Limitations of Dispersion Supported Transmission over Standard Single-Mode Fiber

Cristian Bungarzeanu

***Abstract*— Dispersion supported transmission (DST) is a new technique which combines intensity modulation (IM) and optical frequency modulation (OFM) to allow transmission spans beyond the usual dispersion limit. Using computer simulation, DST limitations are evaluated and optimum values for the frequency deviation and receiver bandwidth are determined. Finally, the maximum transmission distance is estimated for a power penalty of 1 and 2 dB.**

I. Introduction

GROUP velocity dispersion (GVD) is the main limiting factor in high-bit-rate transmission systems operating over standard single-mode fibers. Moreover, parasitic OFM, known as "chirp," occurring in directly modulated lasers decreases drastically the length of the transmission link.

Between several methods intended to overcome GVD limiting effect, DST is very attractive because of its relative simplicity and good capacity [1]. The DST principle of operation is mainly based on the interferometric conversion of an OFM signal into an IM signal across the dispersive fiber link [2]. Thus the light of the laser at a constant power level is switched between the two optical frequencies ν_0 and ν_1, representing the logical "0" and logical "1," respectively. Due to GVD, the two optical frequencies travel with different velocities resulting in peaks and dips of the intensity with respect to the mean average power. These well-defined power fluctuations are filtered at the receiver and interpreted as logical "0" and "1" by a decision circuit. Experimentally, it turned out that an additional IM improves the transmission performances. Thus transmission of 10 Gbit/s in the 1550-nm window over 151 km without repeater and 204 km with one optical amplifier was recently reported [3].

In this letter DST is investigated by numerical simulation in order to estimate the GVD-induced limitations and to optimize critical parameters such as frequency deviation and receiver bandwidth.

II. Transmission System Model

Assuming a monochromatic optical source with the linewidth significantly less than the transmission rate, the complex equivalent low-pass signal at the fiber input is expressed as

$$x_{in}(t) = \sum_k \sqrt{a_k(r-1)+1} \times P(t-kT)\exp\left(j2\pi a_k \Delta\nu t\right) \tag{1}$$

where a_k is 0 or 1, k is an integer, r is the power extinction ratio, $P(t)$ is the pulse function with unity amplitude within the bit time and zero elsewhere, T is the bit duration, and $\Delta\nu = \nu_1 - \nu_0$.

The low-pass equivalent model for the single-mode fiber transfer function which isolates the GVD effect only is given by [4]

$$H(f) = \exp\left[-j\pi DL\frac{\lambda_0^2 B^2}{c}\left(\frac{f-\nu_0}{B}\right)^2\right] \tag{2}$$

where D is the GVD, L is the fiber length, c is the speed of light, $\lambda_0 = c/\nu_0$ is the wavelength related to ν_0, and B is the transmission rate.

At the receiver side, the directly detected signal is expressed as

$$y_d(t) = |\mathcal{F}^{-1}[\mathcal{F}[x_{in}(t)]H(f)]|^2 \tag{3}$$

and the filtered signal at the receiver output is

$$y(t) = \mathcal{F}^{-1}[\mathcal{F}[y_d(t)]H_r(f)] \tag{4}$$

where $\mathcal{F}[\ ]$ and $\mathcal{F}^{-1}[\ ]$ denote the Fourier transform and its inverse and H_r is the transfer function of the receiver filter.

The GVD-induced power penalty in decibels is defined as follows:

$$P_D(L) = 10\log_{10}\left[\frac{\Delta y(0)}{\Delta y(L)}\sqrt{\frac{\Delta f(L)}{\Delta f(0)}}\right] \tag{5}$$

where Δy is the eye-opening related to $y(t)$ and Δf is the receiver electrical bandwidth, P_D expresses the degradation of receiver sensitivity, under the assumption that the receiver noise is unaffected by the signal. Therefore, at a given bit-error-rate (BER), GVD-induced eye closure is compensated by an increase in the signal equal to the power penalty. In a previous approach, only the eye opening was taken into account in the power penalty evaluation, whereas the receiver bandwidth was kept constant [4]. Nevertheless, this assumption is no longer valid for DST systems wherein it is necessary to adjust the receiver electrical bandwidth according to the total GVD [2]. This is why the receiver bandwidth is included in the expression of the power penalty given in (5).

III. Results and Discussion

Numerical simulations have been performed for DST transmission systems operating at $\lambda_0 = 1550$ nm over standard signal-mode fibers with $D = 15$ ps/nm $\cdot$ km.

Manuscript received January 5, 1994; revised February 10, 1994. This work was supported by the Swiss Federal Office of Education and Science within the European Project COST 239.

The author is with the Telecommunications Laboratory, Department of Electrical Engineering, Swiss Federal Institute of Technology, Lausanne, CH-1015 Lausanne, Switzerland.

IEEE Log Number 9402768.

