WARWICK
THE UNIVERSITY OF WARWICK

Manuscript version: Author's Accepted Manuscript
The version presented in WRAP is the author's accepted manuscript and may differ from the published version or Version of Record.

Persistent WRAP URL:
http://wrap.warwick.ac.uk/117458

How to cite:
Please refer to published version for the most recent bibliographic citation information. If a published version is known of, the repository item page linked to above, will contain details on accessing it.

Copyright and reuse:
The Warwick Research Archive Portal (WRAP) makes this work by researchers of the University of Warwick available open access under the following conditions.

Copyright © and all moral rights to the version of the paper presented here belong to the individual author(s) and/or other copyright owners. To the extent reasonable and practicable the material made available in WRAP has been checked for eligibility before being made available.

Copies of full items can be used for personal research or study, educational, or not-for-profit purposes without prior permission or charge. Provided that the authors, title and full bibliographic details are credited, a hyperlink and/or URL is given for the original metadata page and the content is not changed in any way.

Publisher's statement:
Please refer to the repository item page, publisher's statement section, for further information.

For more information, please contact the WRAP Team at: wrap@warwick.ac.uk.

warwick.ac.uk/lib-publications

Limit of Achievable Information Rates in EDFA and Raman Amplified Transmission Systems Using Nonlinearity Compensation

Tianhua Xu[1,2,3], ***Member, IEEE***, **Nikita A. Shevchenko**[3,4], **Zhe Li**[5], ***Member, IEEE***, **Tiegen Liu**[1], ***Member, IEEE***, **Polina Bayvel**[3], ***Fellow, IEEE***

1. Tianjin University, Tianjin, 300072, China
2. University of Warwick, Coventry, CV4 7AL, UK
3. University College London (UCL), London, WC1E 7JE, UK
4. King's College London (KCL), London, WC2R 2LS, UK
5. Finisar Corporation, Horsham, PA 19044, USA
Tel: (4424) 765 28698, Fax: (4424) 764 18922, e-mail: tianhua.xu@ieee.org

(Invited Paper)

ABSTRACT

Optical networks form an integral part of the world-wide communication infrastructure and nowadays over 95% of data traffic is carried over fibres. Erbium-doped fibre amplifiers (EDFAs) and Raman amplifiers have made it possible to extend the usable fibre bandwidth to increase the achievable capacity of optical communications in past decades to meet the ever-growing information rate demands. However, these amplification technologies are now viewed as limiting the accessible optical spectrum to ~5 THz and ~10-15 THz, respectively. Currently, the presence of Kerr effects in fibre channels has been largely regarded as the major bottleneck for enhancing achievable information rates of optical communications. Signal performance degradations due to fibre nonlinearities are more severe in the systems utilising larger transmission bandwidths, closer channel spacing and higher-order modulation formats. In this work, we will study the impact and compensation of Kerr effects to analyse the performance of long-haul optical fibre communication systems using EDFAs and Raman amplifiers. Achievable information rates of such ultra-wideband optical transmission systems will be discussed considering nonlinearity compensation and probabilistic shaping techniques.

Keywords: optical fibre communications, achievable information rate, Kerr fibre nonlinearity, Erbium-doped fibre amplifiers, Raman amplifiers, probabilistic shaping.

1. INTRODUCTION

Optical fibre communications have achieved unprecedented growth and success over past three decades and now stands alone as the enabling technology that underpins the global information infrastructure. Over this period, the throughput (measured in bits per second) of lightwave communications systems increased from 100 Mb/s in 1970 to 10 Tb/s in present day commercial systems, which represents an astonishing 100,000-fold increase. The key technologies that fuelled this surge in capacity were wavelength division multiplexing (WDM), improved fibre design and fabrication, optical amplification and coherent detection [1]. The use of Erbium-doped fibre amplifier (EDFA) and Raman fibre amplifiers negated the need for electronic regenerators and enabled dense WDM transmission, although the success and performance of these amplifier technologies is now seen as limiting the usable fibre bandwidth to approximately 10-15 THz, ultimately limiting the maximum throughput of optical systems [2,3]. Within the usable fibre bandwidth, the throughput can be increased by reducing the spectral guard bands between WDM carriers, increasing the cardinality of the modulation format, or through new forward error correction (FEC) schemes that require lower redundancy without loss in performance [4,5]. The combination of these techniques can be used to increase the spectral efficiency (SE) of each WDM carrier.

