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ON THE USE OF NRZ, RZ AND CSRZ MODULATION FORMATS FOR ULTRA-DENSE WDM AT 40 GBIT/S

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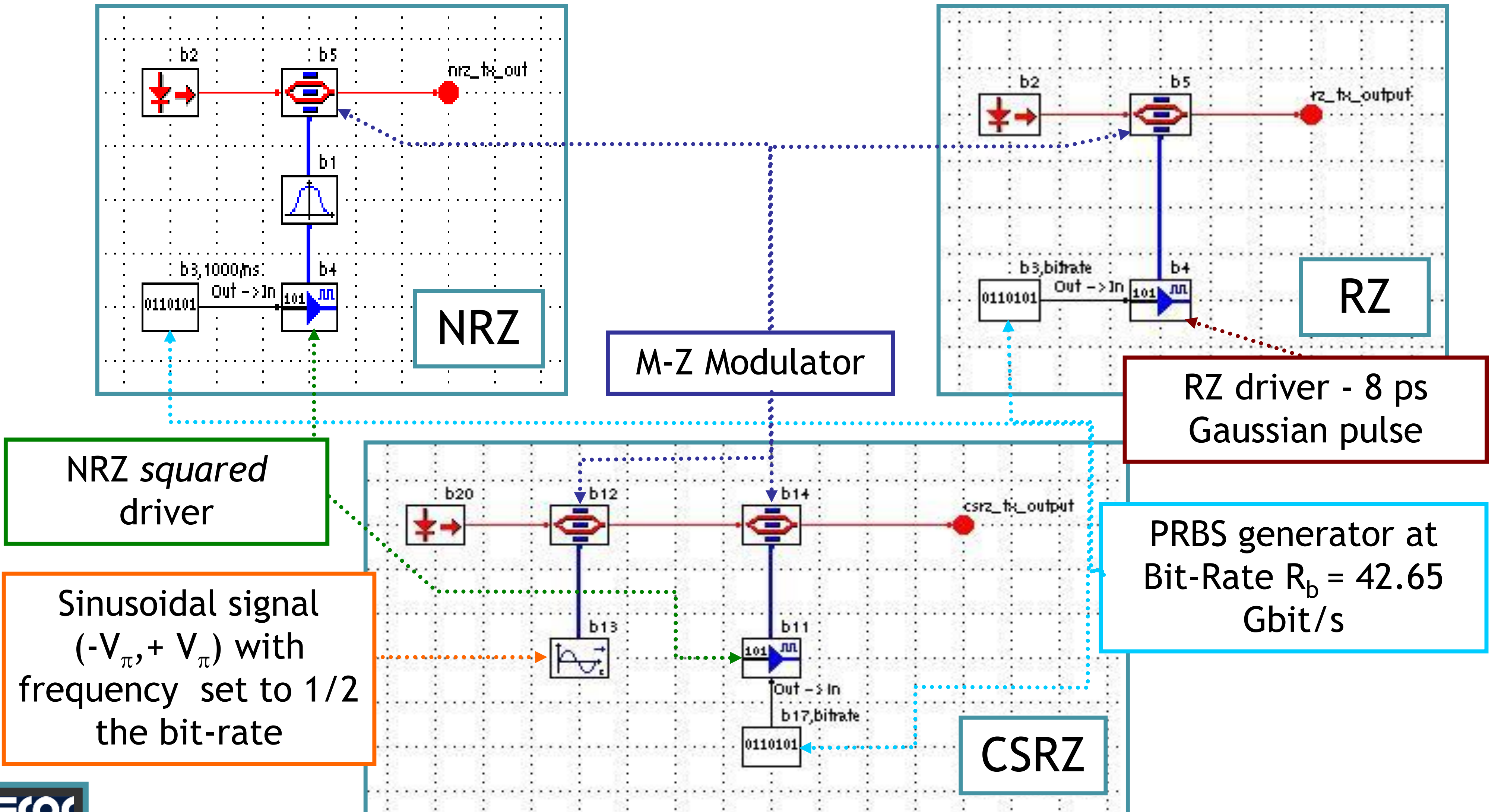
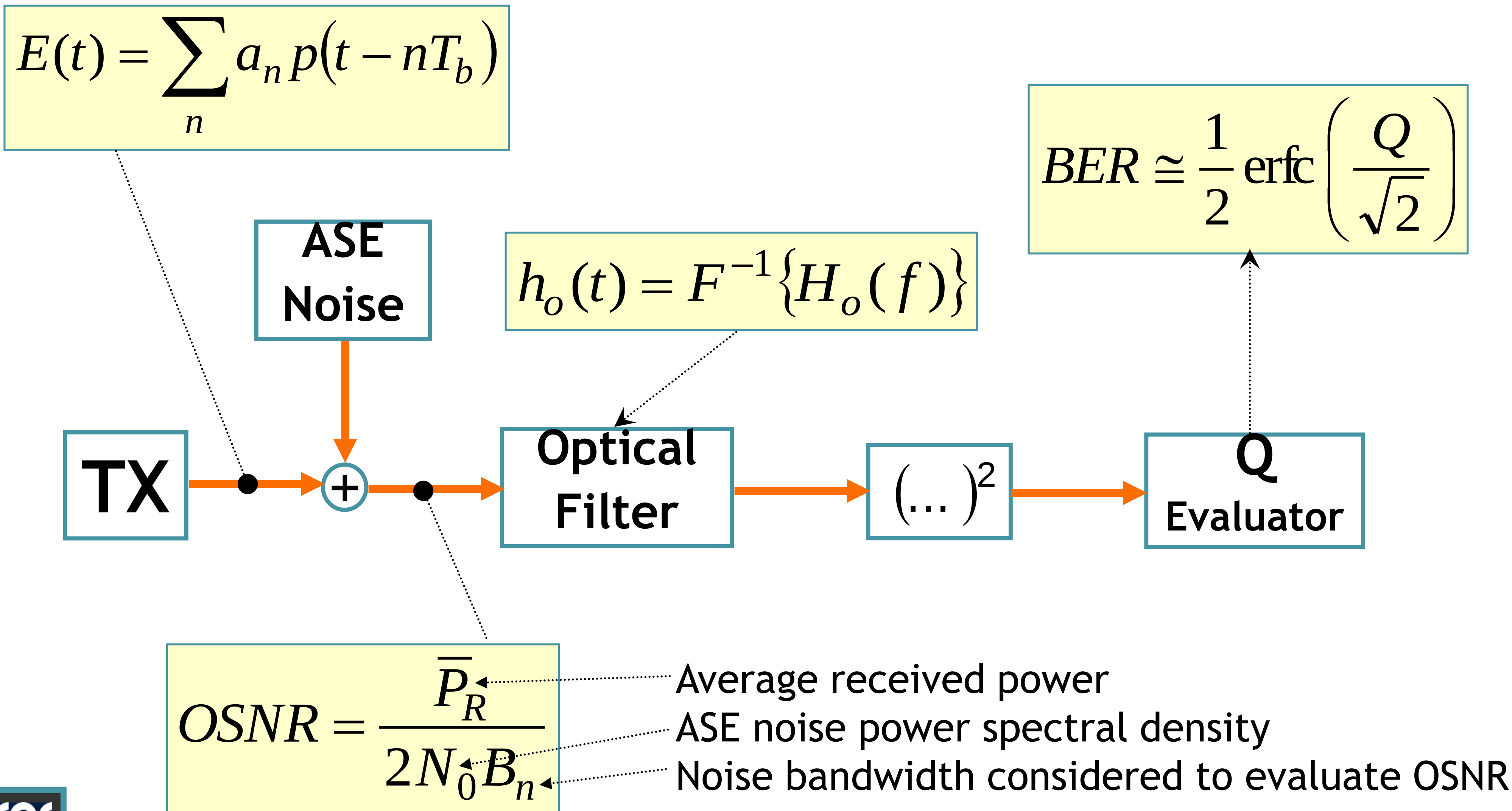
Purpose of the work

