Ultra-Wideband Information Throughput Attained via Launch Power Allocation

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***Abstract*—Maximised information rates of ultra-wideband (typically, beyond $100\ \mathrm{nm}$) lumped-amplified fibre-optic communication systems have been thoroughly examined accounting for the wavelength dependencies of fibre parameters as well as the impact of the inter-channel stimulated Raman scattering (SRS). If the tilted signal spectral profile due to SRS is supposed to be completely undone at every fibre span, the obtained results demonstrate the possibility to approach nearly optimal system performance by launching sub-optimal but practically relevant uniform power profiles.**

***Index Terms*—Fibre-optic communication systems, four-wave mixing, stimulated Raman scattering, launch power optimisation, system throughput.**

I. INTRODUCTION

It is now beyond any doubt that fibre-optic communication systems play a substantial role in the national and international communication infrastructure. Nowadays over 95% of digital data traffic are carried over optical fibre-based networks [1]. A drastic increase in high-capacity data transmission demands, especially, owing to the outbreak of COVID-19 has also been recently observed. In spite of the fact that the overwhelming bulk of the world's fibre-optic communication systems have already undergone a long process of increasing engineering complexity and sophistication, and the information data rates of optical communication systems have already experienced an astonishing increase from $100\ \mathrm{Mbps}$ per fibre in the '70s to $10\ \mathrm{Tbps}$ in current commercial systems, the research challenges of maximising the ultimate information capacity using single mode fibres still remain of much interest.

It is widely accepted that accommodating higher data rates poses greater requirements on optical modulated bandwidth in fibre-optic telecommunication systems. The detrimental effects, which inherently restrict the capacity of ultra-wideband communication systems are the optical nonlinear effects occurred in silica fibres. These are the optical Kerr effect, which manifests itself as the four-wave mixing (FWM) among frequencies components in a wavelength-division multiplexing (WDM) system, as well as the inter-channel stimulated Raman scattering (SRS), which gives rise to the considerable differences in the performance of each individual WDM channel. These differences become even more substantial with increasing either the total input power or the entire modulated bandwidth [2]–[4]. As a consequence, the uniform launch power distributions (flat launch power profiles, i.e., the total optical input power is assumed to be equally split among all WDM channels), commonly used so far, cannot ultimately provide the best system performance. Thus, finding the appropriate launch power distributions maximising the overall system performance is vital to enhance the ultimate system throughput. The point-to-point (p2p) system throughput can be estimated through maximisation of the total Shannon information rate in conjunction with further optimal allocation of the modulated bandwidth (BW). This procedure can be particularly realised by applying the global optimisation algorithms, such as the genetic algorithm (GA) [5] and the swarm intelligence based algorithms [6], returning the optimum launch power values of each individual channel across the whole transmit bandwidth.

II. MODELLING AND OPTIMISATION

A. Noise and Inter-Channel SRS Modelling

Due to the presence of inter-channel SRS, the received signal signal-to-noise ratio (SNR) exhibits significant variations across the entire spectrum. It is thus customary to introduce the frequency-dependent *inverse* SNR, which is decomposed into two main contributions: linear term due to the ASE noise and nonlinear *noise-like* interference (NLI) occurred due to the FWM mixing among signal frequency components, also affected by the SRS, it therefore reads[1]

$$\mathrm{SNR}^{-1}\big[P\left(f_k\right)\big] = \frac{\sigma^2_{\mathrm{ASE}}\left(f_k\right)}{P\left(f_k\right)} + \eta_{\mathrm{SRS}}\left(f_k\right)P^2\left(f_k\right), \quad (1)$$

with the linear noise contribution given by the ASE noise σ^2_{ASE}, and the frequency-dependent nonlinear distortion coefficient $\eta\left(f_k\right)$. The optical launch power per channel distribution function is denoted as $P\left(f_k\right)$, where f_k is the centre frequency of each $k-$channel[2].

