Modeling and Design of Soliton Propagation in WDM Optical Systems

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Abstract - **In the 5G mobile networks, the optical signal transmission will be widely used. Two main applications are important: short links for the access networks and long links in the backbone of the system. In this paper we investigate both applications. For that purpose we developed a method using simulations. Based on our simulation results we present proper methods to avoid distortion, which is caused by interaction between the solitons. Considering the dispersion and nonlinearity of the widely used fibers two different methods can be applied to avoid distortion.**

In short links (3-5 km long) we don't need special compensation methods to avoid interaction between neighbouring solutions. In this case a proper precaution is adequate which means that the 3 dB time duration of the soliton pulse has to be less than the half of the bit time frame. However, in long links (e.g. 100 km long) proper correction procedures are needed not to get collision of solitons. For long links shifted filtering can provide sufficient result.

Besides utilizing the advantages of signal transmission by solitons in a single channel, our investigation covers the wavelength division multiplex (WDM) connections as well, which can provide much higher transmission capacity.

Keywords* - *solitons; wavelength division multiplexing (WDM); nonlinear effects in fibers; second order chromatic dispersion.

I. INTRODUCTION

First, the paper presents the linear and nonlinear effects: dispersion and Kerr effect which influence the propagation of solitons in a fiber. To investigate the soliton propagation considering the disturbing effects we had to get solutions for the nonlinear Schrödinger equation applying proper approaches.

Then the methods improving soliton propagation in fibers are discussed in the case of short and long links. The simulations show that it is possible to attain high quality signal transmission utilizing solitons as information carriers.

While 3G and 4G were created to meet a need for speed on the mobile Internet. 5G fits into a more global project. In the future, we will all be ultra-connected: smartphones, tablets, connected objects, home automation, connected cars, RV helmets, augmented reality, and artificial intelligence. High flow of information is necessary, but not only. The 5G will also bring greater autonomy. It is based on millimetre waves. Our hypothesis is to exploit the soliton waves in the network of 5G.

The wavelength division multiplex (WDM) application of soliton signal transmission is presented with good results. We can state that the high-speed signal transmission by a stream of solitons can be advantageously used for short and long connections in 5 G mobile networks [2]. The laser sources are not strictly monochromatic (line width, SPM, XPM, FWM). However, the soliton pulse can keep its shape during propagation, when there is a proper balance between the second order dispersion effect and the nonlinear Kerr effect, the main physical effects influencing the soliton propagation in optical fibers [3].

The paper simulates two channel WDM optical communication systems in single mode fibre over long haul of 100 km to investigate the effect of SPM, XPM and FWM and for 4 km to show the ability of soliton in long and short distances.

II. WAVELENGTH DIVISION MULTIPLEXING

Wavelength division multiplexing (WDM) is a method of combining multiple signals on the laser beam at various infrared (IR) wavelengths for transmission along fiber. Each IR channel can carry several RF channels. Each multiplexed IR channel is separated, or demultiplexed, into the original signals at the destination.

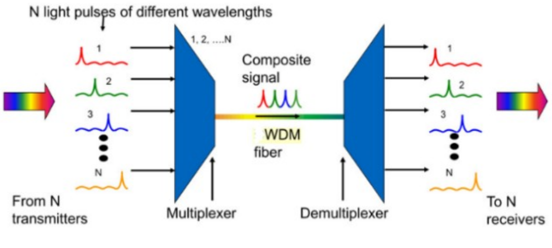

Fig. 1: Optical emission and reception system of the WDM technology

Using FDM or TDM in each IR channel in combination with WDM or several IR channels, data in different formats and at different speeds can be transmitted simultaneously on a single fiber [4].The requirement for the next-generation of WDM systems, known as dense WDM (DWDM), is a channel spacing of less than one nm. It is obvious that using different sources to create the multiple wavelength channels places strict restrictions on their stability, cost, and maintenance [5].

Problems in the optical fiber: The main limitations are caused by:

- Dispersion in the fiber
- Nonlinear effects: Kerr effect (SPM-XPM-FWM)

Problem

How can we compensate the Kerr effect (SPM)? To answer this question we propose the soliton (hyperbolic secant pulse) which solves that problem.

