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Nonlinearity Compensation and Information Rates in Fully-Loaded C-band Optical Fibre Transmission Systems

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Abstract *Nonlinearity compensation and achievable information rates were investigated in fully-loaded C-band communication systems considering transceiver limitations. It is found that the efficacy of nonlinearity compensation in enhancing the achievable information rates depends on the modulation formats and transmission distances.*

Introduction

Soft-decision decoding and multilevel modulation are key technologies to increase data rates in optical communications. Achievable information rate (AIR) is a natural figure of merit in coded communication systems to demonstrate the net data rates achieved by soft-decision decoding[1,2]. Currently, AIRs of optical transmission systems are limited by nonlinear distortions due to the Kerr effect in optical fibres, and these impairments are more severe for systems with larger transmission bandwidths, closer channel spacing and higher-order modulation formats[3-5].

Digital and optical nonlinearity compensation (NLC) techniques, including digital back-propagation (DBP) and optical phase conjugation (OPC), have been developed to mitigate both intra- and inter-channel fibre nonlinearities in optical communication systems[4-6]. Work has been carried out to study the performance of multi-channel NLC (MC-NLC) in terms of AIRs in optical systems, with transmission bandwidth up to 450 GHz[2,4,7]. However, no investigation for MC-NLC has been reported to estimate AIRs over C-band transmission systems.

In this paper, the performance of MC-NLC to enhance the AIRs was investigated in C-band (~4.8 THz) Nyquist-spaced WDM transmission systems, using different modulation formats. Since numerical simulation of fully-loaded C-band systems with a range of modulation formats is computationally intractable, a theoretical model considering modulation format-dependent distortions and transceiver noise limitations was developed to study the performance of such systems. This enabled a realistic study of the efficacy of MC-NLC to enhance AIRs for different modulation formats. The model was used to explore the transmission regimes where MC-NLC can have a significant impact on AIRs in C-band systems, and the bandwidth of MC-NLC required to do so.

Analytical Model

In dispersion-unmanaged optical communication systems, the performance of received signals are degraded by impairments due to amplified spontaneous emission (ASE) noise, fibre nonlinear distortions, as well as system transceiver noise[5,8-10]. The effective SNR of the received signal can be described as[9,10]

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

where P is the average optical power per channel, σ^2_{ASE} is the ASE noise power from the amplifier[8], $\sigma^2_{\mathrm{S\text{-}S}}$ is the signal-signal nonlinear interactions[5,9], and $\sigma^2_{\mathrm{S\text{-}N}}$ is the signal-ASE noise interactions[4,9], σ^2_{TR} is the transceiver noise[10] and $\sigma^2_{\mathrm{S\text{-}TR}}$ is the nonlinear interactions between signal and transceiver noise[10].

If NLC is partially applied over a certain bandwidth, the signal-signal interaction term can be effectively modelled as follows[4,9]

$$\sigma^2_{\mathrm{S\text{-}S}} = N_s^{\varepsilon+1}\left[\eta(B) - \eta(B_{NLC})\right] P^3 \qquad (2)$$

where N_S is the number of fibre spans, ε is the coherence factor, η is the modulation-dependent nonlinear distortion coefficient, B is the bandwidth of the transmitted signal, and B_{NLC} is the NLC bandwidth.

Assuming an equal distribution of transceiver noise arising from transmitter and receiver, the nonlinear interaction between the signal and transceiver noise can be described as[10]

$$\sigma^2_{\mathrm{S\text{-}TR}} = (3/2)\cdot N_s^{1+\varepsilon}\cdot \eta P^3 \cdot \mathrm{SNR}_{\mathrm{TR}}^{-1} \qquad (3)$$

where SNR_{TR} is the maximum achievable transceiver SNR.

