An OSNR Monitor for Optical Packet Switched Networks

Xingwen Yi, Wei Chen, and William Shieh

***Abstract*—Optical packet switched networks bring about new challenges to the research in optical performance monitoring. We present the first experimental demonstration of an optical signal-to-noise ratio (OSNR) monitor capable of direct OSNR monitoring on the packet basis. By measuring the radio frequency noise from optical packets with a special performance monitoring segment, the OSNR monitoring error is found to be less than 0.6 dB for consecutive packets with varying OSNR of 16 to 27 dB. The response time of the OSNR monitor can be around 10 ns.**

***Index Terms*—Optical packet switched network (OPSN), optical performance monitoring, optical signal-to-noise ratio (OSNR).**

I. Introduction

MANY FUNCTIONS of current and future optical networks rely on optical performance monitoring of various optical parameters, including channel power, wavelength, dispersion, and the optical signal-to-noise ratio (OSNR). Hence, optical performance monitoring has drawn tremendous research interest in recent years [1]. On the other hand, optical packet switched networks (OPSN) have been proposed as an effective way to support data-centric internet networks [2]. However, the concept of OPSN creates a host of new challenges in terms of efficient network monitoring and maintenance. Optical performance monitoring for OPSN adds a new dimension to the research topics of performance monitoring. Unlike conventional optical communication networks or optical circuit switched networks, optical channels in OPSN may consist of different optical packets. They could originate from diverse sources and traverse different optical links, which therefore results in a vast dynamic range of optical parameters on the short time span of one packet. OSNR is one of the critical parameters to monitor and we will focus on OSNR monitoring in this letter. Various approaches have been proposed to monitor OSNR. The polarization-nulling method using the polarization properties of signal and amplified spontaneous emission (ASE) noise includes the optimization of a polarization controller [3] and therefore cannot be applied to performance monitoring for a packet varying at a rate on the order of nanoseconds. Another approach using uncorrelated signal-to-ASE beat noise requires precise matching of the receiver pair and may need more calibration procedures [4]. Indirect OSNR monitoring by measuring bit errors for the purpose of determining time-to-live is only sensitive around the threshold OSNR and may not provide enough of a dynamic range for general purpose network maintenance [5]. In this letter, we propose and demonstrate a novel OSNR monitor capable of direct OSNR monitoring based on radio frequency (RF) noise measurement. We find out that the measurement is repeatable and reliable on the packet basis. The OSNR monitoring error is found to be less than 0.6 dB for consecutive packets with varying OSNR of 16 to 27 dB. The response time of the OSNR monitor can be around 10 ns.

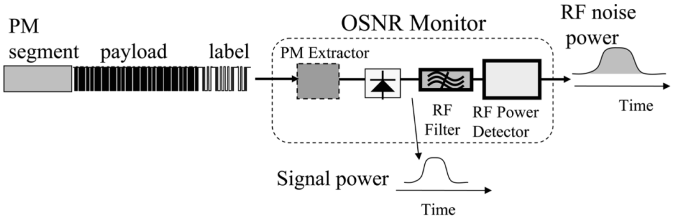

Fig. 1. Conceptual diagram of proposed OSNR monitor.

II. Principle of OSNR Monitor for Packets

Fig. 1 shows the principle of the OSNR monitor for packets. The packet capable of performance monitoring (PM) contains an additional performance monitoring segment (PM segment). In this letter, the PM segment consists of $\sim$10 ns of consecutive "1" bits at 10 Gb/s. At the packet switching node, a part of the input optical signal power is tapped and fed into the OSNR monitor. Inside the OSNR monitor, the PM segment is extracted from the entire packet by using a Mach–Zenhder modulator. The pulse after the PM extractor is fed into a photodiode. The optical signal power is tested after the photodiode. There will be RF spectral components at least in a range of 0–10 GHz for the entire packet contributed by the payload. In contrast, the RF spectral components are absent at high frequency for the extracted PM segment. Fig. 2(a) and (b) shows the measured spectra for the whole packet and extract PM segment, respectively. The OSNR can be calculated by analyzing the optical signal power and RF noise level at the high-frequency range. An RF filter is used to filter out the RF noise of the interested frequency range, as shown in Fig. 2(b). The RF noise level is then detected by an RF power detector. In practice, the optical label processing unit should recover the clock on the label and in return provide the timing information to the OSNR monitor to locate the PM segment. It is not the intention of this letter to