III. THE SOLITON

The soliton is a pulse that has the property of being able to propagate without alteration over extremely long distances by using mutual compensation of linear and nonlinear effects [6]

$$A\,(z=0,\,\tau) = N.\text{sech}\,(\tau) \qquad (1)$$

N is the order of the soliton which is defined by:

$$N= \overline{\frac{L_D}{L_{NL}}} = \overline{\frac{\gamma P_0\ T_0^{\,2}}{\beta_2}} \qquad (2)$$

where P_0, L_D, L_{NL} are respectively the peak power of the pulse, the length of dispersive section and the length of the nonlinear section, β_2 is the second order dispersion index and γ is the attenuation index, T_0 is the duration of the pulse. To determine the order of soliton, we always take the nearest integer.

A semiconductor laser is used to generate pulses in soliton mode. Locking is introduced into the laser cavity by an element that causes interaction between the longitudinal modes and synchronizes them with each other. This locking between modes causes the appearance of a soliton pulse.

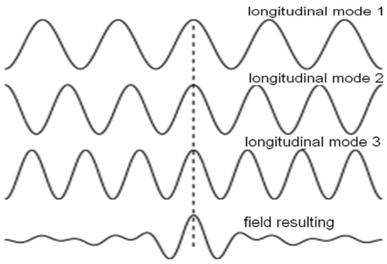

Fig. 2: Mode-locking principle

IV. CHROMATIC DISPERSION (GVD)

Due to chromatic dispersion, temporal pulse broadening appears during the wave propagation. The reason is that the group velocity or delay varies with the wavelength. The optical sources are not strictly monochromatic, therefore we have to consider the following effects:

- The index varies with wavelength (dispersion of DM material).
- The group velocity varies with wavelength (dispersion of DG waveguide) [7].

V. COMPENSATION BETWEEN SPM AND GVD

Self phase modulation (SPM) occurs when an intensity-modulated signal travels through a fiber. The signal is broadened. Except SPM and XPM, all nonlinear effects provide gains to some channels at the expense of depleting power from other channels. SPM and XPM affect only the phase of signals and can cause spectral broadening, which leads to increased dispersion in frequency domain [8].

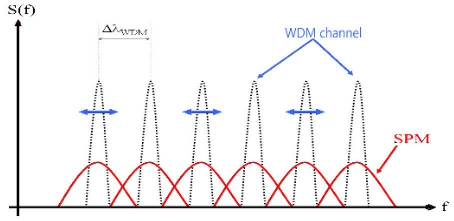

Fig. 3: Illustration of the impact of SPM on a WDM optical signal

a. $L_D >> L_{NL}$, we can consider that the system is primarily dispersive. When a pulse (not chirp) propagates in this medium, it primarily undergoes temporal broadening.

b. $L_D << L_{NL}$, the system is mainly non-linear. In this case, the effect of SPM leads to spectral broadening of the pulse.

c. $L_D \sim L_{NL}$, the influence of dispersion and SPM are equally important to the evolution of the pulse during its propagation. In this case, we can distinguish two situations:

-The dispersive system is normal (D <0): The components of long wavelength (λ) are created on the rising edge of the pulse by the effect of the SPM, they spread faster (because D < 0). Both effects (SPM and DVG) contribute to the temporal broadening of the pulse.

-The dispersive system is abnormal (D> 0): In this case, the components created by the SPM propagate slower; therefore, compensation between the dispersion and SPM is obtained. This compensation (between GVD and SPM) is responsible for pulse trains called "solitons" in a passive optical fiber [9].

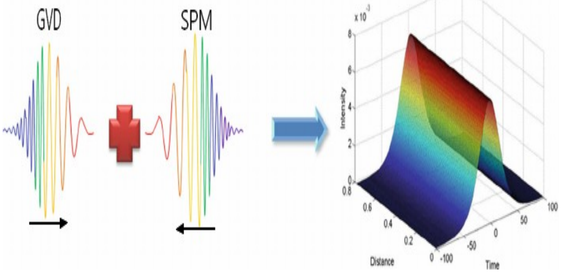

Fig. 4: Offsetting (GVD and SPM)

VI. THE NONLINEAR SCHRÖDINGER EQUATION

The non-linear Schrödinger equation describes the propagation in an optical fiber taking into account both the linear and nonlinear phenomena in the optical fiber.

$$\frac{\partial A\ z,t}{\partial z} + \frac{i}{2}\alpha A\ z,t\ - \frac{1}{2}\beta_2 \frac{\partial^2 A\ z,t}{\partial t^2}\gamma\ A\ 0,t\ {}^2A\ z,t\ = 0 \quad \textbf{(3)}$$

Here A(z, t) is the slowly varying envelope of the electric field, z is the propagation distance, t is time, α is the attenuation, β_2 is chromatic dispersion term**.** For solving the equation in one case we neglect the dispersion part GVD = 0 and in the other case we neglect the nonlinearity part, Kerr effect = 0.

