Investigation on the capacities of optically amplified transmission systems in Geographic Networks

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Abstract. In this work we present a survey of the main optically amplified communication systems that have been proposed to achieve a very high capacity transmission and their performances are analysed by means of the numerical simulations. Assuming different link lengths, guidelines for the implementations of high capacity systems are shown.

1. INTRODUCTION. Telecommunication field has shown a deep evolution in the last years, mainly due to the invention of the optical fibres [1] and other devices as lasers and optical amplifiers [1]. Such an evolution has been demonstrated by means of several experiments that have shown how to transmit signals with a capacity of hundreds of Gbit/s on transoceanic distances [2-4].

At the moment several kinds of optical systems have shown their potentiality, but it is very difficult to identify the best optical system, since such a choice depends on several factors as the physic parameters of the link, the cost, the required information traffic and the transparency of the information.

In this work we present a survey, based on the results found in the environment of the European COST239 project and in the ACTS ESTHER and UPGRADE projects, on the potentiality of the main optical communication systems that have been proposed in the environment of the high capacity transmission. The results have been obtained by means of numerical simulations and the main characteristics of the simulation tools can be found elsewhere [5-6].

Numerical simulation has been a fundamental tool for the study of the optical communication since the analytical theories are not able to take into consideration all the effects that are simultaneously present in a real link. The numerical code used in this work permits to evaluate the performance of optically amplified digital systems including all the effects that are present in a real systems. Such a code can be used also for the study of optical transport networks when devices as splitters, Add/Drop Multiplexing (ADM), Wavelength Converters (WC) and Optical Cross Connect (OXC) are considered. Such a code has been previously checked with other groups of the ACTS projects and it has been found an excellent agreement by the comparison with analytical theories and a good agreement with experiments. This has permitted to consider the simulation tools very reliable.

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The results regards the propagation at 1.5 μm considering both DS and step-index fibers using Erbium Doped Fiber Amplifiers (EDFA). For step-index fibers is also investigated the possibility to operate at 1.3 μm by using Semiconductor Optical Amplifiers (SOAs) [6].

2. MODEL OF THE OPTICAL SYSTEMS. An optical communication is obtained by means of a *transmitter*, a *transmission line* and a *receiver*. According to the modern concept on the optical communication the transmission line is supposed to be composed by optical fibres and optical amplifiers that replace the electrical regenerators that were previously used.

It is common knowledge that high capacity networks operate with signals in digital form. In this environment several optical systems have been proposed that can be distinguished both according the kind of modulation and detection. At the moment the optical systems that show the best properties in terms of simplicity, cost and robustness with respect to the degrading effects of a link, is the one based on an the Intensity Modulation with Direct Detection (IM-DD). For IM-DD systems the shape of the pulse is very important. Conventional IM-DD systems have been based on a rectangular shape, format known as Non Return to Zero (NRZ), but for high capacity transmissions it has been demonstrated that a Return to Zero (RZ) format can permit to increase the system capacity.

Optical fiber. The main limitations of the optical fibers are the chromatic dispersion or Group Velocity Dispersion (GVD) [1], the PMD [7], and the nonlinear effects [1].

The chromatic dispersion is a linear effect that induces a pulse broadening, generating intersymbol interference [1]. The PMD is an effect due to the fact that optical fibers for telecommunications have two polarization modes, even though they are called single-mode fibers. Such modes have two different group velocities that induce a pulse broadening depending on the input state of polarization of the signal [7].

The main nonlinear effects arising in single-mode fibers are Brillouin scattering, Raman scattering and Kerr effect [1].

Brillouin scattering is a backward scattering from acoustic waves, which can generate forward noise at the receiver. It is the lowest threshold fiber nonlinearity, but fortunately it can be easily suppressed in the most part of optical communication systems.

Raman scattering is a forward scattering from silica molecules. Raman response is characterized by a low gain and broad bandwidth (about 5THz) curve. This feature can severely limit the performance of WDM systems, by transferring the energy from one channel to the neighboring channels, if the power channel is too high.

