9 Optimum Modulation Formats For Future 100 Gbit/s Carrier Ethernet

Cornell Gonschior, FH Gießen-Friedberg, Friedberg

Authors
Gonschior, Cornell: Dipl.-Ing. (FH), FH Gießen-Friedberg
Klein, Karl-Friedrich: Prof. Dr.-Ing., FH Gießen-Friedberg
Küppers, Franko: Prof. Dr.-Ing., Optical Sciences Center, University of Arizona, Tucson
Vorbeck, Sascha: Dipl.-Ing., T-Systems Enterprise Services GmbH

Abstract
We investigated numerically the transmission performance of 100 Gbit/s serial transmission intended to be implemented with future Carrier Ethernet. Different modulation formats, e. g. DQPSK and ODB, were compared. The properties analyzed are sensitivity, chromatic dispersion tolerance and system reach. The modulation format found best suitable for 100 Gbit/s was compared to 10x10 Gbit/s WDM transmission.

Introduction
In recent years the public demand for broadband internet access has grown strongly. At the same time the internet traffic increased exponentially, especially due to use of voice and video services. To support this increasing bandwidth demand the network operators and service providers need to upgrade their access, aggregation and core networks. Although some network operators are starting to deploy 40 Gbit/s technology, the 100 Gbit/s technology is considered to be a more reasonable upgrade. Compared to the widely deployed 10 Gbit/s technology this would be a ten fold increase in capacity with an development effort not significantly larger then for 40 Gbit/s.
For this paper computer simulations were used to investigate the physical properties of various modulation formats suggested for 100 Gbit/s serial transmission. The modulation formats that are investigated are *non-return-to-zero* (NRZ), *vestigial sideband* (VSB), *optical duobinary* (ODB), *return-to-zero* (RZ) and *carrier-suppressed return-to-zero* (CS?RZ) *on-off-keying*, *differential binary-phase-shift-keying* (DPSK) and *differential quaternary-phase-shift-keying* (DQPSK) modulation, with and without 50 %-RZ carving. Additionally a 10x10 Gbit/s *dense wavelength division multiplex* (DWDM) system was simulated to compare to a parallel transmission scheme. The carrier frequency in all simulations is 193.1 GHz, corresponding

Table 1: Parameters of the deployed fibers

Type	**Dispersion/ps/** $(nm \cdot km)$	**Dispersion slope/ps/**$(nm^2 \cdot km)$	**Loss/ dB/km**	**Nonlinear coefficient/ 1/**$(W \cdot km)$
SSMF	17	0.056	0.21	1.317
DCF	-100	-0.3294	0.5	5.27

to a wavelength of 1552.5 nm in the ITU-T recommended C-band. The properties that are compared are the sensitivity, the *eye opening penalty* (EOP) versus accumulated *chromatic dispersion* (CD), chromatic *dispersion tolerance* (DT) versus input power and system reach. A *pseudo-random bit sequence* (PRBS) with a length of $2^{10}-1$ bit was used. The simulation tool was PHOTOSS[1] with version 4.00.

Fiber

A reference configuration similar to the system deployed by the Deutsche Telekom AG in Germany is simulated. It employs *standard single-mode fiber* (SSMF) and uses fiber spans of 80 km in length. The *dispersion compensation fiber* (DCF) is also a standard type and its dispersion slope is matched to the SSMFs (see table 1).

The DCF had a length of 13.6 km to compensate the accumulated CD of an 80 km span of SSMF. The relative dispersion slope of the DCF was adapted and is $3.29410^{-3} nm^{-1}$ for both fibers. If not mentioned otherwise, the elastic nonlinear effects were simulated for the fiber.

Modulation formats

The three basic modulation methods NRZ, RZ and CS-RZ are generated with a programmable pulse generator built-in model in the simulation tool. The NRZ signal keeps the maximum level for a series of '1's. For RZ and CS-RZ signals the level of the pulse returns to zero within the bit period. To obtain the CS-RZ format a phase switch of p is introduced after every bit. The ratio of the full-width half-maximum (FWHM) period and the bit period is the dimensionless *duty cycle* (DC): $DC = T_{FWHM}/T_{bit}$. The DCs investigated are the traditional DCs 33 % and 50 % for RZ and 67 % for CS-RZ.

