OSNR Improvement of Coherent Uncompensated Optical Transmission Systems for Various Commercial Optical Fiber Types

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***Abstract*—In this paper, we analyse the theoretical performance of uncompensated optical transmission system using Gaussian Noise (GN) model considering the effect of amplified spontaneous emission (ASE) noise summation and the generation of nonlinear interference (NLI) noise due to the erbium doped fibre amplifier (EDFA) and the number of channels. We optimize the optical SNR (OSNR) for computed NLI and ASE noise on coherent uncompensated optical transmission systems (CUOTS) considering four different commercial optical fibre types (SSMF, PSCF150, LEAF, and SMFULL). The bit error rate (BER) is computed for obtained OSNR considering PM-BPSK, PM-QPSK, and PM-16QAM modulation formats where each format runs at 32 GBaud symbol rate.**

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

I. INTRODUCTION

The future of CUOTS is progressing rapidly for multimedia services and abundant bandwidth. Higher symbol rate per channel and narrower channel spacing are required to increase the performance of CUOTS [1]. To improve the physical layer for CUOTS, scheduling algorithm is considered for nonlinear propagation. There is a problem of wavelength selection and linear routing process without GN model [6], which ensures accuracy and decrease computational complexity [2]. In practice, accuracy and low computational complexity process (CCP) are fundamental to optimize the present existing optical fiber communication network (OFCN). In this case, the solution of nonlinear Schroedinger equation is the way to get optimum performance of OFCN. But it takes quite a long time to simulate the Schroedinger equation and is more complex in CCP. To take into account the effect of chromatic dispersion and Kerr nonlinearity known as NLI noise, GN model is the most appropriate one [3]. Computer simulation tool is more expensive to optimize the optical link, where many input parameters are required and which is a time consuming factor [4].

At present, the Gaussian Noise (GN) model [3], [5], [6] is a tool which overcomes these limitations. The GN model contains different number of spans and span lengths [7].

In OFCN, each Erbium Doped Fiber Amplifier (EDFA) acts as a repeater which is known as span of the link. In the link, optical amplification is performed periodically even though the fiber loss is very low. After each span, the optical signal gets amplified where both -the noise of ASE and NLI are included. In this regard, the optical signal-to-noise ratio (*OSNR*) is decreased periodically. Therefore, more bandwidth is required to upgrade the installed fiber optical link like submarine link. The GN model is a tool to address this problem and develops a novel, swift and accurate technique for CUOTS.

The work is structured as follows: Section II: describes system model; Section III: makes theoretical analysis; Section IV: computes results, and Section V: gives comments and conclusion.

II. SYETEM MODEL

The target of the system model is to carry out the NLI effects on the total optical link of CUOTS. Each optical link can communicate with N number of WDM channels where each channel has a centre frequency (f_c) , channel bandwidth (B_{ch}), channel power (P_{ch}) and channel spacing (Δf) respectively and channels are assumed non identical. The non identical modulated spectrally shaped channel optical carrier signals are passed through the optical filter with -3dB bandwidth which is equivalent to the industrial standard value (ISV) [8] of channel spacing [33GHz]. The fiber specification consists of fiber loss (α), dispersion (D), nonlinearity (γ) and effective length (L_{eff}). These are specified in table I.

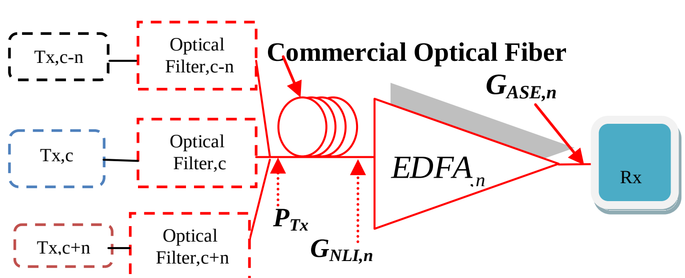

Fig. 1. Transmission systems of OFCN.

The power spectral density (PSD) $G_{NLI,n}$ is measured at the input of n[th] EDFA, produced for n[th] number of span [6], [9] and represented in Fig. 1.

In Fig. 1, $T_{x,c}$ is the center frequency of the super channel, $T_{x,c+n}$ and $T_{x,c-n}$ are the symbols to make total number of channels odd. P_{Tx} is the input launch power to process the system of optical link. The PSD of G_{ASE} is evaluated after each EDFA allowing power amplification and noise figure (F) of EDFA [12]. G_{NLI} is obtained during the optical carrier frequency propagation through the commercial optical fiber cable. By using GN model, we can optimize signal to noise ($G_{ASE}+G_{NLI}$) ratio ($OSNR$) after each span.

