Robustness estimation of software-synchronized all-optical sampling for fiber communication systems

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The robustness of the software-synchronized all-optical sampling for optical performance monitoring is estimated for 10-Gb/s fiber communication systems. It reveals that the software-synchronized algorithm is sensitive to the signal degradation caused by chromatic dispersion and nonlinearity in optical fibers. The influence of timing jitter and amplitude fluctuation of the sampling pulses is also investigated. It is found that stringent requirements are imposed on the quality of the sampling pulse and the tolerance of 1-dB Q penalty is measured. Considering the practically available optical sampling pulse sources, the results indicate that the amplitude fluctuation of the sampling pulses has the dominant impacts on the software-synchronized method.

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As the bit rate per wavelength division multiplexing (WDM) channel increases up to 40 Gb/s or beyond, the electronic access to the data signal for channel monitoring becomes expensive or even impossible. All-optical solution for performance monitoring therefore becomes promising. With the optical sampling technique and employing extremely short sampling pulses, a resolution of less than 1 ps can be achieved. The optical sampling system has been proven to be a very powerful tool for real-time system optimization and signal monitoring[1−5]. In contrast to asynchronous or synchronous all-optical sampling systems, the software-synchronized all-optical sampling system can provide Q values, synchronized eye diagrams, and data patterns in real time, but requires no clock recovery circuit for the data signal or for the sampling pulse to retrieve the required synchronization information[2−10]. A software algorithm based on the Fourier transform of the sampled data, as well as the eye-diagram timing drift, was proposed by Westlund *et al.* to provide the required synchronization information[8−10]. The optical performance monitoring requires that the software can monitor all kinds of signals regardless of the signal degradation, which means that the software-synchronized optical sampling should be signal quality independent. The robustness of the software algorithm against the signal degradation is therefore necessary to be evaluated. In this letter, the robustness against the signal degradation induced by chromatic dispersion and fiber nonlinearity is evaluated for the software-synchronized all-optical sampling for fiber communication systems. The influence of the timing jitter and amplitude fluctuation of the sampling pulse on the performance of monitoring system is also researched.

The system setup for software-synchronized all-optical sampling is shown in Fig. 1. The 10-Gb/s non-return-to-zero (NRZ) optical data signal propagated through the fiber, and then was sampled in a periodically poled lithium niobate (PPLN) chip by optical sampling pulses generated from a mode-locked fiber ring laser (MLFRL). The repetition rate of the sampling pulse was 499.99 MHz, and the pulse width was about 5.7 ps. The optical sampling process was accomplished by the sum-frequency generation (SFG) in PPLN. The length of the PPLN chip was 40 mm, and the single grating period was 30.2 μm. The working temperature was 300 K. The wavelengths of the optical data signal and the sampling pulse were 1.550 and 1.572 μm, respectively. The sampling pulse was filtered out by an optical bandpass filter (BPF), and a photodiode was used to detect the sampling pulse. Then a data acquisition (DAQ) card collected the electrical signal. Finally, a computer processed the electrical signal by the software-synchronized algorithm, by which the eye-diagram of the optical data signal was recovered and the Q value was computed.

Firstly, the robustness of the software-synchronized method against the chromatic dispersion was measured. The fiber for the experiment was G.652 standard single mode fiber (SSMF), the chromatic dispersion of which was 17.0 ps/(km·nm), and the nonlinear coefficient was 2.6 km^{-1}·W^{-1}. To investigate the robustness against the chromatic dispersion, the power of the data signal launched into the fiber was 0.0 dBm for no significant nonlinearity in SSMF, and the signal transmitted in different lengths of SSMF without chromatic

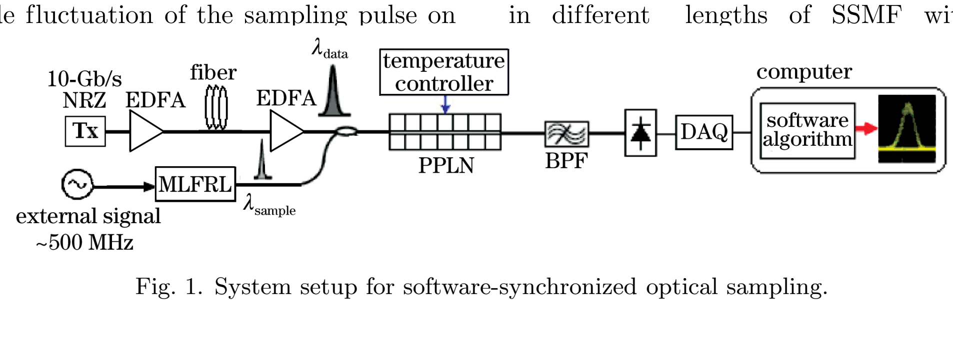

Fig. 1. System setup for software-synchronized optical sampling.

