Receiver Sensitivity Improvement by Impulsive Coding

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***Abstract*—We show that optical receivers operated impulsively are more sensitive than for nonreturn-to-zero (NRZ) operation. Impulsive sensitivity improvements of 5.8 and 4.7 dB are measured for two pin-FET receivers using a modelocked laser transmitter, and compared to theoretical expressions for the NRZ and impulsive Q-factors. We also show that the optimum detection bandwidth for impulsive coding is larger than for NRZ, in contrast to previous models.**

***Index Terms*—Optical communication, optical receivers, ultrafast lasers.**

NONRETURN-TO-ZERO (NRZ) coding, in which optical pulses occupy a full bit period, is the most widely used format in optical fiber communication. It was recognized long ago by Personick, however, that for a given energy per pulse, the performance of a receiver improves when pulses with a duration much shorter than the bit period are used [1]. Interestingly enough, this impulsive receiver sensitivity improvement has never been verified experimentally. Furthermore, the standard theory of receiver sensitivity [1], [2] is not well-suited for the comparison of impulsive and NRZ coding for specific receivers because it constrains the receiver output to a fixed shape (usually a raised-cosine) for all input pulses. This implies the use of pulse-shape dependent equalization networks at the output of the receiver front-end, which is not applicable in general.

In this letter, we show that "impulsive coding" indeed results in improved sensitivities compared to NRZ coding. We also derive the correct expressions for the Q-factors corresponding to NRZ and impulsive coding for a fixed transimpedance receiver front-end. We report impulsive and NRZ sensitivity measurements for two pin-FET receivers and show that they are in good agreement with our theoretical predictions. We further show that the optimum detection bandwidth for impulsive operation is larger than the NRZ one, in contrast to what is suggested by the Personick theory.

The origin of the improved sensitivity for impulsive coding can be qualitatively understood from the transimpedance receiver equivalent circuit of Fig. 1. The response to an impulsive signal is schematically shown on the left of Fig. 1(b). The capacitance C is charged very quickly in this case, with the rise time only limited by the bandwidth of the amplifier gain, and then decays with the RC time constant. For NRZ signals, on the other hand, both rise and fall times are limited by the RC time constant [right-hand side of Fig. 1(b)]. The voltage swing is smaller in this case, since the charge leaks away continuously while the capacitor is charged by the photocurrent. Because the receiver noise is independent on pulse shape, the eye-opening must therefore be larger for impulsive operation. In the following, we perform a quantitative analysis of the NRZ and impulsive Q-factors for the equivalent circuit of Fig. 1 whose transfer function is found in [4]. We denote by $f_{1/2}$ the receiver bandwidth, by B the bit rate, and by $x \equiv f_{1/2}/B$ the receiver bandwidth normalized to the bit rate. $f_{1/2}$ can be reduced below the front-end bandwidth by using a low-pass output filter without changing the receiver low-frequency transimpedance.

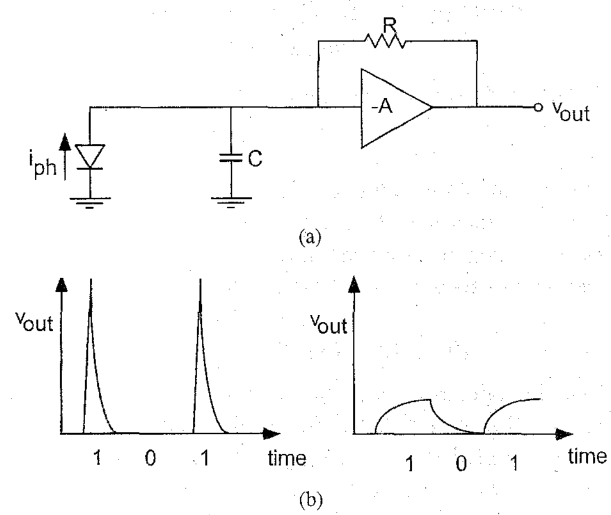

Fig. 1. (a) Equivalent circuit model of a pin-FET transimpedance receiver. R is the feedback resistor, C includes the input capacitance of the FET amplifier, the output capacitance of the photodiode and a contribution from the shunt capacitance across the feedback resistor. (b) Schematic response of this circuit to impulsive and NRZ bit streams.