For generating the VSB modulation an NRZ signal is filtered with a Gaussian optical filter that was modeled from [1]. The lower sideband was partially suppressed and as a side effect

[1] `http://www.photoss.de`

the signal had a chirp.
In order to generate the ODB signal a NRZ signal with the differentially encoded PRBS is low-pass filtered and fed into a *Mach-Zehnder modulator* (MZM) to modulate a CW laser. The low-pass filter is an ideal duobinary generating filter taken from [2]. The bit sequence is correlated and some *intersymbol interference* (ISI) is introduced into the system. But as a side effect the bandwidth of the signal becomes narrower [3].
The five *on-off-keying* (OOK) modulation methods have the same receiver. It consists of an optical band-pass filter, a photo diode and an electrical low-pass filter.
The *phase shift keying* (PSK) formats modulate the phase of the signal, while the amplitude of the signal stays the same. For all other modulation methods simulated the symbol rate is the same as the bit rate, but for DQPSK the symbol rate is half the bit rate. Two bits are combined into one symbol, each symbol representing a phase change with 90° difference between them. The PSK formats are generated with a MZM which modulates the phase of a CW laser. The resulting signal can be carved using another MZM to obtain a RZ format. For DQPSK the whole modulator is mirrored and two different precoded PRBSs are generated, for I and Q channel. Both signals are combined with a 90° shift which results in two subchannels.
For demodulation of the PSK formats a *Mach-Zehnder-interferometer* (MZI) with a delay of one symbol is needed. The two output signals are independently demodulated and added. This delay-and-add is a differential decoder that reverses the differential encoding. For DQPSK only the I channel is received and analyzed.
The DWDM system used for comparison here is similar to deployed ones and has 10 channels at 10 Gbit/s each. For the transmitter ten 10 Gbit/s NRZ programmable pulse generators were set up in parallel with 16 bit delay between adjacent channels for decorrelation. The signals are filtered with a first order Gaussian optical band-pass with 20 GHz FWHM bandwidth and spaced using a ITU grid with 50 GHz channel spacing. The channels received and analyzed are the lower, at 192.85 THz, the center, at 193.1 THz, and the upper channel, at 193.3 THz.

Sensitivity

In order to measure the sensitivity of the various modulation methods a back-to-back situation was created. An OSNR adaption stage follows the modulation generator and feeds the receiver, which is followed by a *bit error rate tester* (BERT). The OSNR was varied and the BER was recorded for every step. The sensitivity is defined as the *optical signal-to-noise ratio* (OSNR) at which the *bit error rate* (BER) is 10^{-9}. See figure 1 for a comparison of all sensitivities.
The RZ formats have a slightly better sensitivity compared to NRZ and it is best for a duty cycle DC = 50 % with 1 dB advantage over NRZ. But the differences are very small and could

not be measured in a real world system. The VSB modulation has a sensitivity that is about 1.5 dB worse than NRZ and the ODB signal has an even lower sensitivity, but can be improved with residual chromatic dispersion, inserted using a certain length of fiber. Because the best eye opening penalty for ODB is at an absolute rest of about 15 ps/nm of accumulated CD.

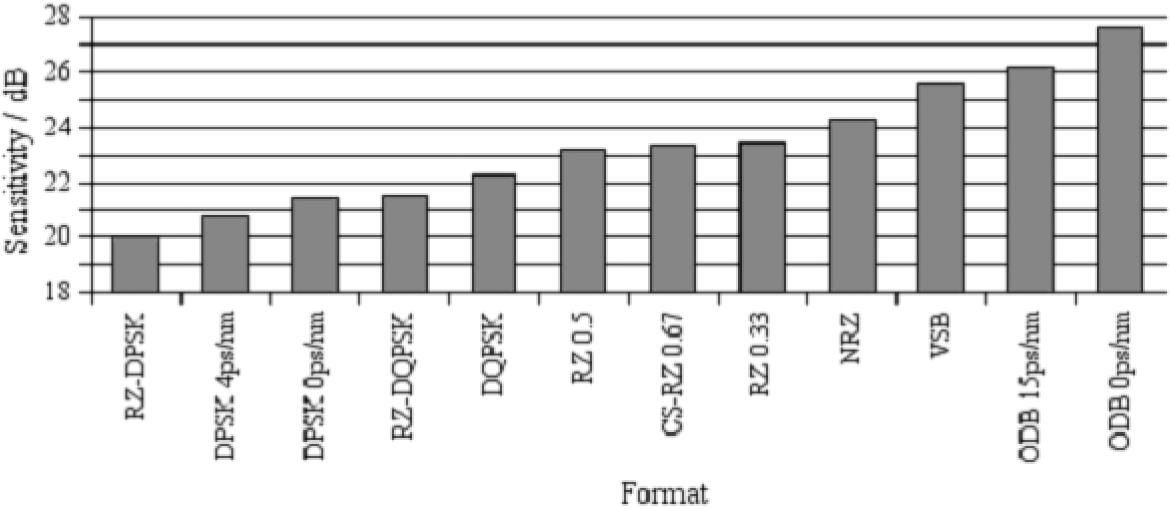

Fig. 1: Comparison of sensitivities of the serial modulation formats.