For the numerical solution of the nonlinear Schrödinger equation we use the Split-Step Fourier (SSF) method [11]. The principle is to study the propagation of the pulse on an extremely short section, which is done by calculation of the Fourier transforms (FT), see Figure 5.

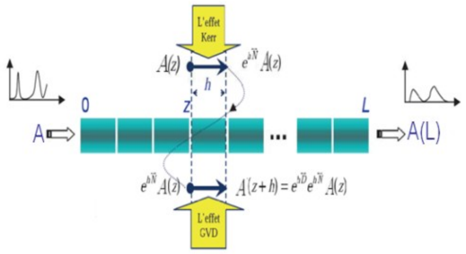

Fig 5 : Schematic illustration for dividing the fiber length into extremely short sections

VII. INTERACTION BETWEEN ADJACENT SOLITONS

When having more than one pulse in a fiber, the presence of adjacent pulses will disturb the soliton significantly by changing its position temporarily. If the neighbouring solitons are in phase, the interaction is attractive (Figure 6) and the solitons move more closely [13].

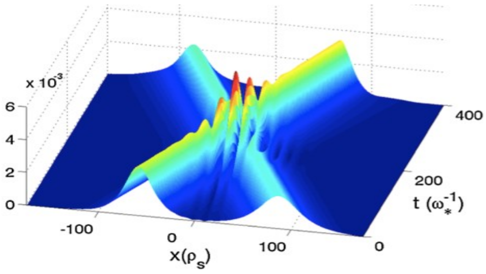

Fig. 6: Collision between two adjacent solitons

VIII. ONLINE CONTROL TECHNIQUES (FILTERING)

Filtering plays a very important role in the transmission of soliton. Beside stabilizing the amplitude it has the following functions:

- ✓ adjusting the spectral width
- ✓ improving the amplitude factor
- ✓ reducing the time jitter

A. *Filtering guiding*

The correction mechanism of timing jitter is used in the case when the centre frequency of the soliton is in an offset state due to the nonlinear interaction with the spontaneous emission noise. The filtering will tend to remove the portion of the spectrum that is far from the initial frequency.

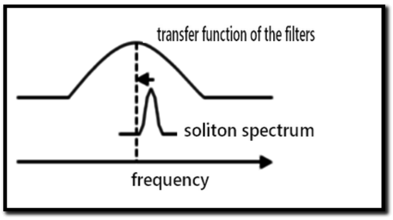

Fig. 7: Guiding principle of filtering

The nonlinear effect and the natural stability of solitons are then recreating the missing frequencies in the middle of the band of filtering. This frequency stabilization therefore eliminates much of the time jitter due to the shift of the spectrum and the dispersion of the fiber. In addition, the line filtering also stabilizes the amplitude of the pulses as the peak power is related to the time width, and therefore to the spectral width. Filtering, which regulates this spectral width, also regulates the amplitude of the solitons and significantly reduces the amplitude fluctuations of the successive pulses. Consider that the effects of regulation and interdependence between the parameters are characteristic of a nonlinear propagation and have no equations in classical linear links. The guiding principle of filtering is shown in Figure 7.

B. *Filtering shifting*

The shifting filtering technique overcomes the main drawback of guiding filtering. The principle is to shift slightly the centre frequency of the filters along the transmission line.

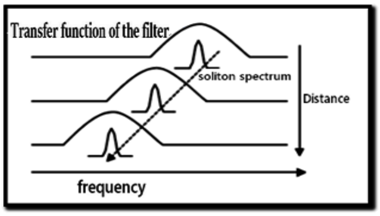

Fig. 8: Principle of the sliding filter.

The stabilization phenomenon has the same origin as previously, accompanied by a shift in frequency of the soliton pulses following the filtering. In contrast, the transmission line becomes opaque to noise, due to its linear behaviour. We can then use narrower filters, beside stronger additional gain, without suffering deterioration of the signal to noise ratio. On the other hand, using periodic filters of Fabry-Perot type, this technique can be adapted to multiplexed wavelength groups [14].

