Role of distributed amplification in designing high-capacity soliton systems

Zhi M. Liao and Govind P. Agrawal

The Institute of Optics, University of Rochester,
Rochester, New York 14627
gpa@optics.rochester.edu

Abstract: We discuss the importance of distributed amplification for high-speed soliton communication systems through numerical simulations by considering the distributed gain provided by stimulated Raman scattering or erbium dopants. Hybrid amplification schemes are also considered. At a bit rate of 40 Gb/s, the use of distributed amplification is found to improve the transmission distance (deduced from the Q parameter) by a factor of up to three for Raman amplification and > 5 for erbium dopants, compared with the case of lumped amplifiers. The increase in transmission distance is by a factor of about two for 80-Gb/s soliton systems when dense dispersion management is used.

OCIS codes: (060.2330) Fiber optics communications; (190.5530) Pulse propagation and solitons

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1 Introduction

The three major obstacles in the design of high-capacity lightwave systems are fiber losses, chromatic dispersion, and fiber nonlinearities [1]. Thus far, the use of erbium-doped fiber amplifiers (EDFAs) in combination with dispersion management has produced commercial WDM systems with single-channel bit rates of up to 10 Gb/s while

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maintaining a practical amplifier spacing (about 80 km). However, the increasing demand is pushing the telecommunication industry toward systems with a capacity $>$ 1 Tb/s. Keeping the single-channel bit rate fixed at 10 Gb/s would require hundreds of WDM channels in such systems. Increasing the single-channel bit rate to 40 or 80 Gb/s would reduce the number of multiplexed channels, reduce the number of components needed, and simplify the network management.

Optical solitons are a natural candidate for long-haul, high-capacity lightwave transmission links [2] because short pulses required at high bit rates also induce large nonlinear effects that must be dealt with. Solitons can use the nonlinear self-phase modulation (SPM) effectively to balance the group-velocity dispersion(GVD) in a dynamic fashion [3]. Most system experiments employ the technique of lumped amplification and place EDFAs periodically along the transmission line for compensating accumulated fiber losses. However, lumped amplification introduces large variations in the soliton energy (or peak power), which limit the amplifier spacing L_A to a fraction of the dispersion length L_D [3]. At high bit rates ($>$ 20 Gb/s), the dispersion length can become quite small, making the use of lumped amplification impractical. Indeed, loss/gain perturbations along the fiber link are the most serious obstacle in designing soliton communication systems.

It has been known for some time that a distributed amplification scheme in which fiber losses are compensated locally all along the fiber in a distributed fashion should perform better for soliton systems [4]. While several recent studies have considered novel dispersion maps and distributed amplification schemes [5]–[8], a systematic study of the system performance that includes the effect of amplifier noise and incorporates both distributed amplification and dispersion management has not yet been performed. In this paper, we report the results of such a study. The performance of single-channel lightwave systems operating at 40 and 80 Gb/s is examined using several different amplification schemes. Two-step as well as dense dispersion-management configurations are used in conjunction with a variety of lumped and distributed amplification schemes. Specifically, we compare the performance of lightwave systems realized using lumped amplifiers, hybrid amplification (backward-pumped Raman configuration with an EDFA), bidirectionally pumped distributed Raman amplification (d-Raman), and distributed EDFA (d-EDFA).

2 Theory

In the d-EDFA scheme, the transmission fiber itself is doped lightly with erbium ions and is pumped periodically using a bidirectional pumping scheme such that just enough gain exists for compensating fiber losses [9]. In the Raman case, we consider bidirectional as well as backward pumping schemes. In both cases, the local gain $g(z)$ varies along the fiber length because of changes in the pump power. We find the gain profile $g(z)$ by solving the appropriate rate equations in each case [1].