Consider the receiver response to a random bit stream, and denote by S_1 and S_0 the minimum and maximum output voltage levels for a "mark" (pulse in the bit slot) and for a "space" (no pulse in the bit slot), respectively. For NRZ coding, we find the receiver output voltage swing $S_1 - S_0 = 2\bar{i}RF_{\text{NRZ}}(x)$, where R is the receiver low frequency transimpedance (i.e., the feedback resistor) and $\bar{i}$ is the average photocurrent (the factor 2 reflects the assumption that, in a long bit stream, as many marks and spaces occur). $F_{\text{NRZ}} \in [0, 1]$ is the bandwidth-dependent inter-symbol interference

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(ISI) penalty ($F_{\rm NRZ} = 1$ for negligible ISI and $F_{\rm NRZ} = 0$ for maximum penalty). A closed-form expression for this factor is found when the feedback amplifier has infinite bandwidth, in which case the front-end impulse function is $h(t) \cong -[R\theta(t)/\tau] \cdot \exp(-t/\tau)$, with $\tau = \sqrt{3}/(2\pi f_{1/2})$, and with $\theta(t)$ being the step function. S_1 and S_0 are then obtained from the response to the words "$\cdots$ 00100 $\cdots$" and "$\cdots$ 11011 $\cdots$," respectively, leading to $F_{\rm NRZ}(x) = 1 - 2\exp(-2\pi x/\sqrt{3})$, for x well above 0.19. This expression provides a good approximation to $F_{\rm NRZ}$ even when the feedback amplifier has a finite bandwidth.

For impulsive coding, we find instead $S_1 - S_0 = \gamma(2\bar{i}R)xF_{\rm imp}(x)$, where the constant γ depends weakly on the ratio of the feedback amplifier and of the receiver bandwidths, and is about $1.2\pi/\sqrt{3}$ when this ratio is close to unity. $F_{\rm imp}$ is the impulsive ISI penalty with the expression $F_{\rm imp}(x) = F_{\rm NRZ}(x)/[1-\exp(-2\pi x/\sqrt{3})]$ obtained when the feedback amplifier has infinite bandwidth. This expression is used as an approximation to $F_{\rm imp}$ for finite feedback amplifier bandwidths. Note that the ISI penalty is larger for NRZ because, in this case, inter-symbol interference reduces the eye opening from the upper and lower rails simultaneously. The most important feature of the impulsive signal is its extra linear dependence on x compared to NRZ. This factor arises because the receiver response to a δ-function pulse is $qh(t)$, where q is the number of carriers created in the photodiode. $h(t)$ scales like $f_{1/2}$ and, for an impulsive bit stream, $q = 2\bar{i}/B$, leading to the additional x dependence.

Detection noise in optical communication links can be attributed almost entirely to the receiver and is independent of the signal level [1], [2]. We, therefore, find for the root-mean-square (rms) voltage fluctuations for "mark" and "space," $\sigma_1 = \sigma_0 = \sqrt{\int df\, S(f)}$, where $S(f)$ is the noise power spectral density of the receiver output. This function has the general form $S(f) = (a + bf^2)|H(f)|^2$, where $H(f)$ is the receiver transfer function, and where the constants a and b arise mostly from thermal noise of the feedback resistor and of the FET channel conductance respectively [1]–[4]. Although recent progress in GaAs MESFET technology has reduced the importance of feedback resistor noise in transimpedance receivers, it is still a significant source of noise for most pin-FET receivers currently available commercially [5]. Integrating the noise power spectrum, we find $\sigma_1 = \sigma_0 \propto \sqrt{af_{1/2} + \alpha b f_{1/2}^3/3}$, where α is close to unity when the transfer function is flat and has a sharp rolloff. In the following, we take $\alpha = 1$. Our final expression for the Q-factors as a function of normalized receiver bandwidth is therefore:

$$Q_{\rm NRZ} = \frac{Q_0}{\sqrt{3x_c^2 x + x^3}} F_{\rm NRZ}(x)$$
$$Q_{\rm imp} = \frac{Q_0 \gamma x}{\sqrt{3x_c^2 x + x^3}} F_{\rm imp}(x) \qquad (1)$$

where $x_c \equiv (\sqrt{a/b})/B$ is the receiver noise corner frequency normalized to the bit rate [2], and Q_0 is a constant depending on the front-end, on the bit rate and on the average photocurrent. These expressions can now be used to find the best receiver bandwidth x for each mode of operation, as well as to accurately predict the impulsive sensitivity improvement of any receiver.

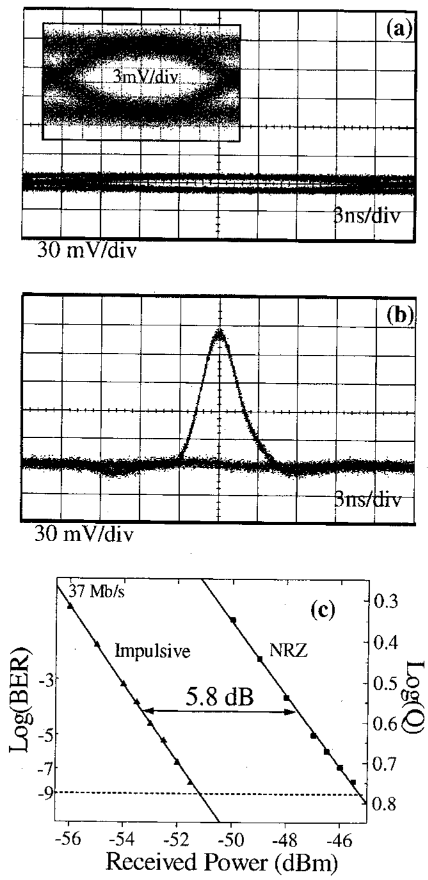

Fig. 2. Eye diagrams for the QDFB-100 front-end at a −45.5-dBm power level. (a) NRZ signaling with a 22-MHz low-pass output filter. The inset shows the same eye diagram with a 10× magnification, (b) impulsive signaling with a 300-MHz low-pass output filter, and (c) BER curves for the same front-end and the same output filters as in (a) and (b). The bit rate in all cases is 37 Mb/s.

It is often assumed that the optimum NRZ detection bandwidth is about 58% of the bit rate. This value is the 3-dB bandwidth of the receiver converting a rectangular NRZ input pulse into an output raised-cosine pulse [3]. Our model shows, however, that the optimum NRZ bandwidth depends on the value of $\sqrt{a/b}$, which controls the frequency dependence of the noise. Using our analytic approximation for $F_{\rm NRZ}$, we find the optimum $Q_{\rm NRZ}$ for x between 0.37 and 0.68 when x_c varies between 0 and ∞, respectively. A similar analysis of $Q_{\rm imp}$ gives an optimum impulsive eye opening when $x = 0.52$ if $x_c \cong 0$, and $x = \sqrt{3}x_c$ in the limit where $x_c \to \infty$. The best receiver bandwidth for impulsive coding is therefore wider than for NRZ coding. This finding is contrary to the conventional wisdom based on the Personick theory which suggest the opposite result [3]. Note, however, that the Personick theory compares *different* receiver circuits for NRZ and impulsive operation, whereas our treatment describes the behavior of the same receiver for both types of coding.

