Evaluation of Nonlinear Propagation Effects on Coherent Optical Transmission Systems for Various Commercial Optical Fiber Types

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***Abstract*—This paper presents the study of Gaussian Noise (GN) model based on power spectral density (PSD) of amplified spontaneous emission (G_{ASE}) noise and nonlinear interference (G_{NLI}). G_{ASE} is the summation of erbium doped fiber amplifier (EDFA) noise in the optical link. G_{NLI} appears for a number of channels in coherent optical transmission systems. We show the computed nonlinear effects on coherent uncompensated optical transmission systems (CUOTS) for different commercial optical fiber types (PSCF150, SSMF, SSMFULL) considering channel spacing, number of span, span length and number of channels respectively.**

Keywords*— Gaussian Noise (GN); Wavelength Division Multiplexing (WDM); Erbium Doped Fibre Amplifier (EDFA)

I. Introduction

At present, CUOTS is receiving increasing interest for its enormous applications in multimedia services and abundant bandwidth. Using higher symbol rate per channel and narrower channel spacing, the performance of CUOTS can be improved [1]. It is observed that the algorithm of scheduling can be used to calculate the nonlinear propagation effects on the optical link. But in this case, we follow the linear routing and wavelength selection problem [2].

Consequently, both accuracy and low computational complexity are required to develop the existing optical fiber communication network (OFCN). In this case, we prefer the nonlinear Schroedinger equation (NSE). Well, but it takes time to simulate the NSE and is more complex to make analysis theoretically. Therefore, we want to emphasize on non linear interference (NLI) noise which is for nonlinearity and chromatic dispersion, called GN model as a P_{NLI} noise [3]. In practice, the commercial optical simulation tool is more expensive to simulate the optical fiber links where it takes many input parameters and is also a time consuming factor [4].

Nowadays, the implied Gaussian Noise (GN) model supplies a tool to come within reach of these problems [3], [5]-[6]. The GN-model can work for span length randomly and for different number of spans [7].

In the optical link, each EDFA acts as a repeater which is denoted as a span in GN model. G_{ASE} occurs after each span which is done periodically though the fiber loss is low. On the other hand, G_{NLI} happens before EDFA for a number of channels. G_{NLI} and G_{ASE} noises degrade the performance of OFCN. At present, the customers demand more bandwidth which requires the upgrading of the present OFCN. In this regard, GN model is the solution and tool which computes very quickly and accurately for OFCN. We computed the NLI effects for 50 number of spans and 100 km span length. We reported the non linear propagation effects for three commercial optical fiber types.

The paper is partitioned as follows: Section II: gives system model for GN model; Section III: presents theoretical analysis of GN model; Section IV: shows simulated results, and Section V: gives discussion and conclusion.

II. Syetem Model

Fig. 1 depicts a typical diagram of CUOTS. The aim of this model is to carry out the non linear propagation effects on the total optical link. Each optical link communicates with N number of channels. In this work we take 100 channels. Each channel has a centre frequency (f_c), symbol rate (R_s), channel bandwidth (B_{ch}) and channel power (P_{ch}) respectively. For CUOTS, all channels are non identical. Each channel allows 32 GBaud symbol rate. The spectrally shaped modulated channels use non identical optical carrier signals passing through the optical filter with -3dB bandwidth. This is equivalent to the industrial standard value [8] of channel spacing- 50 GHz.

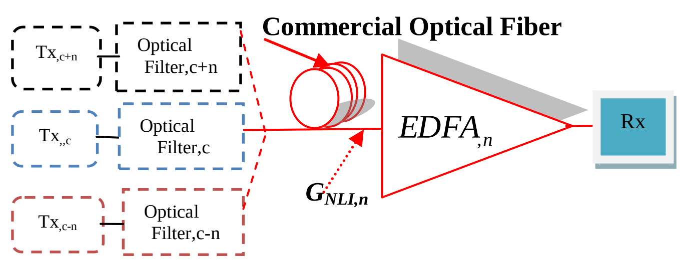

Fig. 1. Transmission systems of OFCN.

We take three commercial optical fibers to compare the effects of nonlinear propagation in the optical link. Each fiber consists of dispersion (D), fiber loss (α), and nonlinearity (γ). The numerical information for commercial fiber is listed in table I. The PSD $G_{NLI,n}$ is the input to n[th] number of $EDFA_{,n}$ and creates n[th] number of span [9] as depicted in the Fig. 1 [6].

