Regular Papers

Technology for Flexibly Monitoring Optical Signal Quality in Optical Communications

Ippei Shake†, *Hidehiko Takara, and Satoki Kawanishi*

Abstract

Optical signal quality monitoring is an important function for optical transport networks and future all-optical networks. To monitor the optical signal-to-noise ratio and/or waveform distortion transparently with respect to the signal format, data format, and signal bit rate, we propose a new optical signal quality monitoring method that uses asynchronous sampling, which is a sampling technique that does not use timing extraction. The use of high-speed asynchronous sampling and the adjustment of the sampling rate enable simple open eye-diagram monitoring and evaluation of a fixed-timing Q-factor (Q_t) at the maximum eye opening timing phase. This method was experimentally verified using an optical signal quality monitoring circuit. We obtained a good relationship between the measured Q_t and Q (which is a Q-factor calculated from the bit error rate (BER)), indicating that the BER was estimated by the measured Q_t with good accuracy. Moreover, as an easier method, we also introduce an average Q-factor (Q_{avg}) evaluation method, which measures the Q_{avg} value from an asynchronous eye-diagram (timing drifted eye-diagram). This method is useful when the sampling rate is low or when adjusting the sampling rate is difficult, although a correction procedure for converting from Q_{avg} to Q is needed. Standardization of our optical signal quality monitoring technology is in progress in the IEC (International Electrotechnical Commission).

1. Introduction

Monitoring the quality of signals is an important aspect of the design, operation, and maintenance of optical transport networks [1]-[3]. From the network operator's viewpoint, monitoring techniques are required to establish connections, establish protection or/and restoration, and perform maintenance. To achieve these functions, monitoring techniques should satisfy some general requirements: they should provide in-service measurement, signal deterioration detection, fault isolation, transparency, scalability, and simplicity. **Figure 1** shows an example of an optical network that accommodates a diverse range of clients and has a flexible optical path configuration. If a fault or signal deterioration occurs, it is necessary to detect the problem to protect/restore and localize the impaired section or node. A fundamental performance monitoring parameter of any digital transmission system is its end-to-end bit error rate (BER). However, the only way to correctly evaluate the BER is to use out-of-service BER measurement, that is to measure it using a known test bit pattern instead of a real signal while the service is not operating. In-service measurement can give only rough estimates by measuring digital parameters (e.g., the error block detection and error count in forward error correction) or analog parameters (e.g., optical power, optical signal-to-noise ratio (OSNR), and Q-factor[*1]).

What has been greatly desired and studied is a signal quality monitoring method that can provide a good measure of signal quality without complex ter-

† NTT Network Innovation Laboratories
Yokosuka-shi, 239-0847 Japan
E-mail: shake.ippei@lab.ntt.co.jp

*1 Q-factor: a parameter for indicating quality. In this paper, the Q-factor is the optical signal quality in optical communications. It is defined by the amplitude distributions of both the mark (1) and space (0) levels of a binary signal.

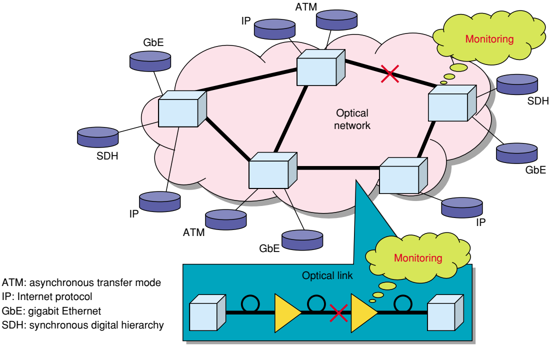

Fig. 1. Optical network with diverse clients (a monitoring function is needed at nodes and repeaters).

mination. When the system BER is too low to be measured within a reasonable amount of time, it is useful to use Q-factor measurement [3]-[10]. However, sampling-based methods basically require synchronization and then some analysis [4], [5], which makes them similar to protocol-aware termination in terms of cost and complexity. In fact, synchronous sampling requires timing extraction using complex equipment that is specific to each bit error rate and each format.