IX. SIMULATION AND RESULTS

A. *Propagation of a fundamental and 3rd order soliton pulse train in an optical fiber*

Figure 9 contains 4 elements, they are: 1st is the clock and (sh) is its output, 2nd is the soliton pulse train the and (SOLT) is the output pulse 3rd is the optical fiber, (Sf) is the output pulse from the fiber. and the last is the output.

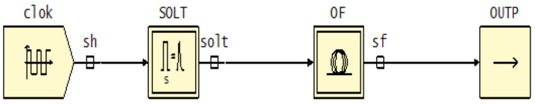

Fig. 9: Block diagram of the optical link based on a process of soliton pulses

Figure 10 shows the power profile of an initial soliton pulse train. This figure also presents the power profile of the fundamental soliton train and the higher order (N = 3) soliton train after propagation in a single mode fiber. The fundamental soliton pulse (N = 1, P_0 = 5 mW) perfectly propagates in the optical fiber, it has retained the characteristics of the soliton (Fig 10. b). We present a higher order soliton pulse (N = 3 with power P_0 = 15 mW) as well. It propagates cyclically, the soliton pulse bursts are formed with spikes periodically increasing its peak power (Fig. 10. c), then turning back to its original shape after a distance $L = L_D / N$ (L = 40 km).

Therefore, the soliton pulse should be strong enough to maintain the Kerr effect, but also small enough to avoid higher order soliton generation.

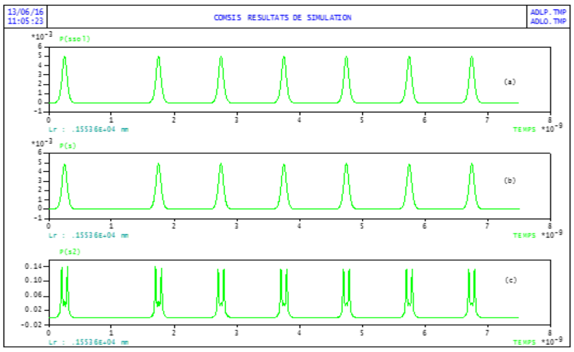

Fig. 10: Evolution of the power profile of a soliton pulse train with the propagation distance L = 40 km.
a): initial soliton train, b): train of fundamental soliton,
c): third order soliton train

Soliton based optical fiber communication systems are more suitable for long haul communication because of their very high information carrying capacity and repeater less transmission. Soliton pulses are not affected (by dispersion) filter long distance communication. By checking the result (Figure 10) for fundamental soliton (N= 1 and 3 both) we can say that soliton pulses shape having similar shape after travelling 40km distances. For N=3 source peak power is increased as compare to N=1.

B. *Soliton transmission in a single channel system for short and long distances*

In this part, we will simulate a single channel optical link to check the possibility of using the soliton as an information carrier in short links (4 km long) in an access network and in the case of long links (100 km long). It contains the following elements: (ABS) is the arbitrary binary sequence, (RZ) is the binary RZ encoder, (SOLT) is the soliton pulse converter, (MZM) is the Mach Zehnder modulator, (OF) is the optical fiber, (CF) is the compensating fiber, (EDFA) is optical amplifier, (PIN) is the photodiode, (GAIN) is an amplifier with 30 dB gain, (FLTR) is a low pass filter, (DIS) is the decision circuit with a threshold, (TAU) is the random delay and finally (OTP) is the output of the transmission channel,

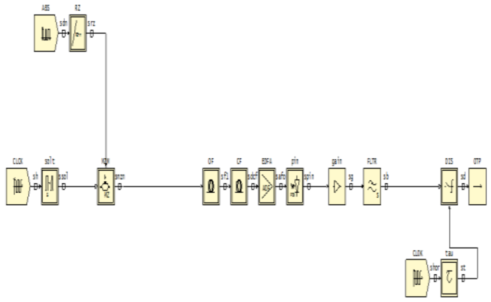

Fig. 11: Block diagram of a single-channel connection using the soliton as an information carrier

Because of non-linearity of the fiber, it is possible that inter-symbol interference occurs. To eliminate it, we can choose a relatively low intensity pulse in the interval between two successive solitons With the parameters of the above detailed components, we will simulate the link with D = 1 Gbit /s throughput to check the possibility of using the soliton as an information carrier. The results of the simulation are shown in (Figure 12-13).

