Intersymbol Interference and Timing Jitter Measurements in a 40-Gb/s Long-Haul Dispersion-Managed Soliton System

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***Abstract*—In this work, we have measured timing jitter in a 40-Gb/s dispersion-managed soliton system. By accurately separating out the Gordon–Haus timing jitter from the overall timing jitter, we have demonstrated that intersymbol interference limits the errorfree propagation distance in our system. Finally, we show that amplitude noise can enhance the measurement of timing jitter, which can lead to inaccuracy in determining the true system limitations.**

***Index Terms*—Optical communications, solitons, timing jitter.**

I. Introduction

In MOST SYSTEMS today, timing jitter and amplitude fluctuations are the key effects that ultimately limit errorfree propagation. As channel capacity increases to 40 Gb/s and beyond, the dependence of the bit-error rate on these effects becomes more sensitive, and they must be more tightly controlled. Thus, a careful experimental determination of timing jitter and amplitude fluctuations is necessary for predicting system performance.

Recently, there have been several experimental demonstrations of long-haul 40-Gb/s based dispersion-managed soliton (DMS) systems [1]–[3]. In most of these experiments, the error-free propagation distance was limited by timing jitter. In most DMS systems, the effects of nonlinear pulse interference are minimized and controlled by careful design of the dispersion map. As a result, most of the accumulated timing jitter can be related to Gordon–Haus effect [4], [5], but as the bit rate per channel reaches 40 Gb/s and beyond, we will show in this letter that the effects of nonlinear pulse overlap can become much more important and ultimately dominate the errors at long distances.

In this work, we experimentally measured the timing jitter in a 40-Gb/s long-haul DMS system using the following two methods: first by measuring the temporal spread of the received eye pattern using a digital sampling oscilloscope, and second, by using a frequency domain analysis of the detected pulse train [6]. We then compare the results with our theoretical model. From these detailed measurements, we investigate the system limitations and tolerance to nonlinear pulse overlap. From the experimental data, analysis, and theoretical modeling, we were able to separate the timing jitter due to pulse overlap from that due to the Gordon–Haus effect.

II. Experimental Setup and Theoretical Model

A 4.5-ps full-width at half-maximum (FWHM) 10-Gb/s pulse train produced from a commercial mode-locked fiber laser (PriTel) was coded with a $2^{23}-1$ pseudorandom binary sequence (PRBS) using a $LiNbO_3$ intensity modulator. The data stream was then optically multiplexed to produce the 40-Gb/s signal. All of the pulses were copolarized. The recirculating loop consisted of four identical dispersion maps, and each map contained 25 km of dispersion-shifted fiber (DSF) with a dispersion of -1.1 ps/nm·km that is followed by 1.5 km of standard single-mode fiber (SMF-28) with a dispersion of 17 ps/nm·km. Each dispersion map contains an erbium–doped fiber amplifier (EDFA) to offset the fiber and other component losses. The optical peak power at the launch point into the dispersion map was 7.6 mW, and the path average dispersion of the map was 0.016 ps/nm·km, while the zero dispersion wavelength was 1551.4 nm. After propagating through the DMS recirculating loop, clock recovery and electrooptical demultiplexing were used to extract the 10-Gb/s clock and data.

In our experiment, we have measured the timing jitter as a function of propagation distance in the loop for two data rates: 40 and 10 Gb/s. The reason for measuring timing jitter at 10 Gb/s is to eliminate the jitter enhancement due to nonlinear interaction caused by pulse overlap. All the system and pulse parameters were kept almost identical between the 40 Gb/s, and the 10-Gb/s tests so that the average power in the 10-Gb/s system was about a factor four lower than in the 40-Gb/s system. We used two experimental methods to determine timing jitter. The first method measures the arrival time of sampled pulses on a digital sampling oscilloscope. The software function of the oscilloscope calculates the standard deviation of the arrival times yielding their temporal spread. The oscilloscope was gated in time by a variable amount relative to the data entering the loop, so that we could obtain jitter as a function of propagation distance. The second method we used is outlined in [6]. In this

