GN-Model Validation over Seven Fiber Types in Uncompensated PM-16QAM Nyquist-WDM Links

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Abstract—We report on a set of transmission experiments over seven different uncompensated fiber links carrying a 22-channel Nyquist-WDM signal comb based on polarization-multiplexed 16-QAM (quadrature amplitude modulation) at $R_S = 15.625$ GBaud ($R_B = 125$ Gb/s). The channel spacing was $\Delta f = 16$ GHz. The experimental transmission performance was compared to analytical GN-model predictions showing good agreement for all seven considered fiber types. Moreover, we used the experimental results for the validation of a fiber figure of merit based on the maximum reach, showing its effectiveness for approximate fiber performance prediction. Within the experimental tests, a maximum transmission distance of 3,810 km at $\text{BER}=1.5 \times 10^{-2}$ was achieved by using a pure-silica-core fiber with $150 \mu\text{m}^2$ effective area, at a net spectral-efficiency-distance product of 24,700 (b-km)/(s-Hz), in good agreement with the GN-model forecast.

Index Terms— fiber comparison, fiber figure of merit, GN-model, nonlinear interference, Nyquist-WDM, PM-16QAM

I. INTRODUCTION

With the development of transmission systems based on coherent detection with digital signal processing (DSP), optical communications are evolving towards the use of Nyquist-WDM (NyWDM) spectral allocation with multilevel modulation formats, to increase link capacity. For this class of systems, it has been found that uncompensated transmission (UT), i.e., operating without any in-line optical dispersion compensation, delivers the best link performance. In the UT scenario, it has been shown that one possible way of modeling the effect of fiber nonlinearity is to approximate its impact as an additive Gaussian disturbance [1-2], called nonlinear interference (NLI). Several non-linear propagation models are available that allow to estimate the power of the NLI produced in a given link, among which [3-9]. In particular, [3-4], [6], [8-9] provide rather similar results. In this work, we focus on the so-called GN-model [8-9]. For completeness, we remark that other non-linearity models refrain from making the additive-Gaussian noise approximation for NLI [10-12]. These models

are outside of the scope of this paper and are left for future investigation.

The main goal of this paper is to assess the practical accuracy of the GN-model by comparing its analytical predictions with a wide set of experimental results. A prior experimental validation of the GN-model was presented in [13] using polarization-multiplexed QPSK (PM-QPSK) and three fiber types, showing good agreement between model and experiment. Here we extend the validation to links based on a higher-order modulation format (PM-16QAM), operating over seven different fiber types. Specifically, we considered a non-zero dispersion shifted fiber (NZDSF), a standard single mode fiber (SSMF), four types of pure-silica-core fibers (PSCF) and a dispersion compensating fiber (DCF), allowing us to explore a wider range of loss, chromatic dispersion and nonlinear parameters than previously done in [13].

A preliminary version of this work was presented in [14]. Here we include a more detailed description of the system setup and of the experiment. In addition, we test the simple analytical fiber figure of merit (FoM) derived in [15] from the GN-model, to assess its capability of providing a quick approximate prediction of different fibers performance.

II. EXPERIMENTAL SETUP

In Fig.1 the transmitter (Tx) structure is shown. The NyWDM system used in the experiment was composed of 22 PM-16QAM channels operating at the symbol rate $R_S = 15.625$ GBaud, corresponding to a bit-rate $R_B = 125$ Gb/s.

The 22 laser sources were allocated between 1555.930 nm and 1558.648 nm and were finely tuned to achieve a channel separation frequency of $\Delta f = 16$ GHz, equivalent to $1.024 R_S$, achieving a gross SE of 7.81 b/s/Hz. An external cavity laser (ECL) placed in the center of the WDM comb was the source for the channel under test, while distributed-feedback (DFB) lasers were used for all other channels.

