Analysis of NRZ- and RZ-DQPSK for 112 Gb/s DWDM transmission

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ABSTRACT
The feasibility of NRZ- and RZ-DQPSK for 112 Gb/s DWDM transmission is analyzed. RZ-DQPSK is more tolerant to cascaded filtering, chromatic dispersion and non-linearities. Cascaded filtering is the most critical issue for 100 GHz channel spacing.
Keywords: DPQSK, 100 Gigabit Ethernet, non-linear analysis, transmission.

1. INTRODUCTION

100 Gigabit Ethernet (100 GbE) is widely regarded as the next step in channel bit rate after 40G. Including coding and FEC overhead, a 100 GbE channel has a bit rate of about 112 Gb/s, so to be compatible with DWDM channel grids, it becomes necessary to use more spectrally-efficient modulation formats than binary modulation schemes such as On-Off-Keying (OOK). Several different techniques, such as multilevel phase-shift-keying (PSK) [1], quadrature-amplitude modulation (QAM) [2], polarisation multiplexing (PolMux) [3], sub-channel multiplexing (SCM) [4], and orthogonal frequency division multiplexing (OFDM) [5] are currently being investigated. Moreover, the recent progress in digital signal processing, combined with the more reasonable requirements in term of phase stability implied by the higher bit rate, are making coherent detection feasible [6], with all the advantages in terms of electronic equalisation [7].

Highly spectrally efficient formats and coherent detection are almost certainly needed for 100 GbE transmission over very long distances (>1000 km) and ultra-dense WDM (25 and 50 GHz channel grids). However, for metro- and regional-network links with 100 or 200 GHz channel grids and pre-installed optical dispersion compensation, less advanced transmission techniques may be sufficient and indeed desirable if that implies lower implementation cost. One attractive technique in this respect is direct-detection differential quadrature phase-shift-keying (DQPSK) [8, 9, 10, 11].

In this paper the transmission properties of DQPSK for 100 GbE are studied by means of numerical simulations. In particular, a comparison is made between NRZ-DQPSK and RZ-DQPSK in terms of tolerance to cascaded filtering, chromatic dispersion, and non-linear effects.

2. NUMERICAL SIMULATION SET-UP

The 112 Gb/s NRZ-DQPSK signal is generated by an ideal nested-MZM transmitter, in which two 56 Gb/s bit sequences of length 2^{15} are pre-coded for differential detection, and used to drive the two MZM's (I and Q quadrature). The original bit sequences are de-Bruijn bit sequences (DBBS), properly modified and delayed [7] in order for the resulting optical signal to be "data-balanced" (equal occurrence of all symbols as well as symbol sequences). An optional pulse carver is placed after the NRZ-DQPSK modulator to generate 50% duty cycle RZ-DQPSK.

The DQPSK signal is passed through a Gaussian filter modelling a wavelength multiplexer (MUX), and subsequently either through a transmission link or directly to the receiver, where the signal is passed through a Gaussian filter modelling a wavelength de-multiplexer (DEMUX). Signal quality is evaluated in terms of OSNR_{req}, defined as the required OSNR to obtain BER$= 10^{-3}$. This is found by adding white Gaussian noise and measuring OSNR (at 0.1 nm) before the DEMUX, and counting errors after differential detection.

3. CONCATENATED FILTERING TOLERANCE

To study the impact of filtering, the 3 dB bandwidth of both MUX and DEMUX are varied simultaneously and OSNR_{req} is measured for each bandwidth value. The results for NRZ- and RZ-DQPSK are shown in Fig. 1(a). It can be observed that RZ shows about 1 dB lower *"back-to-back"* OSNR_{req} (i.e. using optimum filtering bandwidth 95 GHz). Secondly, the filtering tolerance (defined as the 3 dB bandwidth for MUX and DEMUX at which OSNR_{req} degrades by 1 dB with respect to back-to-back) is 60 GHz for RZ and 69 GHz for NRZ. An interesting question is how many pairs of MUX and DEMUX can be tolerated by NRZ and RZ. If we consider each filter to be Gaussian and to have a 3 dB bandwidth B_0, then n cascaded filters will be equivalent to one Gaussian filter with a 3 dB bandwidth $B_0/\sqrt{n}$. For convenience, we have marked in plot

(a) the equivalent bandwidth of n number of MUX/DEMUX pairs for a typical 200 GHz channel grid (for which we chose a 3 dB bandwidth per filter $B_0 = 150$ GHz). This means that up to 4 pairs of filters (i.e. the MUX at the transmitter and the DEMUX at the receiver, plus 3 ROADM nodes) can be tolerated by NRZ if 1 dB penalty is allowed. RZ tolerates up to 6 pairs of filters (i.e. 5 ROADMs).

