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# Numerical analysis and system optimization for 100 Gbit/s carrier Ethernet serial modulation formats

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ABSTRACT

The performance of various modulation schemes for 100 Gbit/s single-channel serial transmission is investigated by means of numerical simulations. Different ASK and PSK modulation formats are compared in terms of total system reach for a $10^{-9}$ BER requirement. RZ-DQPSK format with a 1920 km reach, without FEC and without the support of additional Raman amplification, outperforms all the other schemes including $10 \times 10$ Gbit/s NRZ DWDM inverse multiplexing.



## 1. Introduction

In recent years, the public demand for broadband internet access has grown strongly, fueling the exponential increase of internet traffic. Besides broadband internet access, new high-definition video services along with business customers needs constitute nowadays the key driver for further increasing bandwidth demand. Indeed this demand extends the current broadband leased lines (based on circuit switched layer 1 peer-to-peer and/or virtual private networks) by using dedicated high-speed optical transport hierarchy and wavelength division multiplexing (OTH/WDM) channels.

To support this high bandwidth demand, network operators and service providers need to upgrade their access, aggregation, and core networks. Although some network operators have started to deploy 40 Gbit/s dense wavelength division multiplexing (DWDM) systems, the 100 Gbit/s carrier grade Ethernet technology is already considered a reasonable alternative for a large scale system roll-out of next generation DWDM networks [1,2]. Hence, 100 Gbit/s interface line rates are being already standardized for high-speed Ethernet and for efficient internet protocol (IP) router interconnection applications and will probably be introduced in the mid 2010.

Consequently, a request for long-haul transport supporting this logical interface format will follow as the next step. Besides the purely serial on–off-keying (OOK) transmission solution, multi-level phase shift keying modulation formats (e.g. DQPSK) or inverse multiplexing of several parallel lower-speed DWDM channels (e.g. $10 \times 10$ Gbit/s) may be applied. Moreover, the decision-making process will be mainly dominated by investment costs: transponder complexity and fiber link utilization efficiency. This last requirement includes a high spectral efficiency as well as significant, optically transparent, transmission distances; both of which need to be studied and characterized for all possible modulation format candidates.

This paper investigates numerically the performance of different 100 Gbit/s single-channel serial transmission solutions. They are eventually compared to the alternative inverse multiplexing concept based on a standard 10 Gbit/s per wavelength DWDM scheme. Note that the inverse multiplexing scheme differs from the classical demultiplexing technique in that each of the 10 Gbit/s channels contains a part of the same 100 Gbit/s data stream. Various amplitude shift keyed (ASK) and phase shift keyed (PSK) modulation formats are compared in terms of chromatic dispersion tolerance and system reach under specific conditions representative for real networks. For the first time, to the best of our knowledge, the system reach tolerance (of five different formats) with respect to variations of the single mode fiber (SMF) and dispersion compensating fiber (DCF) input powers is characterized for a fixed $10^{-9}$ BER target. Optical Raman amplification and electronic forward error correction (FEC) are not considered in this study. The compared modulation formats include:

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- Non-return-to-zero, NRZ.
- Return-to-zero, RZ, with various duty cycles.
- Carrier-suppressed-return-to-zero, CS-RZ.
- Differential (quaternary) phase shift keying, NRZ-D(Q)PSK and RZ-D(Q)PSK.
- Optical duobinary, ODB.
- Non-return-to-zero vestigial sideband, NRZ-VSB.
- $10 \times 10$ Gbit/s NRZ (DWDM).

## 2. Simulation set-up and parameters

The simulated system set-up is shown above in Fig. 1. A transmitter block ($T_x$, PRBS $2^{10}-1$) is followed by the first – 100% post-compensated – span of the transmission line consisting of an erbium-doped fiber amplifier (EDFA) with a noise figure (NF) of 5 dB. After the EDFA an amplified optical signal with an average power $P_{SMF}$ is launched into the transmission fiber. A separate EDFA with the same NF is used to control the power launched into the dispersion compensating fiber (DCF), $P_{DCF}$. The receiver block ($R_x$) includes a 100 GHz bandwidth 1st order Gaussian optical filter aimed to remove the out of band noise. One or two delay interferometers are used for optical demodulation in the case of (N)RZ-DPSK and (N)RZ-DQPSK formats, respectively. Finally, balanced detection with electrical (1st order Bessel function) filtering is used to detect the signal. An eye analyzer (EA) provides the eye opening (EO) of the received signal.

