems. Such a multicarrier modulation scheme was reported to provide reach improvements up to 22% in quadrature phase shift keying (QPSK) modulations at 24 GBaud<sup>6</sup>. However, this experimental result was obtained in a single-channel transmission without accounting for cross non linearities stemming from adjacent WDM channels in optical systems. In the meantime numerical and analytical studies have reported<sup>7,8</sup> on the impact of the symbol rate onto non linear tolerance in WDM systems, whose results tend to indicate that symbol rates below 10 GBd may provide optimum performance thanks to improved non linear tolerance.

In this paper, we report on the experimental assessment of non linear tolerance of multicarrier and single-carrier modulations on an uncompensated transmission link made of 100-km long spans of standard single-mode fiber (SSMF). Using polarization division multiplexed (PDM) quadrature phase shift keying (QPSK) data the performance of multicarrier and single-carrier modulations are compared in a WDM

transmission system composed of sixty-four 50-GHz spaced channels. The results are obtained with two symbol rates, namely 24 and 48 GBd, in order to vary the bandwidth efficiency of the systems.

## Experimental setup

We conducted an experimental comparison of the non linear tolerance of single-carrier, 4-carrier and 8-carrier modulations in 50-GHz spaced WDM systems while varying the bandwidth efficiency, which is defined as  $\eta = R/\Delta f$  with R being the symbol rate of one WDM channel and  $\Delta f$  being the spacing between channels. In the case of a multicarrier modulation scheme, R corresponds to the total baud rate of all the subcarriers. As schematically described in Fig. 1, for multicarrier modulation we consider that the spacing between carriers is equal to their bandwidth, namely  $R \cdot (1+\alpha)/N$ , with N being the number of carriers and  $\alpha$  a generic roll-off factor. Therefore, the total bandwidth of multicarrier modulated channels is the same as the bandwidth of the single-carrier modulated ones, and they experienced the same WDM bandwidth efficiency. Considering a constant channel spacing of 50 GHz, we used two total symbol rates of 24 GBd and 48 GBd so that the bandwidth efficiency varies from  $\eta = 0.48$  to  $\eta = 0.96$  respectively.

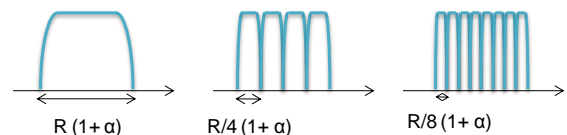


Fig. 1: Single-carrier and multicarrier signals for a roll-off factor  $\alpha$  and a symbol-rate R.

Our test-bed, depicted in Fig. 2-a), consists of

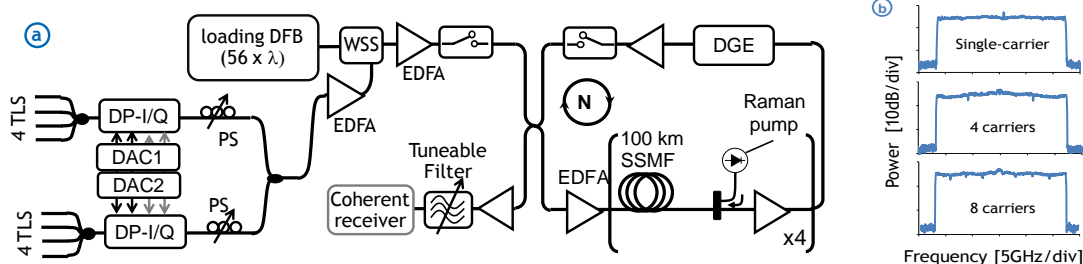


Fig. 2: (a) WDM transmission setup and (b) Spectra of the 24 GBd Signals for Singlecarrier and Multicarrier (4 and 8 carriers).

eight tunable laser sources (TLS) with 100 kHz linewidth, including the laser under test at 1545.72 nm, plus fifty six loading DFB channels. All sixty four channels are spaced by 50 GHz as aforementioned. Our eight TLS are separated into odd and even sets and sent to separate PDM I/Q modulator driven by distinct digital-to-analog converters (DAC) operating at 88-GSamples/s. These two sets are then passed into separate low-speed (<10Hz) polarization scramblers (PS) and spectrally combined through an optical coupler. Loading DFB channels are modulated independently to generate the same format, modulation scheme and symbol rate as our eight TLS channels.