However, for Nyquist-spaced WDM systems (where the spectral guard band is minimised), increasing the SE is determined by the densest constellation that can be used. Denser constellations, however, typically operate well only at high signal-to-noise ratios (SNR). Ensuring such a high SNR in WDM systems operating over a wide spectral range will result in system operation in the Kerr nonlinearity limited regime, with the maximum capacity sometimes referred to as the nonlinear Shannon limit in the literature [6,7]. Key to the growth in both achievable system capacities and reach is the understanding of the impact of Kerr nonlinearities and chromatic dispersion and their interactions with amplifier noise. To maximise system capacity effective fibre nonlinearity mitigation is essential. To further increase the information rate, the probabilistic shaping technique is used to transmit symbol constellations with a non-uniform probability according to a certain probability mass function. As the optimum input distribution for the nonlinear fibre channel is still under investigation, a Maxwell-Boltzmann probabilistic shaping is employed in our work, since it has been proved to be optimal for quadrature amplitude modulation (QAM) constellations in a Gaussian channel [8,9]. In this paper, we consider the joint application of these techniques above and demonstrate the limit of achievable information rate (AIR), spectral efficiency and reach that can be achieved.

2. SYSTEM MODEL

The performance of dispersion-unmanaged optical transmission systems can be described using a concept of effective SNR [10-12], considering the amplified spontaneous emission (ASE) noise from amplifiers and Kerr fibre nonlinearities,

$$\mathrm{SNR}=\frac{P}{\sigma_{\mathrm{eff}}^{2}}\approx\frac{P}{\sigma_{\mathrm{ASE}}^{2}+\sigma_{\mathrm{S-S}}^{2}+\sigma_{\mathrm{S-N}}^{2}}, \tag{1}$$

where P is the average signal power, $\sigma_{\mathrm{ASE}}^{2}$ is the ASE noise power, $\sigma_{\mathrm{S-S}}^{2}$ is the signal-signal interaction, and $\sigma_{\mathrm{S-N}}^{2}$ is the signal-ASE noise interaction. The nonlinear signal-signal interaction can be described as: [13,14]

$$\sigma_{\mathrm{S-S}}^{2}=N_{\mathrm{s}}^{\varepsilon+1}\,\eta P^{3}, \tag{2}$$

where η is the nonlinear distortion coefficient, ε is the coherence factor to describe the increase of signal-signal interaction along the fibre span [15]. The signal-ASE interaction grows quadratically with the signal power and can be described as [16]:

$$\sigma_{\mathrm{S-N}}^{2}\approx 3\varsigma\eta\,\sigma_{\mathrm{ASE}}^{2}P^{2} \tag{3}$$

where the pre-factor ς represents the accumulation of signal-ASE distortion with the transmission distance [17].

When the full-field nonlinearity compensation is applied [18,19], the signal-signal interaction in Eq. (2) can be completely suppressed. For EDFA and Raman amplified systems, the expression and computation of the ASE noise $\sigma_{\mathrm{ASE}}^{2}$ and the nonlinear distortion coefficient η are detailed in Ref [13,14].

3. RESULTS AND ANALYSIS

Based on the aforementioned analytical model, the AIRs of EDFA and Raman amplified optical communication systems have been investigated for different transmission distances under the cases of electronic dispersion compensation (EDC) and full-field NLC (FF-NLC). The probabilistic shaping is also applied for the case of FF-NLC to further improved the system performance. System parameters are described as follows: fibre attenuation of 0.2 dB/km, chromatic dispersion coefficient of 17 ps/nm/km, nonlinear coefficient of 1.2 /W/km, fibre span length of 80 km, symbol rate of 10 Gbaud, channel spacing of 10 GHz. The number of channels is 501 for the EDFA system (~5 THz) and is 1251 for the Raman amplified system (~12.5 THz). The polarisation mode dispersion and the phase noise from the transmitter and local oscillator lasers are all neglected.