To study the system performance numerically, the spatially varying gain $g(z)$ and fiber losses are incorporated into the following generalized nonlinear Schrödinger (NLS) equation [10]:

$$i\frac{\partial A}{\partial z} - \frac{\beta_2}{2}\frac{\partial^2 A}{\partial t^2} + \gamma|A|^2 A = \frac{i}{2}(g-\alpha)A + T_R A\frac{\partial |A|^2}{\partial t}, \tag{1}$$

where $A(z,t)$ is the slowly varying amplitude of the pulse train, β_2 is the GVD parameter, γ is the nonlinear parameter responsible for SPM, and α accounts for the fiber losses. In a dispersion-managed lightwave system, all four parameters (β_2, γ, g, and α) vary with z. The parameter T_R accounts for the Raman-induced frequency shift that

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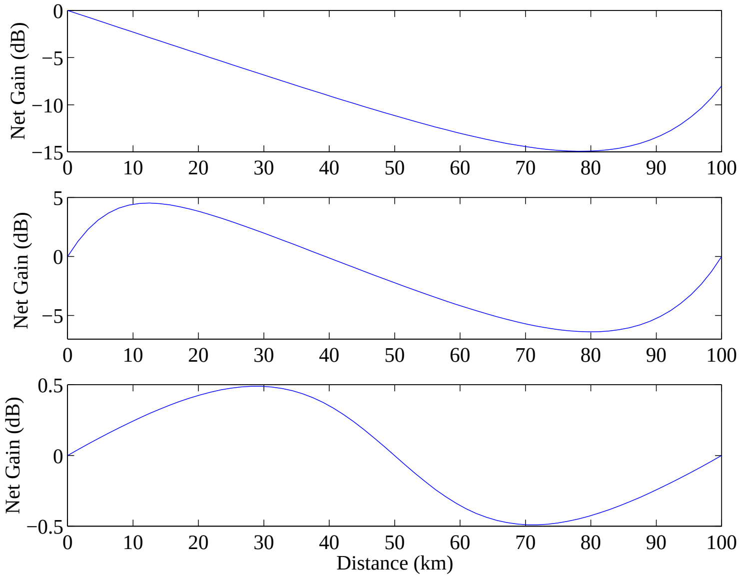

Fig. 1. Net gain $G(z)$ versus distance for hybrid (top), distributed Raman (middle), and d-EDFA schemes (bottom).

becomes important at high bit rates considered here; its numerical value is taken to be 3 fs [10].

For a long-haul system, the distributed gain $g(z)$ is a periodic function with the period L_A. In the lumped case, EDFAs are separated by L_A. In the distributed case, pumping stations are spaced apart by L_A. In both cases, the pump power is chosen such that

$$G(L_A) = \int_0^{L_A} [g(z) - \alpha(z)]\, dz = 0. \tag{2}$$

Note that $G(z) \neq 0$ over the distance L_A because of local gain/loss variations. As a result, the soliton energy varies along the fiber. To avoid excessive generation of dispersive waves, one should optimize the the system design (i.e. dopant density, pump power, etc.) such that $G(z)$ deviates from zero as little as possible. It turns out that $G(z)$ can be made quite small for the d-EDFA scheme by lowering the dopant concentration as much as practical. The d-Raman scheme does not have this degree of freedom since the Raman gain depends only on the pump power. Figure 1 shows how $G(z)$ varies along the fiber over $L_A = 100$ km using $\alpha = 0.2$ dB/km (total loss 20 dB) for the d-EDFA, d-Raman, and hybrid (12-dB Raman gain) schemes. The pump power is 80 mW for the d-EDFA scheme but exceeds 500 mW in the d-Raman case. The gain excursion over the 100-km span is only 0.5 dB for an optimized d-EDFA, but it increases to 5 dB for the d-Raman scheme and to over 15 dB for the hybrid amplification scheme. In the case of lumped amplifiers, $G(z)$ varies by 20 dB since losses accumulate to 20 dB before an EFDA is encountered.