- Verify the viability of NRZ, RZ and CSRZ for ultra-high spectral efficiency DWDM transmission at a FEC-inclusive line-rate of 42.65 Gbit/s.
- Optimization of transmitters and receivers for each modulation format evaluating the optimal bandwidths for optical and electrical filters.
- Test of set-ups based on the use of a narrow optical filter at the transmission side and/or on the launch of spectrally adjacent channels on alternated orthogonal polarization.
- Theoretical results on optimum (matched-filter) receiver are used as a reference for comparisons.

Transmitters



Reference: back-to-back ASE limited system



Optimum performance: matched filter receiver

$$h_o(t) = p^*(-t)$$

$$Q_{opt} = \frac{4 \cdot OSNR \cdot \frac{B_n}{R_b}}{\sqrt{8 \cdot OSNR \cdot \frac{B_n}{R_b} + 2} + \sqrt{2}}$$

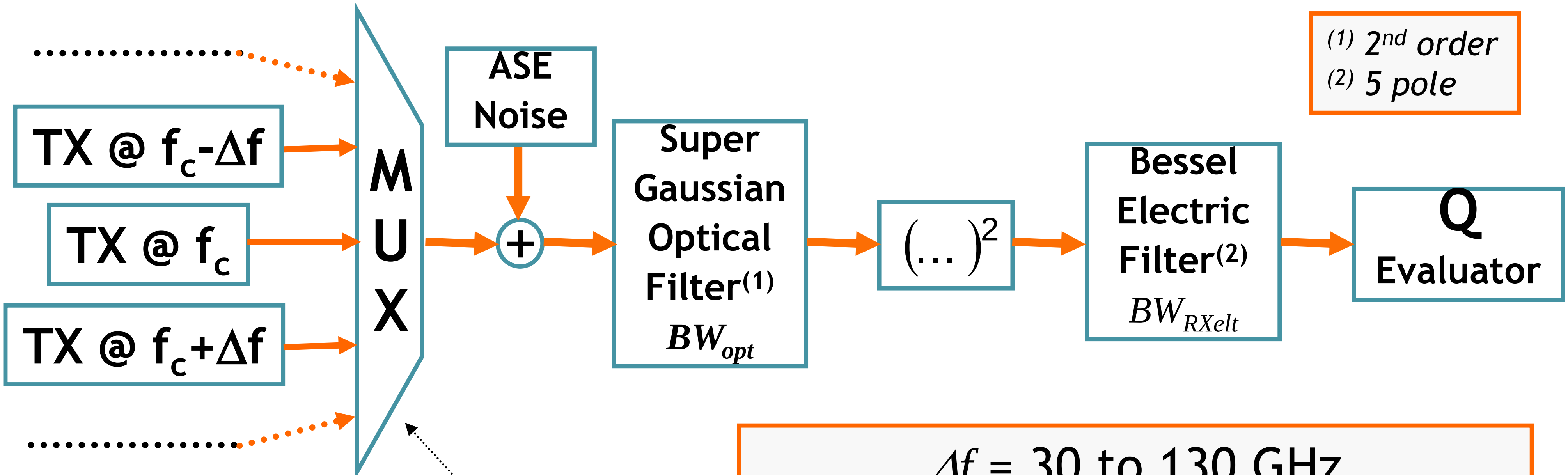
- OC-768 DWDM system
- 50 GHz channel spacing
- 6.7% FEC overhead
- Bit-Rate: R_b=42.65 Gbit/s
- OSNR = 12 dB over B_n = 0.4 nm

$$Q_{opt} = 14.8 \quad [\mathrm{dB}]$$

Reference used to evaluate penalties in this work

$$Q_{penalty} = 14.8 - Q \quad [\mathrm{dB}]$$

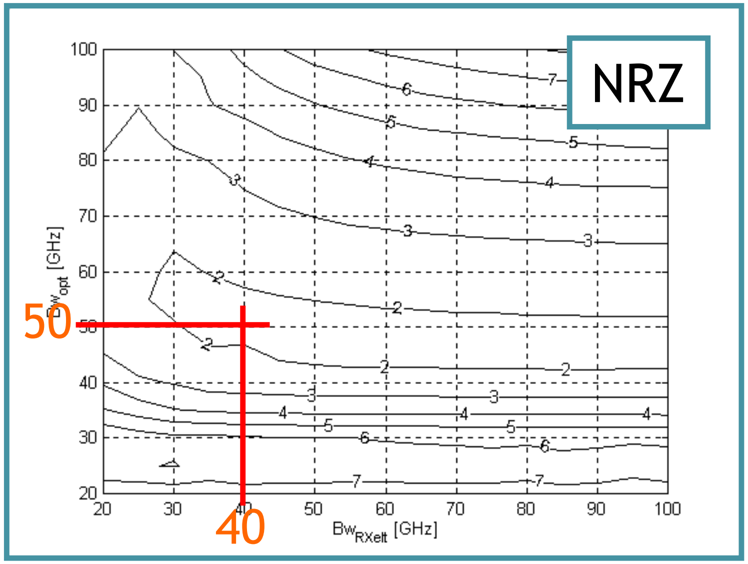
System setup: no TX optical filter



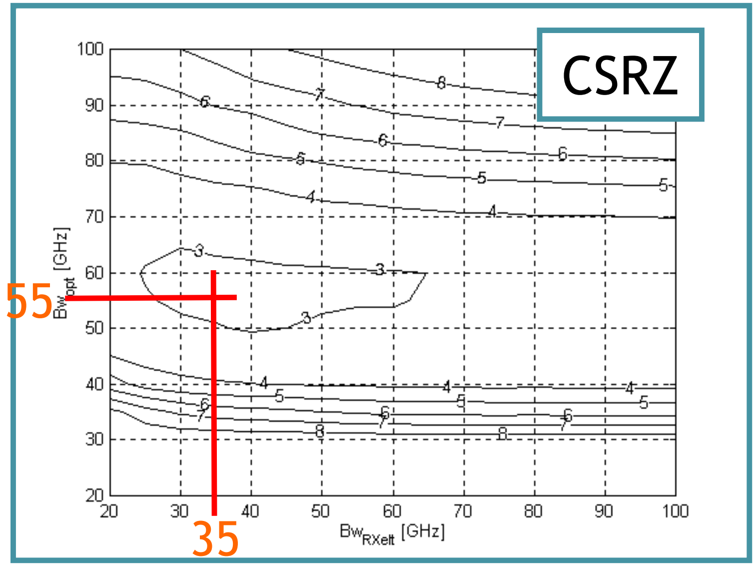
*The components used to combine signals at the transmitter side **do not have filtering effect***