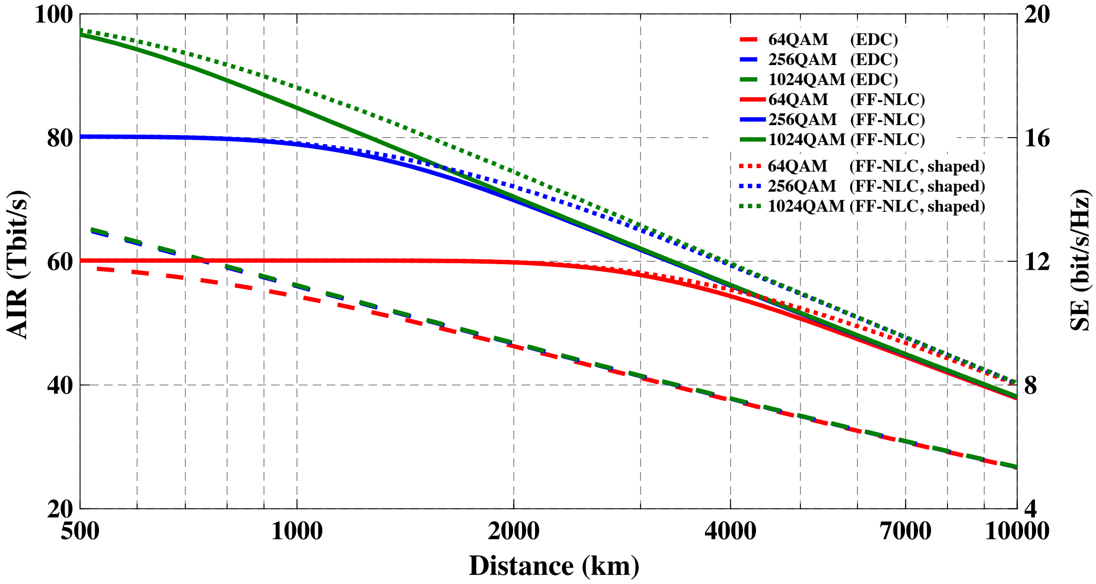

Figure 1. Achievable information rates limit versus transmission distances in EDFA optical transmission systems using nonlinearity compensation and probabilistic shaping.

Fig. 1 and Fig. 2 illustrate the AIRs versus transmission distances for different modulation formats for the EDFA and the Raman amplified optical transmission systems, respectively. It is found that the use of FF-NLC has importantly enhanced the AIRs for all considered modulation formats in both EDFA and Raman based systems. The increase is more significant for higher-order modulation formats. For the highest considered modulation format (dual-pol 1024QAM), the use of FF-NLC produces AIRs of ~70 Tbit/s and ~215 Tbit/s for the EDFA and the Raman systems, respectively, at the transmission distance of 2000 km. This can be further improved by using the Maxwell-Boltzmann probabilistic shaping to realise AIRs of ~75 Tbit/s and ~223 Tbit/s, respectively. It can also be seen that, the 256QAM system can achieve the same AIRs as the 1024QAM system with the use of FF-NLC and Maxwell-Boltzmann probabilistic shaping, when the transmission distance exceeds 3200 km in the EDFA system and 6000 km in the Raman amplified system. This implies that the order of 256QAM is sufficient in these long-haul transmission scenarios.

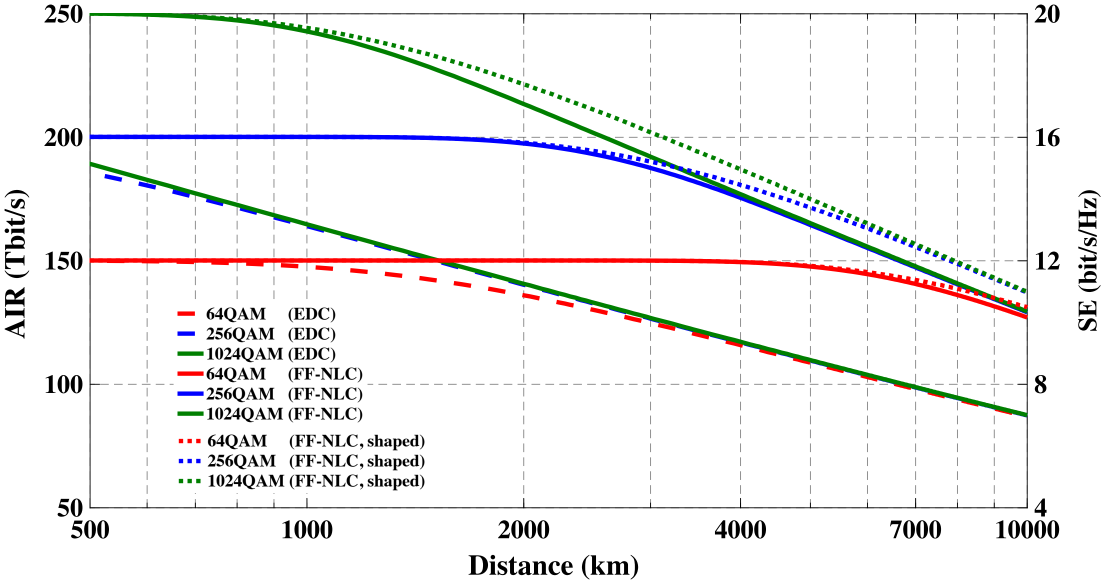

Figure 2. Achievable information rates limit versus transmission distances in Raman amplified transmission systems using nonlinearity compensation and probabilistic shaping.

4. CONCLUSIONS

The use of FF-NLC and probabilistic shaping in enhancing AIRs has been investigated in ~ 4.8 THz EDFA and ~ 12.5 THz Raman amplified optical fibre communication systems with different modulation formats. It is found that, for 2000 km transmission, the application of dual-pol 1024QAM, full-field nonlinearity compensation and Maxwell-Boltzmann probabilistic shaping can achieve AIRs of ~75 Tbit/s for the EDFA system and of ~223 Tbit/s for the Raman amplified system, respectively.