3 Numerical Results

We solve the NLS equation (1) numerically for the three configurations shown in Fig. 1 and compare their performance at a bit rate of 40 and 80 Gb/s to the case of lumped amplifiers. The comparison is made by calculating the Q parameter [1], defined as $Q = (P_1 - P_0)/(\sigma_1 + \sigma_0)$, where P_1 and P_0 are the average powers and σ_1 and σ_0 are the noise levels associated with the 1 and 0 bits. We used a 64-bit pseudorandom

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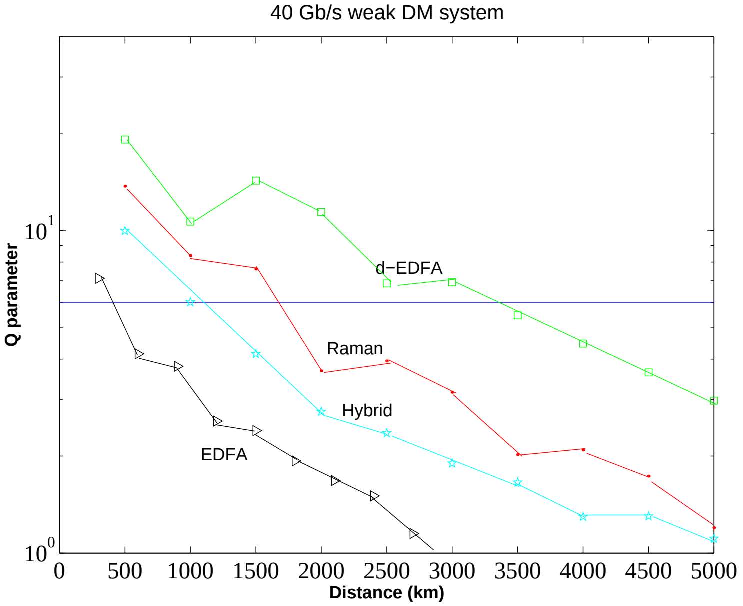

Fig. 2. System performance of the 40-Gb/s soliton system for the four amplification schemes. Horizontal line corresponds to a bit-error rate of 10^{-9}

pulse train for the results shown here. A noise term is added to the NLS equation to account for the distributed noise. In the case of d-EDFA, the noise strength is calculated including variations of the population densities along the fiber. We used a noise figure of 4.5 dB for lumped EDFAs and 3 dB for distributed Raman amplification.

At a bit rate of 40 Gb/s, it was necessary to use a pulse width (full width at half maximum) of $\tau_p = 4.2$ ps. The dispersion map consisted of two 50-km fibers with $\beta_{21} = 0.3$ ps^2/km and $\beta_{22} = -0.38$ ps^2/km, resulting in an average dispersion of -0.04 ps^2/km and a map strength $S = |\beta_{21}L_1 - \beta_{22}L_2|/\tau_p^2 = 1.93$. The launch power and initial chirp were calculated using the results of a variational analysis for dispersion-managed solitons [11]. Changes in the Q factor with transmission distance are shown in Fig. 2 for the four amplification schemes (accuracy is limited by the 64-bit sample size). Figure 3 shows the eye diagrams (filtered by a 30-GHz-bandwidth filter) at a distance of 2000 km for the four amplification schemes. The“eye” is open considerably more when a distributed amplification (Raman or d-EDFA) scheme is employed.

The maximum transmission depends on the acceptable bit-error rate (BER). The $Q = 6$ line in Fig. 2 corresponds to BER of 10^{-9} and shows clearly the advantage of distributed amplification for high-speed lightwave systems. When lumped EDFAs are used, the transmission distance is limited to <500 km but it increases to <3000 km for the d-EDFA scheme. Use of Raman amplification also increases the distance but not as much as d-EDFA because of relatively larger gain variations (see Fig. 1). Double-Rayleigh backscattering may reduce this distance even further. Although an exact analysis of this effect is beyond the scope of this paper, we estimate from Eq. (1) of Ref. [12] that the Rayleigh crosstalk is negligible for the results shown in Fig. 2.