The odd and even carriers separately fed two distinct nested Mach-Zehnder modulators (NMZM). Their driving electrical signals were obtained from two different $2^{15}-1$ pseudo-random binary sequences (PRBSs), generated on a computer and combined to form a 4-level amplitude-shift keying (ASK) signal with non-return-to-zero symbols. Then, the 4-ASK signal was digitally filtered to impose a square-root raised-cosine spectral shape, with roll-off 0.01 and electrical bandwidth equal to half the symbol rate. The samples of the filtered 4-ASK signal were then sent to an arbitrary waveform generator (AWG) Tektronix 7122B running at 23.4375 GS/s, i.e., at 1.5 samples per symbol (SpS). The NMZM in-phase (I)

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and quadrature (Q) driving signals for the even-channels were obtained from the two complementary outputs of the DAC, by de-correlating the Q arm with a delay of 85 symbols (electrical delay line, EDL₁ in Fig. 1). Both I and Q electrical signals were further split and delayed (EDL₂ in Fig. 1) by 134 symbols to generate the NMZM driving signals for the odd-channels. The NMZMs were driven in the linear region of their electro-optic characteristic: the modulation depth on I and Q arms for both the NMZMs was approximately 25%.

TABLE I
FIBER PARAMETERS

Fiber	α_{dB} [dB/km]	A_{eff} [μm^2]	γ [1/W/km]	D [ps/nm/km]	L_S [km]	L_{max} [km]	$A_{O,dB}$ [dB]
SSMF	0.190	75	1.26	16.84	51.06	1940	0.0
NZDSF	0.200	43	2.00	2.58	50.18	602	2.0
PSCF80	0.164	86	1.04	16.36	54.44	2395	0.3
PSCF110	0.161	111	0.81	20.50	53.18	3084	0.4
PSCF130	0.162	131	0.68	20.92	54.42	3374	0.6
PSCF150	0.161	150	0.59	20.69	54.44	3810	0.6
DCF	0.457	16.8	6.03	-166.47	20.11	502	2.5

The signals electrical spectrum at the output of the DAC is shown in Fig. 2a, solid black line. A spurious spectral replica is present in the spectrum, due to aliasing, showing up as a 20-dB attenuated peak at about 16 GHz. The signal was next amplified and, to suppress the aliasing replica, a specifically-designed anti-aliasing (AA) filter was inserted between the electrical amplifiers and the NMZM inputs. The frequency response of the AA-filter is shown in Fig.2a (red dashed line). The electrical power spectrum at the input of the modulator is shown in Fig.2b. The high-frequency attenuation is mainly due to the electrical amplifier frequency response.

Fig. 1. System setup, Tx section

Finally, even and odd channels were optically coupled with a 3 dB polarization maintaining coupler. The resulting single polarization WDM optical signal was split and recombined onto two orthogonal polarizations for PM emulation, using a fiber optical-delay-line of 64 m (ODL in Fig. 1) inserted on the optical path of one polarization for de-correlation. No

optical filtering was applied at the transmitter side.

The PM NyWDM signal comb was launched into the recirculating fiber loop, consisting of two spans of the fiber under test (Fig. 3). A loop synchronous polarization scrambler (LS-PS) was inserted to average out polarization-dependent effects in the transmission link. The loop used erbium-doped fiber amplifier (EDFA) amplification and included a spectrally-resolved gain-equalizer unit (GEQ). The EDFA equivalent noise figure was $F_{dB}=5.5$ dB.

The parameters for the seven investigated fibers are listed in Table I. Fiber loss, effective area, non-linearity coefficient and chromatic dispersion (CD) (α_{dB} , A_{eff} , γ and D respectively) are directly taken from manufacturer or measured on the spool.

Fig. 2. Spectrum of the 4-ASK electrical signal at the DAC output and after the electrical amplifier and the anti-aliasing filter. Anti-aliasing filter frequency response.

Fig. 3. System setup, recirculating loop and Rx section. AOS: acousto-optic switch. VOA: variable optical attenuator.

Extra-losses due to splices between SSMF patch-cords and fiber spools were not-negligible, due to large differences in the mode field diameter. These losses were measured in order to be taken into account in the model predictions. Table I shows the values of the span output splice loss, $A_{O,dB}$, which is also needed to calculate the fiber FoM (Sect. IV). The input loss was calibrated out so that the desired launched power was the one actually sent into each span. PSCF80, PSCF110,

PSCF130, PSCF150 and DCF were supplied by Sumitomo Electric Industries Ltd; SSMF is a FOS-Pirelli fiber and NZDSF is a TrueWave-RS Lucent fiber.