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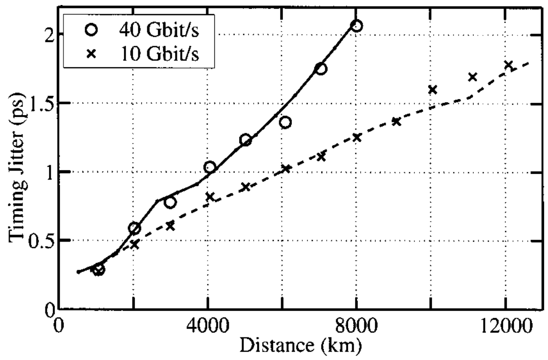

Fig. 1. Timing jitter measurements as a function of propagation distance using a digital sampling oscilloscope. The open circles represent experimental timing jitter data in the case when 40-Gb/s data was transmitted, and the crosses represent the same measurement when 10-Gb/s data is transmitted. The solid and dashed curves represent our theoretical simulation results for the 40- and 10-Gb/s cases, respectively.

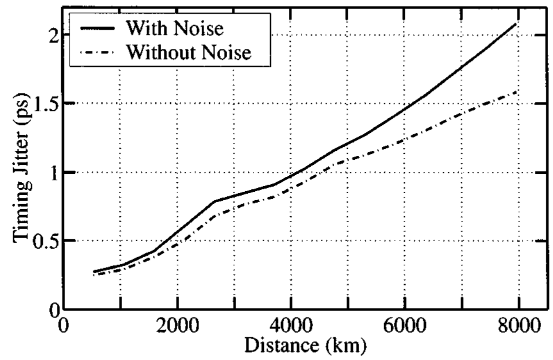

Fig. 2. Theoretical simulation results of the timing jitter as a function of propagation distance for the 40-Gb/s case. The dashed curve represents the jitter when the ASE noise is turned off in the simulation, while the solid curve represents the timing jitter when the ASE noise is turned on.

method, the RF tones of the received data are measured. However, because of the limited electrical bandwidth of our electrical instruments, this method was only applied to the 10-Gb/s case. To obtain the reference electrical spectra without jitter, the first four RF tones were fitted to the electrical spectral profile of the input optical pulse. By doing so, we accounted for the effects of the limited bandwidth of our photodiode and the spectrum analyzer used in these measurements. For the case when timing jitter is present, the RF profile will be narrowed by a factor that is related to the timing jitter. In this method, the amplitude fluctuations and timing jitter are uncorrelated, so that a more accurate timing jitter measurement can be made. The data were collected using an RF spectrum analyzer, such that the tone variation as a function of propagation distance was recorded.

In order to optimize the experiment and obtain a detailed understanding of the system performance, we set up a computer simulation that carefully models our experimental setup. We used a standard split-step Monte Carlo method to simulate the propagation in our recirculating loop [7]. As in the experiment, we considered only one polarization for the pulses. We simulated the sampling oscilloscope measurement by defining a time window at the half maximum point on the simulated eye diagram and measuring the spread of the eye within this window. The distribution was then fitted to a Gaussian profile from which the standard deviation was measured. To simulate the frequency domain approach in [6], we have calculated the central time of the simulated pulses and the resulting distribution was fitted to a Gaussian profile. We then obtained the standard deviation from the profile [8].

III. Results and Discussions

Fig. 1 shows the timing jitter measurements for both the 40- and 10-Gb/s data. The open circles represents the timing jitter in the 40-Gb/s system and crosses show the timing jitter for the 10-Gb/s system. The solid and dashed lines are our theoretical simulation results for the 40- and 10-Gb/s systems, respectively. From these measurements, we can see that the jitter results in the 40-Gb/s data is larger than that of the 10-Gb/s data. Since we kept the same system parameters (path average dispersion, peak power, pulse FWHM, and clock and data recovery) for both the 10- and 40-Gb/s data, the difference between the jitter results can only be due to the contribution of nonlinear pulse overlap (intersymbol interference or ISI) caused by the strong breathing of the optical solitons.

In the system that we investigated, the errorfree propagation distance at 10 Gb/s was limited to about 12000 km, while in the 40-Gb/s system the propagation distance was limited to about 6400 km. At both data rates, the system was optimized to maximize the errorfree propagation in the 40-Gb/s system. It is worth noting that the errorfree propagation for the 10-Gb/s data can be extended to about 18000 km by increasing the path average dispersion, the pulse width, and the optical peak power.