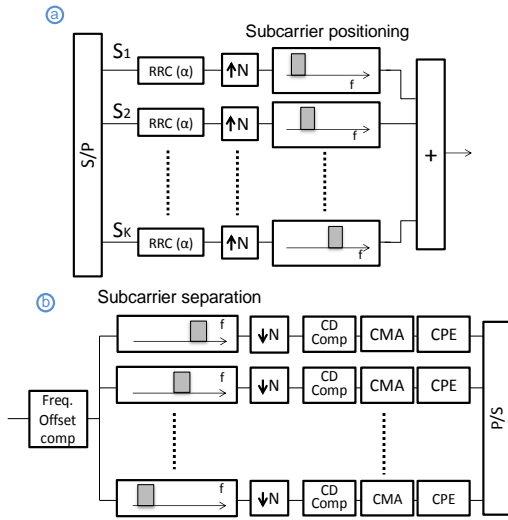


Fig. 3: Multicarrier transmitter and receiver DSP.

For single-carrier modulation, QPSK symbol sequences are generated using multiple delayed decorrelated sequences of  $2^{15}$  bits and filtered by a root-raised cosine (RRC) filter with a roll-off factor of 0.01. In the case of multicarrier generation, the subcarriers are generated digitally according to Fig. 3-a). Symbol sequences are generated using multiple delayed decorrelated sequences of  $2^{15}$  bits which are divided into  $N$  streams, where  $N$  is the number of subcarriers desired. We have computed the correlation of these sequences to ensure that the correlation peak between adjacent carriers is 30 dB below the power of the signal. The sequences of each subcarrier are filtered by the RRC filter with a roll-off factor of 0.01, up converted in frequency domain to their corresponding intermediate frequencies before summation and time domain conversion of the overall multicarrier spectrum. Fig. 2-b) shows the generated spectrum of single, 4- and 8-carrier signals at the symbol of 24 GBd.

After being generated, all channels are recombined using a wavelength selective switch (WSS). The resulting multiplex is boosted

through a single stage erbium doped fiber amplifier (EDFA) and sent into the recirculating loop. The loop consists of four 100km-long spans of SSMF. No dispersion-compensating fiber is used here. Hybrid Raman-EDFA optical repeaters compensates for fiber losses. The Raman pre-amplifier is designed to provide ~10dB on-off gain. Dynamic gain equalization (DGE) is performed thanks to a 50-GHz grid WSS inserted at the end of the loop.

At the receiver side, the channel under test at 1545.72 nm is selected by a tunable filter and sent into a polarization-diversity coherent mixer feeding four balanced photodiodes. Their electrical signals are sampled at 80GS/s by a real-time digital oscilloscope having a 33-GHz electrical bandwidth. For each measurement, five different sets of  $40 \mu s$  are stored. Thanks to polarization scrambling, each recording corresponds to an arbitrary state of polarization at the input of the link. The received samples are processed off-line in a computer to recover the transmitted data as described in Fig. 3-b). Frequency offset compensation is performed in the frequency domain before subcarriers separation. Then digital signal processing of each subcarrier includes chromatic dispersion compensation, polarization demultiplexing and carrier phase recovery (CPE). The length of the CPE algorithm has been optimized for each measurement. Finally their bit error rates (BER) are computed and averaged out to obtain the BER of the channel under test, subsequently converted into  $Q^2$  factor.

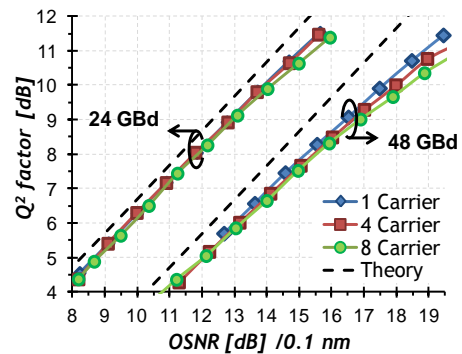


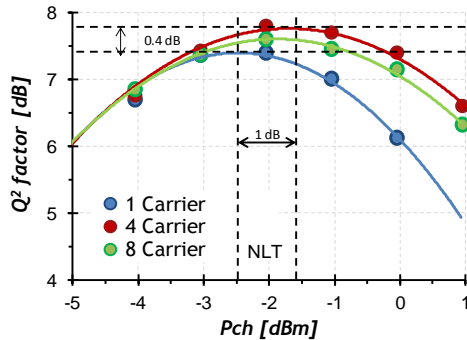
Fig. 4: Back-to-back characterization at 24 and 48 GBd.