The receiver (Rx) was based on a standard coherent Rx scheme (Fig. 3), as reported in [16]. Tx and LO lasers were two distinct ECLs, both with less than 100 kHz linewidth. At the Rx input, a tunable optical filter (TOF) with bandwidth 0.22 nm was inserted to prevent excessive optical power from reaching the photo-detectors. Analog-to-digital conversion was performed by a 50 GSa/s sampling oscilloscope. The off-line Rx DSP consisted of the following functional blocks. First, a re-sampling stage lowered the sample rate from 3.2 SpS down to 2 SpS. Then, a first equalizer stage removed the bulk accumulated CD. It was followed by a multiple-input, multiple-output (MIMO) second equalization stage, adjusted through a multi-modulus constant modulus algorithm (MM-CMA). The frequency offset removal was then performed through a Viterbi&Viterbi carrier phase estimator, modified to work with the 16QAM modulation [17]. Finally, a minimum distance decision algorithm was applied for the symbol decision and consequent bit error-rate (BER) estimation.

III. EXPERIMENTAL RESULTS VS. GN-MODEL PREDICTIONS

UT links performance can be estimated using a generalized optical signal-to-noise ratio ($OSNR_{NL}$), defined as [8]:

$$OSNR_{NL} = \frac{P_{ch}}{P_{ASE} + P_{NLI}} \quad (1)$$

where P_{ch} is the power per channel, P_{ASE} is the ASE noise introduced by the EDFAs and P_{NLI} is the NLI equivalent noise power, both evaluated in the same reference noise bandwidth. Then, BER can be estimated as $BER = \Phi(OSNR_{NL})$, where Φ is the back-to-back (*btb*) measured sensitivity curve for the considered set-up. We characterized Φ following the method suggested in [13]. The results are shown in Fig. 4, together with the theoretical BER vs. OSNR curve (dash-dotted line). BER oscillations at and below 10^{-4} are attributed to small fluctuations in the set-up adjustment, such as the NMZM bias. We chose $BER=1.5 \times 10^{-2}$ as reference value for our subsequent tests. This value can be handled by commercial hard FECs with 20.5% overhead [18]. At this BER, the Tx/Rx pair was affected by a *btb* penalty of 2.5 dB with respect to the theoretical curve. No significant performance difference was seen between single-channel and WDM, thanks to a large extent to the use of the AA-filters in the Tx.

Transmission tests were then performed to measure the maximum reachable number of spans $N_{s,max}$ as a function of the launched channel power P_{ch} . The results are shown¹ in Fig. 5 as markers, for all seven fiber types. The estimated measurement error, expressed as a launch power interval, was ± 0.4 dB. The impact of the uncertainty on the values of set-up parameters was estimated as a $\pm 5\%$ error on $N_{s,max}$. To avoid clutter, error bars are shown in Fig. 5 only at the maximum

reach points. Based on the link and fiber parameters reported in Tab. I, we then estimated P_{NLI} using Eq. (18) from [8] and predicted system performance analytically through Eq. (1). A good agreement between experimental results and analytical curves (solid lines) is shown in Fig. 5, confirming the practical accuracy of the GN-model in estimating the generated P_{NLI} , for a wide set of fiber types. Remarkably, despite its high loss and extremely large non-linear coefficient, a maximum reach of 502 km was obtained using 20km of DCF as transmission fiber. This was possible thanks to its ultra-high dispersion, as correctly predicted by the GN-model.

Fig. 4. Back-to-back BER vs. OSNR (over 0.1 nm), center channel. The dash-dotted line is the theoretical BER vs. OSNR curve.

Fig. 5. Reach vs. P_{ch} for the fibers under test: measurements (markers) and GN-model prediction (solid lines).