Kerr effect is due to the dependence of the refractive index on the field intensity. It mainly manifests as a generation of new frequencies. When a single-channel signal is taken into consideration the Kerr effects induces a spectral broadening and the phase of the signal is modulated according to its power profile [1]. Kerr nonlinearity does not always show a negative impact, in fact in the regime of anomalous dispersion it induces a chirp effect that can compensate the degradation induced by the GVD. Such a compensation can be total if soliton signals are used [1][8]. When multichannel WDM signals are considered the Kerr effect can be more degrading since it induces both a nonlinear crosstalk among the channels that is called Cross Phase Modulation (XPM) and the generation of new frequencies, effect that it is called Four Wave Mixing (FWM).

Neglecting Brillouin and Raman effect, the signal propagation has been simulated by solving the nonlinear Schroendiger equation, that describes the signal propagation in optical fiber, by means of the split-step method.

Optical amplifiers. Two types of optical amplifiers have been considered in this work: EDFAs and SOAs. The behaviour of these amplifiers is quite different: gain saturation is a slow process in EDFAs while it is a fast process in SOAs. As a consequence a static model can be adopted in the first case while amplifier dynamics must be taken into account in the second. Optical amplifiers provide optical gain and add Amplified Spontaneous Emission (ASE) noise. In the case of EDFAs the optical gain can be assumed constant. On the contrary, in the case of semiconductor amplifiers, the instantaneous gain depends on the particular transmitted message and it is found by solving the rate equations [6].

Receiver and evaluation of system performance. In a common receiver the optical signal is transformed in an electrical current by a PIN photodiode, and electrically filtered. The signal timing is recovered by a baseband PLL and a threshold decision device decides the received bit [6]. The adoption of an optical EDFA preamplifiers brings the sensitivity of direct detection receivers quite close to the theoretical limit. After the optical preamplifier and before the photodiode, an optical Fabry-Perot filter is generically located to limit the presence of the ASE noise.

In the simulation code, the PIN photodiode and the electrical front end are simulated by a square law device and a Gaussian noise source that introduces the receiver noise. The electrical filter at the receiver is a second order Butterworth filter whose bandwidth is 0.8R.

The system performance are evaluated in terms of Q factor and time jitter [6][10] since some theoretical works [10], confirmed by experimental demonstration [4], have shown that an error probability lower than 10^{-9} can be achieved with a good approximation if the Q factor is higher than 6 and the standard deviation of the time jitter is lower than 6% of the bit time. This is the condition that we have chosen for the correct operation of an optical system.

2. METHODS TO OBTAIN THE HIGHEST CAPACITIES. The maximum bit-rate that can be achieved in an optical link for a single-channel system depends on several parameters and one of the most important is the GVD distribution along the propagation direction.

According to the GVD distribution we distinguish between regimes of propagation with high and low chromatic dispersion. We assume a regime with low chromatic dispersion when the only distortion induced by the GVD on the signal at the link output can be considered negligible and it is verified when the condition $R^2\overline{\beta_2}\, z \ll 1$ is satisfied, where R is the signal bit rate, z the link length, β_2 the GVD while the term $\bar{*}$ means the average along the link. It has to be pointed out that in such a propagation regime the system performance are not always good, since other effects can degrade the signal propagation as for example the nonlinear effects. Conversely the regime of high chromatic dispersion is when the signal propagation at the output link is deeply modified by the GVD and it manifests when $R^2\overline{\beta_2}\,z>1$. In the normal dispersion region this condition induces a large pulse broadening so preventing a correct system working. In the anomalous region the GVD induced chirp can be partially or even totally compensated by Kerr effect [1], allowing transmission with good performances.

When the local GVD is very low the Kerr effect can induce several signal degradations. Such a degradation can be very detrimental in the propagation of single-channel signals in the presence of ASE noise and in the case of WDM systems. In the first case the nonlinear interaction between signal and ASE induces a large spectral broadening when the link length is very long, conversely in the latter case also for short distance the FWM can induce a strong nonlinear crosstalk among the channels.