## Experimental results

Fig. 4 shows the performance in back-to-back of single-carrier, 4-subcarrier and 8-subcarrier configurations with 24 and 48 GBd PDM-QPSK data together with theoretical expectations. At both symbol rates, although the 8-carrier scheme exhibits higher OSNR penalties at  $Q^2$  factor above 10 dB, which can be attributed to its highest peak-to-average power ratio, it does not exhibit OSNR penalty with respect to single

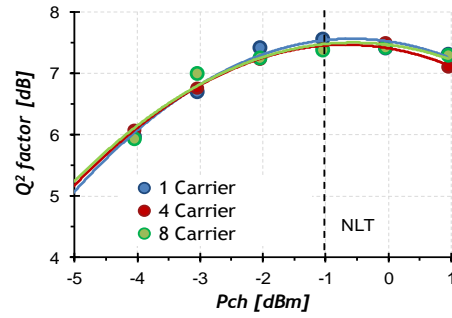
and 4-carrier schemes for lower  $Q^2$  factors.

Next we investigated the tolerance to non linear impairments of single-carrier and multicarrier systems depending on the bandwidth efficiency using our recirculating loop. First we measured their performance using PDM-QPSK modulation and a symbol rate of 24 GBd, leading to a bandwidth efficiency of 0.48. Fig.5 shows the evolution of the  $Q^2$  factor as a function of channel launch power after 20 loop round-trips, corresponding to 8000 km. It can be observed that the 4-carrier and the 8-carrier signals exhibit an optimum channel power near to -1.5 dBm, which is 1 dB higher than the single-carrier one. Moreover, the performance in this optimum power is 7.4 dB for Single-carrier, 7.8 dB for 4-Carriers and 7.6 dB for 8-Carriers, these results indicate that the multicarrier signals outperforms the single-carrier in 0.4 dB and 0.2 dB respectively for 4-Carriers and 8-Carriers. It also shows that the best results are obtained using 4-Carriers that corresponds with a baud rate equal to 6 GBd per carrier. The 0.4 dB performance improvement would be translated into 8% increase in reach with respect to SC.



**Fig. 5:**  $Q^2$ Factor versus launch power after 8000 km for single-carrier, 4-carrier and 8-carrier signals with  $\eta = 0.48$ .

Then, we modulated all 50-GHz spaced channels with the symbol rate of 48 GBd, thus doubling the bandwidth efficiency of the system at 0.96. Fig. 6 shows the performance of the single-carrier, 4-carrier and 8-carrier signals versus launch channel power at the transmission distance of 6400 km, which corresponds to 16 loops. We observe in this figure that all the signals exhibit similar tolerance to non linear impairments and the same optimum channel power of -1 dBm. Contrary to the previous experiment, the three configurations show nearly identical  $Q^2$  factor around 7.5 dB in the optimum power. This result indicates that performance appears weakly dependent on symbol rate when bandwidth efficiency increases close to one in WDM systems.



**Fig. 6:**  $Q^2$ Factor versus launch power after 6400 km for single-carrier, 4-carrier and 8-carrier signals with  $\eta = 0.96$ .

## Conclusions

We have assessed experimentally the benefits of using the multicarrier approach for the mitigation of non linearities in WDM transmission systems. As compared to single-carrier modulation, the multicarrier scheme with 4 carriers enables an 8% increase in transmission reach over an uncompensated transmission link with a bandwidth efficiency of 0.48. We also showed that this benefit is compromised when bandwidth efficiency is increased up to 0.96. Therefore, these results indicate the dependency of non linear tolerance versus symbol-rate tends to disappear as bandwidth efficiency increases. These results are not in perfect agreement with recently reported results by Poggiolini et al<sup>8</sup> and further investigations might be required.

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