III. Theoretical Analysis

We followed the GN model [7] which is based on non identical channels and non identical span. The calculation of PSD of NLI is the sum of the NLI noise spectra produced in each single span, taking into account the span loss and gain occurrence realization in each span [7].

$$G_{NLI}(f_{ch,i}) = \frac{16}{27}\sum_{n_s=1}^{N_s}\gamma^2 L^2_{eff,n_s} \cdot \prod_{n'_s=1}^{n_s-1} g_{n'_s}{}^3 e^{-6\alpha_{n'_s}L_{s,n'_s}} \cdot \prod_{n'_s=n_s}^{N_s} g_{n'_s} e^{-2\alpha_{n'_s}L_{s,n'_s}} \cdot \sum_{n=1}^{N_{ch}} G_{ch,n}G_{ch,n}G_{ch,i}.(2-\delta_{ni})\Psi_{n,i,n_s} \tag{1}$$

In expression (1), $f_{ch,i}$ is the center frequency of i^{th} channel, N_s is the number of span, L_{eff} is the effective length.The expression for effective length (L_{eff}) is defined as follows [9]:

$$L_{eff} = (1-\exp(-\alpha L_s))/\alpha \tag{2}$$

Here, L_s is the span length, $g_{n'_s}$ is gain product of EDFA, N_{ch} is the number of channel, G_{ch} is the power spectral density which depends on channel power and channel line rate and is expressed as the following [13].

$$G_{ch,n} = \frac{P_{ch,n}}{R_s} \tag{3}$$

There are two symbols- δ_{ni} and ψ_{n,i,n_s} which maintain the selection of center frequency and the number of channels. The condition for δ_{ni} is δ_{ni} =1; if $n=i$, otherwise δ_{ni} =0. The other symbol Ψ_{n,i,n_s} accurately performs the strategy of taking into account of coherent accumulation [7]

$$\Psi_{n,i,n_s} \approx \frac{a\sinh(\pi^2(2\alpha_{n_s})^{-1}|\beta_{2,n_s}|[f_{ch,n}-f_{ch,i}+B_{ch,n}/2]B_{ch,i})}{4\pi(2\alpha_{n_s})^{-1}|\beta_{2,n_s}|} - \frac{a\sinh(\pi^2(2\alpha_{n_s})^{-1}|\beta_{2,n_s}|[f_{ch,n}-f_{ch,i}-B_{ch,n}/2]B_{ch,i})}{4\pi(2\alpha_{n_s})^{-1}|\beta_{2,n_s}|} \tag{4}$$

The expression of strategy (4) is applicable in the model when $n \neq i$; otherwise the strategy expression follows the approximation [7]:

$$\Psi_{i,i,n_s} \approx \frac{a\sinh(\frac{\pi^2}{2}|\beta_{2,n_s}|[2\alpha_{n_s}]^{-1}B^2{}_{ch,i})}{2\pi|\beta_{2,n_s}|[2\alpha_{n_s}]^{-1}} \tag{5}$$

asinh is the inverse hyperbolic sine function which controls an array on element-wise factor where both domain and range are complex numbers [12]. Here, the fiber dispersion is β_2 and $B_{ch,i}$ is the channel bandwidth of i^{th} channel. The computed PSD of G_{NLI} is converted to the P_{NLI} which is represented as follows as [13]

$$P_{NLI} = \int_{-\frac{B_n}{2}}^{\frac{B_n}{2}} G_{NLI}(f)df \tag{6}$$

B_n is the optical bandwidth which is used to get the P_{NLI} from G_{NLI}. In our work we take the value of B_n as 12.5 GHz.

IV. Simulation and Results

Following the theoretical model (GN model) presented in section III, we evaluate the P_{NLI} performance of CUOTS considering three commercial optical fiber types. A Matlab software tool is used here to implement the analytical expressions of Gaussian Nonlinear model (GN model) to evaluate the effects of nonlinear interference noise on the total CUOTS considering three variations (PSCF150, SSMF and SMFULL) of different optical fibers types. Three commercial optical fibre types are shown in table I which differ in their specifications.

We choose the following fibers because they are used as a transmission fiber for long haul optical communication link.