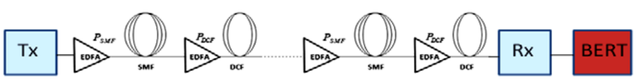


**Fig. 1.** Block diagram of the simulated set-up using the following fiber parameters: $\alpha_{SMF} = 0.21$ dB/km, $D_{SMF} = 17$ ps/nm/km, $\Delta D_{SMF} = 0.056$ ps/nm$^2$/km, $\gamma_{SMF} = 1.317$ 1/W/km $\alpha_{DCF} = 0.5$ dB/km, $D_{SCF} = -100$ ps/nm/km, $\Delta D_{DCF} = -0.3294$ ps/nm$^2$/km, $\gamma_{DCF} = 5.27$ 1/W/km ($\alpha$: attenuation, $D$: chromatic dispersion, $\Delta D$: dispersion slope, $\gamma$: non-linear coefficient).

For ASK formats, BERs are estimated using an analytical bit error rate tester (BERT). This analytical BERT calculates the BER from the received $Q$-factor based on a Gaussian approximation of the optical noise. Although the actual noise distribution is not exactly Gaussian, this method has been demonstrated to give accurate results for low BERs [3,4] and offers therefore an alternative to the prohibitive time-consuming direct bit error counts. In the special case of intensity modulated signals (IM) the BER is thus given by

$$Q = \frac{\mu_1 - \mu_0}{\sigma_1 + \sigma_0}; \quad \mathrm{BER}(Q) = \frac{1}{2} erfc\left(\frac{Q}{\sqrt{2}}\right) \tag{1}$$

where $\sigma_{1,0}$ and $\mu_{1,0}$ are the standard deviation and the mean of the transmitted logical "one" or "zero", and *erfc* is the complementary error function. A more comprehensive mathematical description can be found in Ref. [5].

