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(Article begins on next page)

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***Abstract*—We investigate the performance of Longitudinal Power Monitoring (LPM) algorithms at the small symbol rates achieved with subcarrier multiplexing. We show that at those symbol rates LPM is still effective, albeit with a noisier estimation profile.**

***Index Terms*—Longitudinal Power Monitoring, Subcarrier Multiplexing**

I. Introduction

Longitudinal Power Monitoring (LPM) is a recently proposed technique that allows the estimation of the power profile of an optical link, without the need of additional hardware [1]. The LPM algorithms can be broadly divided into two main categories: correlation-based methods (CM) and Minimum-Mean Squared Error (MMSE)-based methods [2]. Both methods have been applied to systems with relatively large symbol rates [1]–[3], i.e. 64 GBaud and higher, since the performance is directly dependent on the symbol rate [2].

However, the reduction of the symbol rate, by means of Subcarrier Multiplexing (SCM), is advisable for several purposes, such as the reduction of the overall Non-Linear Interference (NLI) [4], for Point-to-Multipoint transmission [5] or to optimize the design of the Digital Signal Processing (DSP) [6]. However, LPM performance has not been thoroughly measured on SCM systems. Consequently, in this work, we present results obtained with a CM-based LPM method over a 10×50-km SMF link at different symbol rates, achieved using SCM.

II. System Setup

The system has been simulated considering four different configurations for the SCM transmitted signal. In particular, it consists of N_{sc} probabilistically-shaped (PS)-64QAM subcarriers, shaped with a Maxwell-Boltzmann distribution with an entropy of 4.41 bit [7]. All the subcarriers are shaped with a root-raised-cosine filter with a roll-off $\rho = 0.05$ and modulated at the same symbol rate R_{s}. The frequency spacing has been set to $\Delta f = 1.1 B_{\text{sc}}$, where B_{sc} is the bandwidth of each subcarrier. Each configuration is characterized by a number of subcarriers equal to a power of 2, i.e., $N_{\text{sc}} = 2^k$, where $k = 0, 1, 2, 3$ indicates the number of the configuration. Similarly, the corresponding symbol rate is equal to $R_s = 64/2^k$ GBaud. Besides, the subcarriers power has been set so that the total transmitted power is $P_{\text{TX}} = 8\,\text{dBm}$ in all cases. This ensures that the four signals are basically equivalent in terms of launch power, total symbol rate and spectral occupancy.

Afterward, the transmitted signal is propagated over a transmission link consisting of 10×50-km spans of SMF fiber ($\alpha_{\text{dB}} = 0.2\,\text{dB/km}$, $\beta_2 = -21.28\,\text{ps}^2/\text{km}$ and $\gamma = 1.3\ 1/\text{W/km}$). At the end of each span an EDFA with noise figure $F = 5\,\text{dB}$ fully compensates for the span loss. Specifically, fiber propagation is simulated according to the split step Fourier method, which implements the Manakov equation [8].

The propagated signal then enters a standard coherent receiver [9], where Chromatic Dispersion (CD) is compensated and each subcarrier is extracted and resampled at 2 sample/symbol. Subsequently, they are separately processed by several DSP blocks implementing matched filtering, LMS-based adaptive equalization and BPS carrier phase recovery [9], [10].

The outputs of this last stage are finally extracted and used to reconstruct the complete received signal that will be the input to the CM-based LPM algorithm [1]. More in detail, the algorithm has been implemented following the algorithmic modifications proposed in [3], with a spatial step $\Delta z = 2\,\text{km}$ and a nonlinear remediation parameter equal to $\epsilon = 0.0001 \cdot 2^k$, according to the considered configuration. In addition, all correlations between received and reference signals are computed using the Pearson correlation coefficient.

Note that the reference signals that are used in the correlation operations have been reconstructed from the originally transmitted sequences, since no FEC-decoding was implemented.

