Receiver Sensitivity of Advanced Modulation Formats for 40 Gb/s DWDM Transmission with and without FEC

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Abstract *Receiver sensitivity of a wide range of current modulation formats including multi-level formats and coherent detection is studied by extensive Monte-Carlo simulations and by experiment. Required OSNR for BER of 10^{-9} with and without FEC is determined.*

Introduction

Growing interest in spectrally efficient modulation formats for 40 Gb/s transmission has led to a variety of advanced formats such as duobinary transmission or DQPSK [1]. Current publications show, however, that there is still potential for further increasing the spectral efficiency using e.g. multi-level formats in conjunction with coherent detection [2].

The intention of this paper is to provide a database regarding the receiver sensitivity allowing for comparison of the most promising formats.

The paper is organized as follows: The modulation formats to be considered as well as the simulation method are introduced briefly. Numerical and experimental results for two formats are compared. A comprehensive database regarding the sensitivity of each specific format for different spectral efficiencies and FEC situations is given, obtained by extensive Monte-Carlo simulations for bit error ratios (BER) as low as 10^{-9}. The database is followed by discussion of the most important results.

Simulating 40 Gb/s modulation formats

Each specific format is generated using external modulation by Mach-Zehnder (MZM) and/or phase modulators (PM), respectively. All receivers are preamplified optically allowing for consideration of BER as a function of OSNR. For clarity, all other impairments like shot and thermal noise, laser phase or laser RIN noise, final extinction etc. are neglected. For variation of spectral efficiency of 0.4 b/s/Hz, 0.8 b/s/Hz and 1.6 b/s/Hz, respectively, the optical bandwidth B_o (FWHM) is varied between 100 GHz and 25 GHz.

Table 1 depicts the data for 40 Gb/s direct detection (DD) formats [NRZ-OOK, RZ-OOK, carrier-suppressed (CS)-RZ-OOK and NRZ duobinary (DB)]. For RZ formats, a second MZM is added driven by clock signal at frequency f_{RZ}. The electrical bandwidth B_e is adapted to symbol rate f_S according to [3]. Table 2 gives the data for differential PSK direct detection formats using Mach-Zehnder delay interferometers (MZDI) and balanced detection (BD). In table 3 the data for the formats using coherent detection is given. The local oscillator having 10 mW output power is assumed to be perfectly synchronized to the optical carrier.

By Monte-Carlo simulation the BER is determined as function of OSNR (0.1 nm) down to a value of 10^{-8}<BER<10^{-9}. Slight extrapolation results in an accurate value of required OSNR for BER=10^{-9}. Each simulation is repeated increasing the bit rate by 7% in order to take into account FEC. While B_e is adapted, for constant spectral efficiency B_o is preserved. Required OSNR for achieving BER=$4{\cdot}10^{-4}$ (standard FEC [8]) and BER=$2{\cdot}10^{-3}$ (super FEC [9]) is determined resulting in BER=10^{-9} after decoding.

	f_{RZ}/f_S	B_e/f_S	additional components
NRZ-OOK	-	0.7	-
RZ-OOK	1	1.1	-
CS-RZ-OOK	0.5	1.0	-
NRZ-DB	-	0.7	- precoder [4] - duobinary filter, $f_c=f_S/4$

Table 1: Direct detection modulation formats

	f_S/GBaud	f_{RZ}/f_S	B_e/f_S	add. comp.
RZ-DPSK	40	1	1.1	- precoder [4]
RZ-DQPSK	20	1	1.1	- precoder [5] - serial PM [6]

Table 2: Differential PSK DD modulation formats

	f_S/GBaud	f_{RZ}/f_S	B_e/f_S	detection
NRZ-OOK-HO	40	-	0.7	homodyne
RZ-PSK-HO	40	1	1	homodyne
RZ-DPSK-HE	40	1	1	heterodyne $f_{IF}=2f_S$ [7]
RZ-QPSK-HO	20	1	1	homodyne
NRZ-16-QAM	10	-	0.7	homodyne