To limit the FWM it is preferable to operate with a local high GVD that is periodically compensated by devices having an opposite sign of the GVD. Such a devices can be simply optical fibers with opportune GVD and such a method is commonly called *dispersion management* [9]. In such a way the accumulated GVD can be very low and the FWM effect strongly limited. The dispersion management is the method that permits to achieve the highest capacity both using RZ and NRZ signal formats [5][9].

To obtain a satisfactory propagation of NRZ signals the overall link dispersion has to be kept very close to zero while, to efficiently propagate solitons, a small amount of anomalous chromatic dispersion is useful.

In the regime of high GVD the signal degradation can be limited by adopting several methods as either the dispersion management or the nonlinear compensation of the GVD by means of the Kerr effect [1]. The nonlinear compensation of the GVD is maximum when the pulse has the shape of an hyperbolic sechant and the peak power satisfies the following relationship:

$$P_k = \frac{\alpha\, L_A\, G\,|\beta_2|}{(G-1)\,\gamma\,\tau_s^2} \qquad (1)$$

where α is the fiber loss, G the amplifier gain and γ the nonlinear coefficient [1][8]; such a pulse is called *soliton.* Soliton signals seem the best pulse shapes to achieve the highest performance, however some effects can limit their propagation condition; such effects are the fiber losses, the nonlinear interactions and the Gordon-Haus effect [8]. The performance of soliton systems can be deeply improved by adopting in-line optical filters [5][8].

A comparison among the performances of different systems operating in DS fibers is presented in figure 1, where the maximum system capacity is reported versus the link length with a dispersion parameter equal to -1.28 ps^2/km and L_A=40 km. The maximum capacity has been obtained by optimizing the system parameters (mainly the input power and the time duration of the pulses) and increasing the bit rate until reaching the condition on the Q and on the time jitter are both satisfied.

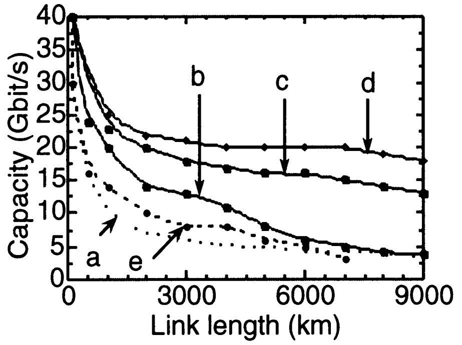

Figure 1: maximum capacity vs link length for links with DS fiber.

In figure 1 the different curves refer to the following systems

a) dispersion limited NRZ transmission,

b) soliton transmission in absence of in-line filters,

c) soliton transmission with fixed filters,

d) soliton transmission with sliding filters,

e) NRZ transmission with nonlinear compensation of the GVD without in-line filters.

All the curves show a decreasing of the capacity as the link length increases and soliton signals always have higher capacity with respect to NRZ signals. Some considerations on the curves (b) of fig. 1 deserve to be made. For very short link length the maximum capacity can be very high since all the degrading effects on the transmission are very weak. For z<3000 km, in the case of soliton signals, the main limiting effect is the soliton interaction; in fact the optimized time duration of the pulses remains almost constant passing from τ_s=5 ps for z= 40 km to 7 ps, while the time distance must grow as a function of the length and it induces a decreasing of the maximum capacity. For distances longer than 3000 km soliton interactions and Gordon-Haus effect become dominant.

In presence of in-line filters the system capacity deeply increases, especially in presence of sliding filters. The capacity of soliton systems is always higher with respect to the case of NRZ.

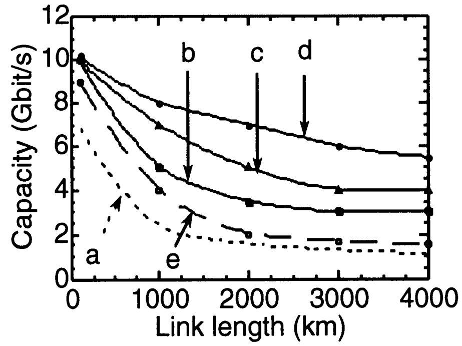

Figure 2: maximum capacity vs link length for links with step-index fiber.