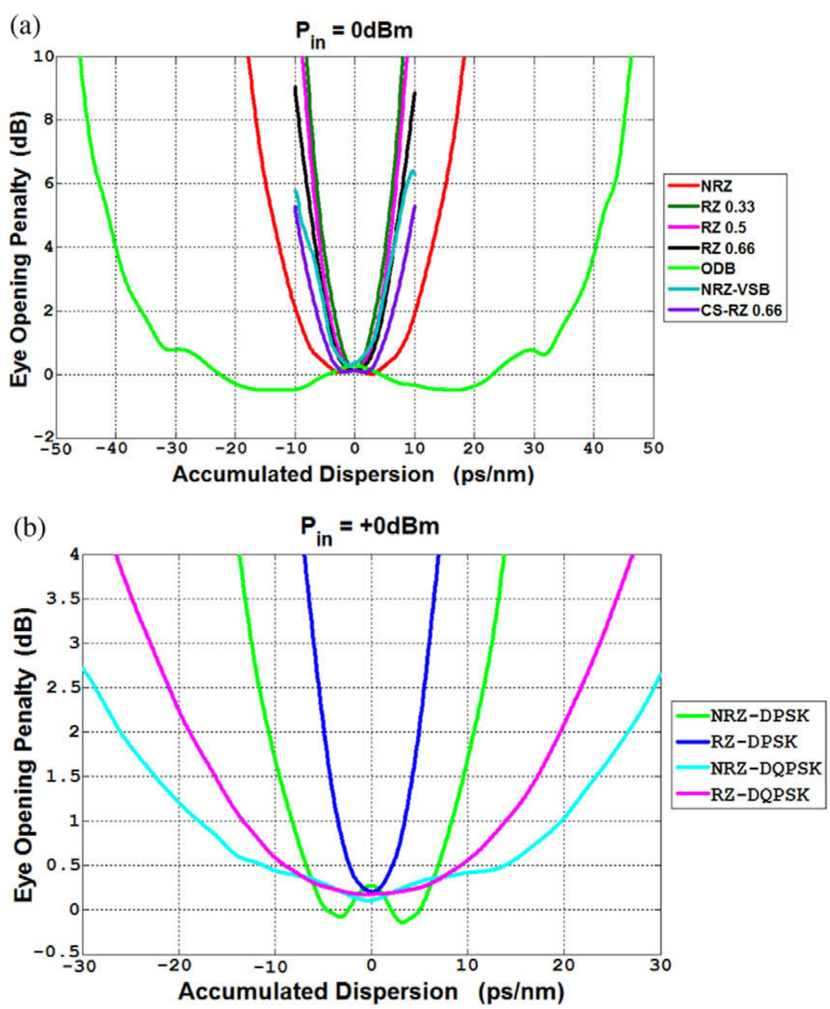


**Fig. 2.** EOP vs accumulated dispersion for different (a) ASK formats and (b) PSK formats.

On the other hand, a fully numerical method based on the tail extrapolation algorithm was chosen for estimating BERs for PSK formats that are affected by the non-linear phase noise present over such distances. Indeed, a direct estimation of the BER from the *Q*-factor can provide in this case inaccurate results, mainly due to the fundamentally non-Gaussian nature of the optical noise in this case, as demonstrated in Ref. [6].

## 3. Dispersion tolerances

When considering such high bit rates, dispersion becomes a serious limitation that network providers have to deal with. Therefore, despite of its deterministic nature, it is particularly important to know precisely the chromatic dispersion compensation (CDC) for each format. In order to estimate the dispersion tolerances (DT), a single-span with only one EDFA (in front of the SMF) and with the DCF length varied in small steps, is compared to a back-to-back scheme. We use the eye opening penalty (EOP) parameter to evaluate the DT of each format since only the CD is considered here without the noise influence. The DT is taken as the region of accumulated dispersion where the EOP remains smaller than 1 dB. Accumulated dispersion here means the total residual dispersion accumulated by the signal while propagating through both the SMF and the DCF fibers. Fig. 2(a) presents the evolution of the EOP with respect to the accumulated dispersion for all the mentioned ASK formats. Whereas Fig. 2(b) shows in the same way this evolution for different PSK formats.

Fig. 2(a) and (b) show the expected trends. Indeed, the EOP increases faster for formats with a broader spectrum, both for ASK and PSK schemes. In addition we see that the ODB format outperforms the whole group due to its very narrow spectrum. Fig. 3 shows as a result the DT taken at 1 dB EOP as mentioned previously. We see that the most tolerant formats are the ODB, NRZ-DQPSK and RZ-DQPSK with an approximate 66, 38 and 27 ps/nm DT, respectively.

It is also important to notice that the (N)RZ-DQPSK scheme, strong of its halved symbol rate, is the most tolerant PSK format to dispersion. Indeed, the DT increases with decreasing symbol rate making the (N)RZ-DQPSK very attractive for $40 \rightarrow 100$ Gbit/s upgrade for the many existing routes initially designed for 10 Gbit/s. Finally, the $10 \times 10$ Gbit/s (DWDM) NRZ scheme with a 50 GHz channel spacing (see Table 1 of Section 4) benefits of a much higher DT with an approximate 1400 ps/nm, but suffers from a significant operational complexity in addition to a very low spectral efficiency.

Fig. 2 was obtained while keeping the input power into the span relatively low (0 dBm as indicated on the top of this figure) so that we can neglect the influence of non-linearities. It is important nevertheless to evaluate the robustness of the investigated DT for an increasing input power. Fig. 4 presents the evolution of the DT with respect to the launched input power for the considered ASK and PSK formats.

