

# Timing and phase jitter suppression in coherent soliton transmission

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We have revisited soliton transmission in the new context of coherent optical detection optimizing and comparing digital backward propagation and in-line optical filtering as a means to suppress soliton timing and phase jitter. We find that in-line optical filtering allows one to improve the reach of the soliton system by up to the factor of 2. Our results show that nonlinear propagation can lead to performance beyond the nonlinear Shannon limit. © 2014 Optical Society of America

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The idea of using soliton pulses as the information carrier was proposed in the early 1990s when intensity modulation (on-off keying) and direct detection were the main technology trend [1,2]. The soliton's property of maintaining its waveform shape by mutual compensation of the dispersive and nonlinear effects in the optical fiber makes the soliton a special type of signal carrier. However, in the past decade, soliton technology lost its appeal because of progress in other transmission technologies such as dense frequency division multiplexing [3], coherent detection, and forward error-correction. Moreover, increasing symbol rates required shorter pulses which, for solitons with their power inversely proportional to the pulse width, implied increasingly significant nonlinear interactions and pattern dependent jitter effects.

Recent progress in coherent communications where the use of optical phase for the coding of information and corresponding multilevel modulation formats allows one to send more bits at the same symbol rate, i.e., the speed at which each symbol is transmitted. For multilevel data coding using  $M$  levels, the information rate gain is  $\log_2 M$ . That allows one to decrease the symbol rate while keeping the total effective bit rate high [4] alleviating the pressure on the soliton pulse width and thus reducing the detrimental jitter effects [5].

Conventional coherent systems are limited by signal dependent nonlinearities, while soliton communication systems are limited by the impact of amplified spontaneous emission (ASE) noise on soliton parameters and by nonlinear pulse-to-pulse and inter-channel interactions. In this Letter, we demonstrate for the first time to the best of our knowledge the existence of a soliton transmission regime where the inherent intra-channel nonlinearity compensation enables transmission beyond the nonlinear Shannon limit for the particular link considered, despite coding information in only one dimension (phase). By studying the underlying physics of phase modulated soliton transmission in the context of coherent detection, we hope that this work will eventually lead to the development of soliton transmission systems which exceed the capacity of conventional digital coherent systems.

Since the soliton system is nonlinear, the noise effects are not simply additive. The noise field affects all the soliton parameters: amplitude, time position, frequency, and phase. Random carrier frequency shift leads to corresponding changes in the soliton's speed that can cause arrival time fluctuations of each pulse in a transmitted pulse train. Thus, the potential advantage of using a soliton carrier is the reduction of noise effects to the finite dimensional space of soliton jitter with promise for new advanced detection and processing techniques.

Here we examine the suppression of the resultant timing and phase deviation (jitter) in coherent soliton transmission systems by optical filtering and/or digital signal processing (DSP) using digital backward propagation (DBP). We compare the suppression of jitter by these two techniques and examine how they improve the transmission of the high order phase modulation formats with solitons.

Figure 1(a) schematically illustrates timing jitter on the eye-diagram, where all received pulses are drawn on the same time interval. It is seen that the peaks of those pulses are shifted in time from their initial position. This noise action is known as the Gordon-Haus effect and neglecting pulse-to-pulse interactions can be estimated as [6]:

$$\sigma_\tau^2 = \langle \Delta t^2 \rangle = \frac{n_2 h}{9} n_{sp} \frac{\alpha D}{\tau A_{\text{eff}}} Z^3, \quad (1)$$

where all the values are in real world units and  $D$  (in ps/nm/km) is the fiber dispersion,  $Z$  is the system length,

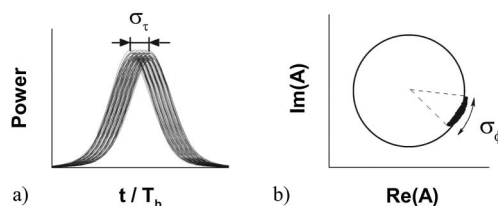


Fig. 1. Timing jitter schematically depicted on (a) the eye-diagram and phase jitter shown on (b) the constellation diagram.

$n_2$  is the nonlinear refractive index,  $\alpha$  is the fiber loss,  $A_{\text{eff}}$  is the fiber effective core area,  $\tau$  is the soliton pulse width (linked to the full width at half-maximum by  $\tau_{\text{FWHM}} = 1.76\tau$ ),  $n_{\text{sp}}$  is the coefficient of the spontaneous emission, and  $h$  is Planck's constant.