- Pure Silica Core Fiber (PSCF150) [10].
- Standard Single Mode Fiber (SSMF), and Single Mode Fiber Ultra Low Loss (SMFULL) specified by International Telecommunication Union (ITU) G.652.

TABLE I. Specification of Different Commercial Optical Fibres[10] -[11]

Fiber Types	α[dB/km]	γ[1/W/km]	D[ps/nm/km]	L_{eff}[km]
SSMF	0.190	1.26	16.84	22.56
SMFULL	0.18	1.1	18	23.5
PSCF150	0.161	0.59	20.69	26.31

TABLE II. Input Optical Transmission systems (OTS) Parameters

OTS Parameters	Industry Standard Values (ISV)
Channels (N_{ch})	100
Operating wavelength (λ)	1550 nm
Channel Spacing (Δ*f*)	50 GHz
Symbol Rate (*Rs*)	32 GBaud
Span Length (*Ls*)	100 km
Number of Span (*Ns*)	50
Noise Figure *(F)*	5 dB
Optical Noise Bandwidth (B_n)	12.5 GHz

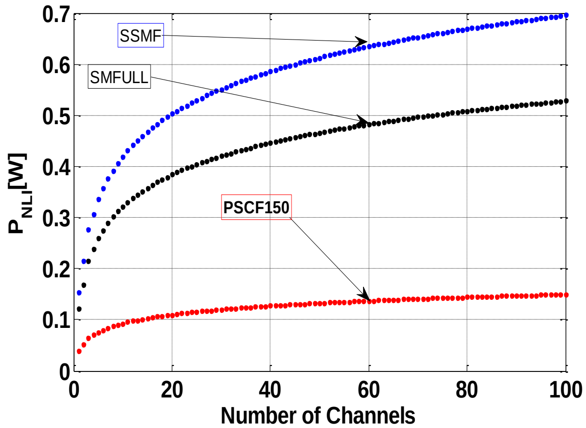

Fig. 2. P_{NLI} versus number of channel for CUOTS with 50 GHz channel spacing and different commercial optical fibers (indexed in table. I). The system is for 50 spans and 100km fiber link; the channel bandwidth is 32 GHz and noise figure is 5 dB.

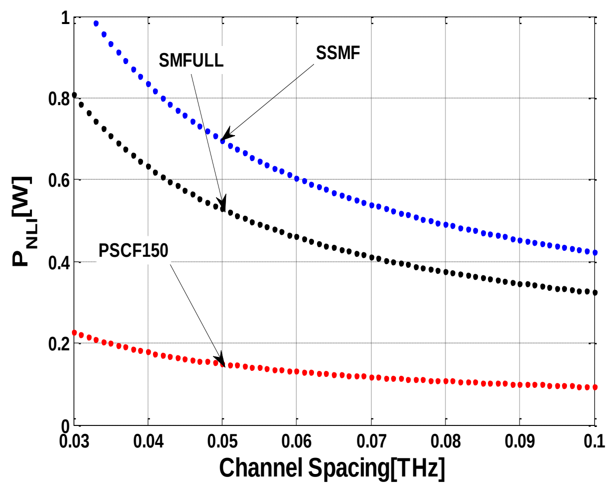

Fig. 3. P_{NLI} versus channel spacing [THz] for CUOTS and different commercial optical fibers (indexed in table I). The system is for 50 spans and 100 km fiber link; the channel bandwidth is 32 GHz and noise figure is 5 dB, respectively.

Both Fig. 2 and Fig. 3 are computed for P_{NLI} versus number of channels and channel spacing for three commercial optical fibers respectively. In Fig. 2, it is found that the P_{NLI} is going up with the number of channels added to CUOTS. This strategy makes impairment in the total optical link. The SMFULL and SSMF are close to each other in Fig. 2. They perform a higher P_{NLI} effects than the performance of PSCF150. In Fig. 3, it is shown that, P_{NLI} is going to slow down when the value of channel spacing is going up. In these results, the SMF couple performs a very higher P_{NLI} effects than the PSCF150. Here the interesting observation is that the Fig. 2 and Fig. 3 both are reciprocal. In Fig. 3, it is shown that SSMF and SMFULL are close to each other when the network parameter of channel spacing is added in the transmitter section. At the same time, PSCF150 is out of SMF couple. But PSCF150 is in better performance for its low nonlinearity specification.