In figure 2 the curves have been obtained for step-index fiber links with a dispersion parameter of -20 ps^2/km. In this case, due to high value of the GVD, the curves are reported up to a maximum length of 4000 km.

The different curves refer to the following systems

a) dispersion limited NRZ transmission,

b) soliton transmission in absence of in-line filters,

c) soliton transmission with fixed filters,

d) soliton transmission with sliding filters,

e) NRZ transmission with nonlinear compensation of the GVD.

The limitation due to the use of the step-index fibers is clearly shown by the comparison between figs.1 and 2.

A method to increase the system capacity is the use of the so called dispersion management. Generally, a good dispersion management is obtained when the product $\beta_2 L_L$ is high enough to reduce the FWM efficiency, but not so high to cause sensible interplay between Kerr effect and GVD.

In figure 3 we report the maximum capacity versus the link length for systems adopting dispersion management realized with only two different fibers.

The reported curves are evaluated in the following conditions

(a) refers to an NRZ system with a constant zero GVD;

(b) refers to an NRZ system using DS fibers and step-index fibers for dispersion compensation, in this case $\bar{\beta}=0$;

(c) refers to an NRZ system using step index fibers and DCFs, even in this case $\bar{\beta}=0$;

(d) refers to a soliton system using step index fibers and DCFs without in-line filtering, in this case $\bar{\beta}=-1.28\ ps^2/km$;

(e) refers to a solitons system using step index fibers and DCFs with sliding filters, even in this case $\bar{\beta}=-1.28\ ps^2/km$;

(f) refers to a soliton system using DS fibers and step-index fibers without in-line filtering, in this case $\bar{\beta}=-0.2\ ps^2/km$;

The position of the compensating fibers was chosen according the results of ref. [9] that showed as in the case of NRZ signals it is better to locate fibers with normal dispersion at the output of the optical amplifiers to avoid modulation instability effects, conversely in the case of the solitons, at the output of the optical amplifiers it is better to locate fibers with anomalous dispersion. The period of the compensation is equal to 80 km in the case of links encompassing DS fibers and 40 for links encompassing step-index fibers.

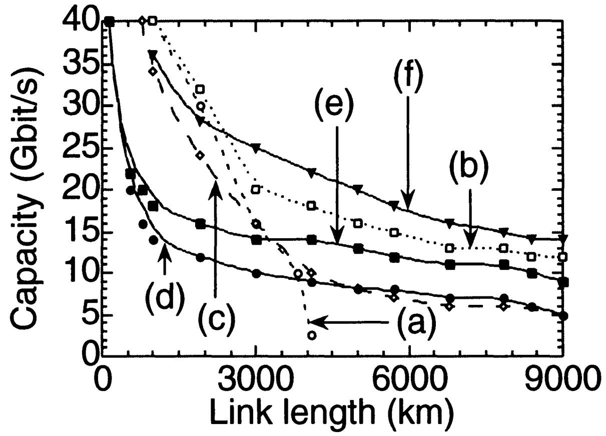

Figure 3: Maximum capacity versus link length for systems adopting dispersion management realized using only two different fibers. The details of the curves are reported in the text.

Curve (a) shows how in the case of the zero constant GVD the nonlinear interaction between signal and ASE is very strong and it deeply reduces the performance for distance longer than 3000 km. For longer distance the dispersion management is required as shown by the curve (b) and c. Curve (a) shows that when dispersion management on DS fibers is adopted, 10 Gbit/s transmission of NRZ signals up to 9000 km is allowed. By comparing the curves (c-e), obtained with dispersion management on step index fibers, for short distances NRZ systems outperform soliton ones while for long distances soliton systems show better performance, particularly when sliding filters are used. However, in cases (d) and (e), higher capacities can be achieved by increasing the average GVD (for an instance around -0.2 ps^2/km), and in particular for distances shorter than 3000 km capacities very similar to the case c can be obtained.