Although the ODB format holds the highest DT for low input powers, Fig. 4(a) shows that it has the steepest decline for input powers higher than 6 dBm, making it the format that suffers the most of non-linearities. On the other hand the (N)RZ-DQPSK formats appear to be the most robust with a DT kept above 20 ps/nm over the range [−4,+8] dBm. The halved symbol rate that benefits this format is behind this robustness. Finally, as the non-linearities are more critical for higher number of spans, these last formats would also constitute good candidates from a system reach perspective as shown in the next section.

## 4. System reach

The maximum system reach is defined as the transmission length for which the BER is $\leqslant 10^{-9}$. For ASK formats the BER is calculated directly from the obtained *Q*-factor. On the other hand, a fully numerical method based on tail extrapolation algorithm, first introduced in Ref. [7], was chosen for the considered PSK formats mainly limited by the non-linear phase noise. In fact, 10 blocks of 1024 bits each were simulated to obtain BER estimates in reasonable times.

The tail extrapolation algorithm provides very low BERs from fewer simulated bits, typically $10^4$, $10^5$ bits. A low BER corresponds to a low likelihood for an error to occur; this information being contained in the tail of the probability density, the extrapolation approach is to deduce the tail evolution from the center of the probability density function (PDF) where high error occurrences can be detected. To realize this extrapolation, we assume that the marks' and spaces' PDFs have a generalized exponential shape described by

$$p_x(x) = \frac{\delta}{2\sqrt{2}\Gamma(\frac{1}{\delta})\varepsilon} \exp\left[-\left|\frac{x-m_x}{\sqrt{2}\varepsilon}\right|^{\delta}\right] \tag{2}$$

where $\Gamma$ is the gamma function and $\varepsilon$, $\delta$ are fitting parameters for a least square fit. The BER is then given by

$$\mathrm{BER} = \int_S^{\infty} p_x(x)dx \approx \exp\left[-\left(\frac{S-m_x}{\sqrt{2}\varepsilon}\right)^{\delta}\right] \tag{3}$$

$S$ being the decision threshold that determines whether the bit is a logical 1 or 0.

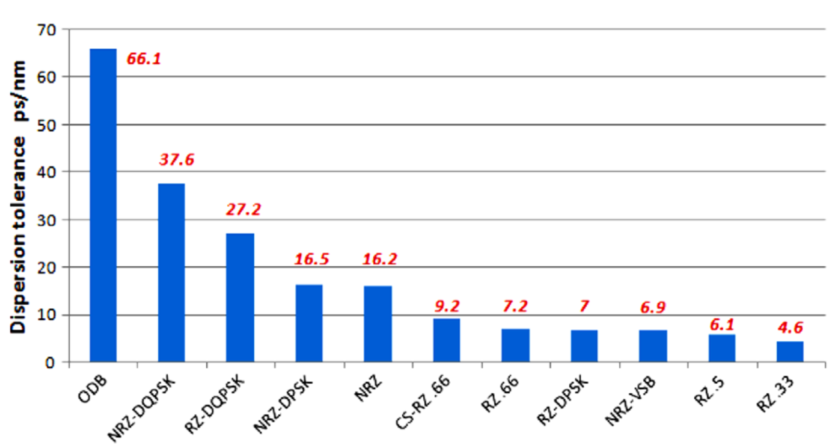


**Fig. 3.** Dispersion tolerances at 100 Gbit/s serial transmission for all ASK and PSK formats.

**Table 1**
System reach in multiples of 80 km SMF spans for a $10^{-9}$ BER target. $\text{Reach}_{\text{ADC}}$ is the alternated dispersion compensation configuration reach. SpecEff refers to the spectral efficiency of the considered format.