This paper proposes a simple Q-factor measurement technique as a cost-effective alternative to BER measurements. This method is a fixed timing Q-factor (Q_t) monitoring method that utilizes the open eye-diagrams captured by asynchronous sampling [6]. Asynchronous sampling allows bit-rate independent Q-factor monitoring, and the same equipment can cover a bit rate range of up to 40 Gbit/s. Average Q-factor (Q_{avg}) measurement through asynchronous sampling [3], [8] is also introduced and compared with Q_t measurement. The experimental results are also summarized.

2. Q_t monitoring

Parameter Q_t is estimated from the open eye-diagrams captured by asynchronous sampling as shown in **Fig. 2**. To obtain well opened eye-diagrams, all sampling points are plotted in time order and superimposed every k (or multiple of k) samples. The following conditions must be satisfied:

$$T_{step} = 1/f_c - 1/\{(n/m)\, f_s\} = 1/(k\, f_s), \qquad (1)$$

where f_s is the signal bit rate, f_c is the sampling clock rate, T_{step} is the sampling time interval, n/m is a value pertaining to the ratio f_s and f_c, n and m are natural numbers, and k is the number of sampling points per time slot. From these equations, f_c is obtained as

$$f_c = (1/k + m/n)^{-1} f_s. \qquad (2)$$

Here, we assume some knowledge of f_s such as the data format (e.g., SONET/SDH (synchronous optical network, synchronous digital hierarchy) or Ethernet). Such information is relatively easy to obtain. Note that when timing extraction is not used, f_s is not accurately known at the signal quality monitoring circuit, so f_c must be determined independently. Moreover, the performance of the sampling clock source causes inaccuracy in the setting of f_c. These inaccuracies in f_s and/or f_c cause Eqs. (1) and (2) to fail. However, high-speed sampling allows us to obtain well opened eye-diagrams even under this condition, which means that Q_t can be evaluated as described in the following theoretical evaluation.

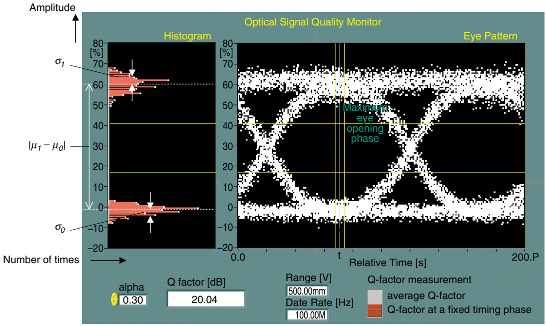

Fig. 2. Open eye-diagram captured by asynchronous sampling and amplitude histograms at fixed timing phase t (N_{samp} = 8000, k = 100, $|df| \approx 0$, f_s =10 Gbit/s, $f_c \approx$ 100 MHz, n/m ≈ 1/10).

We assume frequency detuning df due to the inaccuracy in determining f_s and/or f_c. The time shift of sampling time interval ΔT_{step} due to df is written as

$$\Delta T_{step} = 1/f_c - 1/(f_c + df). \tag{3}$$

When $|N_{samp}\,\Delta T_{step}|$ is $1/(2f_s)$ or less, where N_{samp} is the total sampling number, a well opened eye-diagram is obtained. Therefore, the following condition must be satisfied.

$$f_c \geq (2 f_s\, j\, k\, |df|)^{1/2}, \tag{4}$$

where $N_{samp} = j\,k$ (j and k are natural numbers). For example, when N_{samp} is 250, f_s is approximately 10 Gbit/s, the frequency detuning $|df|$ is 20 ppm (200 kHz), and the requirement for f_c is 1 GHz or more. Therefore, a sampling clock rate on the order of 1 GHz allows our measurement circuit to capture the opened eye-diagrams even when the frequency detuning $|df|$ is 20 ppm. In other words, if the sampling clock rate is on the order of 1 GHz, our measurement circuit tolerates setting inaccuracy in f_s and/or f_c of up to ±200 kHz. Therefore, high-speed asynchronous opto-electrical (OE) sampling[*2] enables us to achieve simple Q-factor monitoring without complicated software calculations, which are required when using the periodogram [7].

