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Bit-rate adaptive optical performance monitoring method for fiber communication systems

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ABSTRACT

A novel bit-rate adaptive method, by varying the optical sampling rates alternatively, is proposed in this paper for optical performance monitoring. Firstly, the theoretical model and the differential software-synchronized algorithm are developed. Then, the results verify that different channel bit-rate can be estimated with high precision irrespective of the modulation formats and signal distortion caused by chromatic dispersion and nonlinearity along the fiber link. Employing the proposed bit-rate adaptive method, the eye diagrams and Q values of 10 Gbit/s, 40 Gbit/s and even higher bit-rate signal can be monitored by a single optical performance monitoring system without any prior knowledge about bit-rate or signal period. The method we propose in this paper has the advantage that different channel bit-rates can be adaptively estimated and the differential software-synchronized algorithm is much simpler.

1. Introduction

As the bit-rate per WDM channel increases up to 40 Gbit/s or beyond, the electronic access to the optical data signal for channel monitoring becomes expensive or even impossible. All-optical solution for performance monitoring therefore becomes promising. With optical sampling technique, employing extremely short sampling pulses, a resolution of <1 ps can be achieved. The optical sampling system has 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 [5–8], the software-synchronized all-optical sampling system can provide Q values, synchronized eye diagrams, and data patterns in real time [9–12], but requires no clock recovery circuit for the data signal or for the sampling pulse to retrieve the required synchronization information. The software algorithms based on the Fourier transform of the sampled data are proposed to provide the required synchronization information [9–12]. In [11], M. Westlund assumes that the bit-rate B of optical data signal is known to within $\pm f_s/2$, and f_s is the optical sampling rate. In [12], T. Kiatchanog assumes that the signal period $T$is known. However, these assumptions are hard to hold if the bit-rate of optical data signal changes, especially for future multi-bit-rate shared fiber links. The ability of optical performance monitoring system to monitor different bit-rate signal adaptively is therefore preferable.

A novel bit-rate adaptive method for optical performance monitoring, by varying the optical sampling rate, is proposed in this paper. The synchronization information is extracted by differentially processing the sampled signals obtained with two different sampling rates. The results demonstrate that, the novel method can monitor the signal of 10 Gbit/s, 40 Gbit/s and even higher bit rate without any prior knowledge about the bit-rate or signal period. The paper is organized as follows: the operation principle of the novel optical performance monitoring system with bit-rate adaptive method is described in Section 2, and then the theoretical model and the differential software-synchronized algorithm are introduced in Section 3. Section 4 is the main results obtained with the bit-rate adaptive method. Conclusions are drawn in Section 5.

2. Optical performance monitoring with the bit-rate adaptive method

Fig. 1 is the setup of optical performance monitoring system for OOK signal with the bit-rate adaptive method, which is similar to that in [11] or [12] at a glance. The difference lies in that the repetition rate of the optical sampling pulses from the mode-locked laser (MLL) is varied alternatively between two values, and the sampled signal is processed by a differential software-synchronized algorithm. The alternatively varied repetition rate can be realized by alternatively tuning the repetition frequency of the external clock imposed on the MLL and the length of the fiber ring generating the optical sampling pulses if an active MLL is employed as in [11], or just tuning the length of the fiber ring if a passive MLL is employed as in [12].

In this paper, an active MLL is used. The optical data signal from the fiber link is combined with the optical sampling pulses by a WDM coupler. The optical sampling gate is essentially a nonlinear AND gate, in which the optical sampling pulses from the MLL serve as the “gate openers”. The sampling rate f_s is varied by controlling the repetition frequency of the external clock imposed on the MLL. The optical samples

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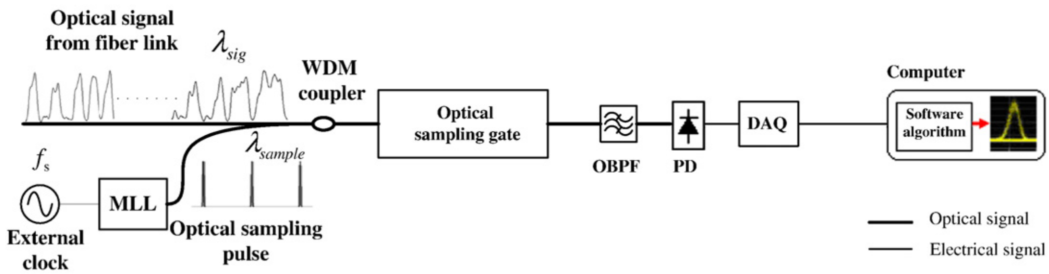

Fig. 1. Setup of the novel bit-rate adaptive optical performance monitoring system for OOK signal.

exiting the sampling gate are filtered by an optical band-pass filter (OBPF), detected by a low bandwidth O/E detector and sampled by a data acquisition card (DAQ) in a computer. The samples obtained with the different sampling rate f_s are differentially processed by the software-synchronized algorithm, and can then be synchronized and reconstructed into an eye diagram corresponding to the input optical data signal.