| Format | Reach (spans) | Reach (km) | $\text{Reach}_{\text{ADC}}$ (km) | $\text{Improvement}_{\text{ADC}}$ (spans) | SpecEff (bit/s/Hz) |
|---|---|---|---|---|---|
| RZ-DQPSK (NZDF) | 35 | 2800 | – | – | 0.94 |
| RZ-DQPSK | 24 | 1920 | 1440 | −6 | 0.94 |
| RZ-DPSK | 20 | 1600 | 1840 | +3 | 0.54 |
| 10 × 10 Gbit/s NRZ | 20 | 1600 | – | – | 0.22 |
| DQPSK | 17 | 1360 | 1280 | −1 | 1.43 |
| DPSK | 15 | 1200 | 1440 | +3 | 0.71 |
| RZ 0.5 | 11 | 880 | 960 | +1 | 0.54 |
| CS-RZ 0.66 | 11 | 880 | 880 | 0 | 0.56 |
| NRZ | 7 | 560 | 640 | +1 | 0.70 |
| NRZ-VSB | 5 | 400 | – | – | 0.69 |
| ODB | 3 | 240 | 320 | +1 | 1.25 |

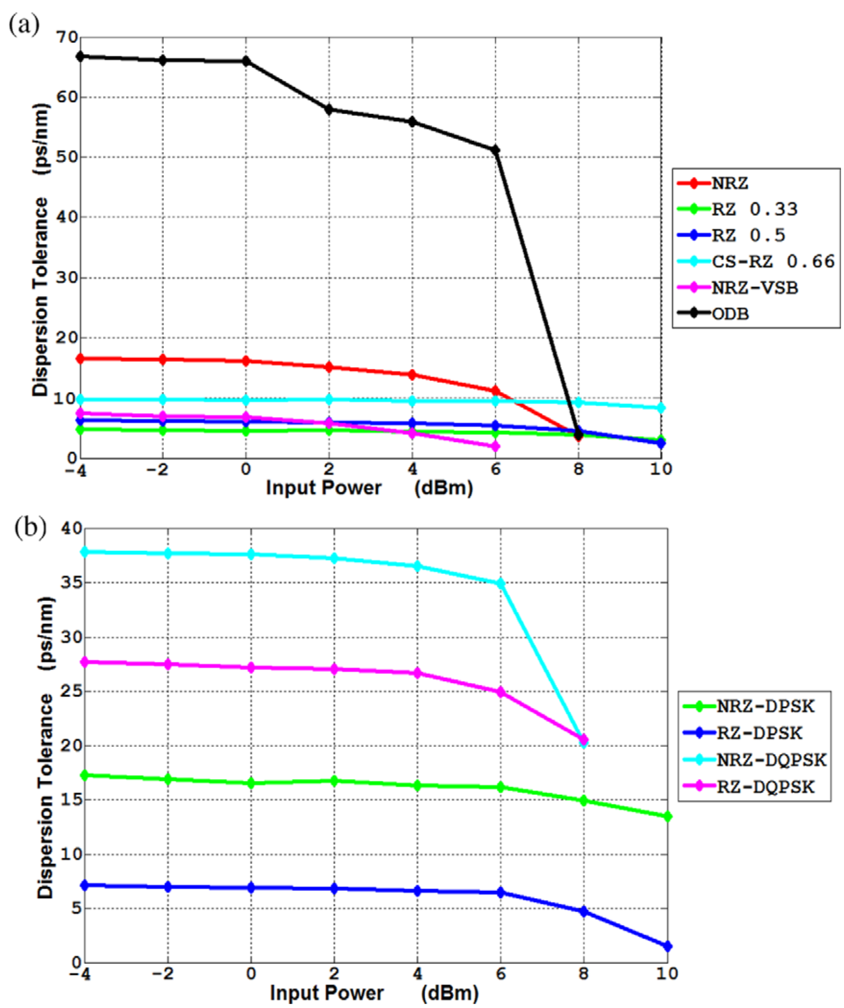


**Fig. 4.** Evolution of the dispersion tolerance for different (a) ASK formats and (b) PSK formats with respect to the launched input power.

