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Performance evaluation of path-averaged soliton pulses in loss-managed 10-Gbps soliton transmission link over a long haul

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Abstract

In this paper, the performance evaluation of path-averaged soliton transmission link for various performance measures viz. OSNR, optical power, extinction ratio, bit error rate (BER) and Q factor at different levels of noise figure and values of pulse width (FWHM) has been carried out. The performance of soliton transmission link is studied, taking into account soliton interaction, amplified spontaneous emission (ASE) noise and noise figure. The model presented considers interaction in a random sequence of solitons and the effect of the ASE noise added in each amplification stage. The influence of ASE noise, noise figure and pulse width with different amplifier spacing on the BER and quality factor has been investigated. It has been shown that these play dominant roles in degrading the performance measures. We have demonstrated the capability of path-averaged (guiding-centre) soliton for a long-haul distance of 17,000 km at a bit rate of 10 Gbps without ASE effect and noise figure in each amplifier span length of 500 km. The average value of quality factor is found to be 16.6 dB and the average BER is of the order of 10^{-12} over the transmission distance of 17,000 km. Further, it has been investigated that a severe system penalty results on the inclusion of ASE effect and noise figure in order to achieve the same level of performance. Thus, the investigations ascertain that in order to maintain the same level of BER and Q factor, the amplifier spacing and total transmission distance reduce considerably.

Keywords: Path-averaged soliton; Long haul; Timing jitter; BER; Q factor

1. Introduction

Soliton communication systems are leading candidates for long-haul light wave transmission links. One normally thinks of the soliton as involving dynamic balance along its path between the dispersive and non-linear terms of the non-linear Schrödinger equation. The ideal soliton can exist in a lossless fiber with a balance between the chirp induced by fiber GVD and fiber non-linearity characterized by self-phase modulation (SPM). In a real fiber, the fiber attenuation $\alpha \neq 0$ and would produce the soliton broadening simply because a reduced peak power weakens the SPM effect necessary to counteract the GVD. Thus at first it was natural to assume that distributed amplification, allowing for

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nearly uniform cancellation of loss, would be necessary for long distance soliton transmission [1,2]. Indeed, the Raman effect, which turns silica fiber into its own distributed amplifier, enabled the first experimental studies of such transmission [3–5]. But with the recent and rapid development of the more practical EDFAs, the question immediately arose, are solitons somehow amenable to transmission through a chain of lumped amplifiers? The principle concept that has emerged in the context of lumped amplification is the path-average or guiding-centre soliton [6,7]. In [6], it has been shown both through analysis and numerical simulations that solitons can maintain their shape in periodically amplified fiber link if amplifier spacing L_A is kept smaller than the fiber dispersion length L_D. Then the non-linear effect accumulated over each L_A is simply determined by the corresponding path-average power. We can then balance the average dispersion with the average non-linear phase shift by adjusting the launched power. Thus the soliton peak power should be adjusted by a factor defined by path-averaged power. This is the concept of path-averaged soliton. Thus by keeping the path-average power constant and equal to the usual soliton power from one period to the next, one can have a perfectly well-behaved soliton.

However, the limitation that $L_A < L_D$ results in unreasonably short amplifier spacing at high bit rates. This limitation comes from the fact that the system is not perfectly periodic when L_A becomes comparable to or exceeds L_D. As a result large perturbations generate spectral side bands and dispersive radiation that degrade the system performance [8–10].

In a long-haul soliton communication system, although lumped amplifiers compensate for fiber losses but the amplification process is accompanied by the emission of spontaneous noise. The noise that is outside the bandwidth of the optical signal can be removed, using an appropriate filter, although it is not possible to remove in-bound noise. This noise co-propagates with the signal. The noise added to the signal by each amplifier induces an uncertainty in the soliton arrival time called jitter. Gordon and Haus showed that the statistics of the jitter due to spontaneous emission noise added by the lumped amplifiers is Gaussian with a variance proportional to the cube of the total distance of the links [11]. Recent experiments have shown significant deviations from the Gaussian distribution [12]. It was pointed out in [13] that soliton interaction, acoustic affects and polarization mode dispersion can lead to deviations from the Gordon–Haus results. However, the soliton interaction is likely to have the dominant effect for high bit rate systems. Further, the performance of first- and second-order path-averaged soliton long-haul transmission link has been investigated in [14] including the impact of third-order dispersion (TOD) at varied chirp. The observations establish that the pulse width (FWHM) remains within the optimal range without and up to certain discrete values of the chirp factor.

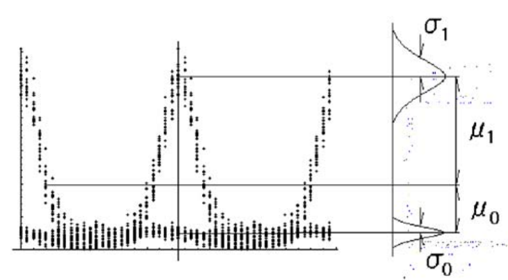
Here, the performance of path-averaged soliton transmission link for various performance measures viz. optical signal-to-noise ratio (OSNR), optical power, extinction ratio, bit error rate (BER), BER with forward error correction (FEC) and Q factor at different levels of noise figure and pulse width (FWHM) has been reported. The influence on the BER and quality factor has been investigated at bit rate of 10 Gbps without and with amplified spontaneous emission (ASE) effect and noise figure at different amplifier spacing. The results have been reported in both the cases for maintaining the average quality factor and BER of the order 16.6 dB and 10^{-12}, respectively.

After introduction in Section 1, Section 2 presents the performance measures. Section 3 details the system description. The results are discussed in Section 4 and the final conclusions are summarized in Section 5.

2. Performance measures

Long-haul transmission links experience performance degradations due to ASE-noise from optical amplifiers along the line. In transoceanic systems, a large number of amplifiers are cascaded; each of them adds noise onto the signal stream. Besides changing the pulse energy, ASE-noise affects the pulse position in non-linear pulse propagation as well. To maintain a safe pulse separation, the pulse width needs to be reduced and peak powers increased, when the channel bit rate is increased. The most widely used performance measures for performance evaluation are the OSNR, Q-factor and BER.

Q-factor represents the signal-to-noise ratio at the receiver decision circuit in voltage or current unit [15]. Fig. 1 shows the Q-factor definition. This definition considers soliton stability, interactions between pulses, timing jitter effects and other effects. In soliton-based systems using relatively higher signal power, we can use relatively short bit patterns because the stability of



$$Q = \frac{\mu_0 + \mu_1}{\sigma_0 + \sigma_1}$$

Fig. 1. Q-factor definition.