Coherent signal transmission over long distances is also limited by the accumulation of nonlinear phase noise. Since the fiber's refractive index is dependent upon the optical intensity through the Kerr nonlinearity, fluctuations in optical intensity created by ASE noise give rise to phase fluctuations [7]. Conversion of amplitude fluctuations into phase fluctuations is known as the Gordon–Mollenauer effect [1]. This effect is schematically shown in Fig. 1(b): pulses with the same initial phase experience random phase fluctuations leading to a cloud-like distortion of the single point constellation diagram. The variance of such fluctuations represents phase jitter that for relatively short distances (fewer than 5 Mm) can be estimated as [8]:

$$\sigma_\phi^2 = \langle \Delta\phi^2 \rangle = \frac{n_2 h}{3} n_{\text{sp}} \frac{\alpha D}{\tau^3 A_{\text{eff}}} Z^3. \quad (2)$$

For soliton systems, both the Gordon–Haus and Gordon–Mollenauer effects can be suppressed through the use of optical filters [9]. We consider here only fixed frequency guiding filters (FFGFs) following [9,10]. Another known method to reduce both types of jitter is optical phase conjugation (OPC) [11,12]. OPC is a technique capable of mitigating both linear dispersion accumulation and nonlinear effects. It has been shown that OPC can reduce phase jitter more than four times [13] and timing jitter by a factor of 2 [6].

In coherent communications one can use DSP, such as the DBP procedure. This technique was developed to suppress nonlinearities in conventional optical fiber systems [13–15]. The main action of DBP is a “digital reversal” of all the deterministic signal distortions that occur during the signal propagation. In real systems, DBP cannot entirely suppress all the effects because of imperfect knowledge of the system and finite processing bandwidth, but nevertheless greatly reduces them.

Our research is the extension of previous work made on aspects of soliton control in fiber links [1,2,6], and this explains the specific choice of system parameters used in our work. With the appearance of new techniques, such as digital back propagation and coherent network systems, soliton transmission lines should be revisited in a new context. For instance, the influence of back propagation on timing and phase jitter has not been studied yet.

To analyze new techniques in terms of previous work, we chose soliton parameters and fiber types close to the ones used before. Although the spectral efficiency of such a system is not high ( $\sim 1$  bit/s/Hz) in modern terms, it is not the main concern of this short Letter since further improvements can be achieved by channel spacing optimization, use of multilevel modulation, and various soliton control methods. Moreover, expanding the concept of traditional solitons to the so-called dispersion managed solitons may offer additional improvements in system performance [1,2,16]. The main point of this work is to resurrect solitons in the coherent communications

context. In particular, we focus here on the study of jitter suppression.

We use as a master model the nonlinear Schrödinger equation [1,15,16]. The model does not include effects such as double Rayleigh backscattering:

$$\frac{\partial A}{\partial z} + i \frac{\beta_2}{2} \frac{\partial^2 A}{\partial t^2} - i \gamma |A|^2 A = i N(z, t), \quad (3)$$

where  $A$  is the complex field envelope,  $\beta_2 = -\lambda^2 D / 2\pi c = -0.63 \text{ ps}^2 \text{ km}^{-1}$  is the dispersive term ( $\lambda$  is the signal wavelength),  $\gamma = 2\pi n_2 / \lambda A_{\text{eff}} = 1.27 \text{ W}^{-1} \text{ km}^{-1}$  is the nonlinear term, and  $N(z, t)$  is a term corresponding to ASE noise accumulation represented by a field that has the statistical properties of additive white Gaussian noise. The spectral noise density per polarization is given by  $N_{\text{ASE}} = \alpha Z n_{\text{sp}} h \nu$ , where  $\nu$  is the signal carrier frequency of 193.6 THz (1550 nm). This model corresponds to a path-average propagation [1], or to a quasi-lossless transmission link [17,18] in which second-order distributed Raman gain exactly compensates for the fiber losses, i.e., the signal maintains constant average power along the entire transmission length. We solve Eq. (3) numerically by using the well-known split-step Fourier method [1,16]. For numerical calculations, parameters were set as follows:  $n_{\text{sp}} = 1$ ,  $\alpha = 0.046 \text{ km}^{-1}$ ,  $\tau = 9 \text{ ps}$ , bit interval  $T_b = 100 \text{ ps}$ , peak and average power of the soliton  $P_0 = 6.09 \text{ mW}$ , and  $P_{\text{AVE}} = 1.1 \text{ mW}$  correspondingly. Modeling of the back propagation procedure was performed by using the same Eq. (3) in the absence of the noise term and taking the spatial step  $dz$  with the opposite sign.