In order to find the optimum BER estimate, $S$ is swept over the actual bit error counts range. For every position, the BER is calculated by counting the number of errors and the optimum one is extrapolated using, first, (2) to deduce the best PDF fit and then (3) to solve for the minimum BER value. Fig. 5(a) presents the balanced detected in-phase (I) eye diagram after demodulation of a 100 Gbit/s RZ-DQPSK channel after five spans. Fig. 5(b) shows the log(BER) evolution when the threshold is swept over the eye range. After extrapolation, the optimum BER corresponds to the intersection of the gray and the green curves.[1]

The SMF and DCF input power levels are varied in order to find the optimum balance between limitations due to noise and due to

[1] For interpretation of color in Fig. 5, the reader is referred to the web version of this article.

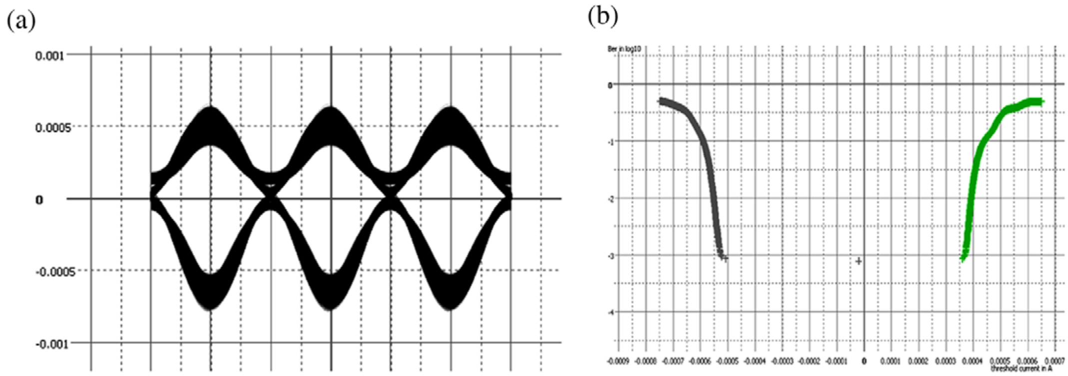


**Fig. 5.** (a) Eye diagram after balanced detection at the receiver side, (b) log(BER) evolution for different threshold values.

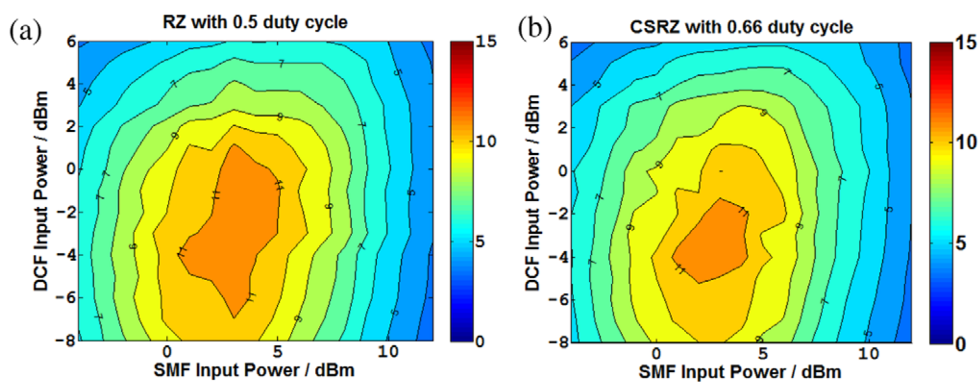


**Fig. 6.** System reach of the two best ASK formats for a $10^{-9}$ BER target. (a) RZ 0.5, (b) CS-RZ 0.66. Note that the third dimension corresponds to the number of spans.