Table 1. Q Values of the Transmitted Signal Measured by the Conventional and Software-Synchronized Methods

SSMF (km)	30	35	40	45	50	55	60
Conventional	9.29	8.88	8.55	8.27	7.80	7.38	6.96
Software	9.30	8.97	8.64	8.01	7.37	6.33	5.30

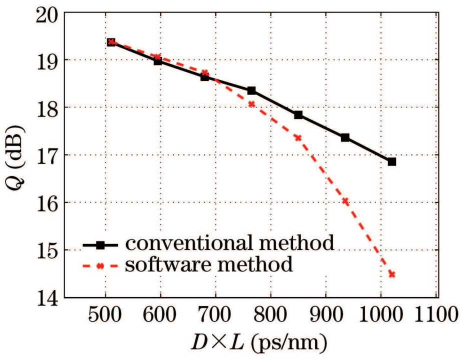

Fig. 2. Robustness of software-synchronized method against chromatic dispersion. Q is defined as $20\lg Q$.

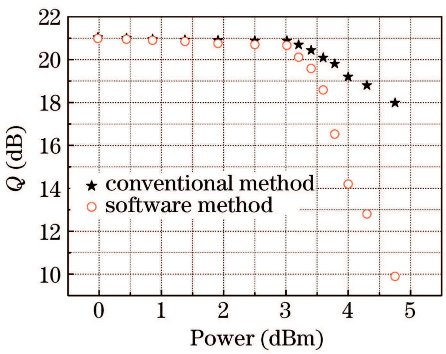

Fig. 3. Robustness of software-synchronized method against fiber nonlinearity.

compensation. Table 1 lists the Q values by the conventional and the software-synchronized methods. The so-called conventional method employs the high speed photo detector to realize optical-to-electrical (O/E) conversion and then measures the signal eye-diagram or Q factor by a high speed oscilloscope. Figure 2 compares the Q values measured by conventional and software-synchronized methods, where Q (dB) is defined as $20\lg Q$. The difference is negligible when the total dispersion is less than 700 ps/nm. But the difference becomes significant when the total dispersion is more than 800 ps/nm, and 1-dB tolerance of dispersion is about 900 ps/nm. Then the fiber nonlinearity was measured. In the experiment, the chromatic dispersion of 40-km SSMF was compensated by dispersion compensation fiber (DCF), the chromatic dispersion of the DCF was −80 ps/(km·nm). Figure 3 shows that the Q value measured by software-synchronized method well matches that by conventional method if the power launched into the fiber is less than 3 dBm. However, if the power launched into fiber is greater than 3 dBm, the significant underestimation of Q values by software method arises because of the excited fiber nonlinearity. If 1-dB tolerance of the fiber nonlinearity is concerned, the software method is limited to about 3.5-dBm power level launched into the fiber.

The results in Figs. 2 and 3 indicate that the software-synchronized method is greatly limited by the signal degradation caused by chromatic dispersion and fiber nonlinearity. It is explained by the fact that moderate rate sampling process misses part of the information carried by the original optical data signal. The multi-point optical sampling and further advanced algorithms are under investigation by our group to improve the robustness of the software-synchronized method.

It is well known that the quality of sampling pulse will impact the performance of the overall system. Due to the random noise imposed on the laser, the amplitude of the sampling pulse will fluctuate. Assuming that the average value is u_0, the standard deviation is $\sigma_{\text{amplitude}}$, the probability density function of the amplitude can be expressed as

$$P(u) = \frac{1}{\sqrt{2\pi}\sigma_{\text{amplitude}}} \exp\left(-\frac{(u-u_0)^2}{2\sigma^2_{\text{amplitude}}}\right). \quad (1)$$

If the amplitude of the sampling pulse is normalized by u_0, Fig. 4 shows that the amplitude fluctuation also leads to the underestimation of the Q value. Q approximately linearly decreases with the amplitude fluctuation. The greater amplitude fluctuation, the greater underestimation occurs to the Q value. To explain this phenomenon, we write the expression of the Q value as

$$Q = \frac{u_1 - u_0}{\sigma_1 + \sigma_0}, \quad (2)$$

where u_1 and u_0 are the average values for "1" and "0" bits, respectively, and σ_1 and σ_0 are the standard deviation values for "1" and "0" bits, respectively. From Eq. (2), we can see that the amplitude fluctuation of the sampling pulse is directly added to the sampled signal, meaning that σ_1 and σ_0 will be greater while u_1 and u_0 keep unchanged, so the Q value by the software-synchronized optical sampling method becomes smaller. As indicated in Fig. 4, the 1-dB Q tolerance of normalized amplitude fluctuation is about 3% with the power launched into SSMF of +3.5 dBm. We also notice that, if the power launched into SSMF is lower, the impact of the sampling amplitude fluctuation is greater. However, with higher power launched into fibers, it will excite the fiber nonlinearity and result in the power fluctuation for "1" and "0" bits, so the impact of the sampling