To obtain the AIRs, we computed soft-decision mutual information (MI) based on a

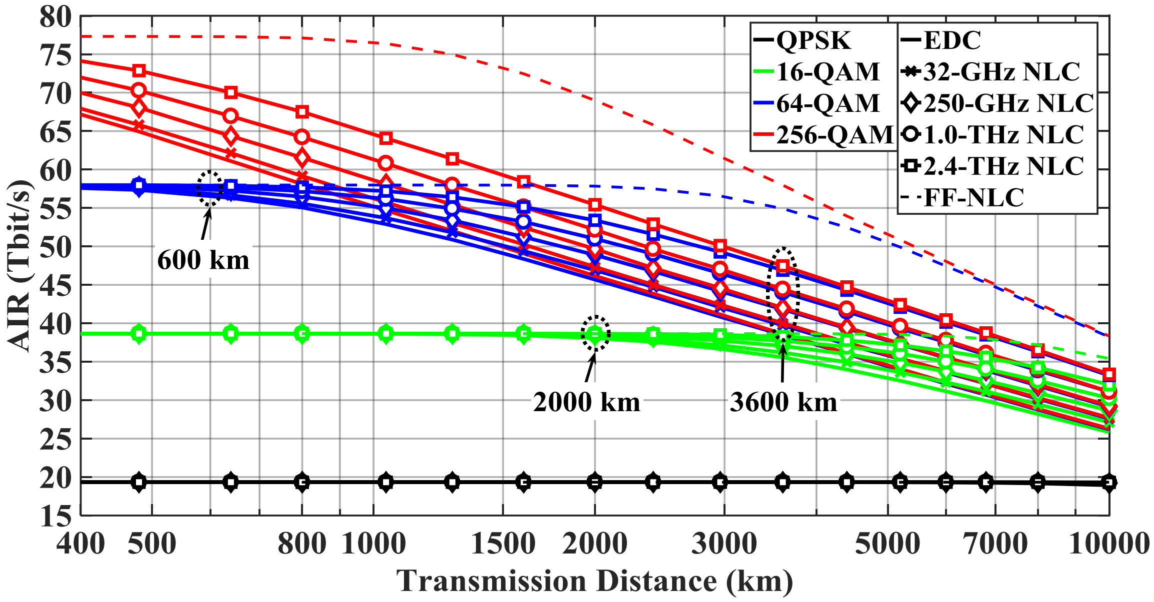

Fig. 1: AIRs versus transmission distances in ideal C-band systems without transceiver noise limitations

Gaussian assumption on the channel[1,2], and this applies to the optimum launch power regimes (in both EDC and MC-NLC cases) in dispersion-unmanaged optical communication systems[2,5,9]. The MI of the central channel was numerically computed using Gauss-Hermite quadrature[1], to estimate the overall AIR of the considered system[2,4]. This leads to a lower-bound on the AIR, since the central channel suffers more nonlinear distortions than outer channels.

Results and Discussions

Based on the theoretical model above, the AIRs of EDFA-based C-band transmission systems have been investigated for the case of electronic dispersion compensation (EDC), partial-bandwidth and full-field NLC (FF-NLC). Both the ideal scheme (without transceiver noise limitation) and a more practical scheme (transceiver SNR of 25 dB) were used to investigate the performance of NLC in C-band optical communication systems. System parameters are detailed in Table 1. Polarisation mode dispersion (PMD) is neglected, since it was shown that the transceiver noise greatly outweighs the impact of PMD[10]. Phase noise from the transmitter and local oscillator lasers, as well as the frequency offset between them are also neglected. In our NLC schemes, 32-GHz refers to the bandwidth of single-channel DBP, 250-GHz refers to current practically possible digital NLC bandwidth[11], and 2.4-THz denotes the highest reported OPC bandwidth[6].

Fig. 1 illustrates the AIR versus transmission distance for different modulation formats in an ideal C-band transmission. It was found that for DP-QPSK, the systems using EDC, partial-bandwidth and full-field NLC show the same (saturated) AIR, for transmission distances of up to 10,000 km. This shows that in an ideal C-band transmission scheme, NLC is not required to enhance the AIR, if the distance is less than 10,000 km in DP-QPSK systems. For DP-16QAM, NLC becomes effective in increasing AIR, for transmission distance greater than 2000 km. For DP-64QAM NLC is effective at distances exceeding 600 km, and for DP-256QAM NLC is effective for all considered distances starting from 400 km. In addition, DP-64QAM shows similar AIRs to DP-256QAM with up to 2.4-THz NLC, if the distance is larger than 3600 km.