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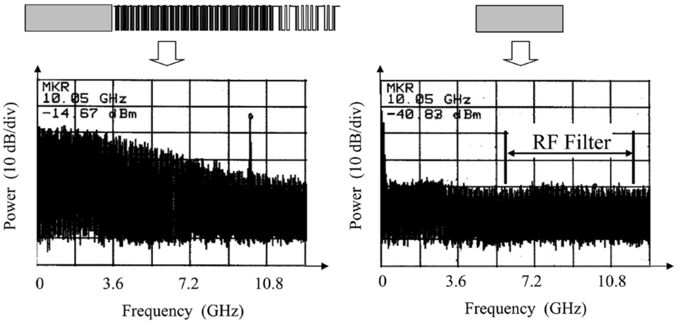

(a) (b)

Fig. 2. RF spectra for (a) whole optical packet and (b) PM segment only.

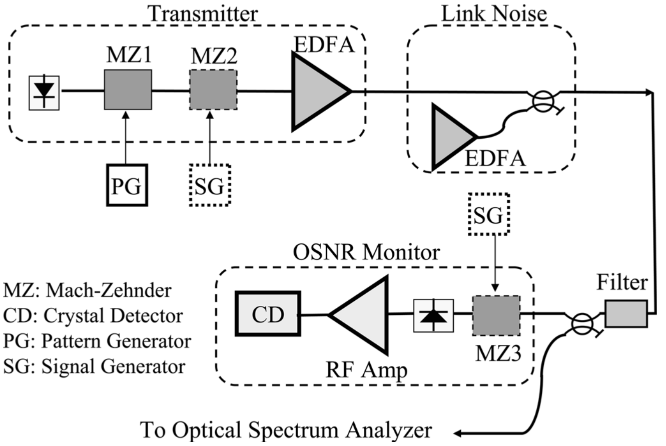

Fig. 3. Experimental setup.

demonstrate the location of the segment. In addition, the accuracy of the pulse-curving timing is quite forgiving, in the order of 1 ns, and the PM segment is only a cw signal.

The OSNR is formally defined as

$$\text{OSNR} = \frac{P_S}{P_{\text{ase}}} \tag{1}$$

where P_S is the optical signal power and P_{ase} is the ASE noise power measured in 0.1-nm noise bandwidth. The RF power density consists of signal-ASE beat noise, the ASE–ASE beat noise, and the relative intensity noise (RIN) noise [6]. Using the OSNR definition in (1), we write the RF power density as

$$\begin{aligned} p(f) &= A_1 \cdot P_S \cdot P_{\text{ase}} + B_1 \cdot P_{\text{ase}}^2 + C_1 \cdot P_S^2 && (2)\\ &= A_1 \frac{P_S^2}{\text{OSNR}} + B_1 \frac{P_S^2}{\text{OSNR}^2} + C_1 P_S^2 && (3) \end{aligned}$$

where $p(f)$ is the RF power density, P_S is the input optical signal power, OSNR is the optical signal-to-noise ratio defined in (1), and A_1, B_1, and C_1 are the constants related to various detection parameters. In general, the RF power density will be frequency dependent, and this effect can be lumped into A_1, B_1, and C_1 coefficients, which can be obtained empirically. Hence, the RF power P integrated in a bandwidth of Be can be expressed as

$$P = \int_{B_e} p(f) \cdot df = A \frac{P_s^2}{\text{OSNR}} + B \frac{P_s^2}{\text{OSNR}^2} + C P_s^2 \tag{4}$$

where A, B, and C coefficients are constants. There are no frequency-dependent parameters in (4); therefore, the RF power in bandwidth Be can be used to estimate the total RF power in the full signal frequency range. Equation (4) shows that the detected RF noise power P is a function of both signal power P_S and OSNR. Consequently, the OSNR can be evaluated by measuring the optical signal power P_S and RF power P using a RF power detector for the extracted PM segment.

