Variable bit rate limiter for on-off-keying optical links

W.S. Chan, F. Tong, L.K. Chen, C.K. Chan and D. Lam

The authors propose and demonstrate a novel variable bit rate limiter (BRL) for OOK optical transmission systems. The BRL operates on the sampling principle with an optical switch inserted anywhere between the terminals in the fibre link.

Introduction: Bandwidth segmentation subjected to various tariffs is a means to ensure full utilisation of the enormous bandwidth available on leased dark fibres. It is therefore of huge interest to the bandwidth providers to ensure that the users are not transmitting at digital data rates much higher than is allowed by their subscription fee. An all-optical device, which imposes limits on transmission data rates, i.e. a bit rate limiter (BRL), is thus needed. However, these devices must neither interfere nor tap the transmitting data in order to provide the necessary security for the users.

Two BRL schemes for OOK modulation format with operations based on interferometric principles were previously proposed [1, 2]. None of these schemes offers a variable bit rate capability, however, and their operations are restricted to low bit rates due to substantial polarisation-dependent phase-induced intensity noise. Here, we propose and demonstrate a simple yet powerful BRL scheme which is non-intrusive in nature and requires little maintenance.

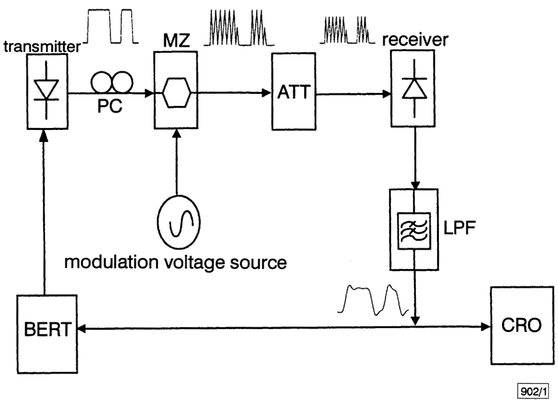

Fig. 1 *Experimental setup*

PC = polarisation controller; MZ = Mach-Zehnder switch (UTP APE MZM-1.5-8-T-1-1) with 3dB insertion loss and extinction ratio 26dB; ATT = optical attenuator; LPF = lowpass filter; CRO = oscilloscope; BERT = bit error rate tester and data pattern generator

Proposed scheme: Our proposed BRL scheme operates on the sampling principle [3], and only requires an optical switch be inserted anywhere in the optical fibre link between the end terminals of the OOK modulated fibre system. Operating asynchronously with the data, the optical switch is modulated at a switching rate f_S much faster than the data transmission rate f_D. By passing the combined signals through the receiver, the high-frequency details of the time slices can be eliminated by the lowpass filtering of the receiver, and the ONE bit appears as a full bit with negligible distortion. However, as f_S approaches f_D, the time-slice of period $1/f_S$ becomes increasingly comparable to the signal period $1/f_D$. This can cause the voltage swing at the bit decision time below the threshold value for the ONE bit, resulting in an increase in bit error rate and even a BER floor. The switch, however, causes no effect on the ZERO bits. An expected 3dB penalty is incurred by the optical power loss at the optical switch. To change the bit rate limit, we can simply alter f_S applied to the switch.

Experiments: The experimental setup is shown in Fig. 1. The optical switch used in the experiment was a Mach Zehnder switch with an insertion loss of 2.8dB and an extinction ratio of 26dB. Fig. 2*a–d* shows the oscilloscope traces of the received transmitted data waveforms before and after filtering, for a lowpass filter bandwidth of 155MHz, f_D = 100Mbit/s, and f_S = 100MHz and 400MHz. For $f_D = f_S$ (Fig. 2*a*), the sinusoidal time slices are clearly visible and only the envelope of the bit pattern can be recognised. The small spike is due to the phase difference between the data and the modulation wave. Substantial distortion can be observed after filtering (Fig. 2*c*). Fig. 2*b* shows the case for $f_S > f_D$. The details of the time-slices in the ONE bit are eliminated by the limited filter bandwidth, and the bit pattern can be reconstructed (Fig. 2*d*).