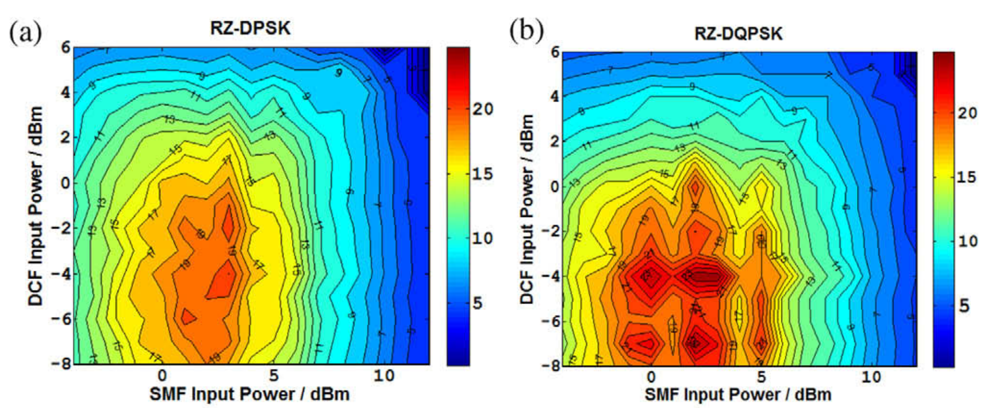


**Fig. 7.** System reach of the two best PSK formats for a $10^{-9}$ BER target. (a) RZ-DPSK, (b) RZ-DQPSK.

fiber non-linearities. The results are presented in Fig. 6 for the two best ASK formats: RZ with 0.5 and CS-RZ with 0.66 duty cycles, respectively. Fig. 7 shows, on the other hand, the two leading PSK formats RZ-DPSK and RZ-DQPSK whereas Figs. 8 and 9 present, respectively, the $10 \times 10$ NRZ (DWDM) scheme over SMF and the RZ-DQPSK one over NZDSF fiber type.

An important observation from Figs. 6 and 7 is the fact that for a given targeted communication distance, the RZ-DPSK and RZ-DQPSK formats give much more input power tolerance than the RZ and CS-RZ schemes. Indeed, if we consider a targeted distance of 10 spans (800 km), the RZ and CS-RZ formats' plots show an SMF input power range of [1,4] dBm and a DCF one of [−6,1] dBm and [−5,−2] dBm, respectively, for these two ASK formats. On the other hand, the RZ-DPSK and RZ-DQPSK illustrate a much more tolerant range of [−5,9] dBm for the SMF input power and [−4,8] dBm for the DCF, for both formats.

Figs. 6 and 7 also show two fundamental results. First, the RZ-DPSK and RZ-DQPSK modulation formats can easily bridge the 1000–1500 km distance range with a numerically estimated BER $\leqslant 10^{-9}$. This first conclusion is very important if we remember that one of the requirements for such systems, in many European size countries, is to always be able to use protection paths, likely to be in this distance range. Second, the considered ASK formats are more suited for metro and short haul applications, due to their low input power tolerance for higher distances applications. Finally, Fig. 8 shows that in addition to a very good dispersion tolerance,

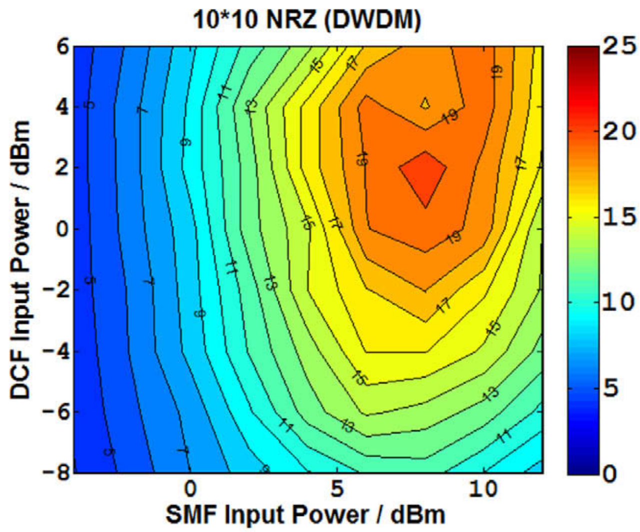


**Fig. 8.** System reach of the $10 \times 10$ NRZ (DWDM) scheme for a$10^{-9}$ BER target. Note that the SMF and DCF input powers accumulated numbers for 10 channels. A simple power shift of $-10$ dB gives the corresponding power per channel.