3. Theoretical model and differential software-synchronized algorithm

In order to reconstruct the eye diagram from the sampled data, it requires that the offset frequency Δf between the signal bit-rate B and the sampling rate f_s, related by $B = Mf_s + \Delta f$, is known. In [11], it is assumed that the signal bit-rate B is known to within $\pm f_s/2$, and then the integer M can be well defined. However, this assumption is hard to hold if the bit rate of optical data signal changes, especially for future multi-bit-rate shared fiber links. In our proposed bit-rate adaptive method, we tune the sampling rate to be f_{s1} and f_{s2} alternatively.

As described in [11], the offset frequency Δf can be conveniently expressed in terms of a corresponding time step Δt (picoseconds per sample), given by

$$\Delta t = \frac{1}{f_s} - \frac{M}{B}, \tag{1}$$

i.e.,

$$\Delta t = T_s - MT_B, \tag{2}$$

where $T_s = \frac{1}{f_s}$, $T_B = \frac{1}{B}$. To achieve the bit-rate information by the software algorithm, the time step Δt should be determined with high precision.

By applying the Fourier transform algorithm as the following on each of the N first samples in data stream X [11]:

$$Y_i = (X_i - \overline{X}), \tag{3}$$

where $\overline{X}$ represents the mean value of N samples, the number of equivalently scanned bit slots S can be determined as a function of N samples.

Presume that Δt_1 and Δt_2 are the corresponding time step for sampling rates f_{s1} and f_{s2} respectively, so satisfy

$$\Delta t_1 = \frac{1}{f_{S1}} - \frac{M_1}{B}, \tag{4 – a}$$

$$\Delta t_2 = \frac{1}{f_{S2}} - \frac{M_2}{B}, \tag{4 – b}$$

$$M_1 = \left\lfloor \frac{B}{f_{s1}} \right\rfloor, \tag{5 – a}$$

$$M_2 = \left\lfloor \frac{B}{f_{s2}} \right\rfloor \tag{5 – b}$$

Here, $\lfloor x \rfloor$ is the integer not greater than x. If $\left| \frac{1}{f_{s1}} - \frac{1}{f_{s2}} \right| \le \frac{1}{B}$ holds, then

$$M_1 = M_2 = M. \tag{6}$$

To set that the time span for DAQ capturing the samples is T for both sampling rates f_{s1} and f_{s2}, the number of samples are expressed as N_1 and N_2 respectively, and the corresponding numbers of equivalently scanned bit slots determined by N_1 and N_2 are indicated as S_1 and S_2, then the following expressions hold.

$$\frac{N_1}{S_1}\Delta t_1 = \frac{N_2}{S_2}\Delta t_2 = \frac{1}{B} \tag{7}$$

To combine Eqs. (4-a), (6) and (7), it is deduced that

$$\frac{M}{B} = \frac{\frac{N_1}{S_1}\frac{1}{f_{S1}} - \frac{N_2}{S_2}\frac{1}{f_{S2}}}{\frac{N_1}{S_1} - \frac{N_2}{S_2}} \tag{8}$$

The time stepΔt_1 and Δt_2 can therefore be expressed as

$$\Delta t_1 = \frac{\frac{N_2}{S_2}\left(\frac{1}{f_{S2}} - \frac{1}{f_{S1}}\right)}{\frac{N_1}{S_1} - \frac{N_2}{S_2}} \tag{9 – a}$$

$$\Delta t_2 = \frac{\frac{N_1}{S_1}\left(\frac{1}{f_{S2}} - \frac{1}{f_{S1}}\right)}{\frac{N_1}{S_1} - \frac{N_2}{S_2}} \tag{9 – b}$$

To substitute Eq. (9-a) to Eq. (7), the bit-rate B can then be estimated as

$$B = \frac{\frac{S_1}{N_1} - \frac{S_2}{N_2}}{\frac{1}{f_{S1}} - \frac{1}{f_{S2}}} \tag{10}$$

It can be seen from Eqs. (9-a) and (10) that, the time step and bit rate are fully determined by the number of equivalently scanned bit slots S_1 and S_2. The complicated and time-consuming iterative algorithm to extract the accurate time step in [11] is therefore avoided.

It is pointed out here that Eqs. (8), (9-a) and (10) are derived by differentially processing the sampled data of two sampling rates f_{s1} and f_{s2}, the corresponding software algorithm for the bit-rate adaptive method is therefore called differential software-synchronized algorithm. The above deduction indicates that the time step is estimated only with the loose requirement of $\left| \frac{1}{f_{s1}} - \frac{1}{f_{s2}} \right| \le \frac{1}{B}$, exempt of the strict assumption that the signal bit-rate B is known to within $\pm f_s/2$ as in [11]. Considering the commercially available external clock signal imposed on MLL, it is practical to tune the sampling rate with resolution of 25 kHz if the repetition rate of optical sampling pulse is 10^2 MHz–1 GHz. It means that $\left| \frac{1}{f_{s1}} - \frac{1}{f_{s2}} \right|$ is less than 1 ps, so the optical signal of bit rate less than 1000 Gbit/s can be monitored with the bit-rate adaptive method (up to date, the lab-recorded single channel bit-