Our proposed technique has three advantages.

1) Good immunity to the interference from the payload/label modulation—because the PM segment is serial with the regular packet and is void of the high-frequency data modulation components in the time slot of the PM segment;
2) high sensitivity—because a large chunk of noise spectrum about a few gigahertz can be integrated to provide reliable and repeatable measurements;
3) in-band ASE noise measurement—eliminates the extrapolation uncertainty using out-band approach, since the measured RF noise is right within the signal bandwidth.

The ~10 ns of time duration of the PM segment may be a large overhead for high-speed transmission and therefore may not be feasible for every packet. However, there may be a need to monitor the OSNR on the time scale of one packet duration, such as 10 ns for a 100-bit length at 10 Gb/s. Intuitively, the PM packet may be best used when an optical packet path is being set up for the incoming packets originated from diverse sources. The computation complexity after detection is moderate to solve the quadratic equation derived from (4). Therefore, the ~10-ns time duration is dependent on the response time of the Agilent crystal detector in our experiment. Thus, it is possible to choose a faster response RF power detector and further shorten the time duration.

III. EXPERIMENTAL SETUP AND RESULTS

Fig. 3 shows the experimental setup. The details of payload label are not relevant for this letter. The transmitter starts from a 1545-nm laser source and a Mach–Zehnder modulator (MZ1) at 10 Gb/s. A second modulator (MZ2) is added to generate two dissimilar packets with different power levels. An erbium-doped fiber amplifier (EDFA) follows the MZ2 and boosts the optical signal. The signal out from the transmitter is coupled with a second EDFA to simulate the link noise. The OSNR of the optical signal is varied by adjusting the bias currents of the EDFA pump lasers. The optical signal contaminated with the noise passes through a 1-nm bandwidth optical filter and split into two branches for the OSNR measurements. One branch uses an optical spectrum analyzer (OSA) as reference and the other branch has the proposed OSNR monitor. Inside the OSNR monitor, the PM segment is first extracted out by using a modulator MZ3, received by a 10-GHz bandwidth photodiode, and amplified with a 6–12-GHz bandpass RF amplifier. The output from the RF amplifier is then fed into a crystal detector (CD, Agilent 8473C) for RF power detection. The CD will output negative voltages

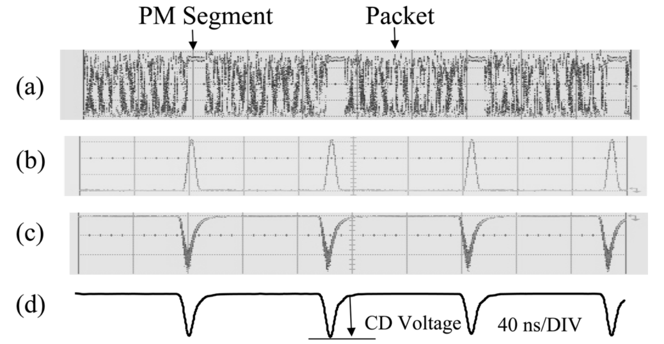

Fig. 4. Oscilloscope traces for (a) original packets, (b) extracted performance monitoring pulse, (c) output from crystal detector, and (d) smoothed output of crystal detector with 100-MHz filter.