In addition, we must confirm the influence of signal wander. Signal wander is sometimes estimated from the group delay due to a change in the transmission fiber caused by temperature fluctuations. When the total sampling number is N_{samp} points, the transmission fiber length is L m, the temperature change is dT °C/s, the group delay coefficient of optical fibers is α ps/m/°C, and the total group delay divided by the total sampling time, Δt_{wander}, satisfies

$$\Delta t_{wander} = \alpha\, N_{samp}\, L\, dT / f_c\,. \tag{5}$$

For example, when α is 0.2 ps/m/°C, N is 250, L is 320×10^3 m, dT is 0.5×10^{-3} °C/s (20°C per 12 hours), and f_c is approximately 1 GHz, the group delay divided by the total sampling time is approximately 7.5×10^{-6} ps, which is small enough to measure the open eye-diagrams. The eye-diagrams, the amplitude histograms at fixed timing phase t, and Q_t are shown in Fig. 2. Parameter Q_t is defined by

$$Q_t = |\mu_1 - \mu_0| / (\sigma_1 + \sigma_0), \tag{6}$$

where μ_i and σ_i are the mean and standard deviation, respectively, of the mark (i = 1) and space (i = 0) level distributions of the amplitude histograms. The midpoint of the timing phase between the two white lines in Fig. 2 is t and the sampling points between the two white lines are used in the estimation.

3. Signal quality monitoring circuit using simple OE sampling*2

The optical signal quality monitoring circuit consists of an OE sampling module, an internal clock source, an O/E converter, and a signal processing circuit, as shown in **Fig. 3**. OE sampling is performed using optical gating with an electrical clock. An electro-absorption (EA) modulator*3 is used as the OE sampling module. The repetition rate of the electrical clock is approximately 1 GHz. The EA modulator and electrical clock source are relatively small and simple compared with the conventional optical sampling components or electrical high-speed sampling modules. In the conventional electrical sampling case, the O/E converter bandwidth should be wider than the signal bit rate. On the other hand, in the OE sampling method, the signal is optically sampled at a repetition rate lower than the signal bit rate, so the O/E converter bandwidth is narrower than the signal bit rate. The signal processing circuit analyzes the sampled signal to determine Q_t and Q_{avg}.

Using this technique, we constructed a prototype optical signal quality monitor. A polarization-independent EA modulator with bandwidth of 40 GHz was used to achieve polarization-independent operation and excellent time resolution (8 ps). The signal bit rate can range up to 40 Gbit/s. We can also measure the wavelength dependence of the Q-factor. The bandwidth allowing a 2-dB decrease from the maximum Q-factor value is 40 nm (from 1543 to 1583 nm). This range is limited by the characteristics of the EA modulator used. By shifting the center wavelength to 1550 nm, we can cover the entire C-band. The main specifications are summarized in **Table 1**.

4. Impact of OSNR on Q_t

Figure 4 shows the relationship between Q_t and Q for 10-Gbit/s NRZ (non-return to zero) optical sig-

*2 Opto-electrical (OE) sampling: a technique in which an optical signal is sampled (gated) with electrical pulses.

*3 Electro-absorption (EA) modulator: an optical device in which the optical absorption coefficient is changed by inducing an electric field. The optical signal launched into the device is modulated by using an electrical signal and changing the optical absorption coefficient.

Table 1. Measured values of main parameters.