Assuming that both the fibre loss and the tilted SNR spectrum due to the inter-channel SRS are ideally equalised by the EDFA gain after each fibre span in a link, and the ASE noise contribution arising from EDFAs at the end of each span:

$$\sigma^2_{\mathrm{ASE}}\left(f_k\right) = N_{\mathrm{s}}\left[G_{\mathrm{EDFA}}\left(f_k\right)-1\right]\cdot\mathrm{NF}\cdot\left(hf_0 + hf_k\right)\Delta f, \quad (2)$$

where N_{s} is the number of fibre spans, NF is the EDFA noise figure, Δf is the channel spacing, hf_k is the $k-$channel averaged photon energy. Here it should be emphasised that both the fibre loss and the inter-channel SRS gain are assumed

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[1] The expressions in this subsection are assumed to be given at a fixed value of the centre BW reference wavelength $\lambda_0 = c/f_0$, with c being the speed of light in vacuum.

[2] Hereinafter, the noise PSD within each channel BW is assumed to be ideally flat. The case of $k = 0$ corresponds to the centre BW channel.

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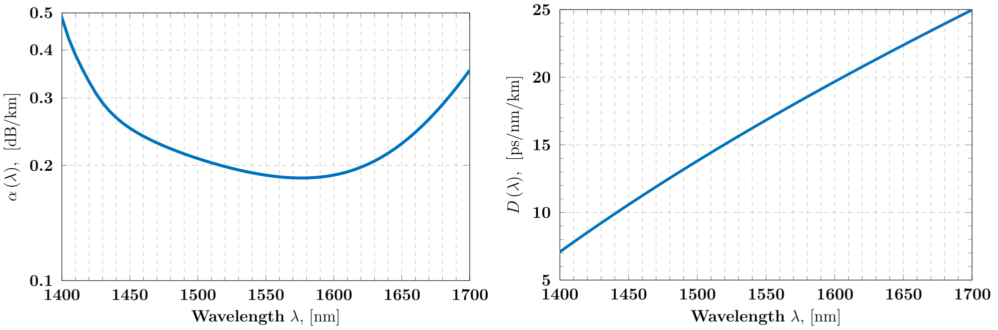
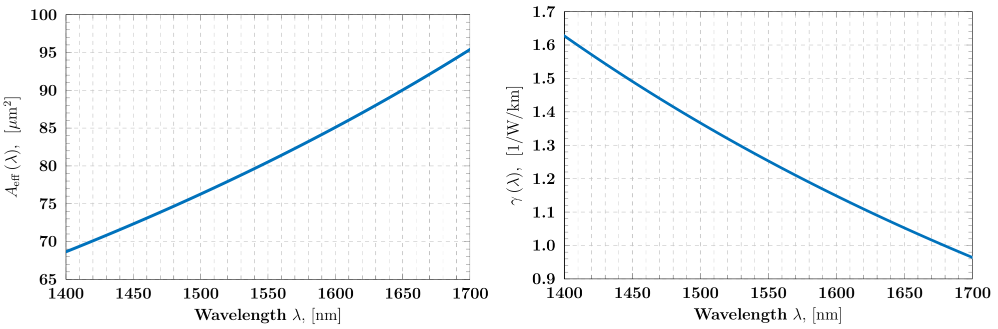


(a) Fibre attenuation parameter $\alpha(\lambda)$

(b) Fibre chromatic dispersion parameter $D(\lambda)$



(c) Fibre effective mode area $A_{\mathrm{eff}}(\lambda)$

(d) Fibre nonlinear coefficient $\gamma(\lambda)$

Fig. 1: Single mode optical fibre parameters spectra: (a) $\alpha(\lambda)$ was bounded by the Rayleigh scattering, the infra-red absorption and OH^{-1} ions peaks [7]; (b) $D(\lambda)$ was obtained by applying the $4-$term Sellmeier fitting; (c) $A_{\mathrm{eff}}(\lambda)$ approximated by using the model in [8]; (d) $\gamma(\lambda) \triangleq 2\pi n_2/(\lambda\, A_{\mathrm{eff}}(\lambda))$ with $n_2 = 2.8 \times 10^{-20}$ m^2/W being the nonlinear (Kerr) refractive index.

to be entirely compensated and ideally equalised by EDFAs after each fibre span, respectively. Hence, the EDFA gain is defined as $G_{\mathrm{EDFA}}(f_k) = P(0, f_k)\, e^{\alpha(f_k)\cdot L_{\mathrm{s}}}/P(L_{\mathrm{s}}, f_k)$ with $P(0, f_k)$ and $P(L_{\mathrm{s}}, f_k)$ being defined as the power at the input and output of the fibre span, respectively; $\alpha(f_k)$ being the fibre loss parameter corresponding to the centre frequency f_k of each $k-$channel, and L_s being the fibre span length.