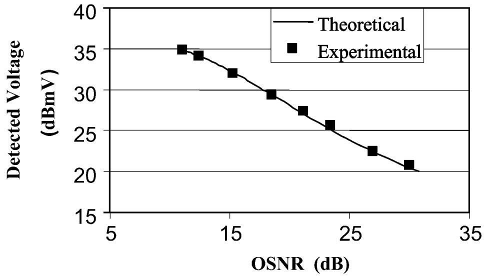

Fig. 5. Voltage output of crystal detector as function of OSNR.

corresponding to the input RF power level. A high-speed oscilloscope is used to record the traces of the packets. An Anritsu 10-Gb/s pattern generator is used to drive the MZ1, while two signal generators are used to drive the MZ2 and MZ3. The oscilloscope and the two signal generators are synchronized to the pattern generator.

We first disable the driving signal for MZ2 for one uniform packet to provide a baseline for the monitor and obtain $A, B,$ and C coefficients. The responsivity versus input optical power of the photodiode and the nonlinear response of the CD are calibrated separately in the experiment. The RF amplifier operates in the linear range because of the relatively low output from the photodiode. The optical power into the photodiode is around -15 dBm and the output voltage of CD changes from -80 to -623 mV when OSNR varies. Fig. 4(a) shows the oscilloscope trace for the transmitted packets. Fig. 4(b) shows the extracted pulse after the MZ3, and Fig. 4(c) shows the output pulse of the CD. The pulse is relatively noisy due to the leakage of the high-frequency components from its input. But after we use a 100-MHz filter, the output is smoothed as shown in Fig. 4(d). We also note the oscilloscope traces in Fig. 4 are trace measurement without averaging. The repeatable values of the CD voltages for consecutive packets in Fig. 4(d) show the reliability of the OSNR monitor.

Equation (4) shows that the measured RF power P is a second-order function of the reciprocal of OSNR. We perform a second-order fit of the CD voltage as a function of the reciprocal of OSNR. The theoretical curve fit is also shown in Fig. 5. The $A, B,$ and C coefficients in (4) are calculated through a second-order curve fit. The maximum error of the measurement data points of 10–30 dB OSNR from the curve fit is 0.6 dB.

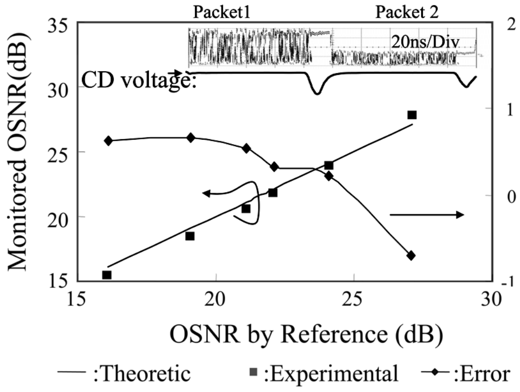

Fig. 6. OSNR monitoring for packets with different OSNR.

Finally, we use the OSNR monitor for consecutive optical packets with varying OSNR. MZ2 in Fig. 3 is driven to generate two dissimilar packets with different OSNR. The power level P_S and noise level P at the output of the CD are recorded for both packets, and (4) is used to calculate the OSNR. To obtain the reference OSNR from OSA, we measure both the optical signal powers of the two dissimilar packets and ASE noise level from OSA. Fig. 6 shows the OSNR monitoring errors as we vary the OSNR for both packets. The plot includes the data points for both packets. The inset of Fig. 6 shows the oscilloscope trace for two consecutive packets with different OSNR and CD output. The CD output pulses clearly demonstrate the real-time noise measurement. The maximum OSNR measurement error is found to be 0.6 dB. The error may come from the imperfect nonlinearity calibration for the CD, which may be reduced in our future investigation.

IV. CONCLUSION

Optical packet switched networks require an OSNR monitor with a fast response and wide dynamic range. We have demonstrated the first experimental demonstration of an OSNR monitor capable of direct OSNR monitoring on the packet basis. By measuring the RF noise from optical packets with a special performance monitoring segment, the OSNR monitoring error is found to be less than 0.6 dB for consecutive packets with varying OSNR of 16 to 27 dB. The response time of the OSNR monitor can be around 10 ns.

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