III. Theoretical Analysis

For PSD of G_{NLI}, we studied the mathematical expression (127)-(129) [7] for non identical span and non identical channels for CUOTS. The PSD of G_{NLI} for each span is measured considering span loss and gain of the EDFA and makes an accumulation of PSD for total number of spans, which is expressed as below [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 the model, $f_{ch,i}$ is the center frequency of the i^{th} channel . At the end of each span , the span loss is compensated due to EDFA where the gain product ($g_{n'_s}$) is 1 linearly. $\boldsymbol{N_s}$ is the number of span. The effective length (L_{eff}) is expressed as [9]:

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

L_s is span length from one span to another span distance and N_{ch} is the total number of channels. The power spectral density $G_{ch,n}$ depends on channel power and line rate of the channel and is expressed as below [13]:

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

Where, $P_{ch,n}$ and R_s are the channel power and symbol rate for the input of the system respectively. Now the symbol δ_{ni} selects the channel with respect to the center frequency. The condition for the symbol δ_{ni} is δ_{ni} =1 when $n=i$ otherwise $\delta_{ni}=0$ .The other symbol Ψ_{n,i,n_s} is a function of the coherent accumulation and operating number of channel, center frequency and number of span [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) works when $n \neq i$ in the model; otherwise the strategy expression follows the simplification as stated below [7] :

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

Where, β_2 is the fiber dispersion, $B_{ch,i}$ is the channel bandwidth of i^{th} channel and *asinh* is the inverse hyperbolic sine function which maintains the array with complex number [14]. The $OSNR$ is used to estimate the BER in CUOTS .The mathematical expression for OSNR [15] is:

$$OSNR = \frac{P_{Tx}}{(G_{ASE}+G_{NLI})B_n} = \frac{P_{Tx}}{P_{ASE}+p_{NLI}} \tag{6}$$

In expression (6), P_{Tx} is the input launch power for the span system, G_{ASE} is the ASE noise power spectral density (PSD), G_{NLI} is the NLI noise PSD and B_n is the optical noise bandwidth which is used to get the P_{ASE} and p_{NLI} from G_{ASE} and G_{NLI} respectively. P_{ASE} and p_{NLI} are the power of ASE and NLI noise respectively. The PSD expression of ASE noise is mathematically expressed [15]:

$$G_{ASE} = N_s Fhf_o(A_s-1) \cong N_s Fhf_o A_s \tag{7}$$

Where, F is the amplifiers' noise figure, h is the Plank's constant and f_o is the center frequency of the super channel. $\boldsymbol{A_s}$ is the span loss expressed as $A_s = \alpha.L_s$. Here variable optical attenuator (VOA) is controlling the loss which is going to set 0 dB to hold the minimum span loss. The improvement of OSNR considering ASE, NLI noise and transmitting input power in the system maintain the following expression [3].

$$OSNR_T^{MAX} = \frac{P_{Tx}}{(G_{ASE}+P_{Tx}{}^3 G_{NLI}B_{ch}{}^{-3})B_n} \tag{8}$$

$$OSNR_T^{MAX} = \frac{P_{Tx}}{(P_{ASE}+P_{Tx}{}^3 p_{NLI}B_{ch}{}^{-3})} \tag{9}$$

In this paper, we use optical bandwidth, B_n =12.5 GHz. B_n is used here to get the OSNR from SNR which is possible for electrical matched filter in the receiver section of the system and expressed in (10) below [6]. The BER for any CUOTS using QPSK or QAM modulation format, including polarization multiplexing (PM) technique is a function of signal-to-noise ratio (SNR) as presented [6] in (11).

$$OSNR = \frac{R_s}{B_n} SNR \tag{10}$$

$$\text{BER}=\psi(SNR) \tag{11}$$

In (11), where ψ is a function which depends on the modulation format to minimize the BER and upgrade the system performance**.** We do the simulation for PM-BPSK, PM-QPSK , and PM-16QAM modulation format respectively. The expression of BER for PM-BPSK, PM-QPSK, and PM-16QAM modulation format is presented [6] below, respectively.

$$BER = \frac{1}{2} erfc(\sqrt{SNR}) \tag{12}$$

$$BER = \frac{1}{2} erfc(\sqrt{SNR/2}) \tag{13}$$

$$BER = \frac{3}{8} erfc(\sqrt{\frac{1}{10} SNR}) \tag{14}$$

IV. SIMULATION AND RESULTS

Following the theoretical GN model presented in section III, we calculate the OSNR in CUOTS considering four commercial optical fiber types with launch power (P_{Tx}) , NLI power (p_{NLI}) and ASE power (P_{ASE}), respectively. We use a Matlab software tool here to compute the analytical expressions of Gaussian Nonlinear (GN) model to optimize the OSNR on the total CUOTS considering four (PSCF150, SSMF, LEAF and SMFULL) different commercial optical fiber types. Four commercial optical fiber types are mentioned in table I whose specifications differed. We select the following optical fibers [10]-[11] because these are operated as a transmission fiber for long haul optical fiber communication link.