Δf = 30 to 130 GHz
For each channel spacing the $Q_{penalty}$ surface is calculated in the (BW_{RXelt}, BW_{opt}) space in order to define the optimal filter bandwidths

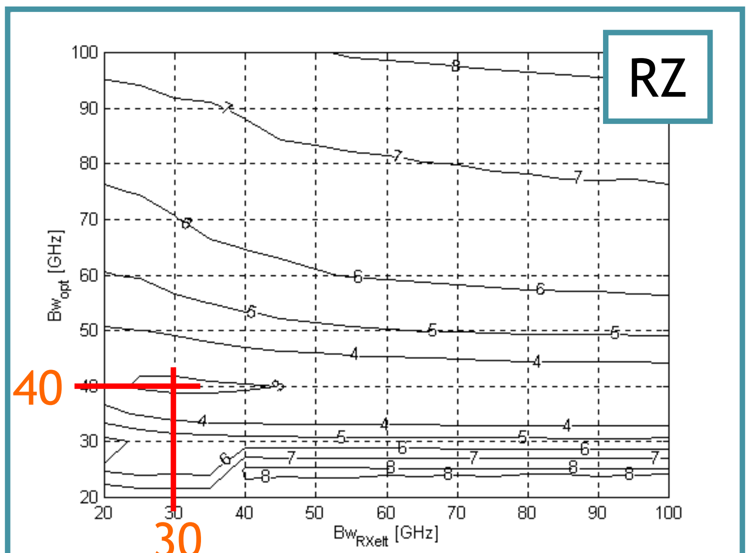
Contour plot of $Q_{penalty}$ surface (Δf=75 GHz)



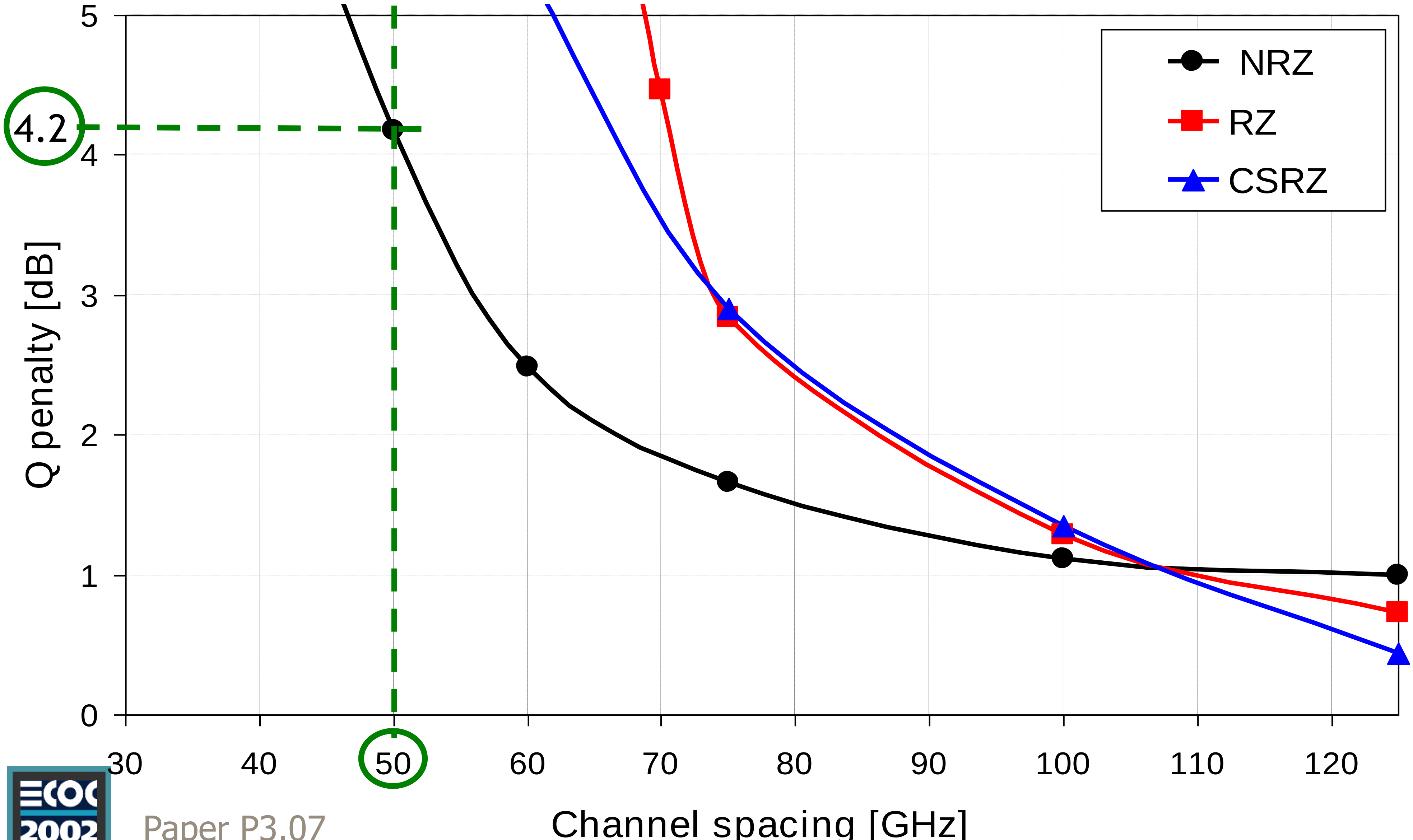
- Without TX optical filter
- Co-polarized channels
- Δf = 75 GHz