For 80-Gb/s lightwave systems, it was necessary to employ the technique of dense dispersion management [8] by choosing the amplifier spacing L_A to be a multiple of the map period L_m. We set $L_A = 40$ km and use 9 map periods over this distance. Each map period consists of 2.32-km and 2.12-km sections with the GVD of ±2.5 ps/(nm-km), resulting in an average dispersion of 0.1 ps/(nm-km) and a map strength of 1.3

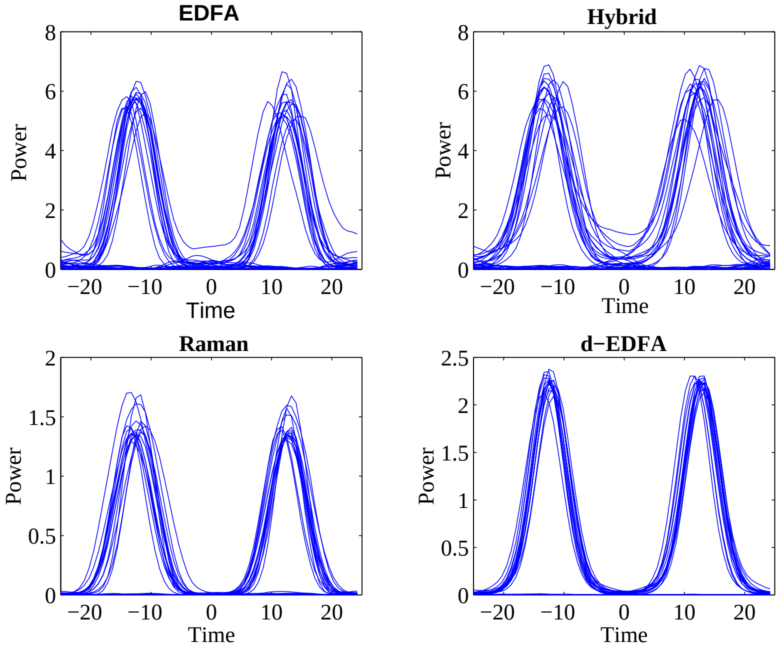

Fig. 3. Eye diagrams at a distance of 2000 km for the 40-Gb/s soliton system for the four amplification schemes.

for the 2.92-ps pulses. Figure 4 shows the performance of such a 80-Gb/s system for the four amplification schemes. The results show again that the transmission distance can be increased using distributed amplification although changes are not as dramatic as in Fig. 2. Note also that the Raman and d-EDFA schemes are comparable in Fig. 4. These difference are due to the use of dense dispersion management for the 80-Gb/s system, which reduces the extent of pulse breathing and pulse-to-pulse interactions.

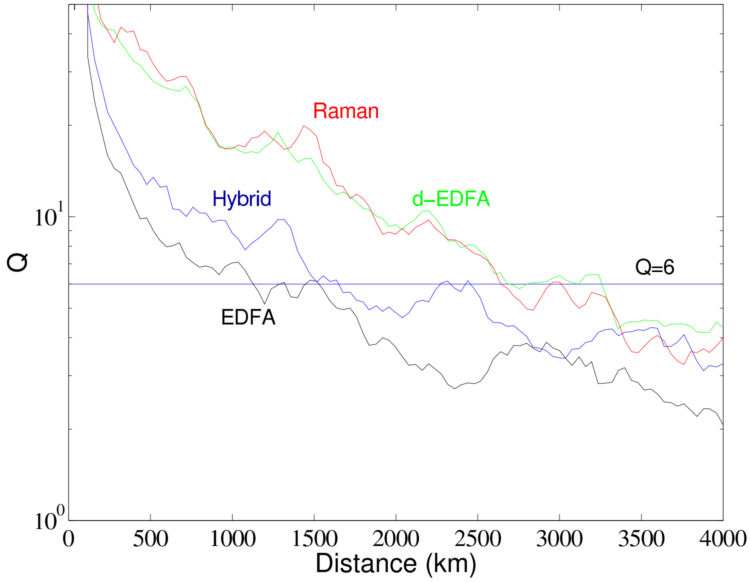

Fig. 4. System performance of a 80-Gb/s system for the four amplification schemes.