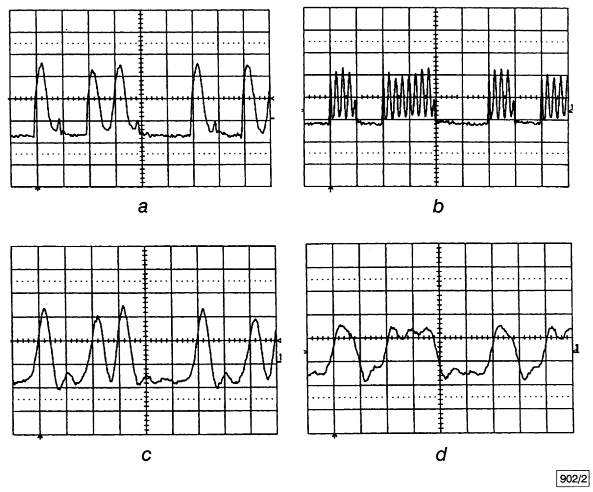

Fig. 2 *Received oscilloscope waveform traces for data rate f_D = 100 Mbit/s, and different switching rates f_S*

a f_S = 100MHz (before filtering)
b f_S = 400MHz (before filtering)
c f_S = 100MHz (after filtering)
d f_S = 400MHz (after filtering)
An RF-filter with 3dB bandwidth of 155MHz was used after the photodetector in the experiments. Horizontal and vertical scales for all graphs are 10ns/div and 50mV/div, respectively. Data bit pattern is 0101100101

Bit error rate measurements were performed using a 2^{10}–1 NRZ PRBS data modulated at 600Mbit/s. The transmitter used was a DFB laser under direct modulation, and the switch was modulated with a sinusoid at a frequency starting from f_S = 2GHz and was reduced to 550MHz. As f_S approaches f_D, a steep rise in power penalty (at $BER = 10^{-9}$) is observed (shown as dots in Fig. 3). Using a 1dB power penalty as a criterion, the suitable bit rate limit f_D/f_S is found to be ~0.75. Various data rates ranging from 200Mbit/s to 718Mbit/s were also tested at a fixed f_S = 800MHz. Fig. 4 plots the power penalty ($BER = 10^{-9}$) against f_D/f_S, with f_S being fixed at 800MHz. Similar conclusions can be drawn from arguments represented in Fig. 3. Experiments on other switching frequencies were also performed, and similar results and conclusions were obtained.

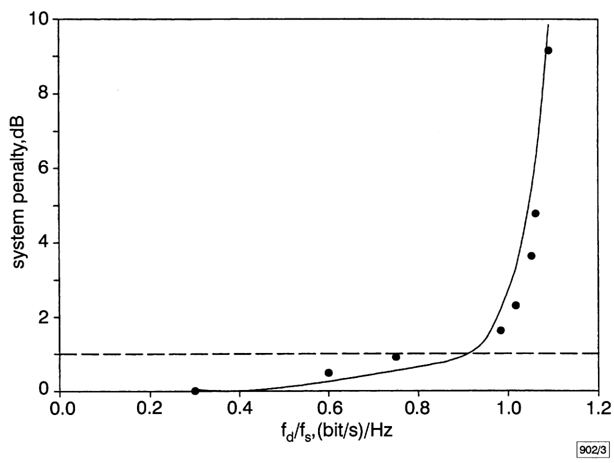

Fig. 3 *System penalty against f_D/f_S, showing both experimental and theoretical results*

Data rate used was 600 Mbit/s (2^{10}–1 PBRS, NRZ) and 3dB bandwidth of RF filter was 455MHz
● experimental
——— theoretical

Simulations: Our simulation model is derived from the basic bit error rate theory with modifications to include the bit slicing, and the inter-symbol interference arising from the bit pattern. In our model, the modulation $g(t)$ is embedded in the input signal of long strings (10^4) of randomly generated bit sequence (2^{10}–1 NRZ PRBS) given by $g(t) = 1+\sin[0.5\pi \sin(2\omega f_s t+\phi)]$, with ϕ being the initial phase that is randomly generated for each run. The arrived signals at the receiver can thus be written as $S(t) = k[S_o(t)g(t)]*h(t)$, where k is a constant factor derived from fibre attenuation, coupling loss, responsivity etc., $h(t)$ is the transfer function of the low pass filter, and $S_o(t)$ is the input signal. The amplitudes of received signals are then sampled and grouped into a_{11}, a_{12}, a_{13}, ... for the ONE bits and a_{01}, a_{02}, a_{03}, ... for the ZERO bits. A histogram of N bins can then be constructed for the received ONE bits, with D_{1M} and A_{1M} represent the occurrence frequency and the mean value of the mth bin, respectively. Similarly, a histogram for the ZERO bits can also be obtained.