Note that optimal bandwidths are different for each channel spacing

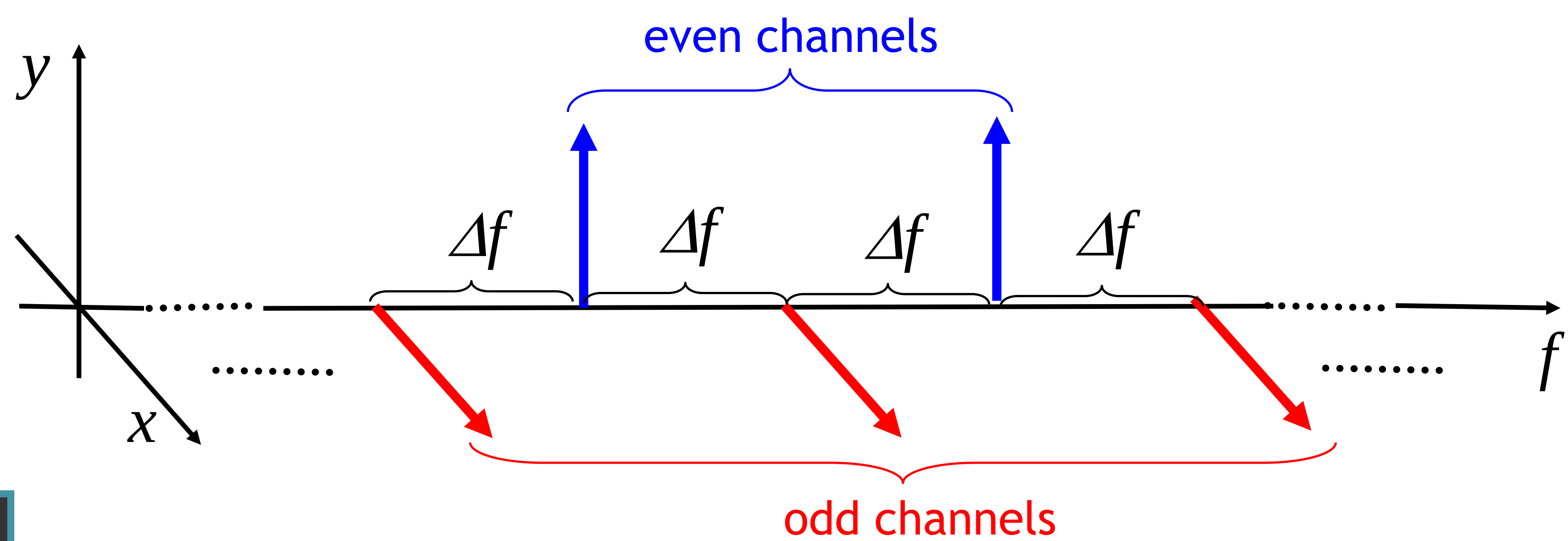


Results without TX filter co-pol

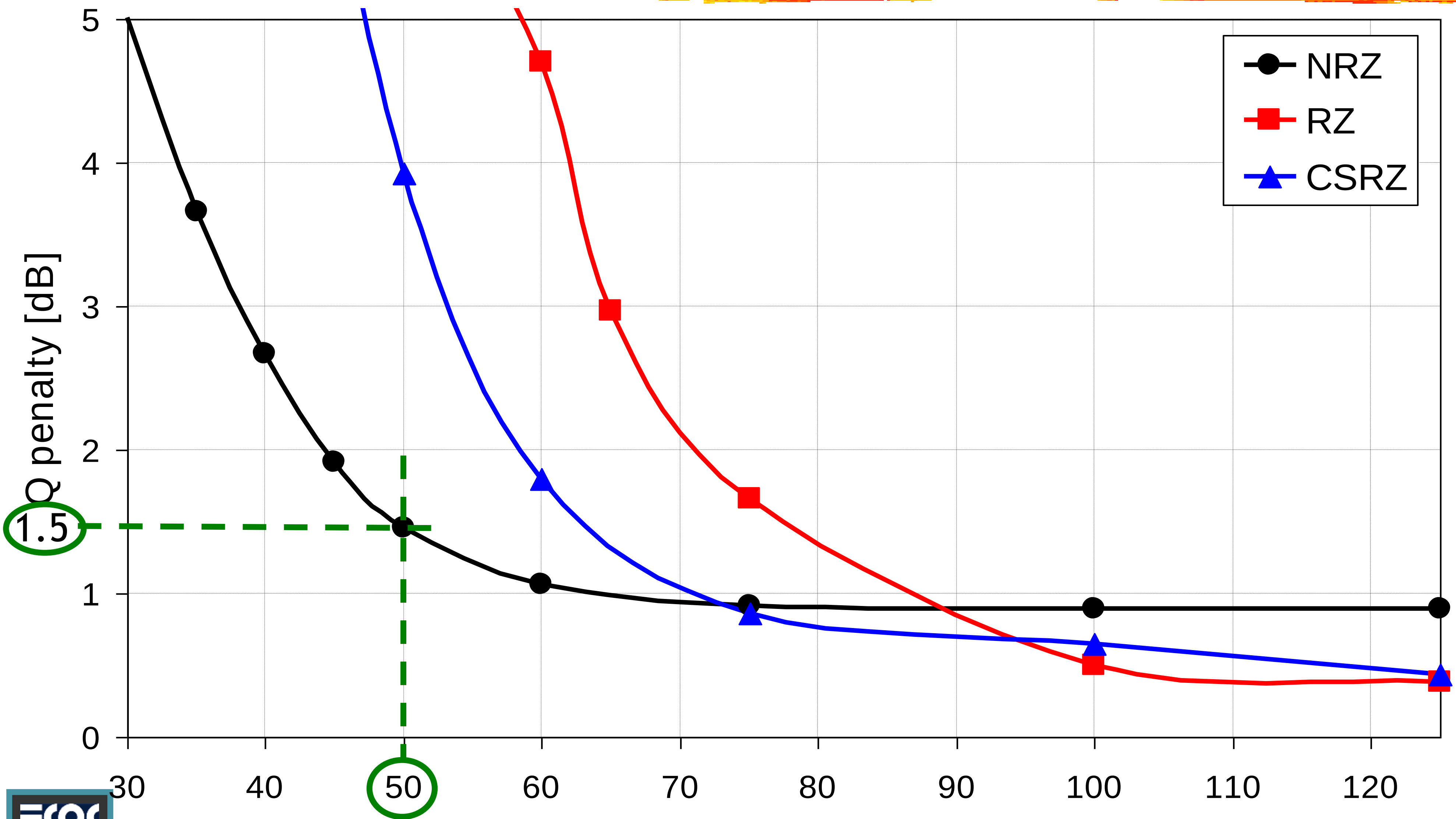


X-pol in order to improve performance

In order to improve system performance we tested the transmission of spectrally adjacent channels on alternate orthogonal polarization