Soliton signals in links with dispersion management adopting DS fibers and compensation with step-index fibers (f) allows the system to achieve the highest capacity for distances longer than 3000 km, also in absence of sliding filters. This is due to the low average GVD that limits the nonlinear interaction, the soliton instability and the Gordon-Haus effect; furthermore the dispersion management permits to operate with higher input powers that permit to achieve higher signal-to-noise ratio and to reduce the time jitter with respect to the case with constant GVD. For distance shorter than 3000 km the capacity is a bit lower with respect to the NRZ signals since, also if low, the residual average GVD induces a stronger limitation with respect to the case with zero average GVD. It has to be pointed out, that for a GVD tending to zero, NRZ should be preferred since the nonlinear interaction between signal and ASE for RZ signal is worse and it is due to the higher input power required by the RZ signals with respect to the NRZ to obtain the same SNR.

Our results show that when dispersion management is used, single-channel soliton systems permit to achieve higher capacities with respect to NRZ on long distances and such capacities can be improved if in-line sliding filters are adopted.

Dispersion management is a fundamental method to increase the capacity also in WDM systems since it permits the reduction of the FWM effect and to increase the capacity of the channel bit rate.

Systems based on the Wavelength Division Multiplexing (WDM) permits to increase the capacity with respect to single-channel systems. Also for WDM systems the system performance and in particular the channeling characteristics depends on the GVD distribution. For an example in links encompassing step-index fibers it is preferable the use of a systems with many channels at low bit rate (622 Mbit/s or 2.5 Gbit/s), while in the case of DS fibers a lower number of channels but with higher bit rate (2.5, 5 and 10 Gbit/s) is preferable [5]. In both the cases the use of the dispersion management permits a large increasing of capacity especially if high channel bit rates are required.

Also the choice of the signal format depends on several links parameters. As shown by the simulations soliton WDM systems allows us to better exploit the fiber capacity, but also NRZ signals offer very high potentiality. The better solution seems the one of using different signal formats, both soliton and NRZ, within of the same optical bandwidth, depending on the value of the GVD in which the channel propagates [11].

4. GUIDELINES FOR IMPLEMENTATION OF HIGH CAPACITY SYSTEMS

From the results obtained by the simulations we can present some guidelines for the implementation of optical systems. We distinguish several classes depending on the link length: Short distances (z<500 km), medium distance (500 km<z<2000 km) and long distance (z>2000 km).

Short distance.

DS fibers. For distances up to 500 km single-channel capacities of 20 Gbit/s can be achieved both with NRZ and soliton signals. For soliton signal in-line filters are not required. By means of the dispersion management 40 Gbit/s can be reached both with solitons and with NRZ signals. By means of the WDM techniques, assuming particular channel bit-rates and frequency spacing, capacities up to 200 Gbit/s can be reached. Such WDM capacities can be increased by using compensation techniques to equalize the gain of the optical amplifiers.

Step-index fibers. Operating with erbium amplifiers at the wavelength of 1.5 μm, in the case of single-channel systems the capacity is lower of a factor equal to 4 with respect to the systems operating with DS fibers. The dispersion management is fundamental to transmit signal at 10 Gbit/s both by using solitons and NRZ signals. By means of the WDM technique the same capacities of the DS fibers can be reached, even though the channel bit rate of 10 Gbit/s can be used only in the presence of dispersion management.

Operating with SOA at 1.3 μm, for distance up to 500 km single-channel capacity around 15 Gbit/s can be achieved both with solitons and NRZ signals without dispersion management.

Medium distance

DS fibers. For a link up to 2000 km, single-channel system capacities of 20 Gbit/s can be obtained for NRZ signals by or operating with a GVD close to zero either by using dispersion management. For solitons such a performance can be obtained by using either in-line filters, or dispersion management, or with alternate polarizations [4] or using a constant GVD lower than 0.5 ps/nm/km. Conversely 10 Gbit/s can be obtained without any great complexities for soliton signals, while for NRZ signals the operation around the zero dispersion wavelength is required. By means of the WDM techniques a total capacity of 100 Gbit/s can be obtained, but limitations on the granularity are present and in particular only channel bit rate at 2.5 and 10 Gbit/s should be used. Using the same channel bit rate and assuming compensation techniques to equalize the gain of the optical amplifiers, total capacities of 200 Gbit/s can be reached.