For the PSK formats numerical noise was used, which should give more realistic results than analytic Gaussian noise. The values received are only a little bit better than values reported from the experiments in [4] and [5]. The modulations with the RZ carving have a sensitivity that is also about 1 dB better than DPSK and DQPSK. The sensitivity for DPSK was improved with a residual CD of 4 ps/nm.

All three channels of the 10x10 Gbit/s that were analyzed had a sensitivity of about 14.9 dB.

Eye opening penalty

To calculate the dispersion tolerance the first step is to measure the eye opening penalty for a range of accumulated chromatic dispersion. The pulse spreading increases with accumulated

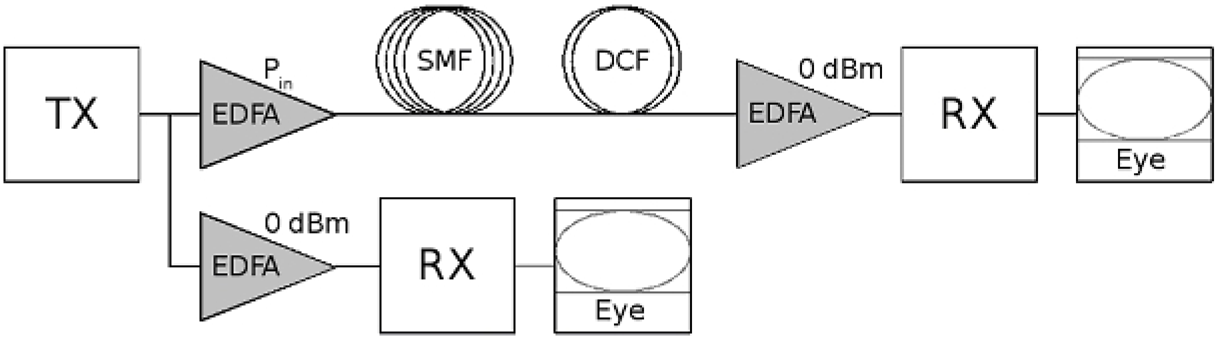

Fig. 2: Setup for EOP simulation with transmission path atop.

CD for a fixed spectral bandwidth leading to lower *eye opening* (EO). The EOP was calculated as the logarithmic ratio of a reference and a transmission path: $EOP = 10 \cdot log_{10}(EO_{b2b}/EO_{path})$. Where EO_{b2b} is the EO of a reference and EO_{path} the EO of the transmission path with 80 km SSMF span and a DCF (see fig. 2). The length of the DCF was varied around the compensation point of 13.6 km. The EOP is also supposed to increase with the input power P_{in} into the transmission fiber, because of the increase of nonlinear effects.

The SSMF was simulated with nonlinear effects, the DCF was not, to ensure no additional degradations due to nonlinear effects in the DCF are added. The *erbium-doped fiber amplifiers* (EDFAs) all have a noise figure of NF = 5 dB.

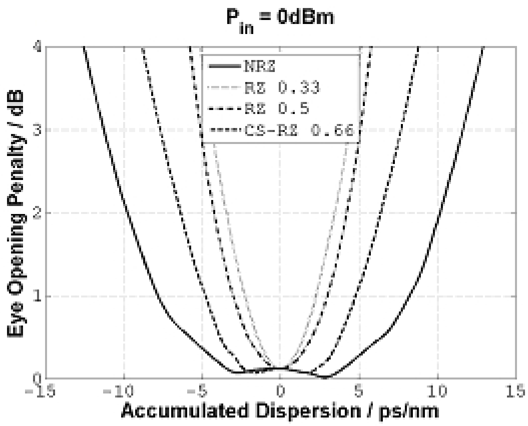

Fig. 3: EOP for RZ and CS-RZ with a P_{in} of 0 dBm compared to NRZ.

For a lower duty cycle of the RZ format the EOP is higher at the same level of accumulated CD (see fig. 3). The CS?RZ format is slightly better and does not degrade as fast as the RZ format with accumulated CD.