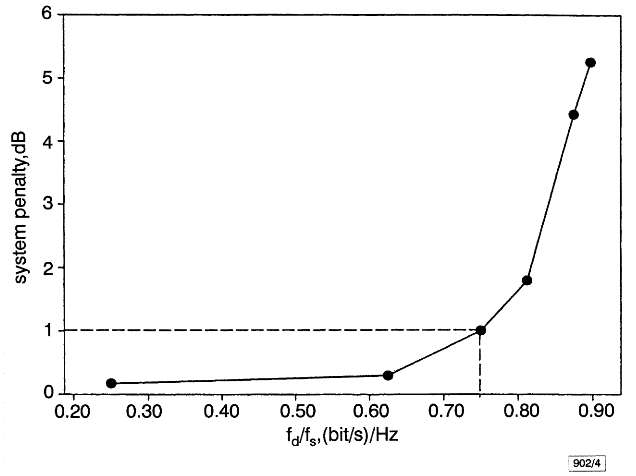

Fig. 4 *System penalty against f_D/f_S, f_S being fixed at 800 MHz while f_D was varied from 200 to 718 Mbit/s (2^{10}–1 PBRS, NRZ)*

3dB bandwidth of RF filter used is 455 MHz
● experimental
——— theoretical

We can then write the probability of error for the ONE bit, P_{E1}, and the ZERO bit, P_{E0}, as

$$P_{e1} = \frac{1}{2U_1}\sum_{m=1}^{N} D_{1m}\,\mathrm{erfc}\left(\frac{A_{1m}-v_{th}}{\sigma_{1m}\sqrt{2}}\right) \qquad (1a)$$

$$P_{e0} = \frac{1}{2U_0}\sum_{m=1}^{N} D_{0m}\,\mathrm{erfc}\left(\frac{v_{th}-A_{0m}}{\sigma_{0m}\sqrt{2}}\right) \qquad (1b)$$

where $U_1 = \Sigma D_{1M}$ and $U_0 = \Sigma D_{0M}$, and vth is the decision threshold given by $2v_{TH} = <a_{0K}> + <a_{1K}>$. In these expressions, the noise variance σ_{1M} for the ONE bit is

$$\sigma_{1m} = \sqrt{\sigma_t^2 + \sigma_{s1m}^2 + \sigma_{RIN1m}^2} \qquad (2)$$

where σ_T^2 is the thermal noise, σ_{S1M}^2 is the shot noise for the ONE bits, and σ_{RIN1M}^2 is the relative intensity noise for the ONE bits. The noise variance σ_{0M} for the ZERO bits can be calculated similarly. Assuming the occurrence probability is identical for the ONE bit and the ZERO bit, the $BER = (P_{E1}+P_{E0})/2$ can be written as

$$BER = \frac{1}{4U_0}\sum_{m=1}^{N}\left[D_{1m}\,\mathrm{erfc}\left(\frac{A_{1m}-v_{th}}{\sigma_{1m}\sqrt{2}}\right) + D_{0m}\,\mathrm{erfc}\left(\frac{v_{th}-A_{0m}}{\sigma_{0m}\sqrt{2}}\right)\right] \qquad (3)$$

The system penalty derived from the simulation (the solid line) is shown in Fig. 3. The filter function used is a ninth order Butterworth lowpass filter. The results agree very well with the experimental data.

Summary: We have proposed and demonstrated a novel variable optical BRL for fibre links using OOK modulation format. Our BRL consists of an optical switch inserted anywhere along the fibre link. The bit rate limiting effect was demonstrated at f_D = 600 Mbit/s and similar results were obtained for other data rates. Both experiments and simulations were performed and good agreement was shown.

9 October 1997
Electronics Letters Online No: 19980122

W.S. Chan, F. Tong, L.K. Chen and C.K. Chan (*Department of Information Engineering, The Chinese University of Hong Kong, Shatin, Hong Kong*)

D. Lam (*JDS FITEL Inc., Nepean, Ontario, K2G 5W8 Canada*)

References

1 TUR, M., GOLDSTEIN, E.L., BRACKETT, C.A., MENENDEZ, R.C., and COQUIN, G.: 'An optical all-fiber bit-rate limiter'. Proc. 13th ECOC, Helsinki, 1987, pp. 385–388
2 TUR, M., GOLDSTEIN, E.L., and BRACKETT, C.A.: 'Effect of laser phase noise on a class of bit rate limiter', *Electron. Lett.*, 1988, pp. 126–128
3 NYQUIST, H.: 'Certain topics in telegraph transmission theory', *Trans. AIEE*, 1928, **47**, pp. 617–644