Parameters	Measured values
Sampling rate	≦1 GHz
Time resolution	≦8 ps
Signal bit rate	≦43 Gbit/s
Wavelength range	≧40 nm (1543 – 1583 nm)
Available input power	–5.0 to +5.0 dBm
Polarization dependence	<1.0 dB

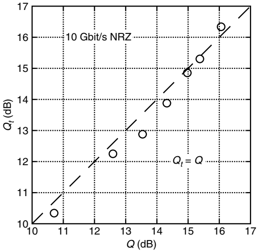

Fig. 4. Relationship between a fixed timing Q-factor (Q_t) and a Q-factor calculated from BER (Q) for 10-Gbit/s NRZ signals.

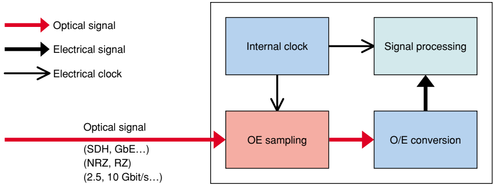

Fig. 3. Block diagram of optical signal quality monitoring circuit.

nals at different signal OSNR values. The OSNR is defined as the ratio between the optical signal power and optical noise. The OSNR value is changed by adding amplified spontaneous emission (ASE) noise to the optical signal. Parameter Q_t is obtained by using the procedure described in the previous section, and parameter Q is derived from the measured BER using the Gaussian assumption. We set t to the time where the eye was most widely opened. Good relationships are recognized in the figure, and the slope of the relationship equals 1. Note that the values of Q_t basically equal those of Q. This means that it is possible to obtain the BER value directly if we estimate Q_t. For instance, when the measured Q_t value is 16.4 dB for a 10-Gbit/s optical signal, the BER of the signal is recognized to be 10^{-10}. The important feature of the technique is that the slope of the relationship between Q_t and Q when the OSNR is changed does not change because Q_t is measured from the open eye-diagram. Therefore, it is useful to estimate the absolute value of the Q-factor, which is directly related to the BER.

5. Q_{avg} monitoring and impact of OSNR on Q_{avg}

Here, we propose the average Q-factor (Q_{avg}) method. This can be used when an open eye-diagram cannot be obtained because no information regarding the signal bit rate is available and the sampling rate cannot be adjusted, when the inaccuracy of f_s and/or f_c is large, or when it is difficult to perform high-speed sampling. In these cases, it is impossible to obtain an open eye-diagram, so we must evaluate an asynchronous eye-diagram, which is a timing drifted eye-diagram. We proposed an algorithm for evaluating Q_{avg} from an asynchronous eye-diagram [3]. **Figure 5** shows an asynchronous eye-diagram obtained by asynchronous sampling. Parameter Q_{avg} is evaluated using asynchronous amplitude histograms in which unwanted cross-point data is included. It is defined by

$$Q_{avg} = |\mu_{1,avg} - \mu_{0,avg}| / (\sigma_{1,avg} + \sigma_{0,avg}), \tag{7}$$

where $\mu_{i,avg}$ and $\sigma_{i,avg}$ are the mean and standard deviation, respectively, of the mark (i = 1) and space (i = 0) level distributions. The asynchronous eye-diagram includes unwanted cross-point data, which decreases the measured value of Q_{avg}. Thus, it is necessary to remove the cross-point data. In this way, we set two threshold levels: $\mu_{th1} = \mu_1 - \alpha\mu$ and $\mu_{th0} = \mu_0 + \alpha\mu$, where $\mu = |\mu_{1,avg} - \mu_{0,avg}|$ and coefficient α is defined to lie between 0 and 0.5 [3]. **Figure 6** shows the relationship between Q_{avg} and Q for 10-Gbit/s NRZ optical signals at different signal OSNR values. The relationship is good although the slope is not 1 and it is necessary to use a correction factor for evaluating the BER. Since the influence of the cross-point data still

