Impact of Extinction Ratio on Return-to-Zero Coding Gain in Optical Noise Limited Receivers

Martin Pauer and Peter J. Winzer, *Associate Member, IEEE*

***Abstract*—We experimentally confirm recent theoretical predictions, suggesting that return-to-zero (RZ) signals generated by means of a pulse carver or separate pulse source (Type I) perform better in the presence of finite data modulator extinction than RZ signals riding on a pedestal of constant optical power (Type II). As a consequence, the usually observed receiver sensitivity gain of RZ over nonreturn-to-zero is reduced (or even turned negative) for Type II RZ signals with poor data extinction. For Type I RZ signals, the RZ coding gain is largely unaffected by data modulator extinction.**

***Index Terms*—Extinction ratio, optically preamplified receiver, return-to-zero (RZ) coding.**

I. Introduction

As IS well known, the sensitivity of direct detection optical receivers can be considerably improved using return-to-zero (RZ) coding instead of nonreturn-to-zero (NRZ) coding, both for optical noise limited receivers and for thermal noise limited receivers [1], [2]. Near quantum limited performance has been reported when optimizing receiver parameters, in particular the optical filter bandwidth preceding the photodetector [3], [4]. While the effects of suboptimum optical and electrical filtering have been thoroughly investigated [4], [5], only little can be found regarding the influence of finite extinction ratios on the sensitivity gain brought by RZ coding [6], [7]. Recent analyses on that subject [8] predict a different evolution of the RZ gain as a function of extinction ratio for two different types of RZ signals, referred to as Type I and Type II RZ signals in this letter. Type I signals are generated by carving pulses out of an optical NRZ signal using a separate, sinusoidally driven RZ modulator [9], or by imprinting information on a pulse train emerging from a mode-locked laser [10]. Depending on the extinction ratio of the NRZ data modulator, the resulting waveform is characterized by a pattern of strong and weak pulses. Type II signals, on the other hand, represent RZ pulses riding on a pedestal of constant power. Such waveforms are produced either by driving a single modulator with an electrical RZ signal [11], or by using the rising and falling edges of the electrical NRZ data signal to produce optical RZ pulses [12], [13].

It is the purpose of this letter to experimentally confirm theoretical predictions [8] which indicate that modulation of a pulse source (Type I) is more robust to finite modulator extinction ratios than single-step RZ generation (Type II).

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M. Pauer is with the Institut für Nachrichtentechnik und Hochfrequenztechnik, Technische Universität Wien, Wien A-1040, Austria (e-mail: mpauer@nt.tuwien.ac.at).
P. J. Winzer is with Bell Labs, Lucent Technologies, Holmdel, NJ 07733 USA.
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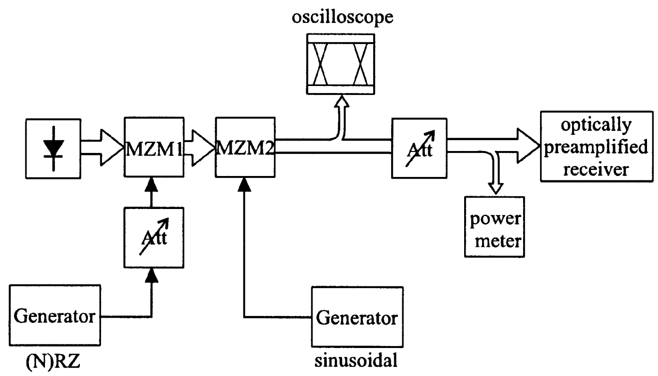

Fig. 1. Laboratory setup of transmitter and receiver.

II. Experimental Setup

As shown in Fig. 1, light from a distributed feedback laser operating at 1550 nm was first modulated by means of a single-drive $LiNbO_3$ Mach–Zehnder modulator (MZM1). In the case of pulse carving (Type I), MZM1 was fed by an NRZ signal, and RZ pulses with a duty cycle of about 38% were generated by sinusoidally driving a second $LiNbO_3$ Mach–Zehnder modulator (MZM2) at the clock frequency of the 2.5-Gb/s data signal. Leaving MZM2 unmodulated and driving MZM1 with electrical RZ signals of 50% and 25% duty cycle, respectively, we obtained Type II RZ signals. By adjusting bias and drive voltage to MZM1, we could continuously tune the extinction ratio of the RZ and NRZ output signals.