The bit sequence to be transmitted (Figure 12-13-a), (in our case, "1100001011111") modulates the stream of solitons (Figure 14-15. b), the resulting signal represents the transmission of information (Figure 12-13-c). The presence of a soliton gives the binary "1" and its absence provides the binary "0".

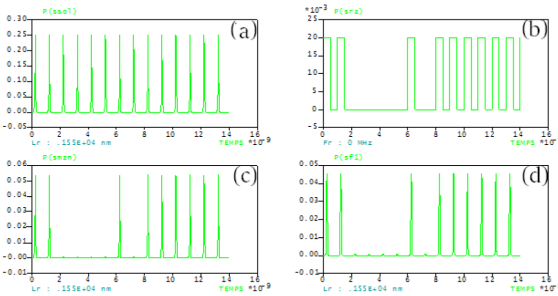

Fig.. 12: The outputs from different blocks of the link in the case of L=4 km long
a): stream of solitons (optical carrier), b): the bit sequence,
c): soliton stream modulated at the input of the fiber,
(d) the outputs of the modulated signal

The modulated soliton stream is transmitted through an optical fiber with the length L = 4 km in the first case and L=100 km in the second case to show the possibility of using the soliton as an information carrier (Figure 12-13-d). The modulated signal is received by a photodiode.

The soliton has proved its capacity to using it as an information carrier in short link due to the remarkable property of being able to propagate without alteration. But we can remark in Figure

(13-d) that the received signal is subjected to an attenuation which is due to the optical fiber loss.

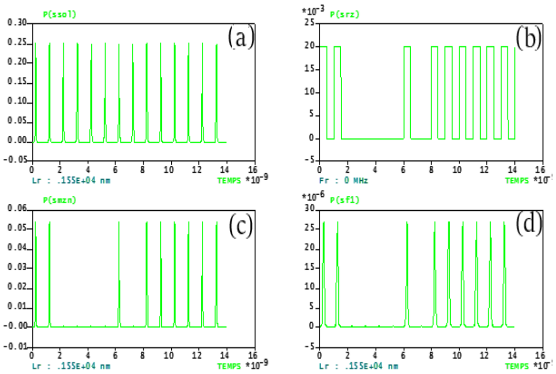

Fig.. 13: The outputs from different blocks of the link in the case of (L=100 km long)
a): stream of solitons (optical carrier), b): the bit sequence,
c): soliton stream modulated at the input of the fiber and
(d) the outputs of the modulated signal

As a conclusion, we can state that the theory of using the soliton as information carrier is verified in long distance also, and to correct the problem of attenuation we add an EDFA optical amplifier.

C. Soliton transmission in a multichannel system

We now present a complete simulation of the WDM system using solitons as information carriers (Figure 14) at four wavelengths which are between 1549.4 nm and 1556.8 nm, with a spacing of 1.6 nm (200 GHz). The soliton carriers are modulated by random binary sequence of user data with 1 Gbit/s. The resulting signal is in RZ format.

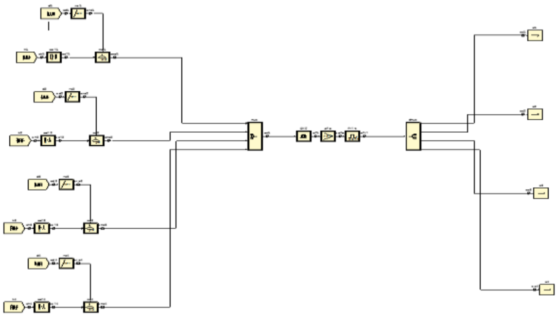

Fig 14: Block diagram of the 4 channel soliton WDM system

The encoded data of all the users are multiplexed by the optical multiplexer and then transmitted through a single mode optical fiber, followed by an EDFA (Erbium-doped fiber amplifier) with a gain of G = 30 dB, and a filter with an optical bandwidth of 20 GHz. Multiplexing the signal finally arrives at the demultiplexer having the same characteristics as the multiplexer. The simulation results are presented in Figure 15.