III. Results and Discussion

Fig. 1 shows the results obtained for the four configurations. Each configuration has been simulated 10 times and the resulting estimated power profiles have been averaged in the end. This allows to reduce the impact of noise and mitigate the distortions affecting the signals used in the LPM algorithm. Indeed, the SCM signal goes through several resampling and filtering operations needed to process each subcarrier individ-

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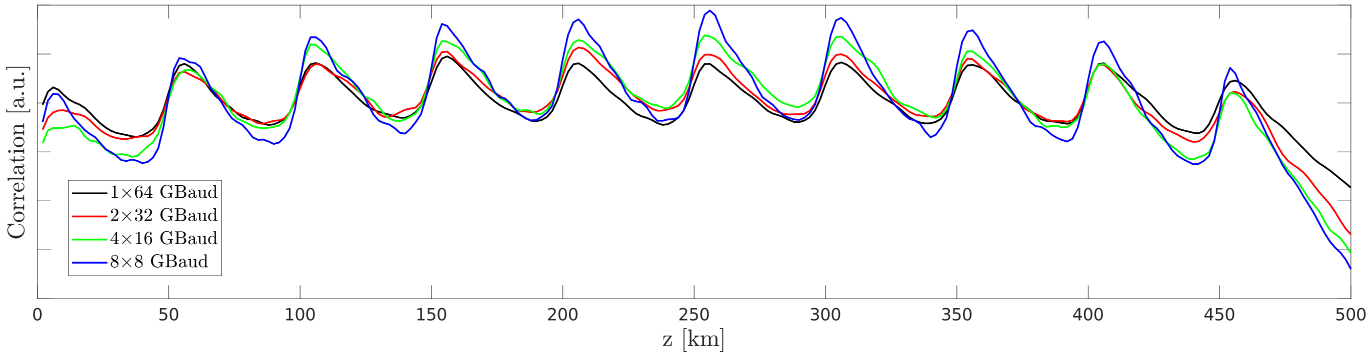

Fig. 1. Estimated power profiles for the four configurations.

ually in the DSP and to reconstruct the originally received SCM signal.

Moreover, the mean value of the averaged profiles has been subtracted from them to ease the visualization and comparison of the results. This also justifies the expression adopted for the nonlinear remediation parameter ϵ. In the considered CM-based LPM algorithm ϵ governs the mitigation of the nonlinear effects. Usually this parameter is set to a small, fixed, value [1]. However, the amount of mitigated nonlinearity influences the correlation and, consequently, the scale of the estimated profiles. Therefore, to aid visualization, ϵ was increased with smaller symbol rates, following a simple heuristic expression; nevertheless, for all practical purposes, the optimization of this parameter is not necessary and falls out of the scope of this work.

Finally, probabilistic shaping has been applied to the transmitted symbol sequences mainly to improve the estimation in the initial part of the transmission link, where the cumulated CD is lower, and to avoid the use of CD predistortion [2].

That clarified, the LPM algorithm managed to yield relatively good results in all the configurations considered. It is possible to notice, though, that the estimation noise tends to increase as the number of subcarriers increases. This is most likely due to the distortions discussed above, since they tend to cumulate as the number of subcarriers involved in the reconstruction of the SCM received signal increases. However, this aspect does not represent a major impairment because the averaging operation results to be effective at mitigating it.

Finally, the average Generalized Mutual Information (GMI) is reported in order to prove that the performances of the four configurations are also equivalent.

Fig. 2 shows the average GMI in function of the number of subcarriers N_{sc} employed, computed as the mean value of the GMI values retrieved from all the processed subcarriers from a specific configuration. The values are all in the same range, around 3.74 bit/symb. The low values are due to the fact that high launch powers are desirable for LPM applications ($P_{\text{TX}} = 8\,\text{dBm}$ in this work) and generally far from the optimal launch powers for communication purposes [2].

To conclude, we have demonstrated the applicability of LPM with a CM-based LPM algorithm in the scenario of SCM systems. Indeed, despite the noisier profiles, it proved to have a performance that is still comparable with the one obtainable in a single-carrier scenario.

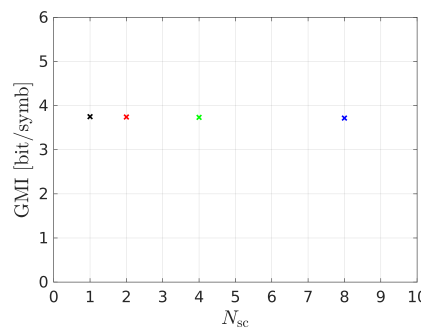

Fig. 2. Average Generalized Mutual Information (GMI) for different numbers of subcarriers.

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