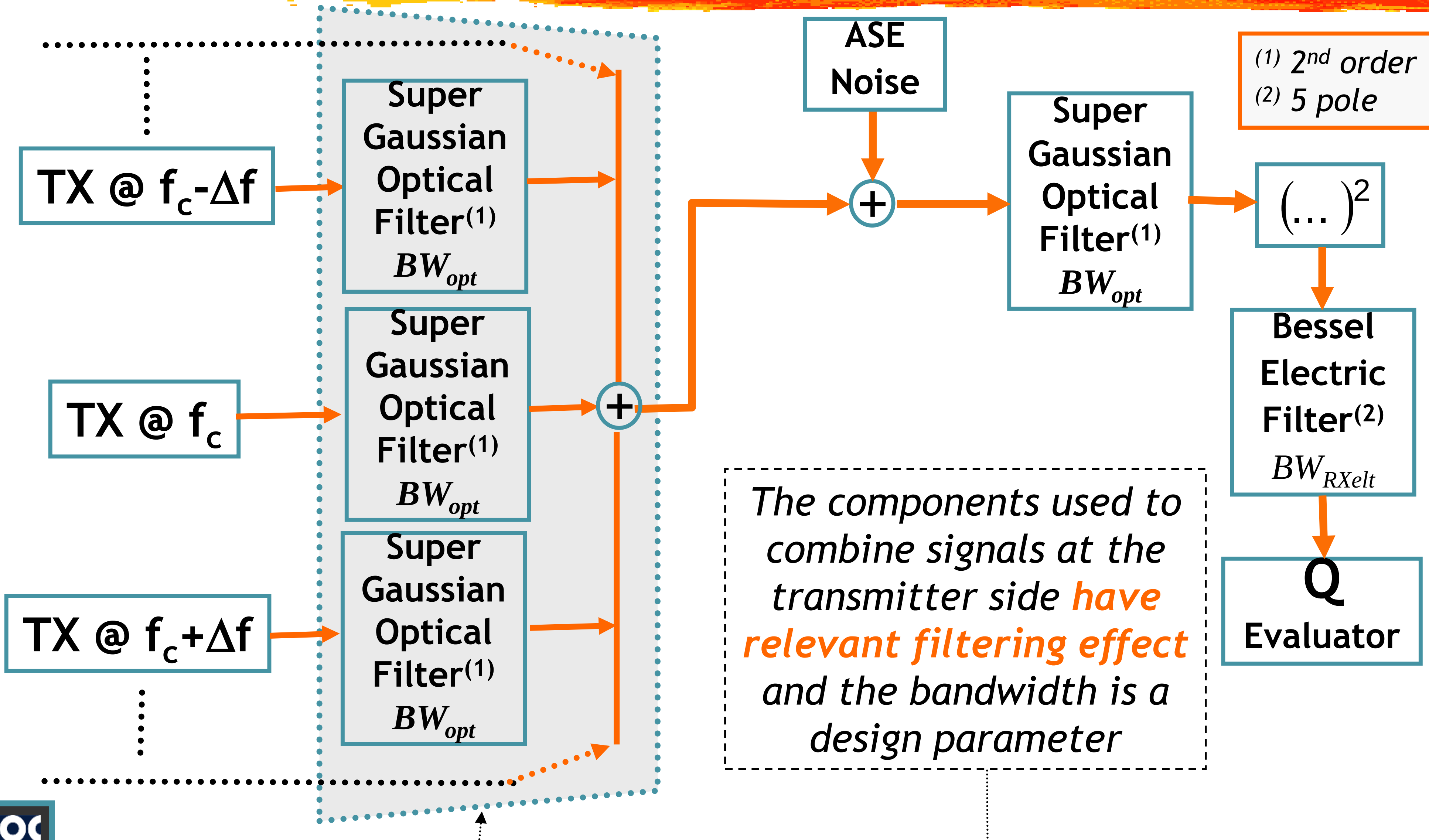
Results without TX filter X-pol



Comments on setups without TX filter

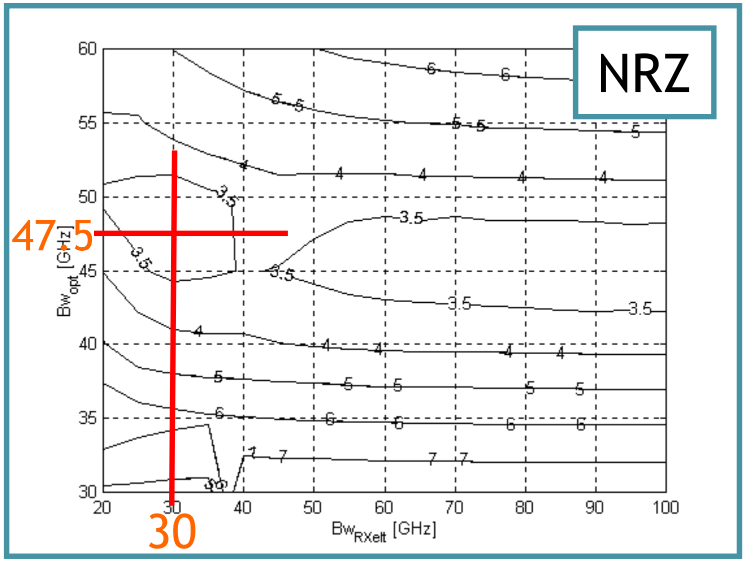
- Without the use of a narrow transmission optical filter **none of the analyzed modulation formats is suitable for transmission with Δf = 50 GHz** and $Q_{penalty} < 1$ dB.
- In this case the use of alternate orthogonal polarization for spectrally adjacent channels **(X-pol) may improve performance.**
- Among the analyzed modulation formats the one with **best performance is NRZ**, that in the X-pol case allows transmission at Δf = 50 GHz with $Q_{penalty} = 1.5$ dB.

Using narrow TX optical filter

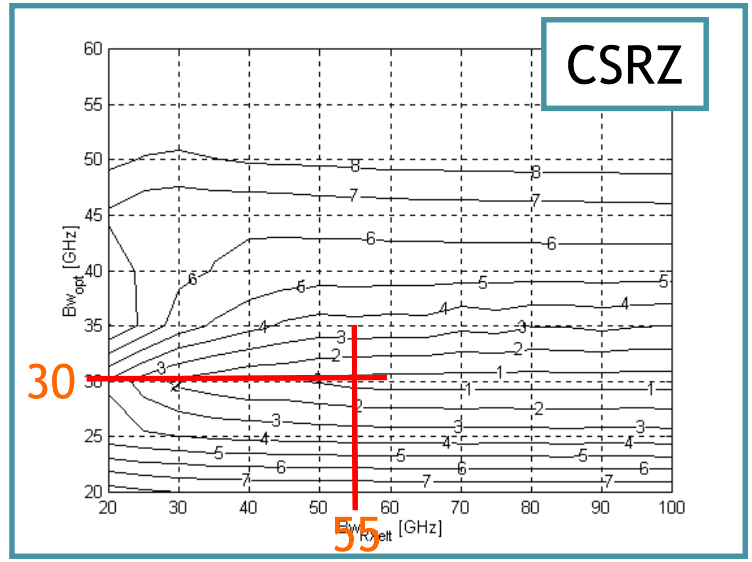


The components used to combine signals at the transmitter side ***have relevant filtering effect*** *and the bandwidth is a design parameter*

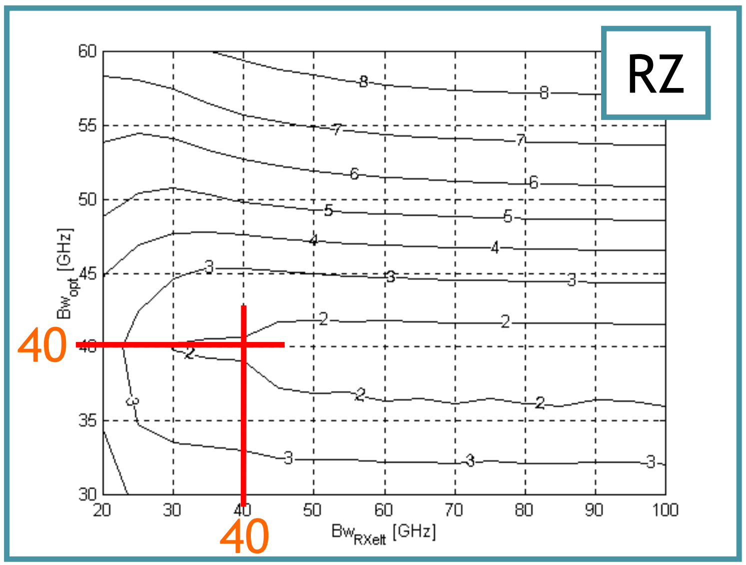
Contour plot of $Q_{penalty}$ surface (Δf=75 GHz)