We use soliton carrier pulses with a continuously distributed phase modulation and a single amplitude level. A similar approach was used for the Nyquist format considered in [15]. For such modulation, the phase of the soliton is defined by a random process and the constellation diagram represents a circle. To estimate the phase jitter of such a modulation format, one back-rotates the phases of all the pulses at the receiver by their individual initial phases as described in [15]. In the absence of noise, this procedure maps the initial constellation circle into a point, a constellation after linear noise distortion into a cloud on the real axis, and a constellation after nonlinear noise propagation into a shifted cloud [see Fig. 1(b)]. For each numerical run, we use a random sequence of  $2^{15}$  symbols propagating in a single spectral channel.

Figure 2 shows the accumulation of timing and phase jitter and their suppression by DBP. The black square symbols represent the evolution of the two jitter terms after physical signal propagation without any attempt to control the nonlinear impairment through DSP or filtering. Colored symbols represent post-processed data. For each set, a signal is first propagated over fixed transmission distances,  $L_i$ , of 5 (red), 10 (blue), 15 (green), and 20 (brown) Mm, after which we plot the jitter as a function of the “virtual” length of the back propagation stage, up to full back propagation of the complete transmission distance, with the x-ordinate representing the sum of the physical propagation distance (again, shown by the black square symbols) and the DBP “virtual” distance (shown by colored symbols).

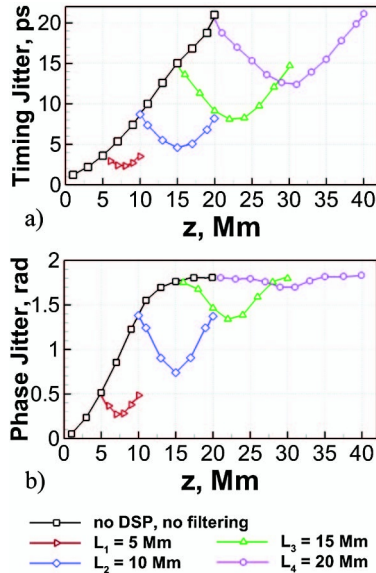


Fig. 2. Accumulation of (a) timing and (b) phase jitters with distance and their suppression by following DBP for a set of transmission distances  $L_i$ .

As seen, in both cases (timing and phase jitter), DBP reduces the jitter substantially. It is seen that the optimum length of DBP is a fraction (about half) of the total transmission distance providing the smallest achievable value of jitter after post-processing. For an NRZ system, the primary burden of DBP is to remove nonlinear pulse distortions from the signal channel; consequently, the DBP should compensate for the full transmission distance. The signal is then limited by the interaction between signal and noise [19]. However, uniquely for a soliton system, pulse distortion is compensated in line, and the DBP compensates for these signal noise interactions, expressed as timing and phase jitter. Since they arise both from pulse-to-pulse interactions and from signal interaction with noise added along the transmission line, the jitter cannot be fully suppressed.

Our numerical simulations show a reduction in timing jitter of over 40% for transmission up to 20 Mm. Phase jitter reduction is similar for transmission distances up to 10 Mm, but becomes less efficient for longer distances.

Next, we compare DBP to in-line guiding filtering, implemented similar to [1,9]. The filter has a broad Gaussian shape [1] serving to guide the spectrum of the soliton channel. The filter spacing along the transmission line was taken to be 100 km.

Figure 3 displays the comparison between the optimized DBP procedure (length of DBP stage selected for minimum jitter) and guiding filtering. The application of filters assumes no additional DSP procedures, i.e., no digital back propagation is used at the end of the transmission line. For reference, Fig. 3 also shows the performance without either DBP or filters, and the theoretical predictions of Eqs. (1) and (2). It is seen that for distances less than 5 Mm the performance of both approaches is about the same. However, for signal propagation over 5 Mm, the FFGF reduces both timing and phase jitter more efficiently than DBP. Both timing and phase effects are caused by the presence of noise in the optical fiber