IV. FIBER FIGURE OF MERIT: EXPERIMENT VS. THEORY

To compare different fiber types, a fiber figure-of-merit FoM was proposed in [15], based on a suitable approximation of the GN-model. Its definition is:

$$FoM = \frac{2}{3} \left\{ 10 \log_{10} \left(\frac{\alpha_{dB}}{\gamma} \right) + 10 \log_{10} \left(\sqrt{\frac{|D|}{\alpha_{dB}}} \right) - \alpha_{dB} L_S - A_{O,dB} - F_{dB} \right\} \quad (2)$$

The derived quantity $\Delta FoM = (FoM_{F2} - FoM_{F1})$ expresses the change (in dB) on the maximum supported number of spans when the system fiber is changed from one type (subscript F1)

¹ This figure is slightly different than the one shown in [14] because the insertion loss, due to splicing and connectors, was re-characterized and it was found that some corrections were needed. The correct values are shown in Table I, column $A_{O,dB}$.

to another (subscript F2). The choice of the reference fiber F1 is arbitrary and here we assume it to be SSMF. If the fibers F1 and F2 have the same L_s and the parameter F_{dB} is kept constant, then ΔFoM also represents the change (in dB) on the actual *maximum reach*.

We first want to validate the theoretical ΔFoM found through Eq. (2) versus its corresponding experimental values, calculated using the measured $N_{s,max}$ by means of the practical definition:

$$FoM = 10 \log_{10} (N_{s,max}). \quad (3)$$

Note that our experiments did not use the same L_s with all fibers but this circumstance does not impair the validation procedure. Once Eq. (2) has been validated, we can carry out a theoretical fiber comparison using the same L_s in the calculations.

The validation results are shown in the first two rows of Tab. II. The agreement between theory and experiments is within 0.1 dB for all PSCFs. For NZDSF and DCF the error is larger but still limited to 0.5 dB. Overall, the simple and compact Eq. (2) appears to be accurate enough for a

TABLE II

 ΔFoM VALUES FOR THEORY/EXPERIMENT COMPARISON AND PREDICTIVE EXAMPLES

ΔFoM [dB]	Fiber						
	SSMF	NZDSF	PSCF 80	PSCF 110	PSCF 130	PSCF 150	DCF
Experiment	0.0	-5.0	0.5	1.8	2.1	2.6	-1.8
Eq.(2)	0.0	-5.5	0.6	1.8	2.0	2.5	-1.3
Exp. parameters	0.0	-5.5	0.6	1.8	2.0	2.5	-1.3
Eq.(2), $L_s=50$ km $A_{0,dB}=0$ dB	0.0	-4.3	1.2	2.3	2.8	3.2	-8.9
Eq.(2), $L_s=100$ km $A_{0,dB}=0$ dB	0.0	-4.6	2.0	3.3	3.7	4.1	-17.8

preliminary assessment of the potential performance of different fibers.

In the third and fourth row of Tab. II we impose the same span length and we also assume that $A_{0,dB}$ is zero. This way, we concentrate on the pure propagation properties of each fiber. The found ΔFoM values show for instance that using PSCF 150 at $L_s=50$ and 100 km, the maximum reach can be extended by 3.2 dB (109%) and by 4.1 dB (157%) vs. SSMF, respectively. NZDSF is instead under-performing, with a considerable gap of -4.3 and -4.6 dB vs. SSMF.

V. CONCLUSIONS

In this paper, we have presented an extensive validation of the GN-model based on measurements carried out on seven different fiber types using 22 PM-16QAM Nyquist WDM channels. The comparison has been based on the evaluation of the system maximum reach and confirms that the GN-model effectively predicts system performance with good accuracy.

Moreover, such tests confirmed the important role of dispersion in increasing system reach in UT links. For this particular test we decided to use DCF as transmission fiber. Despite its very high non-linear coefficient and loss, a relatively long reach (500 km) was achieved, as predicted by the GN-model, thanks to the DCF very high dispersion value.

We also used the experimental data to validate the fiber Figure of Merit proposed in [15]. This FoM was found to be

sufficiently adequate for an approximate estimation of the performance of different fiber types.

As predicted by both the GN-model and the FoM, an effective way of improving system reach is the use of ultra-large effective area fibers, with high dispersion, such as PSCFs. The longest experimental reach was in fact found using PSCF150, 24% higher than the commercial PSCF110 and almost double that of SSMF. The resulting net spectral-efficiency-times-distance product (SEDP) of 24,700 (b-km)/(s-Hz) improved the value reported in [16] by 6%, showing once again that the combination of Nyquist WDM PM-16QAM and large effective area PSCF can be a promising solution for high spectral efficiency ultra-long-haul links.

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