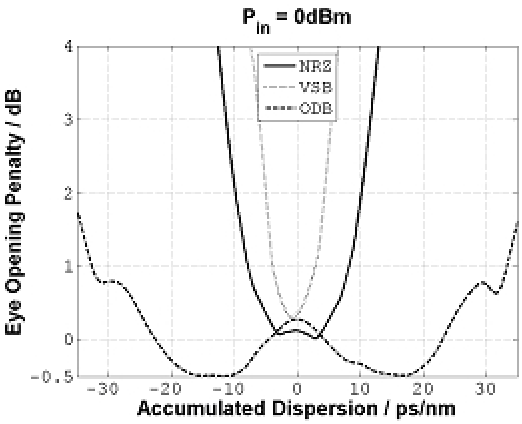

Fig. 4: EOP for VSB and ODB with a P_{in} of 0 dBm compared to NRZ.

The VSB signal cannot hold up to the NRZ signal (see fig. 4), its minimum EOP is not only about 0.2 dB higher, but the curve is narrower. The chirped pulse causes a slight minimum shift to negative accumulated CD values. Despite the higher EOP of the ODB signal when completely compensated the EOP decreases with accumulated CD until $\pm 15 ps/nm$ then increases. This gives the curve a distinctive 'W' shape.

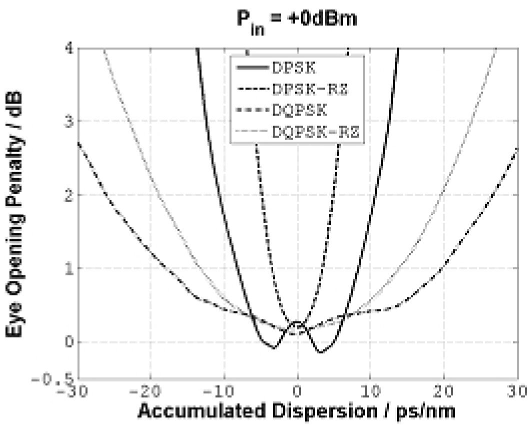

Fig. 5: EOP for DPSK and DQPSK with and without 50 % -RZ carving with a P_{in} of 0 dBm.

The DPSK signal has a similar EOP developing to NRZ, only the center part is 'W' shaped, as ODB (see fig. 5). The shape is lost with the RZ carving of the DPSK signal. The DQPSK has only half the bandwidth of the DPSK signal, therefore the curve is wider. Again the RZ carved signals have a narrower EOP curve.

Dispersion tolerance

In this paper the dispersion tolerance is defined as the distance between the negative and positive points of accumulated chromatic dispersion where the EOP is 1 dB. If the EOP curve

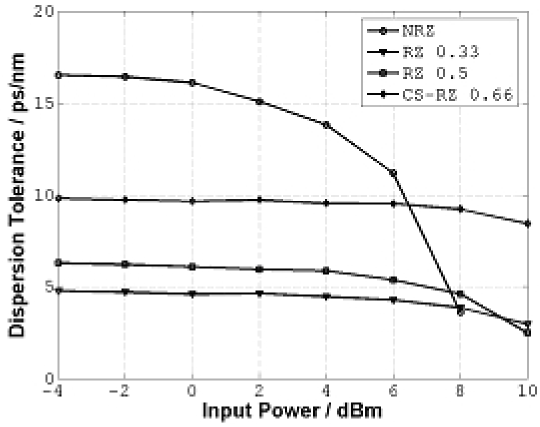

Fig. 6: Dispersion tolerance for RZ and CS-RZ compared to NRZ.

passes the 1 dB line more than twice, then only the part where the EOP is lower than 1 dB is used for the DT calculation. If the DT is plotted versus the input power P_{in} of the transmission fiber it shows how the modulation formats manage nonlinearities.

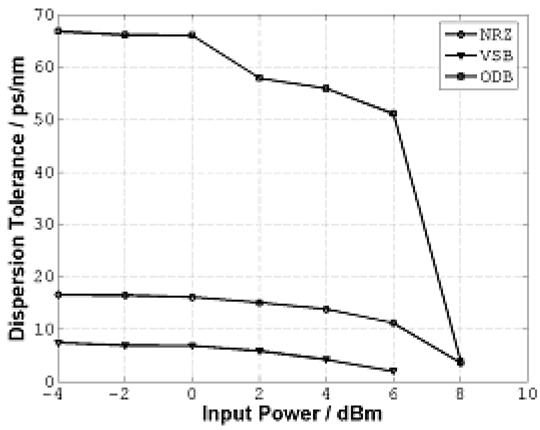

Fig. 7: Dispersion tolerance for VSB and ODB compared to NRZ.