- Pure Silica Core Fiber (PSCF150).
- Standard Single Mode Fiber (SSMF), and Single Mode Fiber Ultra Low Loss (SMFULL) confirmed by International Telecommunication Union (ITU) G.652.
- Large Effective Area Fiber (LEAF): affirmed by International Telecommunication Union (ITU) G.655.

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
LEAF	0.22	1.5	3.8	19.5
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})	27
Operating wavelength (λ)	1550 nm
Channel Spacing (Δf)	33 GHz
Symbol Rate(Rs)	32 GBaud
Span Length (Ls)	100 km
Number of Span(Ns)	50
Optical Noise Bandwidth (B_n)	12.5 GHz
Noise Figure (F)	5 dB
Total Bandwidth (B_{WDM})	864 GHz

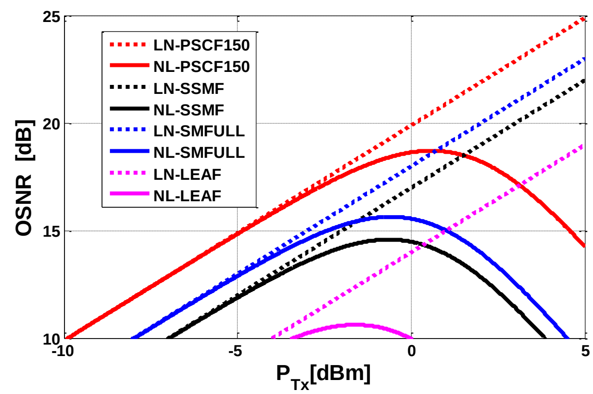

Fig. 2. OSNR [dB] versus P_{Tx} [dBm] where dashed lines: linear propagation (LN); solid lines: non-linear propagation (NL) for CUOTS with 33GHz channel spacing and different commercial optical fibers (indexed in table I). The system is for 50 spans and 100 km fiber link; the channel bandwidth is 32 GHz for 27 channels.

The Fig. 2 shows the results for CUOTS considering system performance OSNR (dB) versus input power (dBm) for different types of commercial optical fibers. In Fig. 2 we put the results of linear and nonlinear regime together. Linear is only for the ASE noise combination in the optical links. For linear confirmation, it is reported that, for input launch power -10 dBm to 5 dBm, the linear curve is 10dB to 25dB which goes through variation linearly, i.e. for 1 dBm it's changed 1dB. For non linear propagation, it is found that for best launch power the improvement of OSNR (dB) is 18.7 dB, 15.6 dB, 14.6 dB and 10.6 dB for PSCF150, SMFULL, SSMF and LEAF commercial optical fibres, respectively. While SSMF and SMFULL are close to each other nonlinearly, LEAF and PSCF150 have a gap of huge range nonlinearly.

We have calculated the BER for required OSNR considering extensive commercial optical fibre types with optical launch power. We put here the results of BER in linear and nonlinear regime together.

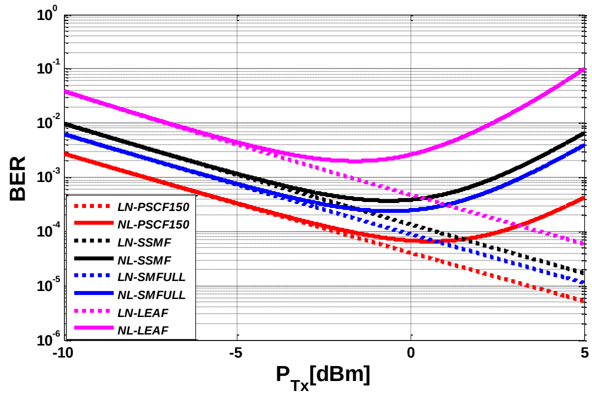

Fig. 3. BER (PM-BPSK) versus optical input power (dBm) where dashed lines: linear propagation (LN); solid lines: non-linear propagation (NL) for CUOTS with 33GHz channel spacing and different commercial optical fibers (indexed in table I). The system is for 50 spans and 100km fiber link; the channel bandwidth is 32GHz for 27 channels.