The validity of our model is tested with two pin-FET receivers: 1) an Optical Communication Product STZ-01 with a bandwidth of 87 MHz and 2) a Lasertron QDFB-100 with a bandwidth of 140 MHz. A modelocked erbium-doped fiber ring laser [6] with a repetition rate $B = 36.7$ MHz and a 1.5

TABLE I
COMPARISON OF MEASURED IMPULSIVE SENSITIVITY IMPROVEMENTS AT 37 Mb/s WITH THE PREDICTIONS OF (1)

Front-end	Coding	Output Filter Bandwidth (MHz)	Detection Bandwidth Normalized to Bit Rate (x)	ISI Penalty (F)	Measured Sensitivity (dBm)	Measured Improvement (dB)	Predicted Improvement (dB)
STZ-01	NRZ	22	0.6	0.77	-44.8	4.7	4.2
	Impulsive	300	2.4	1	-49.5		
QDFB-100	NRZ	22	0.6	0.77	-45.4	5.8	5.4
	Impulsive	300	3.8	1	-51.2		

The ISI penalty factors are derived from the approximate analytic expressions introduced in the text. When the low-pass 300-MHz filter is used, the detection bandwidth equals the front-end bandwidth (87 MHz for STZ-01 and 140 MHz for QDFB-100). x_c in (1) is 1.55 for STZ-01 and 3.05 for QDFB-100.

nm FWHM filter centered at 1.56 μm are used to produce pulses with a duration on the order of 2.5 ps. These pulses are about a thousand times shorter than the response time of our receivers. Data are externally encoded on the modelocked pulse stream with an electroabsorption modulator [7] driven with an NRZ signal synchronized to the laser repetition rate. NRZ sensitivities, on the other hand, are measured using a distributed-feedback laser at 1.56 μm incorporating an electroabsorption modulator for data encoding [8]. For both impulsive and NRZ operation, output low-pass filters are used before detection to optimize the sensitivities. The difference in impulsive and NRZ signal levels is apparent in Fig. 2, which shows eye diagrams for identical received power levels for the Lasertron front-end. Bit-error-rate (BER) curves for impulsive and NRZ coding for this receiver are also displayed and show a 5.8-dB impulsive sensitivity improvement. Table I summarizes our measurements for both receivers, and compares experimentally observed sensitivity improvements with the ones calculated using our model. The agreement between these values is very good and is further improved if the ISI penalties are evaluated numerically using the exact receiver transfer function. The parameters of the model were obtained by fitting the impulse function of both front-ends as well as the magnitude of their transfer function and their noise spectra. The noise corner frequencies, in particular, were found to be $\sqrt{a/b} \cong 57$ MHz for the STZ-01 and $\sqrt{a/b} \cong 112$ MHz for the QDFB-100. Our model predicts maximum impulsive eye opening for both front-ends when negligible post-filtering is performed, in agreement with our experimental results.

The two receivers considered here clearly have excess bandwidth for NRZ operation at 37 Mb/s. However, we can predict the impulsive sensitivity improvement from expressions (1) for a typical communications receiver designed for NRZ. Such a receiver usually has a bandwidth equal to about 80% of the bit rate to allow for component variation and aging. Assuming a noise corner frequency equal to 75% of this bandwidth and $\gamma \cong 1.2\pi/\sqrt{3}$, as for the receivers tested in our experiment, we find that such a receiver would show a 2.5-dB sensitivity improvement under impulsive coding.

In conclusion, we observe large sensitivity improvements (5.8 and 4.7 dB) for two pin-FET receivers operated impulsively at 37 Mb/s. These measurements are well described by (1). Our derivation of the impulsive and NRZ Q-factors shows that the optimum impulsive detection bandwidth is wider than the NRZ one. Impulsive coding can be realized in communication links by using modelocked lasers as transmitters. Spectral slicing of femtosecond lasers, for example, can be used in fiber access networks to provide short pulse excitations to many wavelength channels, thus distributing the cost of the source over many users [9]. For longer propagation distances, dispersive pulse broadening can be managed and compensated before detection using appropriate fiber dispersion maps and dispersive elements like chirped fiber gratings to preserve the impulsive sensitivity improvement. Semiconductor lasers are not generally suitable for impulsive operation because of their poor "on–off" extinction ratios. We note, finally, that the concept of using short pulses excitations for receivers has also been investigated in the context of nuclear instrumentation [10] and optical interconnections [11].

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