From figure 6 it is easy to see that with a higher duty cycle the RZ signal has more DT. For $P_{in} = 0dBm$ the NRZ modulation has about three times as much DT as RZ 0.33. For $P_{in} = 8dBm$ their DT is about the same, 3.5 ps/nm, and shows that the RZ format is more resistant against nonlinear effects. If the DT values for a linear case are expressed in length of SSMF, then 16.1 ps/nm for NRZ is about $\pm 470m$ and 5 ps/nm for RZ 0.5 is about $\pm 150m$. Therefore the use of *fiber Bragg gratings* (FBGs) in the *dispersion compensation module* (DCM) of a real world system will be necessary. The CS-RZ modulation is more stable in respect to nonlinear effects than RZ although it has a higher DC.

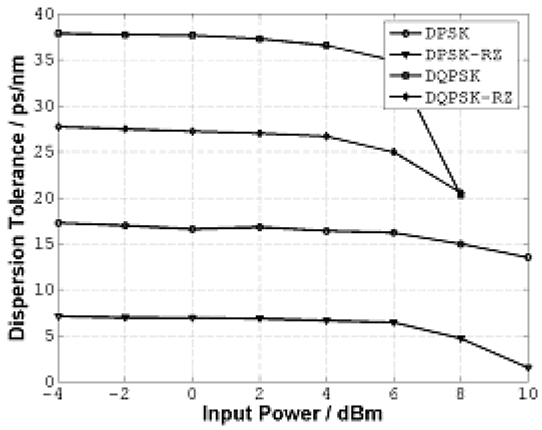

Fig. 8: Dispersion tolerance for DPSK and DQPSK with and without 50 % -RZ carving.

The VSB signal has a low DT compared to NRZ and the maximum input power it can handle is 6 dBm (see fig. 7). ODB on the contrary can hold a high DT at 6 dBm, but than collapses. Its maximum of 66 ps/nm relates to about $\pm 2km$ of SSMF and the 51 ps/nm at 6 dBm is about $\pm 1.5km$.

The DPSK modulation can manage the nonlinear effects very good up to 10 dBm input power (see fig. 8). The RZ carved DPSK does comparably well, but at a lower DT level. The DT of about 37 ps/nm for the DQPSK signal with low input power corresponds to about $\pm 1km$ of SSMF.

The dispersion tolerance scales with the square of the pulse width. Thus about 1600 ps/nm are anticipated for 10 Gbit/s. Due to *inter-channel interference* (ICI) the actual DT is 1400 ps/nm. It corresponds to about $\pm 41km$ of SSMF. All three channels have almost the same DT developing and at an input power of 15 dBm still have a DT of more than 800 ps/nm ($\pm 23.5km$ of SSMF).

System reach

The maximum system reach without *forward error correction* (FEC) was tested by simulating an appropriate number of SSMF spans with a length of 80 km each. A span consisted of an EDFA with a noise figure of 5 dB, the transmission fiber, a second EDFA and a fully

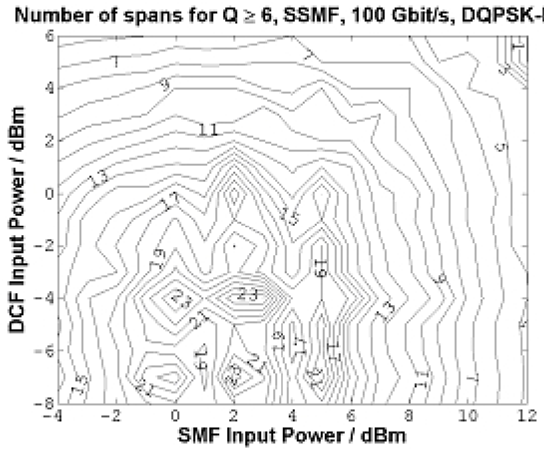

Fig. 9: System reach for RZ-DQPSK

compensating DCF. This complies with a post-compensation scheme. Both fibers are simulated with nonlinear effects. After each span a receiver and a BERT were placed which calculated the Q factor. A BER of 10^9 corresponds to a Q factor of about six. The input power into the SSMF and into the DCF was varied. The Q factor was recorded for every step. In the analysis of the results the number of spans, for which $Q \geq 6$ was given, was plotted on the z-axis versus SSMF and DCF input power on the x- and y-axis respectively. See figure 9 for the resulting plot of the RZ-DQPSK modulation.