Step-index fibers. Operating with erbium amplifiers at the wavelength of 1.5 μm, the dispersion management is fundamental to transmit signal at 10 Gbit/s both by using solitons and NRZ signals, conversely several controls on the average GVD and on the periodical compensation are required to have 20 Gbit/s. By means of the WDM technique the same capacities of the DS fibers can be reached, using channel bit rate down to 155 Mbit/s, while channel bit rate of 10 Gbit/s can be used only in the presence of dispersion management.

For these distance SOA links show more severe limitations with respect to links with erbium amplifiers, due to the strong saturation effects and to high power of the ASE noise. 10 NRZ signals can be transmitted up to 800 km, while soliton signals up to 2000 km if sliding filters are used.

Long distance

DS fibers. 10 Gbit/s NRZ signals can be transmitted only by means of dispersion managements, while for solitons no particular requirements is necessary but a right choice of the pulse duration and of the transmitted power. 20 Gbit/s can be reached by means of solitons signals in presence of dispersion management, or in-line filtering. The WDM techniques permit to reach capacities around 100 Gbit/s by using NRZ signals with unequally frequency spacing in the case of constant GVD and equally spacing with dispersion management. A bit higher capacity can be reached by means of solitons with in-line filters in links with constant GVD and without in-line filters in links with dispersion management. Higher capacities can be obtained by using the compensation techniques to equalize the gain of the optical amplifiers.

Step-index fibers. Operating with erbium amplifiers at the wavelength of 1.5 μm, in the case of single-channel systems 10 Gbit/s can be obtained with an accurate choice of the link parameters if dispersion management is used. Soliton signals with dispersion management permit a much better performance, especially if in-line filters are used or by adopting alternate polarizations. In the case of WDM systems the same capacities of DS fibers can be obtained if channel bit rate smaller of a factor equal to four are considered.

SOA links are not suggested for these distances.

Considerations on the capacities of transport networks. The numerical method used for the study of point-to-point links can be adopted also for the performance evaluation of signals propagating in path encompassing ADMs, OXCs and WCs. In many cases, for these devices, their transfer function and the noise contribution can be evaluated without too difficulty and as a consequence they can be introduced in our simulation code. Preliminary results have shown that 8 channels at 2.5 Gbit/s can be transmitted in networks with path 1000 km long having either OXCs or ADMs located every 100 km.

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REFERENCES

[1] G. P. Agrawal, 'Fiber-Optic Communication Systems' John Wiley & Son, INC, 1992.

[2] L. F. Mollenauer, P. V. Mamyshev, M. J. Neubelt, Optics Letters, **19**, 704, 1994.

[3] M. Nakazawa, et al. Electronics Letters, **31**, 565,1995.

[4] F. Favre, D. Le Guen, Electronic Letters, **31**, 991, 1995.

[5] F. Matera, M. Settembre, Journal of Lightwave Technology, **14**, 1 (1996).

[6] M. Settembre et al, J. of Lightwave Technology **15**, 962 (1997).

[7] F. Matera, C. Someda, "Anisotropic and Nonlinear Optical Waveguides" 1992 Elsevier Science Pubblishers

[8] A. Hasegawa, Y. Kodama, "Solitons in Optical Communications" *Clarendon press*, Oxoford 1995.

[9] F. M. Knox, W. Forysiak, N. Doran, J. of Lightwave Technology **13**, 1955 (1995).

[10] J. V.Wright, S. F. Carter, proc. of *Nonlinear Guide-Wave Phenomena*, Cambridge (UK), 1991, pp. 6-9.

[11] N. S. Bergano, et al. proc. of OFC'97, Dallas (Texas) 16-21 February 1997, PD21