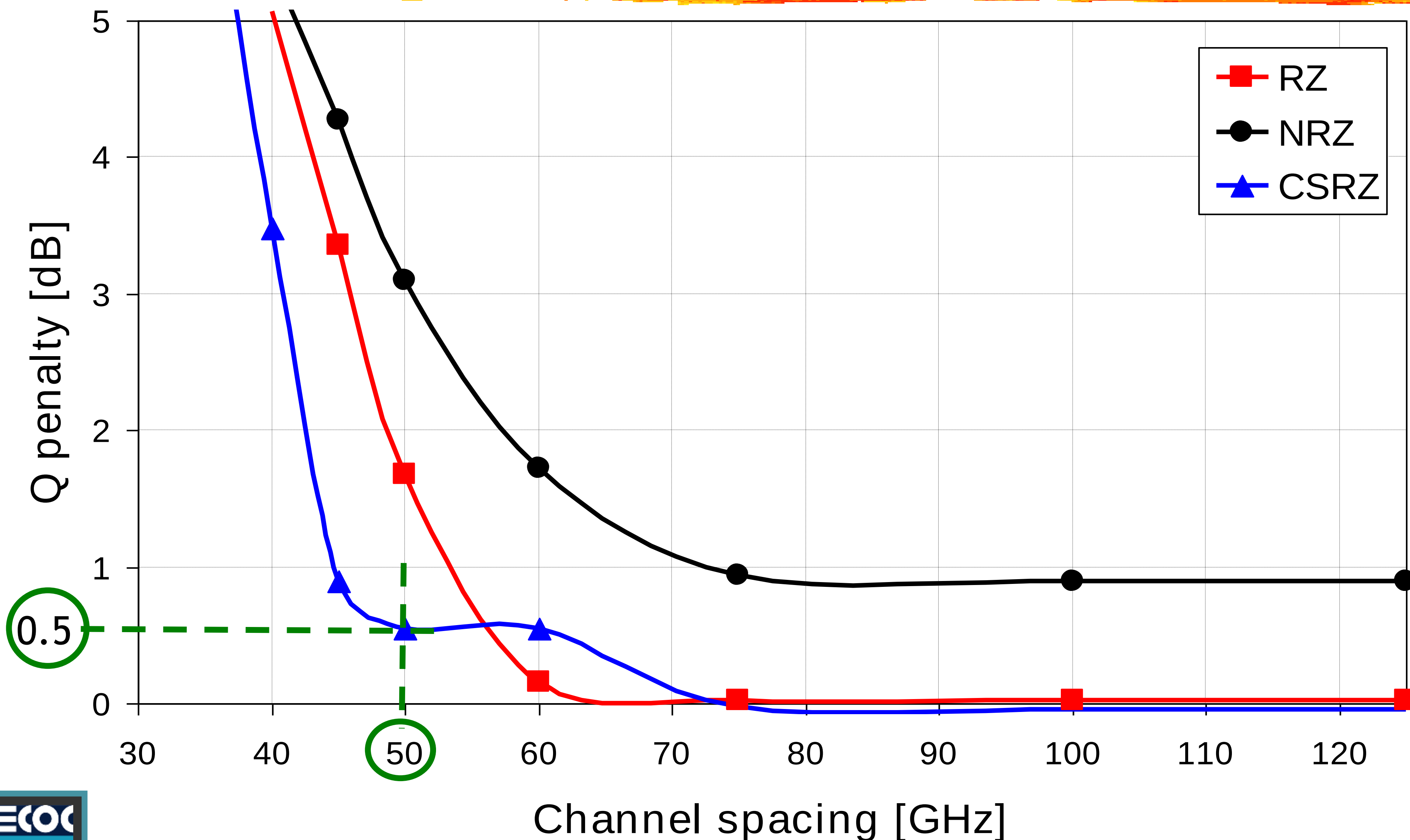
- With TX filter
- Co-polarized channels
- Δf = 75 GHz



Note that optimal bandwidths are different for each channel spacing

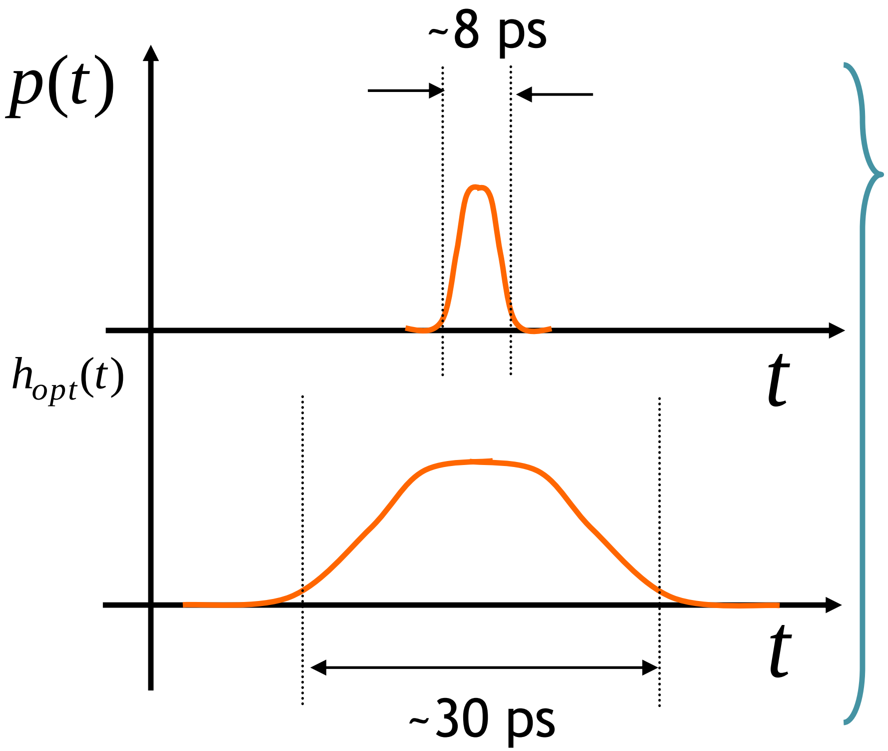


Results with TX filter co-pol



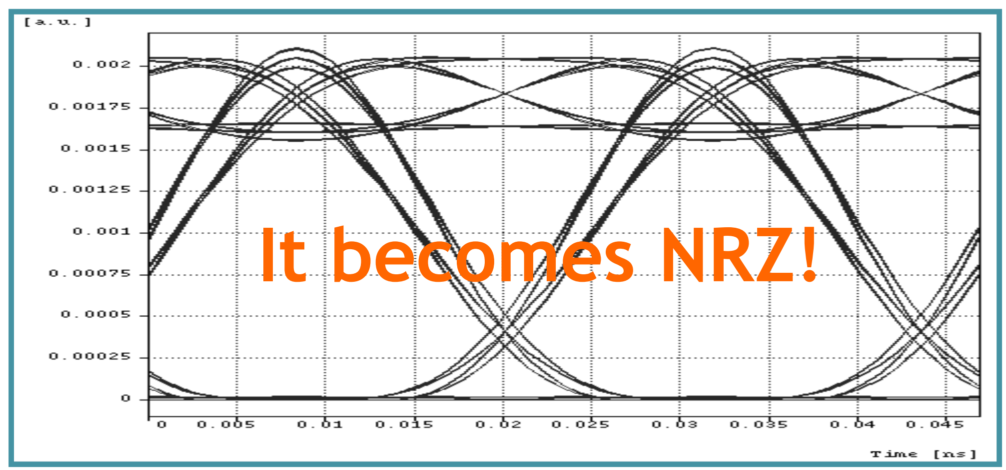
What happens to RZ?