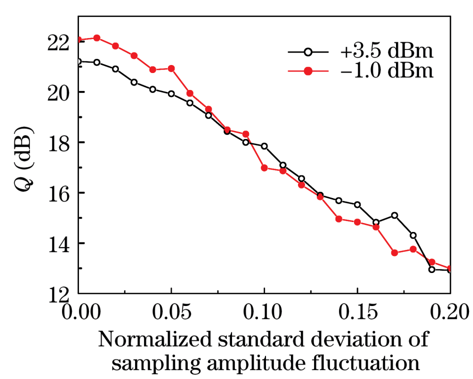

Fig. 4. Influence of sampling pulse amplitude fluctuation on Q values by the software method.

amplitude fluctuation is relatively smaller.

The timing jitter commonly accompanies the sampling pulse generated by MLFRL. It is reasonable to assume that the sampling time follows the Gaussian distribution, i.e.,

$$P(t) = \frac{1}{\sqrt{2\pi}\sigma_{\text{time}}} \exp\left(-\frac{t^2}{2\sigma_{\text{time}}^2}\right), \tag{3}$$

where σ_{time} is the standard deviation of the sampling time and normalized to the bit duration T_{b}. In Fig. 5, the Q value fluctuates with the timing jitter at the beginning, and then decreases with the timing jitter. When the power launched into SSMF is −3.0 dBm, the fluctuation of the Q value is less than 0.1 dB if the timing jitter is smaller than $T_{\text{b}}/17$ (5.8824 ps), meaning that Q is not significantly influenced by timing jitter in this range. Then, if the timing jitter increases, the error of the Q value will increase sharply. The 1-dB tolerance of timing jitter is about $T_{\text{b}}/13$. However, if the power launched into SSMF is 3.5 dBm, the fluctuation of the Q value is greater than 1.0 dB with the timing jitter of $T_{\text{b}}/17$. Therefore, we can conclude that the timing jitter of the sampling pulse has greater influence if the power launched into SSMF is higher.

In practice, the amplitude fluctuation coexists with the timing jitter for the optical sampling pulse. Figure 6 shows the variation of the Q value with the timing jitter under different amplitude fluctuations. The power launched into SSMF is −3.0 dBm in this figure. It can be seen that, with the increase of amplitude fluctuation, the Q fluctuation with the timing jitter becomes serious.

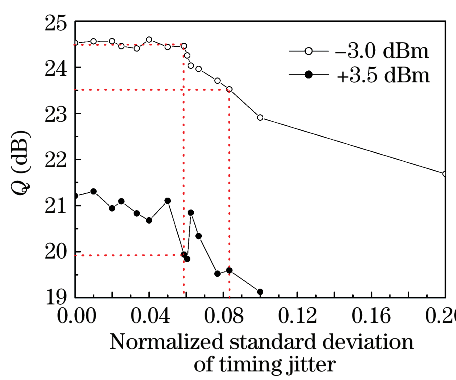

Fig. 5. Influence of timing jitter on Q values by software method.

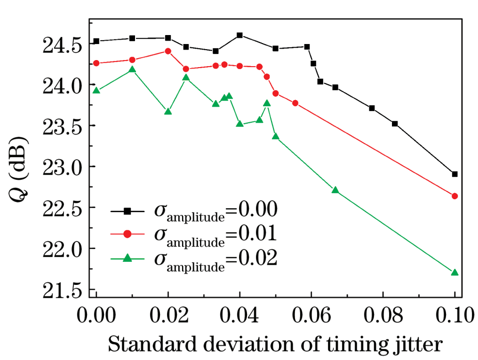

Fig. 6. Variation of Q values estimated by software method with the amplitude fluctuation and timing jitter. The power launched into SSMF is −3.0 dBm.