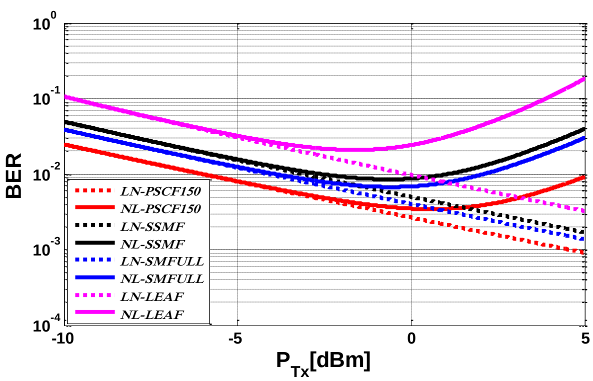

Fig. 4. BER (PM-QPSK) versus optical input power (dBm) where dashed lines: linear propagation (LN); solid lines: non-linear propagation (NL) for CUOTS with 33GHz channel spacing and different commercial optical fibers (indexed in table I). The system is for 50 spans and 100km fiber link; the channel bandwidth is 32GHz for 27 channels.

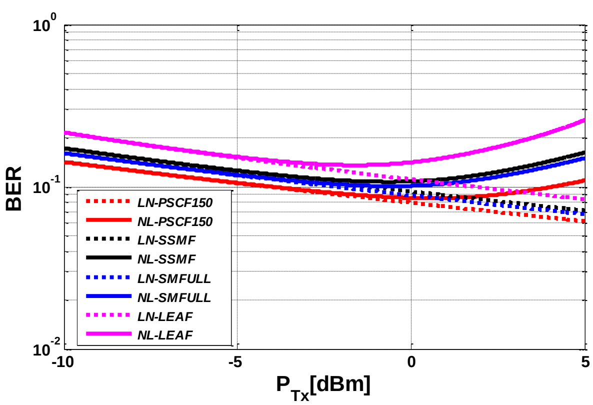

Fig. 5. BER (PM-16QAM) versus optical input power (dBm) where dashed lines: linear propagation (LN), solid lines: non-linear propagation (NL) for CUOTS with 33GHz channel spacing and different commercial optical fibers (indexed in table I). The system is for 50 spans and 100km fiber link; the channel bandwidth is 32GHz for 27 channels

To determine the BER, we move from ONSR to SNR scenario which is possible by using the matched electrical filter in receiver section. In Fig. 3, we estimate the BER for PM-BPSK modulation format using 32Gbaud symbol rate where the format carries 2 bits per symbol and produces a line rate which is 64 Gb/s. In this illustration, for the best launch power, the $10\log_{10}$(BER) is -25, -22,-20 and -10 for PSCF150, SMFULL, SSMF and LEAF respectively. In Fig. 4, we optimize the BER for PM-QPSK modulation format considering ISV of 32 Gbaud symbol rate where the modulation format follows 4 bits per symbol and makes a line rate of 128 Gb/s. In the results of Fig. 4, it is found that for best launch power the $10\log_{10}$(BER) is -16, -14,-13 and -7 for PSCF150, SMFULL, SSMF and LEAF respectively. In Fig. 5, we jump to test the BER in PM-16QAM modulation format with 32Gbaud symbol rate where the format conveys 8 bits per symbol. As a result, the line rate is here 256 Gb/s for PM-16QAM channels. In Fig. 5, it is shown that for best launch power the $10\log_{10}$(BER) is -8.5, -8,-7.6 and -6 for PSCF150, SMFULL, SSMF and LEAF, respectively. We found that PSCF150 plays a good performance for its low nonlinearity specification parameter as a transmission fiber for long haul communication. The couple of SMF is better than the LEAF. They are very close to each other in BER performance. The fiber LEAF is out of PSCF150 and SMF couple in BER performance results.

V. Discussion and Conclusion

A theoretical GN model is computed with Matlab software tool to optimize the OSNR for different commercial optical fibers in CUOTS. There are two types of noises in CUOTS such as NLI and ASE noise which degrade the system performance. We have determined the OSNR considering input transmitting power, NLI noise power (p_{NLI}) and ASE noise power (P_{ASE}) respectively. For the same GN model we have used different transmission fiber, but they behaved in a different way for their specifications. Among the four optical fibers, PSCF150 gives good performance for long haul transmission because of its low fiber loss and contains the potentiality to face the problem of submarine link. This optimization scenario results can help to optimize the existing optical network. We have shown here the BER for obtaining OSNR. Bit error rate (BER) is dominated here by NLI noise and ASE noise in the optical link which estimate the system performance. For PSCF150, it is found that the BER is below 1E-4, 1E-2 and 1E-1for PM-BPSK, PM-QPSK and PM-16QAM modulation format respectively with 32 GBaud, 50 number of spans and 100 km span length.

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