The NRZ modulation has a maximum system reach of about 7 spans equaling 560 km. The VSB modulation does worse, it achieves 5 spans. This is due to its bad eye opening penalty performance. Despite great dispersion tolerance the ODB modulation has the worst system reach of 3 spans. When a residual chromatic dispersion of 17 ps/nm is inserted before the receiver then the system reach can be extended by another span to 4 spans.

The maximum system reach of the RZ modulation format degrades from 13 spans for DC = 0.33 to 11 spans for DC = 0.5. Although it has a higher duty cycle CS-RZ keeps up with RZ modulation and has 11 spans as well.

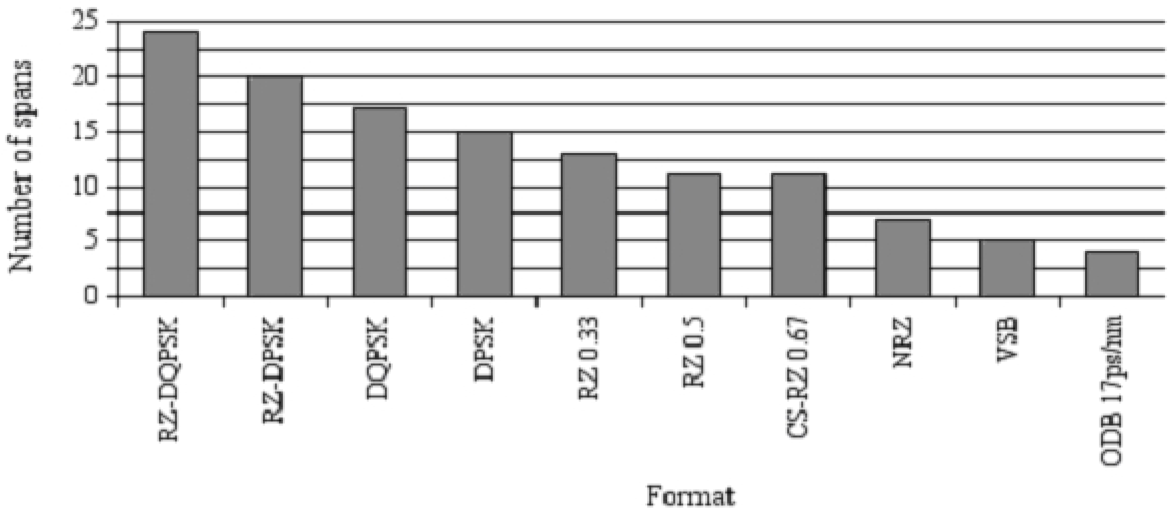

Fig. 10: Comparison of maximum system reach for the serial modulation formats.

The DPSK modulation has a system reach of 15 spans, which is more than for RZ and CS-RZ. With a 50 % -RZ carving the system reach can be enhanced to a total of 20 spans which is 1600 km. The DQPSK maximum reach is 17 spans, but the RZ carving improves the reach to 24 spans. With more than 1900 km this is the overall best and corresponds with the experiment in [5].

The lower channel of the 10x10 Gbit/s DWDM system dictates the system reach and limits it to 20 spans equaling 1600 km. Thus 10x10 Gbit/s transmission is 4 spans short of the RZ-DQPSK.

Conclusion

We presented the properties of various modulation formats for 100 Gbit/s transmission. The ODB format is proposed for in-house connection, because no compensation is needed for up to 2 km of SSMF. Due to its simple modulation and satisfying system reach the NRZ format is proposed for metropolitan and regional networks. DPSK is chosen over an RZ 0.33 or 0.5 format for a long-haul network, because of its better dispersion tolerance and better resistance against nonlinear effects. The proposal for ultra long-haul serial transmission is RZ-DQPSK, simply because of its enormous reach. When comparing the serial transmission performances with the 10x10 Gbit/s DWDM it is obvious that the 10x10 Gbit/s DWDM is only worse in system reach and easier to implement. This approach will be first introduced for 100 Gbit/s systems because of the available technology.

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Contact

Cornell Gonschior
Labor für optische Nachrichtentechnik
Fachhochschule Gießen-Friedberg
Wilhelm-Leuschner-Straße 13
61169 Friedberg/Hessen
e-mail: cornell.p.gonschior@iem.fh-friedberg.de