In order to evaluate the NLI noise power of a Nyquist-spaced WDM system, one has to follow the GN model [9]

$$\eta_{\mathrm{SRS}}(f_k) = \frac{16\,\gamma^2(f_k)}{27\,R_S^2}\int_{-\infty}^{\infty}\int_{-\infty}^{\infty} df_1 df_2 \left\{\mathrm{rect}\left(\frac{f_1+f_2-f_k}{\mathrm{BW}}\right)\right. \cdot \left.\left|\,\varphi(f_k, f_1, f_2\,|\,L_{\mathrm{s}}, N_{\mathrm{s}})\;\rho(f_k, f_1, f_2\,|\,L_{\mathrm{s}})\,\right|^2\right\}, \tag{3}$$

with the symbol rate R_S, the rectangular function $\mathrm{rect}(x)$, the phased-array factor $\varphi(f_k, f_1, f_2\,|\,L_{\mathrm{s}}, N_{\mathrm{s}})$. The appropriate modification of the FWM efficiency factor:

$$\rho(f_k, f_1, f_2\,|\,L_{\mathrm{s}}) = \int_0^{L_{\mathrm{s}}} d\zeta\, e^{\,i\,\Delta\beta(f_k, f_1, f_2)\zeta}\, \Delta\rho(f_k, f_1, f_2, |\,\zeta)\,, \tag{4}$$

where $\Delta\beta(f_k, f_1, f_2)$ is the FWM mismatch factor, and $\Delta\rho(f_k, f_1, f_2\,|\,\zeta)$ defines the signal power distance evolution in the presence of inter-channel SRS effect (see, e.g., [2], [3]).

B. Information Throughput Optimisation

The unconstrained optimisation problem implies to find the optimum launch power distribution shape $P_{\mathrm{opt}}(f_k)$ that maximises the overall information rate, it thus reads

$$P_{\mathrm{opt}}(f_k) = \underset{P(f_k)\,:\,\lambda_0 = \mathrm{const}}{\operatorname{argmax}} \left\{\sum_k \mathsf{C}\left[P(f_k)\,|\,\lambda_0\right]\right\}, \tag{5}$$

where the maximisation is assumed to be taken over all possible unconstrained launch power per channel values[3], at each fixed value of the reference centre BW wavelength λ_0. The functional C in (5) defines the $k-$channel Shannon information rate (i.e., the Gaussian channel capacity upper bound) measured in bits per channel use, it yields

$$\mathsf{C}\left[P(f_k)\,|\,\lambda_0\right] \triangleq 2\,\log_2\left(1 + \mathrm{SNR}\left[P(f_k)\,|\,\lambda_0\right]\right).$$

The corresponding throughput (measured in $[\mathrm{bit/s}]$) obtained via optimising the launch power distribution is thus given by

$$\mathsf{T}^*(\lambda_0) = R_S \sum_k \mathsf{C}\left[P_{\mathrm{opt}}(f_k)\,|\,\lambda_0\right]. \tag{6}$$

Finally, the ultimate p2p link throughput can be attained by means of allocating the transmit BW as follows

$$\mathsf{T} = \max_{\lambda_0} \mathsf{T}^*(\lambda_0)\,. \tag{7}$$

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[3] The global unconstrained launch power optimisation was independently carried our by using both the GA [5] and the particle swarm optimisation (PSO) algorithm [6] enhanced by the gradient descent optimisation algorithm.

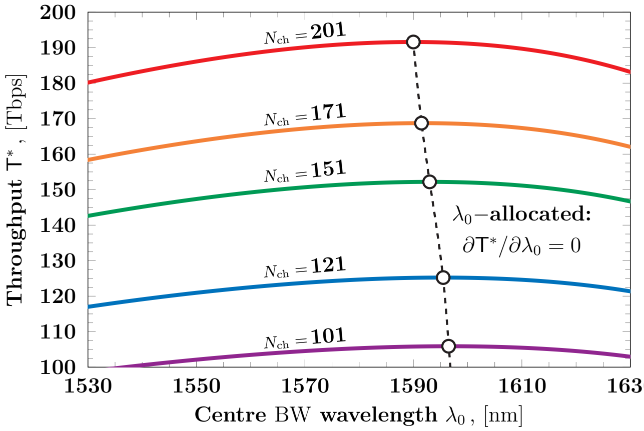

Fig. 2: System throughput T^* after launch power optimisation given by Eq. (6) as function of the centre BW wavelength λ_0 for different number of WDM channels N_{ch} with a channel spacing of 100 GHz each. The dashed line indicates the values of the wavelength defining the optimal allocation of modulated BW to maximise the throughput.