Signal at the output of the TX optical filter → $$E_F(t) = \left\{ \sum_n a_n p(t - nT_b) \right\} * h_{opt}(t)$$



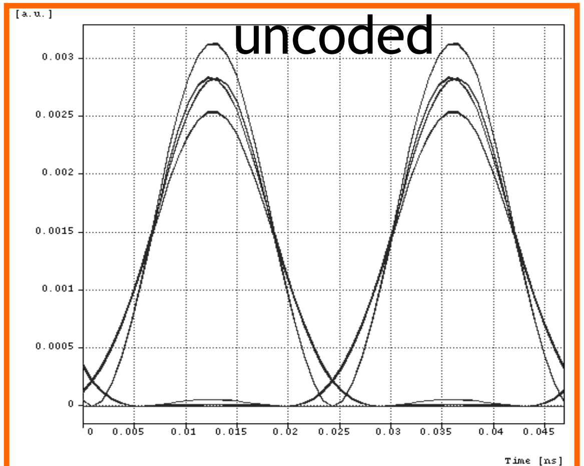
$$p(t) \approx \delta(t) \rightarrow E_F(t) \approx \sum_n a_n h_{opt}(t - nT_b)$$

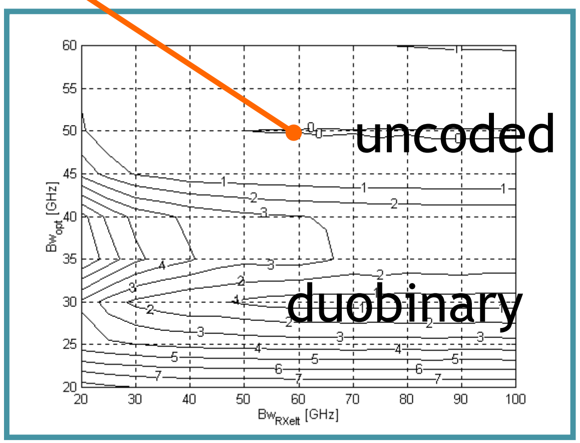
Noiseless eye-diagram after TX filter



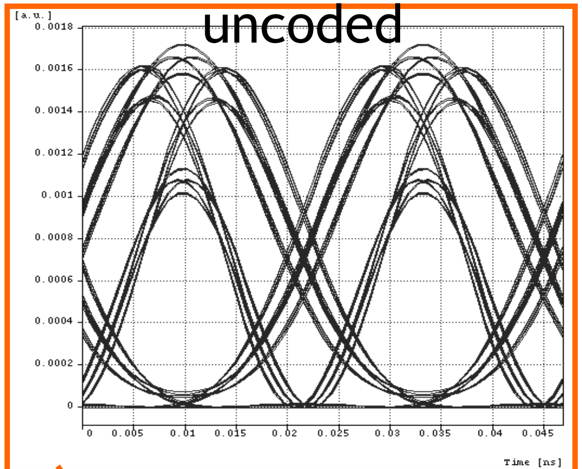
What happens to CSRZ?