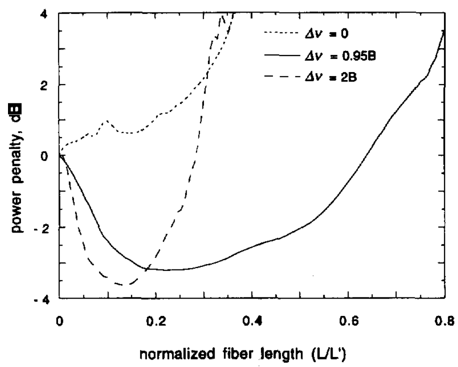

Fig. 1. GVD-induced penalty versus normalized fiber length for a transmission system operating at $\lambda = 1550$ nm over standard single-mode fiber ($D = 15$ ps/nm· km). Three cases are considered: $\Delta\nu = 0$, which corresponds to chirp-free conventional IM, $\Delta\nu = \Delta\nu_0 = 0.95B$, representing the optimum DST frequency deviation, and $\Delta\nu = 2B$. IM extinction ratio is $r = 1.5$.

The input waveform represents an NRZ-coded pseudorandom sequence of 128 bits intended to accurately simulate the intersymbol interference. The IM extinction ratio considered is $r = 1.5$. The final results have been obtained by averaging over 40 runs. The receiver baseband filter is a first-order Bessel low-pass filter. Excepting the case $\Delta\nu = 0$, the 3-dB bandwidth Δf has been optimized for each pair ($\Delta\nu$, L) in order to minimize the power penalty. To facilitate comparisons and generalization the fiber length is referred to the quantity:

$$L' = \frac{\pi c}{\lambda_0^2 B^2 D} \tag{6}$$

and the frequency is normalized to the transmission rate.

The behavior of the power penalty was investigated for different fiber lengths with the frequency deviation varying between 0 and $2B$. Thus the optimum frequency deviation related to the power penalty global minimum was found to be $\Delta\nu_0 = 0.95B$ if the fiber length exceeds $0.5L'$. Therefore, the results reported in this letter have been obtained for $\Delta\nu = \Delta\nu_0$.

The DST power penalty as function of fiber length is shown in Fig. 1 with respect to the chirp-free conventional IM. The negative power penalty, effective between 0 and $0.64L'$ represents an improvement of the receiver sensitivity and is due mainly to an important decrease in electrical bandwidth. The 4-dB difference in power penalty between $0.57L'$ and $0.78L'$, which correspond at 10 Gbit/s to 151 km and 204 km, respectively, is about the sensitivity degradation reported in [3] for a BER of 10^{-10}. For fiber lengths greater than $0.75L'$, P_D increases rapidly, indicating the apparition of a BER floor, a fact experimentally confirmed [3].

The optimized receiver bandwidth is illustrated in Fig. 2. These surprisingly low values have been experimentally verified. Thus the bandwidths used in the two experiments reported in [3] are represented for comparison by filled triangles. The quite good agreement suggests that the optimum filter bandwidth is practically independent of $\Delta\nu$.

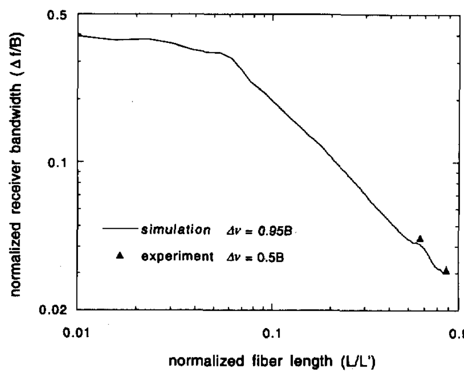

Fig. 2. Optimum receiver bandwidth. Filled triangles represent experimental values reported in [3] for a DST system at $B = 9.95$ Gbit/s over 151 km ($0.57L'$) and 204 km ($0.78L'$) of standard single-mode fiber.

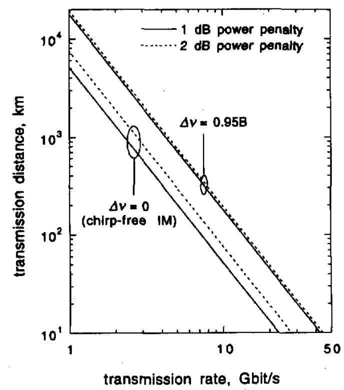

Fig. 3. Transmission distance for systems operating at $\lambda = 1550$ nm over standard single-mode fibers with $D = 15$ ps/nm· km.

Finally, the relationship between transmission distance and transmission rate is illustrated in Fig. 3 showing the superiority of DST with respect to conventional chirp-free IM systems.

IV. Conclusions

GVD-induced limitations in DST transmission systems have been evaluated by computer simulation. It turned out that for a 1-dB power penalty the transmission distance is more than three times the one allowed by chirp-free IM systems. Moreover, simulation results show good agreement with available experimental data.

References

[1] A. Matheus, "Comparison of soliton propagation with other dispersion minimizing techniques for high bit-rate data transmission on standard monomode fibers," presented at the *EFOC and N'93*, The Hague, Netherlands, June–July, 1993, paper 49.

[2] B. Wedding, "New method for optical transmission beyond dispersion limit," *Electron. Lett.*, vol. 28, no. 14, pp. 1298–1300, 1992.

[3] B. Wedding and B. Franz, "Unregenerated optical transmission at 10 Gbit/s via 204 km of standard singlemode fiber using a directly modulated laser diode," *Electron. Lett.*, vol. 29, no. 4, pp. 402–404, 1993.

[4] A. F. Elrefaie, R. E. Wagner, D. A. Atlas, and D. G. Daut, "Chromatic dispersion limitations in coherent lightwave transmission systems," *J. Lightwave Technol.*, vol. 6, pp. 704–709, 1988.