Experimental verification of optimum filter bandwidths in direct-detection (N)RZ receivers limited by optical noise

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Introduction: Performance optimization of direct-detection receivers in the presence of optical noise (e.g. optically preamplified receiver) is of major interest for the design of high speed communication networks. Sensitive receivers reduce transmitter or mid-span amplifier requirements, extend link distances, and provide additional margins. For the emerging class of free-space communication systems, where no in-line amplification is possible, sensitive receivers are the key to maximize the link distance for given, technologically limited, transmit powers.

Simulations using advanced Gaussian noise statistics [1] have revealed optimum combinations of optical and electrical receiver bandwidths for both NRZ (non-return-to-zero) and RZ (return-to-zero) coding. In this paper we present measurements performed at a data rate of $10Gb/s$ to experimentally verify these theoretical results. In the case of RZ coding we reached a sensitivity of 52 photons per bit (ppb) at a bit-error ratio $BER = 10^{-9}$, which is about $1.4dB$ above the quantum limit. To the best of our knowledge, at $10Gb/s$, this result is the best previously reported sensitivity for optically preamplified on-off-keying (OOK).

Experimental setup: The used (N)RZ transmitter consisted of a DFB laser with an integrated electroabsorption modulator (EAM), driven by an electrical NRZ data signal (see Fig. 1). In order to achieve high extinction ratios ($> 20dB$), an additional LiNbO_3 Mach-Zehnder modulator (MZM) was used for data modulation. For RZ coding we used a second MZM for pulse carving, generating pulses with a duty cycle of 30%. At the receiver the signal was amplified by a low-noise (noise figure $F = 3.3dB$), high-gain ($G = 38dB$) erbium-doped fiber-amplifier (EDFA) introducing amplified spontaneous emission (ASE) proportional to its gain. As a consequence of the large gain, detection noise was dominated by signal-ASE (variance $\sigma^2_{s,\text{ASE}}$ after electrical filtering) and ASE-ASE ($\sigma^2_{\text{ASE,ASE}}$) beat noise [1]. All other noise terms like shot noise σ^2_{shot} and, especially, thermal noise σ^2_{th} of the detection electronics were negligible. The ratio (simulated and measured) of the dominating noise terms $\sigma^2_{s,\text{ASE}} + \sigma^2_{\text{ASE,ASE}}$ to the noise terms $\sigma^2_{\text{shot}} + \sigma^2_{\text{th}}$ before the sampling unit was $\gtrsim 50$ for the "0"-bit and $\gtrsim 500$ for the "1"-bit. To efficiently suppress the ASE-ASE beat noise, the amplified signal was filtered by a narrow-band Bragg grating of $3dB$-bandwidth B_o (insertion loss $\sim 6dB$). The $40\,GHz$-wideband photodiode performing the optoelectronic conversion was followed by a $18\,GHz$ low-noise amplifier, resulting in an overall conversion gain of $1370V/W$. Different 5^{th}-order Bessel lowpass filters were used to set the electrical bandwidth of the detection chain. For the effective 3dB-bandwidth B_e used in our calculations, we took the $13.5\,GHz$ lowpass characteristic of the bit-error ratio tester's (BERT) input network into consideration. By controlling the receiver input power P_i, we obtained the receiver sensitivity n_s at $BER = 10^{-9}$ given in photons per bit (ppb) and as a sensitivity penalty $\gamma_q = 10 \log n_s/n_q$ $[dB]$ relative to the quantum limit of $n_q = 38ppb$.

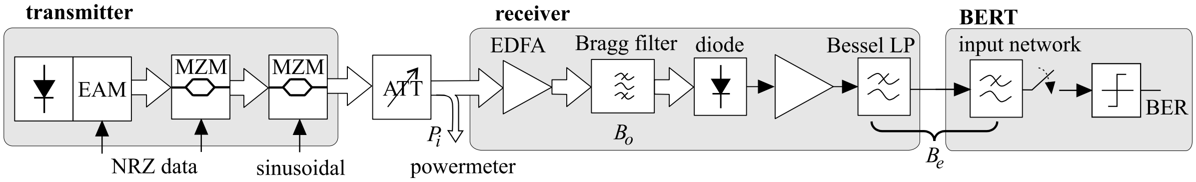
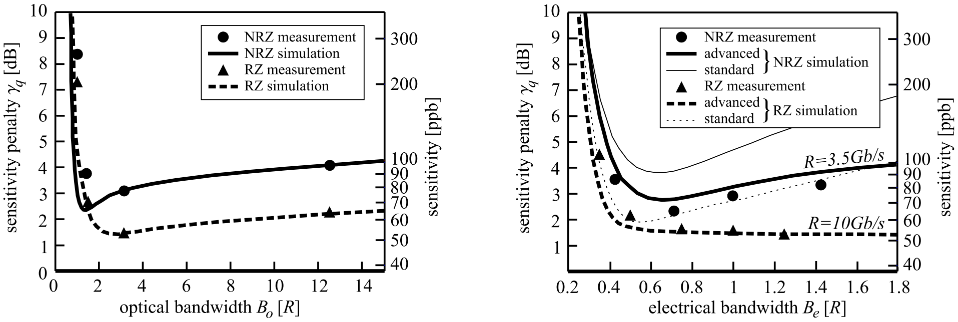