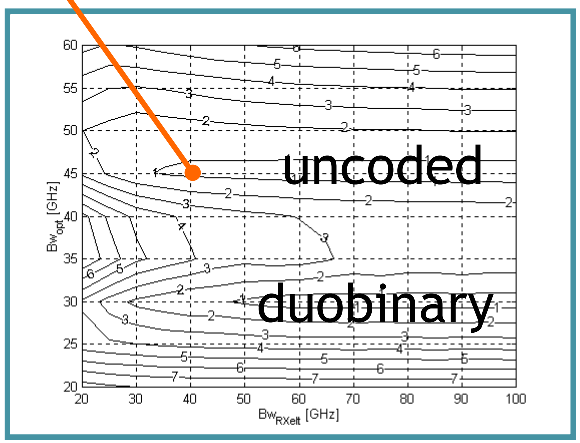
Δf = 75 GHz



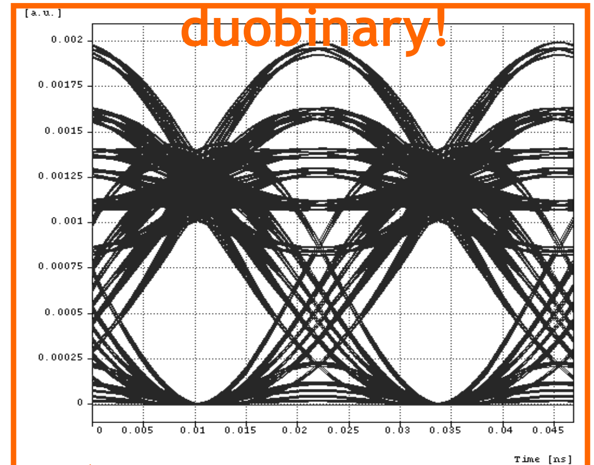


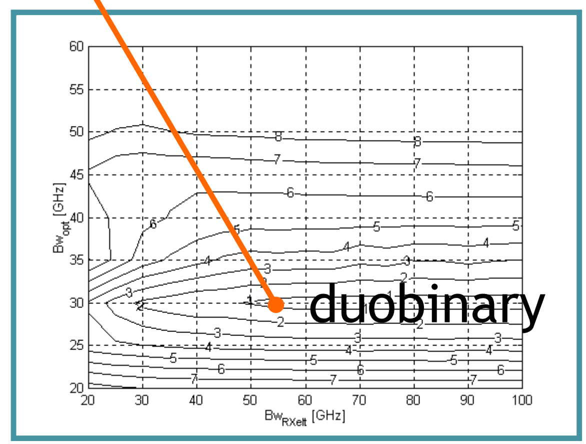
Δf = 60 GHz



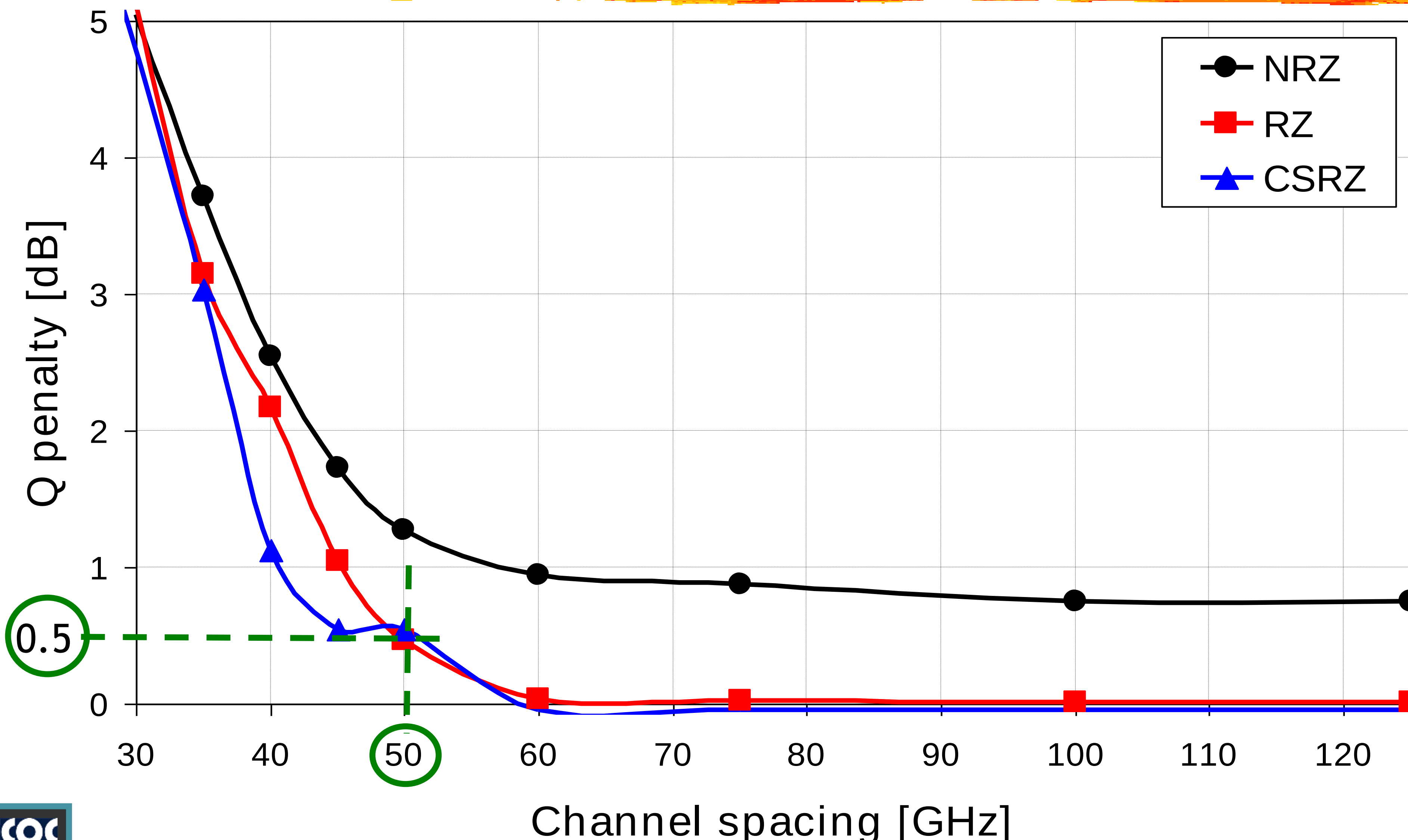


Δf = 50 GHz





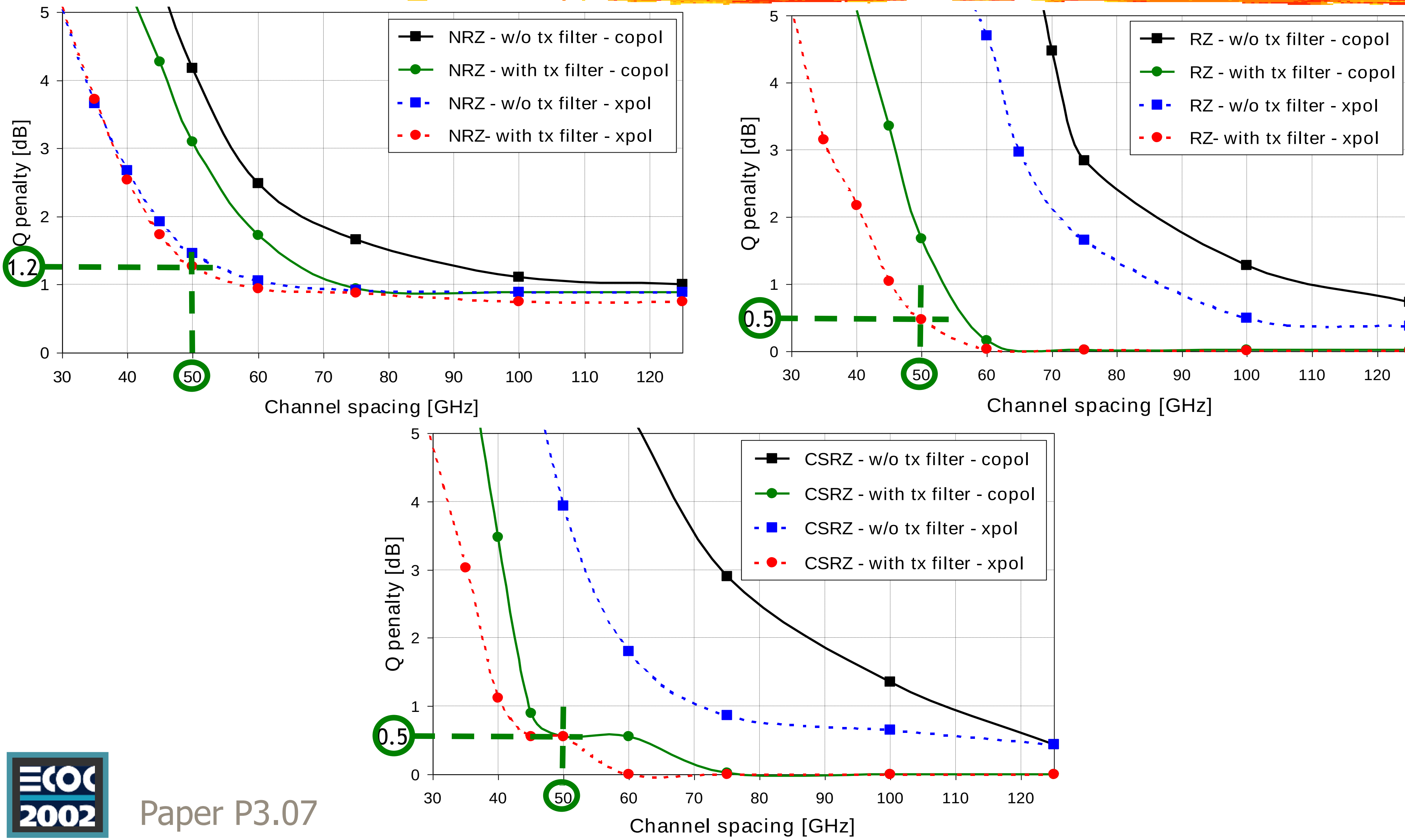
Results with TX filter X-pol



Comments on the use of TX optical filter

- TX optical filter gives **advantages to RZ and CSRZ.**
- TX optical filter may transform **CSRZ into a duobinary coded NRZ** with narrow spectral occupancy that allows its use down to Δf=50 GHz with $Q_{penalty}$=0.5 dB without launch of alternate orthogonal polarization.
- **RZ becomes NRZ** with pulse shape given by the tx optical filter implying the RX optical filter is *almost matched* to the pulse. It implies better performance than NRZ even if $Q_{penalty}$=0.5 dB with Δf=50 GHz needs launch of alternate orthogonal polarization.
- **NRZ does not experience large performance improvements** with the use of TX optical filters. Using this system configuration NRZ has the worst performance among the three analyzed formats, even if launch of alternate orthogonal polarization on adjacent channels is used.

Summary of results



Conclusions

- *Standard* (no TX filter) RZ and CSRZ modulation formats are not suitable for use in UDWDM systems with Δf < 100 GHz, while *standard* NRZ can go down to $\Delta f \approx$ 75 GHz with $Q_{penalty}$ = 1 dB.
- Introducing an optical filter at the transmitter side, RZ and CSRZ can reach Δf = 50 GHz with a penalty smaller than 0.5 dB. Good performance of CSRZ is due to duobinary coding introduced by the TX optical filter, while RZ performs well because it becomes NRZ with pulse shape *almost matched* to the RX optical filter.

Acknowledgements

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