Tab. 1: C-band transmission system parameters

Parameters	Value
Symbol rate	32 Gbaud
Channel spacing	32 GHz
Central wavelength	1550 nm
Number of channels	151
Attenuation coefficient	0.2 dB/km
CD coefficient	17 ps/nm/km
Nonlinear coefficient	1.2 /W/km
Span length	80 km
EDFA noise figure	4.5 dB

Fig. 2 shows the AIR versus transmission distance for different modulation formats, in more practical C-band transmission systems with a transceiver SNR of 25 dB applied. It is still found that NLC is not necessary for DP-QPSK transmission for enhancing the AIR when the distance is less than 10,000 km, and for DP-16QAM NLC becomes effective to increase the AIR at transmission distance exceeding 2000 km. Differently, for both DP-64QAM and DP-256QAM NLC is effective for all considered distances. For EDC, 32-GHz and 250-GHz (digital) NLC, DP-

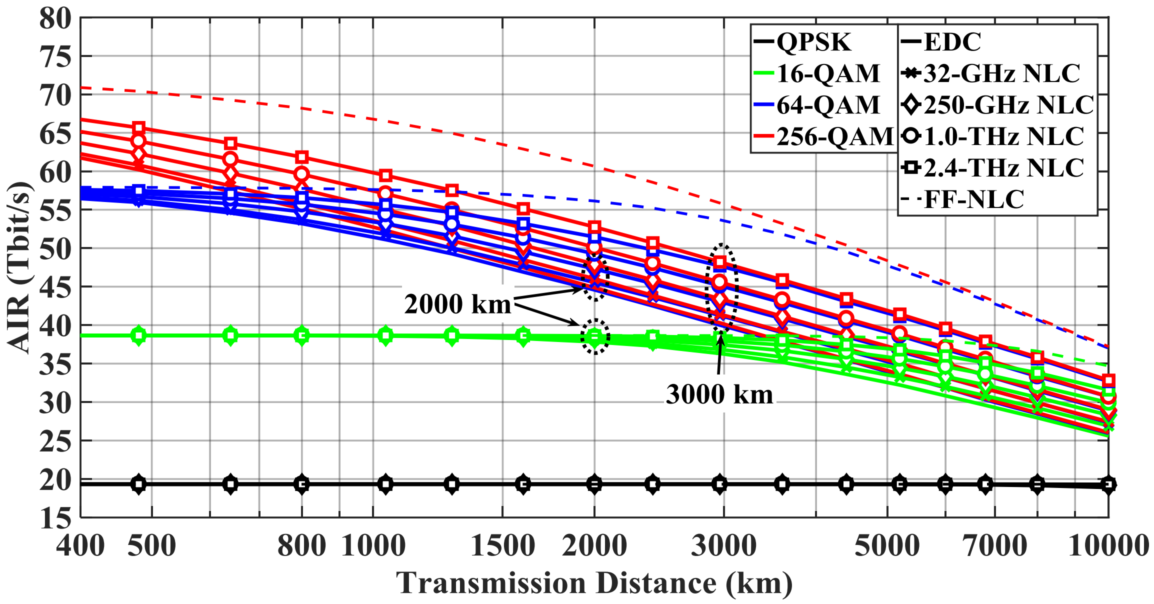

Fig. 2: AIRs versus transmission distances in the C-band systems with a transceiver SNR of 25 dB

64QAM shows similar AIRs as DP-256QAM system, for distances greater than 2000 km. For NLC with bandwidths up to 2.4-THz, DP-64QAM performs the same as DP-256QAM at distances exceeding 3000 km. Compared to ideal C-band schemes, transceiver noise limitation has a marginal impact on the AIRs of DP-QPSK and DP-16QAM systems, however, it degrades more significantly the performance of DP-64QAM and DP-256QAM systems.

Conclusions

The gains achievable from the use of MC-NLC in enhancing AIRs has been investigated in fully-loaded C-band (~ 4.8 THz) Nyquist-spaced WDM optical fibre communication systems, considering the impact of different modulation formats. Modulation dependence and transceiver noise were included to model the practical C-band transmission. It was found that, in C-band transmission schemes, the efficacy of MC-NLC in enhancing the AIRs depends on the modulation format and transmission distance scenarios. The distance thresholds, at which MC-NLC becomes effective, are lower for higher-order modulation formats. For DP-QPSK systems, NLC is not necessary for transmission distances of up to 10,000 km. In addition, transceiver noise arising in practical systems have a marginal impact on the AIRs of DP-QPSK and DP-16QAM systems, while limiting the AIRs more substantially in DP-64QAM and DP-256QAM systems.

Our work gives an insight into the application of NLC in fully-loaded C-band optical systems, considering current transceiver limitations.

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