The situation is different for 100 GHz channel grids. In plot (b) we have marked the equivalent bandwidth of n MUX/DEMUX pairs for $B_0 = 75$ GHz. As can be seen, adding even one single ROADM node increases OSNR_{req} considerably for both NRZ and RZ. Using flat-top filters—rather than Gaussian—would probably help but only to some extent (a commercially available flat-top filter we found was roughly a Gaussian of order 1.35, for which the OSNR_{req} penalty for two pairs of filters becomes 2 dB: better than the 2.6 dB obtained with Gaussian filtering, but not a major difference).

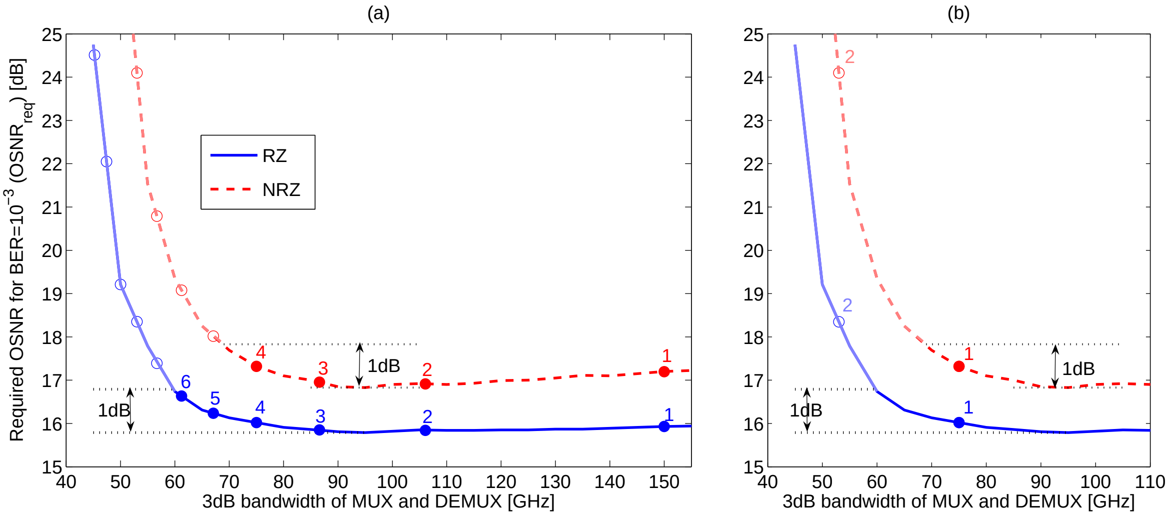

Fig. 1. Filtering tolerance of NRZ- and RZ-DQPSK; the numbered circles ($n = 1, 2, ...$) mark the equivalent bandwidth of n pairs of concatenated filters with 3dB bandwidth $B_0 = 150$ GHz (a), and $B_0 = 75$ GHz (b).