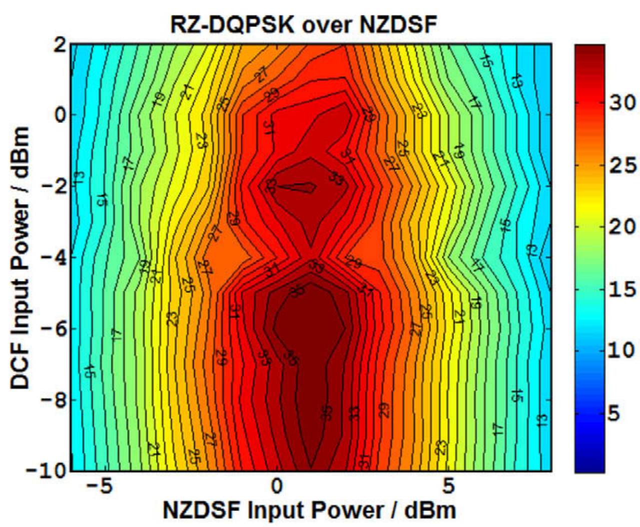


**Fig. 9.** System reach of RZ-DQPSK using NZDSF also for a $10^{-9}$ BER target.

the $10 \times 10$ Gbit/s NRZ DWDM scheme has a good system reach of 1600 km. The main disadvantages remain its very low spectral efficiency as shown below and its significant operational complexity from an operator's point of view.

Table 1 summarizes the obtained results in terms of system reach and spectral efficiency of all the considered ASK and PSK formats. Additionally, this chart presents the system reach, also for a targeted $10^{-9}$ BER, of an alternating dispersion compensation scheme which is known for its ability to extend link lengths [8,9]. The RZ-DQPSK format, providing the longest system reach, was also investigated for a non-zero dispersion shifted fiber type (NZDF). This lead to another significant reach extension of 11 more spans to a total of 2800 km as shown in Fig. 9 and Table 1.

Table 1 illustrates the two categories that appear when considering system reach. Indeed, the entire PSK formats are found to have a minimum reach of 1200 km with a maximum of 2800 km for the RZ-DQPSK format using the NZDF fiber type. On the other hand the ASK schemes range between 240 km and 880 km for the RZ format with 0.5 duty cycle. Furthermore, despite all its advantages mentioned previously, the $10 \times 10$ Gbit/s NRZ (DWDM) scheme has the worst spectral efficiency with 0.22 bit/s/Hz, making its use comparably inefficient for 100 Gbit/s carrier Ethernet.

Finally, in these simulations, (N)RZ-DPSK formats are found to have less reach than (N)RZ-DQPSK despite a higher robustness to non-linearities. This result might find an explanation in the fact that the total input power into the DCF was kept relatively small to prevent long simulation times due to the DCF high non-linear coefficient $\gamma_{DCF}$ = 5.27 1/W/km. Indeed the DCF role in our case was just to compensate exactly for the accumulated dispersion, the non-linearities coming mainly from the propagation in the SMF over several spans. Moreover, the system reach was considered for a $10^{-9}$ BER requirement based on an extrapolation that has its intrinsic error for such low BERs; this can affect the accuracy of the found reach values as well. Nonetheless, for an alternated dispersion compensation scheme, the (N)RZ-DPSK reach normally outperforms the (N)RZ-DQPSK one as shown in column 4 of Table 1.

## 5. Conclusion

Performance of 100 Gbit/s serial transmission was investigated by means of numerical simulations. While the ODB format was found to be the most tolerant to dispersion (for low enough input powers), making it suitable for short haul 10 → 40 Gbit/s upgrade, the RZ-DQPSK format, with 1920 km reach and 0.92 bit/s/Hz spectral efficiency, outperforms all other schemes including the $10 \times 10$ Gbit/s NRZ DWDM inverse multiplexing that suffers from a very low spectral efficiency. A higher spectral efficiency can also be added to this format using polarization [10] or new subcarrier multiplexing techniques [11].

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