At the receiver, an optical attenuator in combination with a power meter was used to set the receiver input power. The optically preamplified receiver consisted of a low noise erbium-doped fiber amplifier (noise figure $F = 3.3$ dB, gain $G = 38$ dB). To reduce the impact of amplified spontaneous emission (ASE) beat noise, we employed a fiber Bragg grating (3-dB bandwidth $B_o = 125$ GHz) in combination with a circulator. A broad-band photodiode was used for optoelectronic conversion. Using a low-noise electrical preamplifier, we arrived at an overall optoelectronic conversion gain of 1370 V/W. The overall electrical transfer function of the receiver had fifth-order Bessel lowpass characteristics, with a 3-dB bandwidth of 1.5 GHz, which is about optimum for NRZ coding.

Using the histogram feature of a digital sampling oscilloscope, the extinction ratio

$$\zeta = P_1/P_0 \tag{1}$$

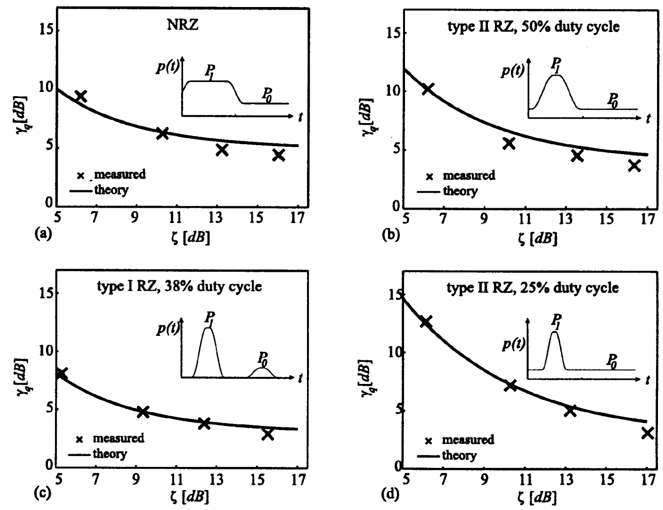

Fig. 2. Receiver sensitivity for BER $= 10^{-9}$ as a function of the extinction ratio ζ for NRZ coding and (a) different types of RZ signals. Crosses are measured points, lines are calculated using a simple Q-factor-based analysis. (b) and (d) The sensitivities of Type II RZ signals show a stronger dependence on ζ than those of (a) NRZ coding and (c) Type I RZ signals.

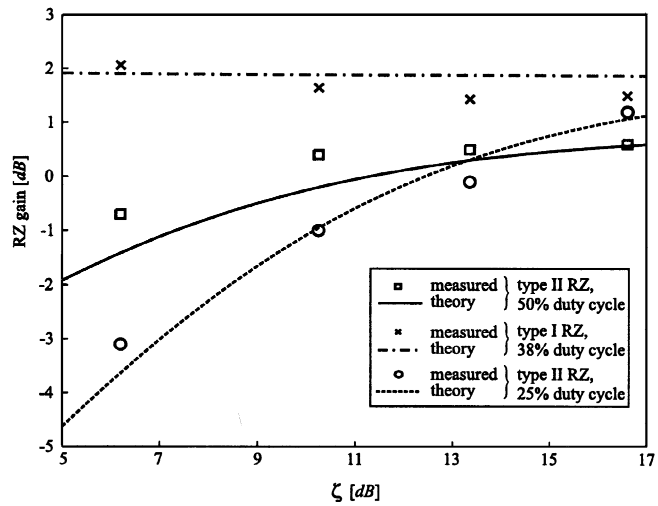

Fig. 3. RZ gain as a function of the extinction ratio ζ for two different types of RZ coding, and for different RZ duty cycles. In case of Type I RZ signals, the RZ gain is unaffected by reduced NRZ modulator extinction ratios, while for Type II RZ signals, the performance of RZ can even fall short of the NRZ performance (negative RZ coding gain).

of the incoming optical signal was measured by determining the mean "1"-bit power level P_1 and the mean "0"-bit power level P_0 in the eye diagram at times of maximum eye opening [14].

III. Measurements

Fig. 2 shows, as a function of the extinction ratio ζ, the receiver sensitivity penalty γ_q, i.e., the average input power normalized to the quantum limit of 38 photons per bit, for a bit-error ratio (BER) $= 10^{-9}$. The results for NRZ are shown in Fig. 2(a), Type I RZ is depicted in Fig. 2(c), and Type II RZ is given in Fig. 2(b) and (d). Crosses indicate measured points, whereas lines are derived using a simple theory based on evaluating the Q factor [6]