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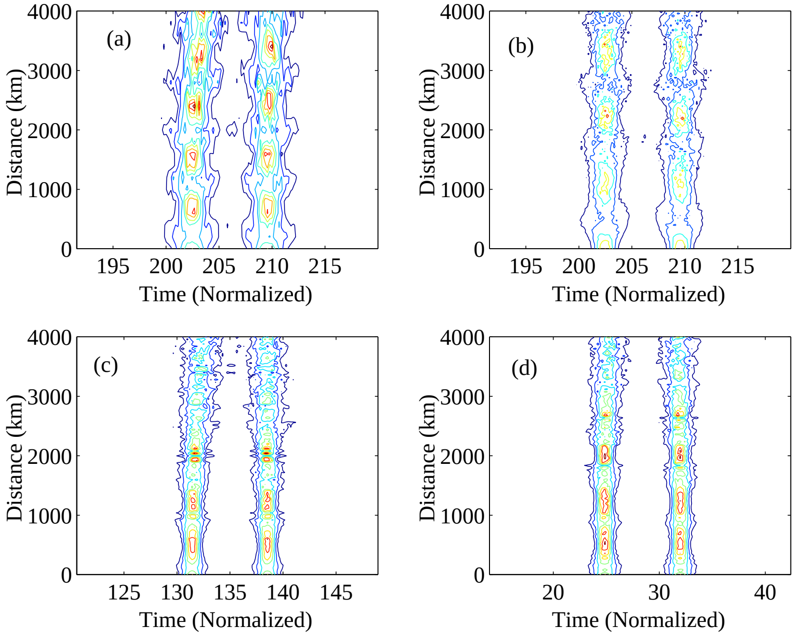

Fig. 5. Pulse-to-pulse interaction for a 80-Gb/s soliton system for (a) lumped, (b) hybrid, (c) distributed-Raman, and (d) d-EDFA schemes.

To understand the role of soliton interaction, we show in Fig. 5 through the contour plots the evolution of a pair of solitons as it propagates through the fiber link for the four amplification schemes (for the 80-Gb/s system). The lumped-amplifier case is the worst. The use of distributed amplification reduces pulse-to-pulse interactions considerably. The best situation occurs in the d-EDFA case for which soliton energy remains nearly constant. It appears that dispersive waves resulting from energy variations affect the system performance considerably.

4 Conclusions

In conclusion, we have shown that the use of distributed amplification may help to increase the total transmission distance of ultra-high-bit-rate soliton systems. The extent of improvement depends not only on the amplification scheme but also on details of the dispersion map. Simulations for a 40-Gb/s system, employing the traditional two-step dispersion map and a 100-km amplifier spacing, show an increase of more than a factor of 5 in the transmission distance when d-EDFAs are used in place of lumped EDFAs. The use of distributed Raman amplification (complete or partial) also helps but the increase in transmission distance is more modest (up to a factor of 3). Simulation results for a 80-Gb/s soliton system employing dense dispersion management (9 map periods over 40-km amplifier spacing) show an increase of up to a factor of 2 in the maximum distance with the use of distributed amplification. In all cases, the improvement is related to reduction in dispersive waves and pulse-to-pulse interaction when soliton energy remains nearly constant over the map period. We have also found that distributed amplification can reduce the timing jitter by a factor of 2 or so. These results point to the necessity of using distributed amplification for future high-capacity lightwave systems. The benefits of Raman amplification have already been observed in several recent transmission experiments [13].

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