III. RESULTS AND DISCUSSION

To estimate the performance of the ultra-wide systems with a modulated bandwidth beyond 100 nm, apart from the SRS effect, a proper consideration and modelling of the wavelength-dependencies of single mode optical fibre parameters become also essential. Fig. 1 illustrates the variations of fibre parameters, such as the fibre loss (a), the chromatic dispersion (b), the effective mode area (c) and the fibre nonlinear parameter (d). These variations were quantified within a range of $1400-1700$ nm. Except for the loss profile, the monotonic behaviour has been observed for the rest of fibre parameters.

Without loss of generality, we focus on an ideal polarisation-multiplexed Nyquist-spaced WDM transmission system over the 100 GHz grid. All fibre spans and EDFAs are assumed to be identical with a length of $L_{\text{s}} = 80$ km, and the noise figure of $\text{NF} = 4.5$ dB, respectively. Following the GN model approach originally developed in [9], Eqs (1)-(4) now take into account both the wavelength variations of fibre parameters and the impact of SRS. Fig. 2 shows that the maximised throughput obtained by optimising the non-uniform launch power profile exhibits a concave behaviour with regard to the centre BW wavelength. It is also observed that the allocated values of λ_0 corresponding to the maximum values of throughput T^* are shifting with increasing the total number of WDM channels. Moreover, the λ_0−allocation can lead to an extra improvement of the system performance. In addition, Fig. 3 illustrates that the ultimate system throughput T can be nearly achieved by using the pragmatic sub-optimal flat launch power profiles with a fixed value of power per channel.

IV. CONCLUSION

This work analyses the bounds on the scaling between the ultimate p2p link throughput and the total number of channels in an ideal Nyquist-spaced WDM transmission system. These bounds were estimated numerically by making use of a non-uniform launch power per channel profile optimisation. The extra increments were also attained by allocating the centre bandwidth wavelength. The results also show that the optimal throughput can be nearly approached by operating with practically feasible sub-optimal flat launch power profiles assuming the SRS spectral tilt is entirely equalised at every fibre span.

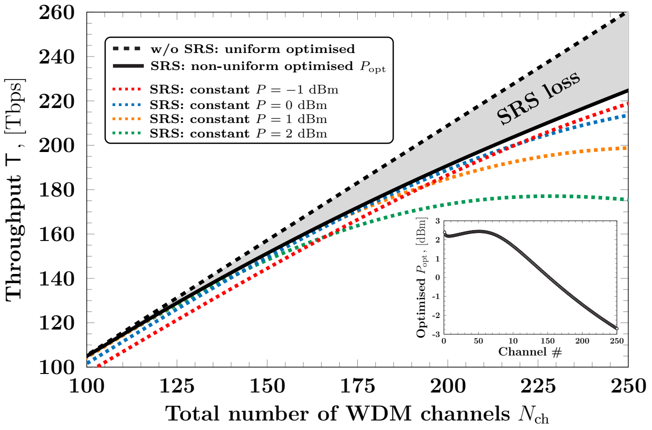

Fig. 3: Ultimate p2p link throughput against the total number of 100 GHz Nyquist-spaced WDM channel. Dashed black curve indicates the bound estimated in the absence of SRS effect, whereas the solid black curve is obtained by the non-uniform launch power optimisation (Eqs (5)-(7)). Practically relevant uniform constant launch power profiles with different values of power per channel are depicted by the coloured dotted lines. The embedded sub-figure shows the optimised launch power profile for $N_{\text{ch}} = 251$ at $\lambda_0 = 1570$ nm. Note that in this case the total launch power is about 24.8 dBm that slightly exceeds the typical 21.3 dBm eye safety limits for class 1M.

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