Our work explores the achievable performance in transmission over the standard single mode fibre which corresponds to the billions of km of optical fibre infrastructure already installed. However, the analyses are compatible with other fibre types, such as ultra-low loss and large effective area fibres, and can be used to estimate the achievable capacity of any future fibre infrastructure including the photonic crystal and hollow core fibres being researched as well as all future space-division multiplexed systems.

ACKNOWLEDGEMENTS

This work is supported by EU Horizon 2020 RISE grant 778305 and UK EPSRC program TRANSNET. The authors would like to thank Mr. D. Semrau, Mr. B. Karanov, Dr. L. Galdino, Dr. D. Lavery and Dr. R. I. Killey from University College London for helpful discussions and contributions.

REFERENCES

[1] G. P. Agrawal: *Fiber-optic communication systems, 4th ed.*, John Wiley & Sons, New Jersey, 2010.
[2] R.J. Essiambre and R.W. Tkach: Capacity trends and limits of optical communication networks, *Proc. IEEE*, vol. 100, pp. 1035-1055, May 2012.
[3] P. Bayvel *et al.*: Maximizing the optical network capacity, *Philos. Trans. R. Soc. A: Math. Phys. Eng. Sci.*, vol. 374, pp. 20140440, Dec. 2016.
[4] P.J. Winzer: Scaling optical fiber networks: challenges and solutions, *Opt. Photon. News*, vol. 26, pp. 28-35, Mar. 2015.
[5] T. Xu *et al.*: Nonlinearity compensation and information rates in fully-loaded C-band optical fibre transmission systems, in *Proc. ECOC*, Gothenburg, Sweden, Sep. 2017, paper P2.SC6.30.

[6] P. P. Mitra and J. B. Stark: Nonlinear limits to the information capacity of optical fibre communications, *Nat.*, vol. 411, pp. 1027-1030, Jun. 2001.

[7] A.D. Ellis *et al.*: Performance limits in optical communications due to fiber nonlinearity, Adv. Opt. Photon., vol. 9, pp. 429-503, Sep. 2017.

[8] G. D. Forney *et al.*: Efficient modulation for band-limited channels, *IEEE J. Sel. Areas Commun.*, vol. 2, pp. 632-647, Sep. 1984.

[9] F. R. Kschischang and S. Pasupathy *et al.*: Optimal nonuniform signaling for Gaussian channels, *IEEE Trans. Inf. Theory*, vol. 39, pp. 913-929, May 1993.

[10] P. Poggiolini: The GN model of non-linear propagation in uncompensated coherent optical systems, J. Lightwave Technol., vol. 30, pp. 3857-3879, Dec. 2012.

[11] M. Secondini *et al.*: Achievable information rate in nonlinear WDM fiber-optic systems with arbitrary modulation formats and dispersion maps, *J. Lightwave Technol.*, vol. 31, pp. 3839-3852, Dec. 2013.

[12] T. Xu *et al.*: Modulation format dependence of digital nonlinearity compensation performance in optical fibre communication systems, *Opt. Express*, vol.25, pp. 3311-3326, Feb. 2017.

[13] D. Semrau *et al.*: Achievable information rates estimates in optically amplified transmission systems using nonlinearity compensation and probabilistic shaping, *Opt. Lett.*, vol.41, pp. 121-124, Jan. 2017.

[14] N.A. Shevchenko *et al.*: Achievable information rates estimation for 100-nm Raman-amplified optical transmission system, in *Proc. ECOC*, Düsseldorf, Germany, Sep. 2016, paper 878-880.

[15] A. Carena *et al.*: EGN model of non-linear fiber propagation, *Opt. Express*, vol. 22, pp. 16335-16362, Jun. 2014.

[16] R. Dar *et al.*: Accumulation of nonlinear interference noise in fiber-optic systems, *Opt. Express*, vol. 22, pp. 14199-14211, Jun. 2014.

[17] N.A. Shevchenko *et al.*: Modeling of nonlinearity-compensated optical communication systems considering second-order signal-noise interactions, *Opt. Lett.*, vol.42, pp. 3351-3354, Sep. 2017.

[18] T. Xu *et al.*: Equalization enhanced phase noise in Nyquist-spaced superchannel transmission systems using multi-channel digital back-propagation," *Sci. Rep.*, vol.5, pp. 13990, Sep. 2015.

[19] G. Liga *et al.*: On the performance of multichannel digital backpropagation in high-capacity long-haul optical transmission, *Opt. Express*, vol.22, pp. 30053-30062, Nov. 2014.