Achievable Information Rates in C-band Nonlinear Coherent Optical Communication Systems

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***Abstract*—Information rates of C-band Nyquist-spaced optical fiber communication systems with erbium-doped fiber amplifier (EDFA) and distributed Raman amplification (DRA) schemes were discussed. Results indicate that the nonlinearity compensation performance depends on transmission distances and modulation formats.**

***Keywords*—optical communication, achievable information rate, EDFA, Raman amplifier, nonlinearity compensation**

I. Introduction

In order to meet ever-growing demands on data traffic, optical fiber communication networks are gradually developing towards the transmission with a large capacity and a long reach. The application of erbium-doped fiber amplifiers (EDFAs) as well as distributed Raman amplification (DRA) have significantly enhanced the transmission bandwidth to C-band and beyond, with the combination of signal multiplexing technologies. The achievable information rate (AIR) is a natural figure of merit that illustrates the achieved net data rates in coded communication systems [1]-[3]. However, a significant limiting factor on AIR is the nonlinear distortions due to the optical Kerr effect in fibers [4],[5]. Nonlinearity compensation (NLC) methods were demonstrated to efficaciously alleviate the impact of intra- and inter-channel nonlinearities and to improve AIRs in transmission systems [6],[7]. In this paper, AIRs in C-band Nyquist-spaced WDM coherent optical transmission systems are studied when EDFA and DRA are applied, accounting for different modulation formats, transmission distances, and the values of NLC bandwidth.

II. System Model

Considering the amplified spontaneous emission (ASE) noise, the Kerr-type nonlinearity, and the transceiver noise, the signal-to-noise ratio (SNR) of the received signal in the optical system can be described as [8]-[10]

$$\mathrm{SNR} \approx \frac{\mathrm{P}}{\sigma_{\mathrm{TR}}^2+\sigma_{\mathrm{ASE}}^2+\sigma_{\mathrm{S-S}}^2+\sigma_{\mathrm{S-ASE}}^2+\sigma_{\mathrm{S-TR}}^2} \qquad (1)$$

where P is the average optical power per channel, σ_{TR}^2 is power of the transceiver noise, σ_{ASE}^2 is the power of the ASE noise power from the amplifiers, $\sigma_{\mathrm{S-S}}^2$ is the power of the signal-signal nonlinear interactions, $\sigma_{\mathrm{S-ASE}}^2$ is the power of the signal-ASE noise interactions, $\sigma_{\mathrm{S-TR}}^2$ is the power of the nonlinear interaction between signal and transceiver noise.

When the multi-channel NLC (MC-NLC) is used over a certain bandwidth, the $\sigma_{\mathrm{S-S}}^2$ can be modeled as follows [9]-[12]

$$\sigma_{\mathrm{S-S}}^2 = N_s^{\varepsilon+1}[\eta(B)-\eta(B_{\mathrm{NLC}})]\,P^3 \qquad (2)$$

where N_s is the number of fiber spans, η is the nonlinear distortion coefficient, ε is the coherence factor, B is the modulated bandwidth, and the B_{NLC} is the NLC bandwidth.

Detailed explanations and calculations of these terms can be found in reported studies and our previous works [5]-[12].

III. Results and Discussions

Based on the model in Section 2, AIRs of the C-band Nyquist-spaced coherent optical fiber transmission systems with EDFA- and DRA-amplification have been investigated, considering different compensation schemes such as electronic dispersion compensation (EDC) and multi-channel NLC (MC-NLC). The MC-NLC is operated with 32 GHz bandwidth for the case of single-channel compensation, 250 GHz for present maximum digital NLC bandwidth [11], and 4.96 THz for full-field NLC (FF-NLC) bandwidth.

Parameter values used in the theoretical model are described as the following: the carrier wavelength is 1550 nm, the symbol rate is 32 GBd, the channel spacing is 32 GHz, the span length is 100 km, the number of channels is equal to 155, the transceiver SNR is 25 dB, the fiber loss is 0.2 dB/km, the fiber CD coefficient is 17 ps/nm/km, the CD slope is 0.067 ps/nm^2/km, the nonlinear coefficient is 1.2 /W/km, the EDFA noise figure is 5.5 dB, the Raman gain is 0.35 /W/km, and finally the Raman pump loss is 0.25 dB/km.