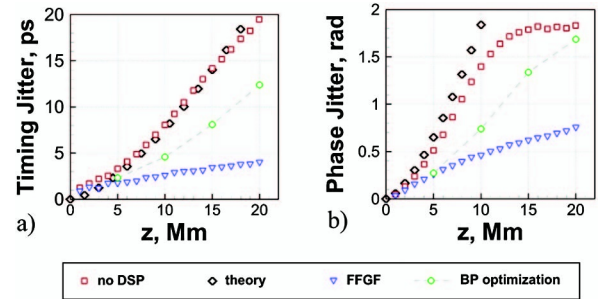


Fig. 3. Comparison of (a) timing and (b) phase jitters growth: “theory”—theoretical curve, “no DSP”—numerical curve corresponding to simple forward propagation (in the absence of back propagation or filtering), “FFGF”—jitters suppression by means of guiding filtering, and “BP optimization”—suppression by means of optimized back propagation procedure at the receiver.

system. The back propagation procedure can reduce these effects, but with noise accumulation growth, both effects become irreversible. However, the presence of the filter in a fiber system reduces both the total noise level and its impact on soliton jitter.

To evaluate the corresponding system performance improvements, we use the conventional error vector magnitude (EVM) function defined as follows:  $EVM = \sqrt{\sum_{i=1}^{N_s} E_{err,i} / (N_s E_0)}$ , where  $N_s$  represents the number of transmitted symbols,  $E_{err,i}$  the power of the error vector of the  $i$ th symbol (which shows where the initial constellation point was shifted to after transmission), and  $E_0$  the power of the initial signal vector.

Figure 4 shows that the use of guiding filters can significantly reduce the EVM in a coherent soliton transmission system. EVM has a format dependent relationship with the bit error rate (BER) [20]. Considering  $BER = 2 \times 10^{-2}$  as a transmission threshold for FEC recovery to an error free state, we can use the predicted EVM to determine corresponding “error-free” transmission distances: for BPSK modulation format the corresponding value is  $EVM = 57\%$ , for QPSK – 44%, and for 8-PSK – 22%.

In Fig. 4, the EVM thresholds and corresponding transmission limits are shown for these three different modulation formats. For instance, the reach of a single channel 10 Gbaud binary phase modulation—BPSK—system using these link parameters can be increased from 5.5 to

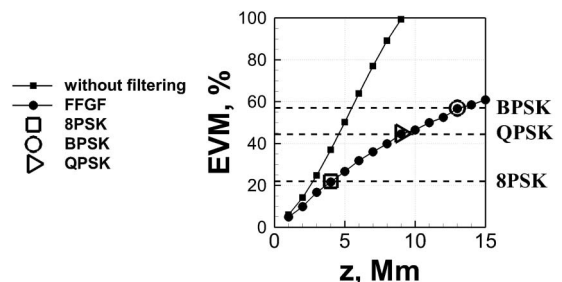


Fig. 4. EVM as a function of transmission distance with horizontal lines symbolizing EVM levels for “error-free” transmission of different phase modulation formats. Additional points symbolize calculations made for discrete formats (BPSK, QPSK, and 8-PSK).



13 Mm through the use of guiding filters. Alternatively, at the same reach (5.5 Mm), the use of filters allows the bit rate to be doubled. Filtered solitons with 8-PSK modulation, corresponding to 30 Gbps channel rate can be applied up to distances of 4 Mm. It is seen that optical filtering enhances the EVM performance of coherent soliton transmission by up to a factor of 2 compared to transmission without filtering and DSP, and up to 1.5 times as compared to the optimized DBP procedure. Note that the standard Gaussian noise (GN) model [21,22] suggests that this system should achieve distances of 19, 7, and 3 Mm for BPSK, QPSK, and 8-PSK, respectively. Here we show that coherent soliton transmission can provide without optimization, 13 (lower than conventional system), 9, and 4 mm falling beyond the standard GN model and close to the enhanced GN model [23] which suggests the GN model underestimates reaches by up to 0.8 dB.

We examined the suppression of timing and phase jitter in coherent soliton transmission by two methods: DBP implemented at the receiver and by in-line optical filtering that was applied every 100 km.

We conclude that, in soliton transmission, in-line optical filtering provides better line performance than ideal DBP because of the decreasing accumulated noise level. Moreover, we analyzed the applicability of various phase modulation formats in terms of the EVM performance measure and showed their transmission limits. Our results demonstrated the potential of coherent soliton transmission that can be achieved with more detailed comprehensive studies.

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