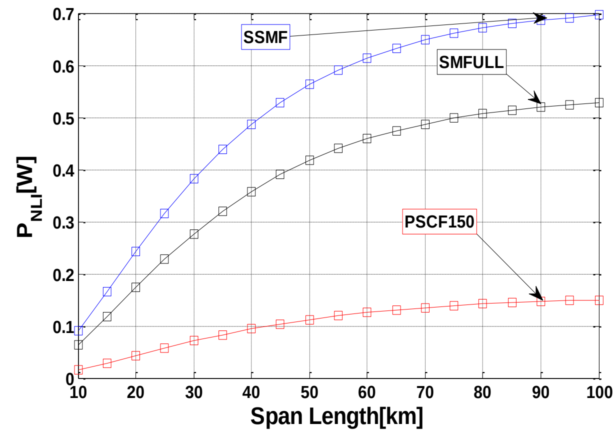

Fig. 4. P_{NLI} versus span length [km] for CUOTS with 50 GHz channel spacing and different commercial optical fibers (indexed in table I). The system is for 50 spans and 100 km fiber link; the channel bandwidth is 32 GHz and noise figure is 5 dB.

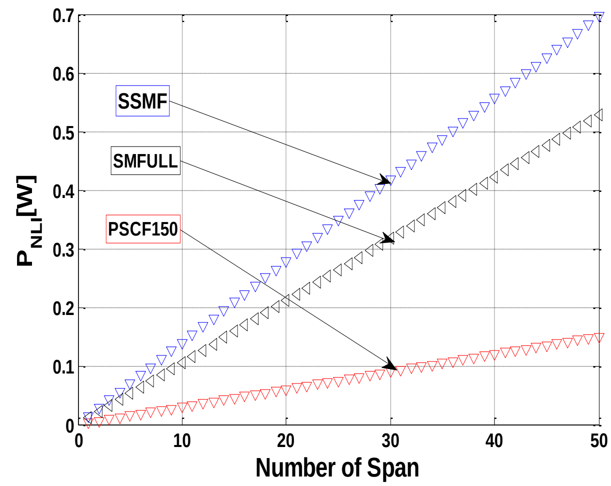

Fig. 5. P_{NLI} versus number of span for CUOTS with 50 GHz channel spacing and different commercial optical fibers (indexed in table I). The system is for 100 km fiber link; the channel bandwidth is 32 GHz and noise figure is 5 dB, respectively.

The P_{NLI} noise due to number of channels in CUOTS versus span length and number of span are shown in Fig. 4 and Fig. 5 respectively. Here span length plays a great important role to select the amplifier spacing which minimizes the cost of the system and determines the total optical link length. We use three different types of commercial optical fibers (PSCF150, SMFULL and SSMF) for GN model to determine the low nonlinear effects in the CUOTS. The Fig. 4 and Fig. 5 are computed to find out the NLI noise effects on the whole network. In Fig. 4, it is found that the effect of P_{NLI} is going up when the span length is added in the network. In this case, we do the simulation for three different fibers. The PSCF 150 shows the very low nonlinear effects for its low non-linearity value than SSMF and SMFULL respectively. SSMF demonstrates the high nonlinear effects in the network compared to other commercial optical fibres. In Fig. 5, we run Matlab software tool considering number of spans. It shows here that the trend of NLI effects is going up with respect to the number of spans in the Gaussian nonlinear model. In this case, we use the three same fibers. As in usual case, PSCF150 shows better performance than SSMF and SMFULL respectively.

V. Discussion and Conclusion

An analytical GN model is simulated with Matlab tool to evaluate the aspects of non linear propagation generation on CUOTS considering different commercial optical fiber types. But, assembly of the fiber is different for their non linearity specifications. There are two disturbing noises in CUOTS- they are NLI and ASE noise. They degrade the system performance. We work on nonlinear interference noise generation in this paper. This work helps to determine the OSNR by adding the ASE noise with NLI noise. The most important finding is that, for the same GN model, three commercial optical fibers behave in a different manner. This study improves the optical network and minimizes the cost of the optical link. In our simulation, it is observed that the PSCF150 performs a low nonlinear propagation effects on the CUOTS and reserves a potentiality to solve the problem of long haul communication like submarine link.

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