AIRs versus transmission distances of C-band (~4.96 THz) EDFA-amplified Nyquist-spaced optical fiber systems with different modulation formats are illustrated in Fig. 1. For DP-16QAM system, MC-NLC clearly shows its effectiveness in improving AIRs when transmission distance exceeds 1000 km. For higher modulation formats, e.g. DP-64QAM, DP-256QAM, and DP-1024QAM, MC-NLC has a beneficial effect on AIRs for all considered distances from 800 km to 10000 km. Interestingly, for DP-256QAM and DP-1024QAM, AIRs show similar values at the same transmission distance and MC-NLC

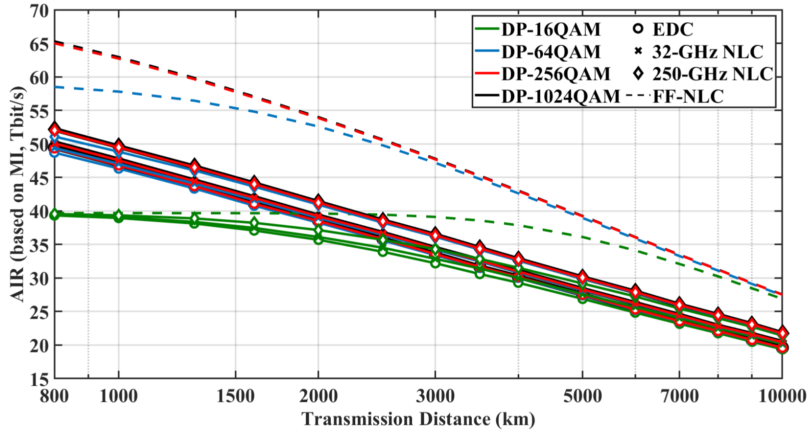

Fig. 1. AIRs versus transmission distances in EDFA-amplified C-band systems using EDC and MC-NLC with a transceiver SNR of 25 dB.

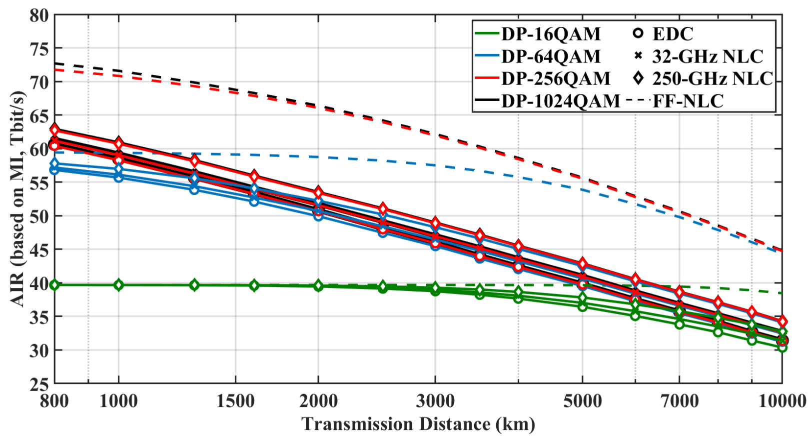

Fig. 2. AIRs versus transmission distances in DRA-amplified C-band systems using EDC and MC-NLC with a transceiver SNR of 25 dB.

bandwidth. This indicates that the DP-256QAM is sufficiently high in order for improving AIRs in current long-distance optical fiber communication systems. Similar trends of AIRs versus transmission distances in DRA-amplified C-band systems for different modulation formats are shown in Fig. 2. For DP-16QAM systems, MC-NLC shows the enhancement of AIRs at the transmission distances beyond 2500 km. For all modulation formats, AIRs of DRA-amplified systems can achieve higher values than the EDFA-amplified systems, in both EDC and NLC schemes. There is also a minor difference between the AIRs of the DP-256QAM and the DP-1024QAM systems, which indicates the highest-order modulation format suggested in long-haul transmission. The use of FF-NLC in the DP-256QAM DRA system can realize an AIR of ~45 Tbit/s at a transmission distance of 10000 km.

IV. Conclusions

AIRs of Nyquist-spaced C-band (~4.96 THz) WDM optical fiber transmission systems amplified by EDFAs and DRAs have been examined using different signal compensation schemes and modulation formats. Results in our works indicate that by taking into account the physical layer impairments and transceiver noise limitations of current optical links, the MC-NLC holds a positive effect in improving AIRs, depending on modulation formats and transmission distances.

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