Theoretical models show that the onset of ISI, caused by intrachannel nonlinear pulse interactions, depends strongly on the ratio of the pulse FWHM to the bit period [9]. At the maximum expansion point in our system, this ratio for the 40-Gb/s system was 12 ps/25 ps $= 0.48$ and reaches about 9% of the maximum possible pulse-to-pulse interaction. In order to investigate the importance of ISI in the 40-Gb/s system, we ran a theoretical simulation in which the amplified spontaneous emission (ASE) noise was turned off. The result of this simulation is shown in Fig. 2. The solid line represents the timing jitter when both ASE noise and ISI are present, while the dashed line shows the timing jitter when the ASE is turned off. From this comparison, we find that the effect of ISI on the timing jitter in our 40 Gb/s is larger than that of the ASE. These results are consistent with those in Fig. 1, where the difference between the 40- and 10-Gb/s data is due to the ISI jitter. As a result, we conclude that errorfree propagation can be extended to approximately 10000 km by reducing the effect of ISI in our 40-Gb/s DMS-based system. ISI is a strong function of $\gamma = (\beta_1 L_1 - \beta_2 L_2)/\tau^2$, where β_1, β_2 are the dispersions of two types of fiber used in the map, L_1, L_2 are the lengths of each of the fiber components, and τ is the FWHM temporal duration of the pulse [10]. Simulations indicate that a 15% reduction in the map length, and hence, γ will increase the transmission distance to $\approx$10000 km. Details of these simulations including tolerance to system parameters will be presented in a future publication.

Fig. 3 shows the jitter measurements using the method outlined in [6] for the 10-Gb/s system along with the scope jitter results. The open diamonds represent the timing jitter measurements using [6], while the crosses are the jitter measurements

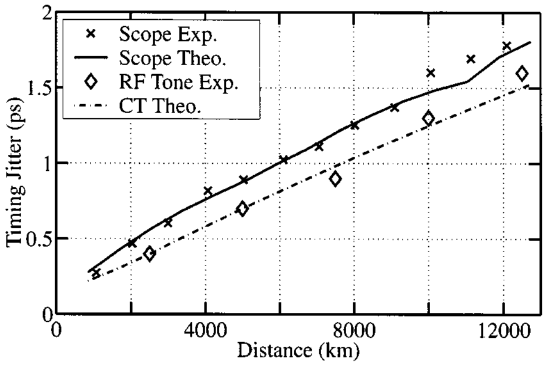

Fig. 3. Comparison between the 10-Gb/s timing jitter measured using the digital sampling oscilloscope and the RF tone method. The crosses represent the jitter measurements using the sampling scope, while the open diamonds represent the jitter measured using the RF tone method. The solid and dashed curves represent our theoretical simulation results outlined in this letter.

using the sampling scope. The solid and dashed curves represent our theoretical simulations using the histogram and the central time method, respectively. By using the technique in [6], the measured timing jitter is not affected by amplitude fluctuations. As a result, the timing jitter measured using this method is about 10%–20% smaller than that using the sampling scope. The timing jitter results using the RF tone represent the true timing jitter in the system, while the timing jitter measured using the sampling scope is enhanced by the influence of amplitude fluctuations. From these results, we can see that timing jitter becomes a very critical parameter that needs to be carefully monitored and measured. In the system that we have studied, we are limited primarily by timing jitter that is induced by ISI.

IV. Conclusion

In this work, we experimentally and theoretically measured the timing jitter in a 40-Gb/s DMS system. Experimentally, we used a digital sampling oscilloscope and an RF tone method [6] to calculate the timing jitter. The investigation shows that the transmission is limited by ISI. Our results indicate that reducing the map length by ≈15% will reduce the ISI and significantly increase the transmission distance. In addition to that, our results shows that amplitude fluctuations can enhance the timing jitter measured by a sampling oscilloscope, resulting in larger jitter values which in turn result in an inaccurate conclusion about the true limiting factors of system.

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