Table 3: Coherent detection modulation formats

Simulation and measurement: A comparison

For simulation all impairments beyond ASE noise are neglected. Consequently, sensitivity obtained by simulation is expected to be higher than sensitivity obtained by experiment. For comparison, back-to-back experiments were carried out for NRZ-OOK and CS-RZ-OOK with B_o=50 GHz. The results are given in fig. 1. For CS-RZ-OOK, at BER=10^{-9} a difference of 6.2 dB between simulation and measurement is obtained. Carrying out matched simulation shows that the main difference is attributed to final extinction e_r of 13 dB (according to experiment) resulting in remaining difference of 3.7 dB. Having in mind that for simulation thermal noise in transmitter and receiver are neglected as well as sampling point and decision threshold can be optimized at arbitrary accuracy, this difference is acceptable. The same behavior is found for NRZ-OOK. Thus, depending on extinction ratio in order to obtain values of practical relevance, values for receiver sensitivity given in the next section should be scaled by 3 dB to 6 dB depending mainly on e_r.

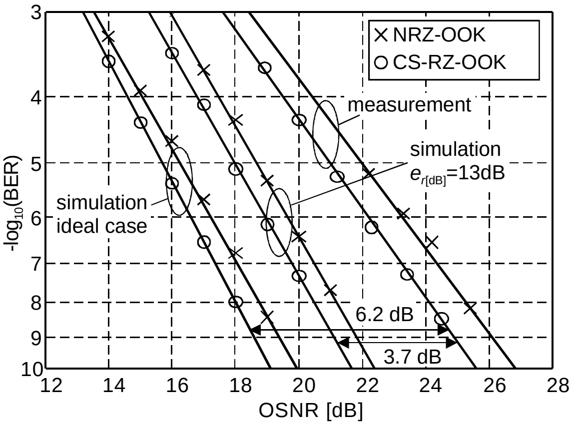

Figure 1: Comparison of simulation and measurement

Simulation results and discussion

The simulation results for the setups with 40 Gb/s data rate are given in table 4. For each modulation format, B_o=50 GHz results in higher or at least equal sensitivity compared to 100 GHz. This can be explained as B_o=50 GHz is closer to the matched filter case. Of all formats, RZ-PSK with homodyne detection performs best. Moreover, the result for RZ-DPSK @ B_o=100 GHz of 15.6 dB is close to the value of 17.85 dB (0.1 nm) reported in [10] with $e_{r[dB]}$=25 dB.

	25 GHz	50 GHz	100 GHz
NRZ-OOK	22.7 dB	19.5 dB	19.8 dB
RZ-OOK	20.8 dB	18.1 dB	18.3 dB
CS-RZ-OOK	23.2 dB	18.6 dB	18.8 dB
NRZ-DB	20.2 dB	20.7 dB	22.4 dB
RZ-DPSK	18.4 dB	15.3 dB	15.6 dB
RZ-DQPSK	17.5 dB	17.5 dB	17.7 dB
NRZ-ASK-HO	22.6 dB	19.3 dB	19.4 dB
RZ-PSK-HO	17.9 dB	15.0 dB	15.0 dB
RZ-DPSK-HE	18.4 dB	15.4 dB	15.6 dB
RZ-QPSK-HO	14.9 dB	15.0 dB	15.2 dB
NRZ-16-QAM	21.3 dB	20.9 dB	20.9 dB

Table 4: Required OSNR (BER=10^{-9}) without FEC.

The situation changes completely for a bandwidth of 25 GHz. Here, only the formats having high spectral efficiency (i.e. duobinary, (D)QPSK and 16 QAM) do not suffer sensitivity reduction due to signal distortion from spectral truncation. The best performer is RZ-QPSK with homodyne detection. From the set of further conclusions the following ones are picked out: Although homodyne detection is an interesting strategy offering the opportunity of more powerful equalization techniques, for OOK and PSK modulation the sensitivity gain is low in the range of a few tenths of dB. On the other hand, as stated in [6] for QPSK modulation the gain is significantly larger and shows values of about 2.5 dB.