$$Q = \Delta i/(\sigma_1 + \sigma_0) \tag{2}$$

where $\Delta i = i_1 - i_0$ denotes the electrical eye opening at the sampling instant, and σ_1 and σ_0 are the noise standard deviations for a logical "1" and "0," respectively. Noise was dominated in our receiver by the signal-dependent signal–ASE beat noise and the signal-independent ASE–ASE beat noise. (This was verified experimentally by comparing the individual noise variance contributions, measured with a digital sampling scope.) The theoretical predictions in Fig. 2 use the conventional approximations to the beat noise terms [15], slightly modified to take into account the influence of the electrical filter on the filtered RZ pulse amplitudes [16]. The sensitivity penalty for a given duty cycle d and extinction ratio ζ was then obtained by solving (2) for $Q = 6$. Slight quantitative differences between measurement and theoretical prediction are partly attributed to the simple, Q-factor-based analysis, and partly to difficulties in experimentally determining ζ, as internal offsets within the oscilloscope can have a significant impact [17]. (To improve the accuracy of our extinction ratio measurements, we calibrated the dynamic responsivity of the sampling oscilloscope, from dc to the gigahertz range, by measuring its response to a constant power as well as to sinusoidally modulated optical power waveforms of equal average power.)

Note from Fig. 2(b) and (d) that the sensitivities of Type II RZ signals show a significantly stronger dependence on ζ than those of NRZ coding [Fig. 2(a)] and Type I RZ signals [Fig. 2(c)], indicating the different behavior of the two types of RZ coding. Evaluating the RZ coding gain (the ratio of receiver sensitivities for NRZ and RZ signals), our results reveal a marked qualitative difference between the two types of RZ signals. Fig. 3 shows our measurements (squares, crosses, and circles) together with the theoretical predictions (lines). For RZ coding of Type II, both measurement and theory show that the RZ gain drops considerably as ζ decreases. The requirements on ζ are more severe the lower a duty cycle is employed. Initially, RZ coding with 25% duty cycle yields a higher RZ gain than RZ coding with a duty cycle of 50%, but its sensitivity degrades faster as ζ is decreased. The two curves intersect at about $\zeta = 13$ dB, which is also supported by our measurement results. Note that negative RZ gains are possible for Type II RZ signals, meaning that NRZ can outperform RZ for poor modulator extinction. In contrast, the RZ gain achieved by Type I signals is insensitive to changes in ζ. Type I RZ signals maintain their coding gain over NRZ signals, independent of NRZ modulator extinction. (The independence of the RZ coding gain on extinction ratio does, of course, *not* mean that the absolute receiver sensitivity is unaffected by reduced modulator extinction. It just means that NRZ and RZ degrade by the same amount.) The constant nature of the calculated RZ gain over ζ is due to our simple theoretical model; more accurate simulations show a reduction of the RZ gain by a few tenths of a decibel with poor extinction ratio, depending on the NRZ pulse shape [8].

IV. Discussion

The reason for the different behavior of Type I and Type II RZ signals is twofold, and is quantitatively detailed in [8]. First, in case of a finite extinction ratio, the relation between peak and average optical power differs for the two modulation types. Both types of RZ signals require the same *peak* power to obtain identical eye openings, which implies a larger *average* optical power requirement for Type II signals than for Type I signals, since more energy is contained in the pedestals of Type II signals than in the residual "0"-bit pulses of Type I signals. The difference in the ratio of average power to peak power between the two signal types grows as ζ or duty cycle are reduced.

Second, and for *optical* noise limited detection only (as in an optically preamplified receiver), finite extinction ratios lead to higher beat noise between signal and ASE in the "0"-bits. Once this signal-dependent noise source is on the order of or larger than the signal-independent noise terms, it increases the overall detection noise and degrades receiver performance in addition to degradations brought by the reduced eye aperture [7], [8]. Since it is the electrically filtered signal that determines the amount of beat noise, the "0"-bit beat noise is less significant for Type I signals, where the residual "0"-bit pulses are attenuated due to band-limiting optoelectronics. The constant "0"-bit power level for Type II signals, on the other hand, does not experience this bandlimiting effect, leading to higher "0"-bit beat noise. Thus, Type II signals suffer more severely from enhanced "0"-bit beat noise at a given extinction ratio than Type I signals.

V. Conclusion

Our measurements have confirmed earlier theoretical predictions, suggesting that RZ signals generated by means of a pulse carver or pulse source (Type I) perform better in the presence of finite data modulator extinction ratios than RZ signals riding on a pedestal of constant optical power (Type II). As a consequence, the usually observed RZ coding gain is reduced (or even turned into a coding *loss*) for Type II signals with poor data extinction. For Type I signals, the RZ coding gain is largely unaffected by data modulator extinction.

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