In the figure 15-A (a) presents the spectral profile of 4 initial solitons which are multiplexed by a WDM multiplexer, and (b) shows the 4 solutions after propagation in an optical fiber. Then (c) exhibits the soliton spectrum after the amplification with an EDFA amplifier. Finally (d) presents the 4 solutions at the end of the transmission line terminated by a filter. The EDFA and the filter were added to correct the noise problem of the interaction due to fluctuations in the multiplexed spectrum after propagation in the fiber due to interactions between the solutions. Finally the 4 solitons are separated and they are shown in (Fig. 15-b).

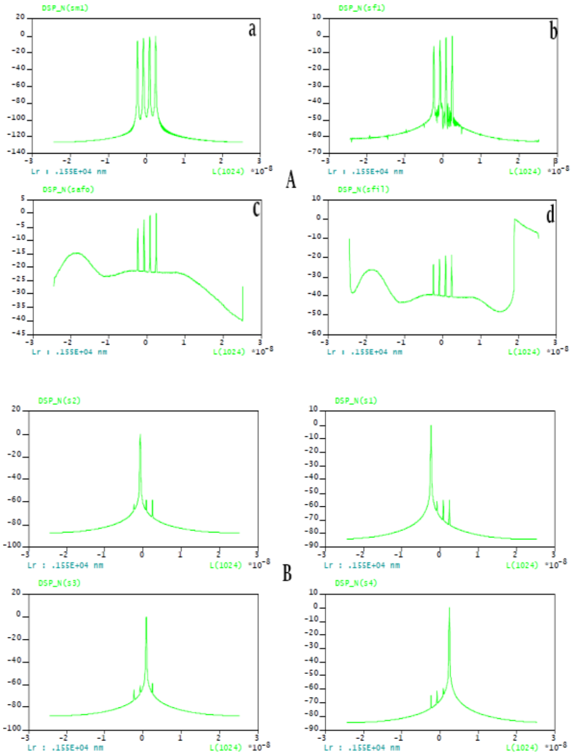

Fig. 15: Simulation results of the WDM system with solitons in 4 channels.
a): 4 multiplexed soliton channels in the blocks of the link,
b): -transmission and reception of the 4 multiplexed soliton channels.

From the results obtained, we find that the EDFA and filter improve system performance. There is a remark as well that with the solitons, the initial channels are recuperated at the output (Fig. 15-b). Thus, this type of pulse is very well adapted to the WDM technique and allows a high spectral efficiency (flow rate ratio, optical modulation bandwidth), which allows cost optimization.

In a multichannel system we can suffer from the collision of solutions. To avoid this problem we have to choose proper parameters for the pulses. In a first step, we proposed that T_0 = T_b where:T_0: total pulse width, and T_b: bit time width. Then, T_0 = T_b = 1 ns as shown by Figure 16. Since we have several coded pulses of the bit "1",each one is attached to the other one we will have the problem of overlapping between the soliton pulses.

Fig 16:T_0=T_b

Then, the total width of the pulse is deprived.

T_b = 1ns, $T_0 = (T_b / 10) = 0.1$ ns,$T_{mh} = T_0/1.763 = (0.1/1.763) = 0.56$ ps. This way: $T_0 > T_b$, as shown in Figure 17. So if we have several separated pulses, therefore we will not have the problem of overlapping, see Figure (18).

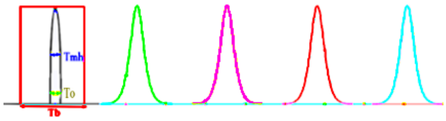

Fig 17:T_0>T_b

X. CONCLUSIONS

The 5G mobile networks utilize a very dense cellular structure which requires high capacity optical systems for signal transport between the central station and the radio base stations. The wavelength division multiplex (WDM) type optical communication offers a significantly increased transmission capacity. However, one of the key issues is how we can reduce the pulse broadening and the interaction between the neighbouring channels due to the nonlinear effects. The optical soliton offers the solution to this question.

It has been shown that the soliton pulse can keep its shape during propagation, when it is based on a proper balance between the second order dispersion effect and the nonlinear Kerr effect, the main physical effects occurring during the pulse propagation in optical fibers. The soliton can be sufficiently strong to resist the Kerr effect and at the same time it can be not strong enough to avoid the generation of higher order solitons. The theoretical hypotheses on the design principles of soliton transmission in WDM systems have been confirmed by simulations. It has been shown that due to online filtering processes, soliton systems can now provide their benefits. Finally, we showed how solitons can be used as information carriers both for short and also for long distances.

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