Tables 5 and 6 show the results for the setups with 43 Gb/s gross data rate using either Standard FEC or Super FEC. Comparing the results with table 1, net coding gain can be determined which was shown to differ for each individual modulation format [5].

Compared to results without FEC, RZ-PSK and RZ-QPSK with homodyne detection are still the formats showing highest sensitivity for low resp. high spectral efficiency. However, the difference in sensitivity between particular formats decreases due to different gradients of the BER-curves. This can be interpreted as higher coding gain for those formats. As an example, for B_o=50 GHz using super-FEC RZ-DPSK shows coding gain of (15.3-10.0) dB=5.3 dB, while RZ-DQPSK and NRZ-16-QAM show (17.5-11.3) dB=6.2 dB and (20.9-13.5) dB=7.4 dB.

	25 GHz	50 GHz	100 GHz
NRZ-OOK	18.1 dB	14.6 dB	15.1 dB
RZ-OOK	16.2 dB	13.7 dB	13.9 dB
CS-RZ-OOK	19.7 dB	14.2 dB	14.5 dB
NRZ-DB	15.0 dB	15.7 dB	17.4 dB
RZ-DPSK	14.5 dB	11.2 dB	11.4 dB
RZ-DQPSK	12.6 dB	12.6 dB	13.0 dB
NRZ-ASK-HO	18.0 dB	14.3 dB	14.3 dB
RZ-PSK-HO	13.1 dB	10.2 dB	10.2 dB
RZ-DPSK-HE	14.5 dB	11.2 dB	11.6 dB
RZ-QPSK-HO	10.2 dB	10.2 dB	10.4 dB
NRZ-16-QAM	15.2 dB	15.1 dB	15.1 dB

Table 5: Required OSNR (BER=10^{-9}), Standard FEC.

	25 GHz	50 GHz	100 GHz
NRZ-OOK	16.4 dB	13.3 dB	13.8 dB
RZ-OOK	14.7 dB	12.6 dB	12.8 dB
CS-RZ-OOK	18.0 dB	13.0 dB	13.3 dB
NRZ-DB	13.6 dB	14.4 dB	16.0 dB
RZ-DPSK	13.2 dB	10.0 dB	10.2 dB
RZ-DQPSK	11.3 dB	11.3 dB	11.7 dB
NRZ-ASK-HO	16.4 dB	12.9 dB	13.0 dB
RZ-PSK-HO	11.5 dB	8.8 dB	8.8 dB
RZ-DPSK-HE	13.1 dB	10.0 dB	10.4 dB
RZ-QPSK-HO	8.9 dB	8.9 dB	9.1 dB
NRZ-16-QAM	13.5 dB	13.5 dB	13.5 dB

Table 6: Required OSNR (BER=10^{-9}), Super FEC.

Conclusions

Based on extensive Monte-Carlo simulation, receiver sensitivity of advanced modulation formats is investigated. For spectral efficiency of 0.4 b/s/Hz and 0.8 b/s/Hz, PSK using homodyne detection shows best performance while for 1.6 b/s/Hz homodyne QPSK is the most promising format.

References

1 G. Charlet et al., *OFC 2006*, paper OThI3, 2006.
2 M. Seimetz, *NFOEC 2006*, paper NWA4, 2006.
3 P.J. Winzer et al.,*JLT*, vol.19, pp.1263-1273, 2001.
4 W. Kaiser et al., *PTL*, pp. 884-886, 2001.
5 M. Serbay et al., *ECOC2005*, pap. We4.P.10,2005.
6 C. Wree et al., *OFC 2003*, paper ThE5, 2003.
7 A.H. Gnauck et al.,*OFC 2005*, paper PDP31, 2005.
8 ITU-T G 975
9 ITU-T G 975.1
10 A.H. Gnauck et al., PTL, vol. 15, pp. 99-101, 2003.