With $\sigma_{\text{amplitude}} = 0$, the fluctuation of the Q value will be less than 0.1 dB if the timing jitter is less than $T_{\text{b}}/17$. With $\sigma_{\text{amplitude}} = 0.01$, the fluctuation of the Q value will be 0.2 dB when the timing jitter is $T_{\text{b}}/22$. With $\sigma_{\text{amplitude}} = 0.02$, which is common for the available high power optical sampling pulses, the Q value is not accurate and stable anymore. To get the accurate Q value by the software-synchronized optical sampling, $\sigma_{\text{amplitude}} \leq 0.01$ and $\sigma_{\text{time}} \leq T_{\text{b}}/20$ must be satisfied for the sampling pulse. Fortunately, the timing jitter of currently available MLFRL can be less than 1 ps, so it does not affect the Q value by the software method. We can therefore conclude that the influence of sampling amplitude fluctuation is dominant.

Finally, we employed the software-synchronized method to monitor the 10-Gb/s return-to-zero code of 50% duty ratio (0.5RZ) optical signal. Figure 7 shows that the variation of the Q value with the sampling amplitude fluctuation is almost parallel for NRZ and 0.5RZ formats. It means the same influence of the sample amplitude fluctuation on both modulation formats. Figure 8 shows the variation of the Q value with the sampling

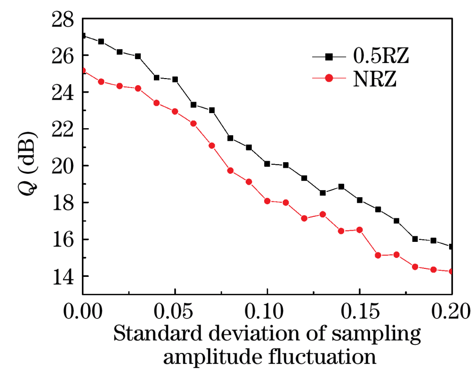

Fig. 7. Comparison of Q values for NRZ and 0.5RZ formats. The power launched into SSMF is −3.0 dBm.

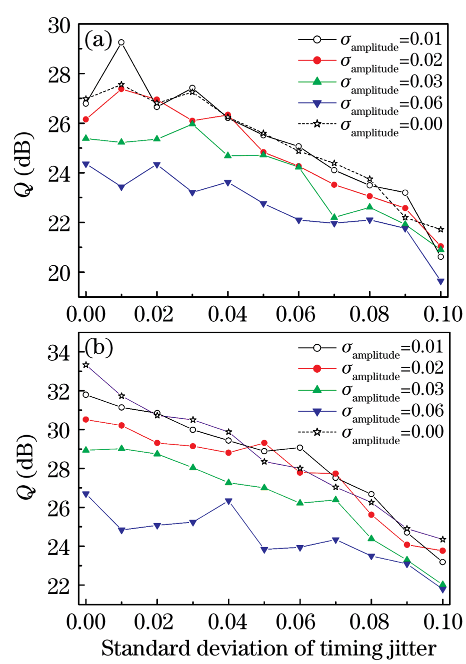

Fig. 8. Variation of Q estimated by the software method with the amplitude fluctuation and timing jitter. The power launched into SSMF is (a) −3.0 dBm and (b) +5.0 dBm.

timing jitter under different values of sampling amplitude fluctuation. The sampling amplitude fluctuation additionally causes the Q value to fluctuate with the timing jitter. But as the sampling amplitude fluctuation increase to 6%, the underestimation of Q values induced by the timing jitter is dominant. As shown in Fig. 8, for 0.5RZ format, the Q value is also more sensitive to the timing jitter if the power launched into the fiber is higher. If considering the timing jitter of sampling pulse to be less than 1 ps, the underestimation of the Q value is mainly caused by the sampling amplitude fluctuation. If comparing it with Fig. 6, we can see that the Q value of 0.5RZ format is more sensitive to the timing jitter than that of NRZ.

It is important to evaluate the robustness of the software-synchronized optical sampling for monitoring the performance of the fiber communication system. The research in this letter reveals that, with large chromatic dispersion and fiber nonlinearity, the software method will underestimate the Q value. It is due to the missing of information during the sampling process. We propose that, with multi-point sampling and advanced software algorithms, the robustness of the software method will be improved and the result will be presented in the future. The influence of the amplitude fluctuation and timing jitter of the optical sampling pulse is also researched. The results show that the amplitude fluctuation will lead to underestimation of the Q values by the software-synchronized method, and the timing jitter of the current MLFRL does not significantly affect the Q values for NRZ format. We also compare 0.5RZ and NRZ format signals when they are monitored by the software-synchronized method. The Q value for 0.5RZ format is more sensitive to the sampling timing jitter than NRZ format. The higher power launched into fibers, the greater influence of sampling timing jitter imposed on both 0.5RZ and NRZ formats. Considering the practically available sampling optical pulse sources, the influence of the sampling amplitude fluctuation is dominant even if the higher power is launched into the fiber.

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