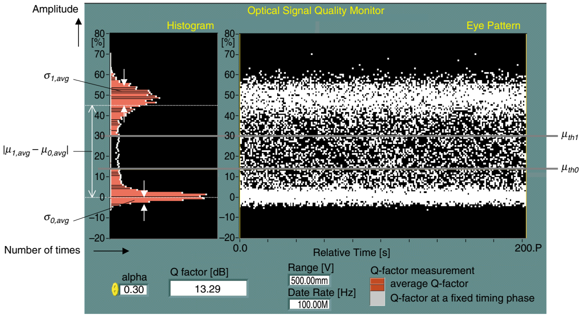

Fig. 5. Asynchronous (drifted) eye-diagram captured by asynchronous sampling and asynchronous amplitude histograms (N_{samp} = 8000, f_s =10 Gbit/s, $f_c \approx$ 100 MHz, n/m ≈ 1/10).

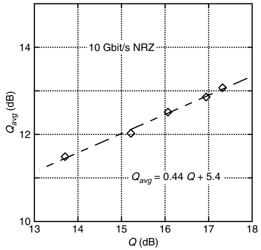

Fig. 6. Relationship between an average Q-factor (Q_{avg}) and a Q-factor calculated from BER (Q) for 10-Gbit/s NRZ signals.

remains, the slope of this relationship changes with the optical band-pass filter bandwidth or other parameters in the signal quality monitoring circuit [3]. In this case, the relationship should be measured in advance and the correction factor should be determined to obtain the BER value.

6. Conclusion

Using a new procedure for evaluating the fixed timing Q-factor (Q_t), we have devised a simple method of monitoring the Q-factor using open eye-diagrams captured by high-speed asynchronous OE sampling. We designed a signal quality monitoring circuit and experimentally confirmed its ability to estimate the BER for 10-Gbit/s NRZ signals. We also showed that the circuit offers two modes: Q_t and average Q-factor Q_{avg} evaluation. This technique and circuit will form a powerful solution for satisfying the performance monitoring requirements of future optical networks.

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Ippei Shake

Research Engineer, Advanced Photonic Transmission Research Group, Photonic Transport Network Laboratory, NTT Network Innovation Laboratories.

He received the B.S. and M.S. degrees in physics from Kyoto University, Kyoto in 1994 and 1996, respectively. In 1996 he joined NTT Optical Network System Laboratories, Yokosuka, Japan. Since then he has been engaged in R&D of high-speed optical signal processing and high-speed optical transmission systems. His research interests also include optical networks and optical performance monitoring. He is a member of IEEE and the Institute of Electronics, Information and Communication Engineers (IEICE) of Japan.

Hidehiko Takara

Senior Research Engineer, Advanced Photonic Transmission Research Group, Photonic Transport Network Laboratory, NTT Network Innovation Laboratories.

He received the B.S., M.E., and Ph.D. degrees in electrical engineering from Keio University, Kanagawa in 1986, 1988, and 1997, respectively. In 1988, he joined NTT Transmission Systems Laboratories, Kanagawa, Japan. Since then, he has been engaged in research on ultrahigh-speed/large-capacity optical transmission systems and optical measurement techniques. He is a member of IEEE and IEICE. He received a paper award from IEICE in 1993 and was awarded the Kenjiro Sakurai Memorial Prize from OEIDA in 1996 and the Electronics Letters Premium from the IEE in 1997.

Satoki Kawanishi

Senior Research Engineer, Advanced Photonic Transmission Research Group, Photonic Transport Network Laboratory, NTT Network Innovation Laboratories.

He received the B.E., M.E., and Ph.D. degrees in electronic engineering from the University of Tokyo, Tokyo in 1981, 1983, and 1993, respectively. In 1983 he joined the Yokosuka Electrical Communication Laboratory, Nippon Telegraph and Telephone Public Corporation (now NTT), Kanagawa, Japan, where he has been engaged in R&D of high-speed optical transmission systems and optical signal processing using photonic crystal fiber. He is a member of the Optical Society of America, IEEE, IEICE, and the Japan Society of Applied Physics. He received Paper Awards from IEICE in 1993 and1995 and an achievement award from IEICE and the Sakurai memorial award in 1996.