Figure 1: *Experimental setup: (N)RZ transmitter and optically preamplified direct detection receiver.*

Measurement results: Figure 2(a) shows the receiver sensitivity at a data rate of $R = 10Gb/s$ as a function of the optical bandwidth B_o at a constant effective electrical bandwidth of $B_e = 0.75R$ for NRZ coding, and $B_e = 0.9R$ for RZ. The simulations (lines) are in excellent agreement with the measurements, and reveal a narrow optimum at $B_o = 1.35R$ for NRZ. In the case of RZ, the broad minimum at $2.7R$ shows that the optical bandwidth is less critical with regard to sensitivity than in the case of NRZ. At the optimum optical bandwidth we achieved a sensitivity of $52ppb$ ($\pm 2ppb$ measurement uncertainty) for RZ, which is about $1.4dB$ above the quantum limit.

The influence of the effective electrical bandwidth B_e is shown in Fig. 2(b) at a constant optical bandwidth of $2.86R$ ($3.12R$) for NRZ (RZ). NRZ coding has a clear minimum at $B_e = 0.65R$. In



(a) (b)

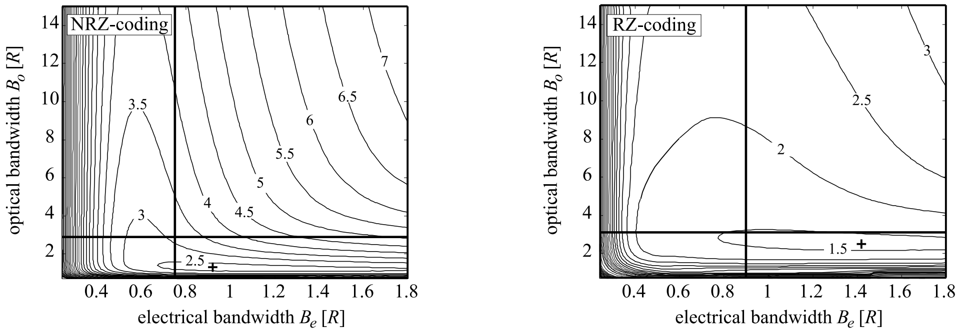
Figure 2: *Measured (dots) and simulated (lines) receiver sensitivity as function of (a) the optical bandwidth scaled to the data rate R and (b) the electrical bandwidth for both, NRZ and RZ coding.*

the case of RZ, the sensitivity is almost independent of the electrical bandwidth over a wide range (provided that the optical bandwidth is close to the optimum), which is typical for RZ receivers limited by signal-ASE noise [1].

Note, the NRZ experiment was done at a reduced data rate of $R = 3.5Gb/s$, since at higher data rates the measurements were strongly influenced by the limited bandwidth ($13.5GHz$) of the BERT. For NRZ the optimum electrical bandwidth is a careful trade-off between filter-induced intersymbol interference (ISI) and noise reduction. The input network of the BERT causes additional (unknown) signal distortions and therefore strongly affects the results at $10Gb/s$. Since ISI plays only a minor role for RZ coding, the limited BERT bandwidth was not an issue for RZ experiments.

Our simulations using the advanced Gaussian noise statistics (thick lines in Fig. 2) predict the measurements very accurately. In contrast, the commonly used expressions for receiver noise [2] (thin lines) produce errors of up to $3dB$, which clearly demonstrates the superiority of the advanced Gaussian approximation [3].

Further simulations: The contour plots in Fig. 3 give the simulated sensitivity penalty γ_q as a function of the optical and electrical bandwidth for the setup of Fig. 1. The measurements of Fig. 2 are represented by the straight vertical and horizontal lines in the plots. The figure shows at a glance the optimum bandwidth constellations, which differ significantly for NRZ and RZ coding [1]. Further, system tolerances to bandwidth variations can immediately be assessed.



(a) (b)

Figure 3: *Simulated sensitivity penalty γ_q relative to the quantum limit as a function of the optical and electrical bandwidth for (a) NRZ coding and (b) RZ coding.*

Conclusions: We experimentally verified the optimum electrical and optical filter bandwidths of optical direct detection receivers dominated by ASE noise. It is shown that the advanced Gaussian noise approximation predicts the measurements much better than the standard Gaussian noise formulae. The RZ receiver features a sensitivity of $1.4dB$ above the quantum limit at a data rate of $10Gb/s$.

References

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