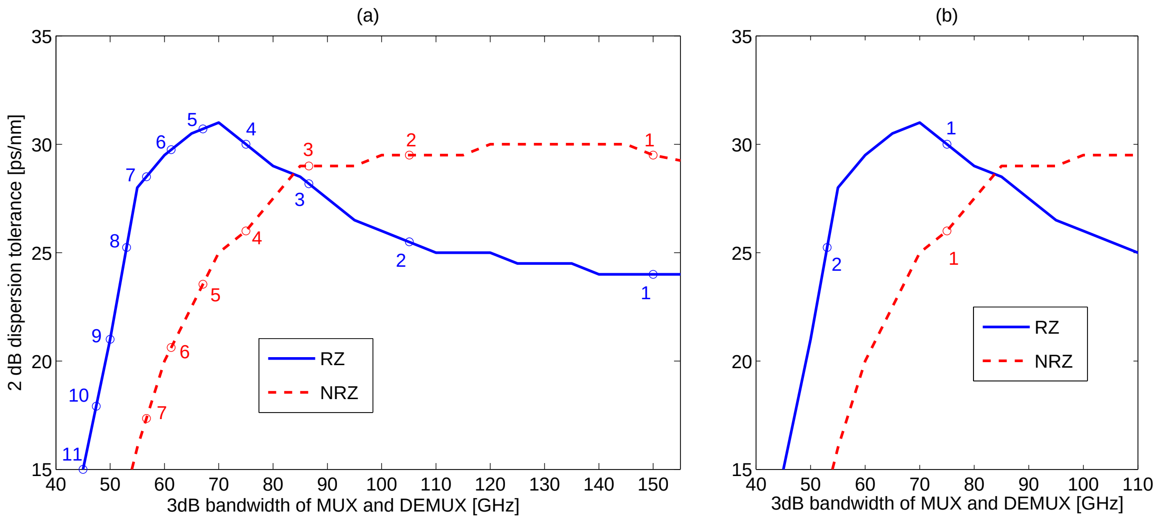

Fig. 2. Chromatic dispersion tolerance for NRZ- and RZ-DQPSK, as a function of MUX and DEMUX bandwidth; the numbered circles ($n = 1, 2, ...$) mark the equivalent bandwidth of n pairs of concatenated filters with 3dB bandwidth $B_0 = 150$ GHz (a), and $B_0 = 75$ GHz (b).

4. CHROMATIC DISPERSION TOLERANCE

Because filtering has such an impact on transmission performance, chromatic dispersion tolerance (defined as the amount of residual dispersion causing a 2 dB increase in $OSNR_{req}$) is studied for different values of MUX and DEMUX bandwidth, as shown in Fig. 2. It can first be observed that the amount of tolerated chromatic dispersion (for the number of acceptable ROADMs found in the previous section) is between ± 25 and ± 31 ps/nm. Secondly, it can be seen that NRZ is more dispersion tolerant for broad cascaded filtering bandwidth (i.e. for 200 GHz channel grids with up to 2 ROADMs), while RZ is more tolerant for narrower filtering (several ROADMs or 100 GHz channel grid).

5. NON-LINEAR TRANSMISSION ANALYSIS

Finally, the impact of intra-channel non-linear effects is studied by transmitting the signal through a link consisting of 7×80 km standard single-mode fiber (SSMF) spans with 100% in-line compensation by means of dispersion compensation fiber (DCF). Power into the SSMF is varied from -2 dBm to 5 dBm (the launch power into DCF is constantly 5 dB lower than in the SSMF), and residual dispersion is set to zero. The non-linear index is set to 2.1 W^{-1}/km and 3.4 W^{-1}/km for SSMF and DCF, respectively. Dispersion is 17 ps/nm/km and 90 ps/nm/km, respectively, while loss is 0.2 dB/km and 0.7 dB/km. The optical amplifiers are noise-free. As can be seen in Fig. 3, RZ-DQPSK shows a non-linear threshold (defined as the launch power at which $OSNR_{req}$ is degraded by 1dB) of 2.2 dBm, more than 1 dB higher than NRZ. This should give enough margin to achieve acceptable OSNR values after a few hundred kilometres.

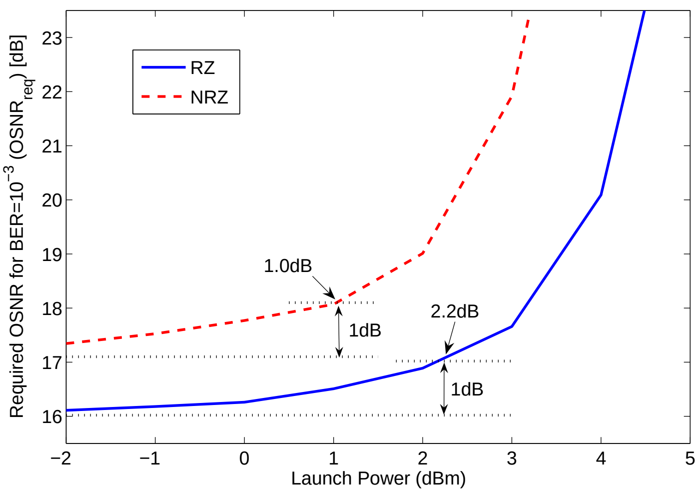

Fig. 3. Power tolerance for NRZ- and RZ-DQPSK transmission over a 7×80 km link.

6. CONCLUSION

We have analysed, by means of numerical simulations, the transmission properties of NRZ- and RZ-DQPSK for medium-haul distances (560 km) and DWDM channel grids (100 and 200 GHz). Chromatic dispersion tolerance (between ± 25 and ± 30 ps/nm) is not a major issue if in-line compensation is installed (typically the case in the scenario of link upgrade from 10 and 40 Gb/s), but per-channel tuneable compensation at the receiver is a must. The main limiting factor seems to be cascaded filtering: the use DQPSK for 100 GbE transmission on a 100 GHz channel grid would probably not tolerate in-line ROADMs. On a 200 GHz grid a few nodes would be tolerated (more easily by RZ than NRZ). Intra-channel non-linear effects were also studied and the non-linear threshold was found to be between 1 and 2 dBm for the 7×80 km link we studied.

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