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Fibre optic communication system design guides

Part 12: In-band optical signal-to-noise ratio (OSNR)

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National foreword

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Fibre optic communication system design guides – Part 12: In-band optical signal-to-noise ratio (OSNR)

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FIBRE OPTIC COMMUNICATION SYSTEM DESIGN GUIDES –

Part 12: In-band optical signal-to-noise ratio (OSNR)

FOREWORD

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IEC 61282-12, which is a technical report, has been prepared by subcommittee 86C: Fibre optic systems and active devices, of IEC technical committee 86: Fibre optics.

The text of this technical report is based on the following documents:

Enquiry draft	Report on voting
86C/1341/DTR	86C/1364/RVC

Full information on the voting for the approval of this technical report can be found in the report on voting indicated in the above table.

This publication has been drafted in accordance with the ISO/IEC Directives, Part 2.

A list of all parts in the IEC 61282 series, published under the general title *Fibre optic communication system design guides*, can be found on the IEC website.

The committee has decided that the contents of this publication will remain unchanged until the stability date indicated on the IEC website under "http://webstore.iec.ch" in the data related to the specific publication. At this date, the publication will be

- reconfirmed,
- withdrawn,
- replaced by a revised edition, or
- amended.

A bilingual version of this publication may be issued at a later date.

FIBRE OPTIC COMMUNICATION SYSTEM DESIGN GUIDES –

Part 12: In-band optical signal-to-noise ratio (OSNR)

1 Scope

The purpose of this part of IEC 61282, which is a Technical Report, is to provide a definition for in-band optical signal-to-noise ratio (OSNR) that is applicable to situations where the spectral noise power density is not independent of the optical frequency, as assumed in the OSNR definition of IEC 61280-2-9, but is significantly shaped across the optical bandwidth of the signal. Considering the development of multiple measurement methods for different use cases, as detailed below, it is desirable to establish a definition of in-band OSNR that is independent of the method used and, furthermore, is consistent with the OSNR definition of IEC 61280-2-9 in the case of frequency-independent noise power density.

2 Normative references

The following documents, in whole or in part, are normatively referenced in this document and are indispensable for its application. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

IEC 61280-2-9:2009, *Fibre optic communication subsystem test procedures – Part 2-9: Digital systems – Optical signal-to-noise ratio measurement for dense wavelength-division multiplexed systems*

3 Terms and definitions

3.1
optical signal-to-noise ratio
OSNR
ratio of total signal power of an optical signal to the amplified spontaneous emission (ASE) noise power spectral density within the optical spectrum of the signal, wherein the power spectral density is normalized to a chosen reference bandwidth

Note 1 to entry: This definition is consistent with the one in subclause 3.1 of IEC 61280-2-9:2009, when the noise power spectral density is constant across the spectral range of the signal, but is used in this document as a generalized collective term for the following set of in-band OSNR definitions that have differing values when the noise power spectral density is not constant across the spectral range of the signal.

3.2
$\mathbf{OSNR_{int}}$
spectrally-integrated in-band optical signal-to-noise ratiospectrally integrated ratio of time-averaged power spectral density of a signal to the power spectral density of the amplified spontaneous emission (ASE) noise, normalized to a chosen reference bandwidth

Note 1 to entry: The spectrally-integrated in-band OSNR, R_{int}, is calculated as

$$R_{\text{int}} = \frac{1}{B_{\text{r}}} \int_{\lambda_1}^{\lambda_2} \frac{s(\lambda)}{\rho(\lambda)} d\lambda \quad (1)$$

where:

$s(\lambda)$ is the time-averaged signal power spectral density, not including ASE, expressed in W/nm;

$\rho(\lambda)$ is the ASE power spectral density, independent of polarization, expressed in W/nm;

B_r is the reference bandwidth expressed in nm (usually 0,1 nm if not otherwise stated);

and the integration range in nm from λ_1 to λ_2 is chosen to include the total signal spectrum.

Note 2 to entry: OSNR_{int} is usually expressed in dB as 10 log(R_{int}).

3.3
OSNR_{avg}
weighted-average in-band optical signal-to-noise ratio

ratio of time-averaged optical signal power to the spectrally weighted average power spectral density of the amplified spontaneous emission (ASE) noise, where the weighting is proportional to the normalized signal power spectral density, and the weighted average power spectral density is normalized to a chosen reference bandwidth

Note 1 to entry: The weighted-average in-band OSNR, R_{avg}, is calculated as

$$\mathrm{R} = \frac{1}{\mathrm{B_r}} \frac{\mathrm{s}}{\frac{\int_{\lambda_1}^{\lambda_2} \rho(\lambda) s(\lambda)\, d\lambda}{\mathrm{s}}} = \frac{1}{\mathrm{B_r}} \frac{\mathrm{s}^2}{\int_{\lambda_1}^{\lambda_2} \rho(\lambda) s(\lambda)\, d\lambda} \mathrm{R} = \frac{1}{\mathrm{B_r}} \int_{\lambda_1}^{\lambda_2} \frac{s(\lambda)}{\rho(\lambda)} d\lambda$$

where:

$s(\lambda)$	is the time-averaged signal power spectral density, not including ASE, expressed in W/nm;
s	is the total signal power, i.e. the wavelength integral of $s(\lambda)$, expressed in W;
$\rho(\lambda)$	is the ASE power spectral density, independent of polarization, expressed in W/nm;
ρ_{avg}	is the spectrally weighted average noise power density, expressed in W/nm, where the weighting is proportional to the normalized signal power spectral density;
B_r	is the reference bandwidth expressed in nm (usually 0,1 nm if not otherwise stated);

and the integration range in nm from λ_1 to λ_2 is chosen to include the total signal spectrum.

Note 2 to entry: OSNR_{avg} is usually expressed in dB as 10 log(R_{avg}).

3.4
OSNR_{max}
maximal-noise in-band optical signal-to-noise ratio

ratio of time-averaged optical signal power to the maximal power spectral density of the amplified spontaneous emission (ASE) noise within the wavelength range of the total signal spectrum, normalized to a chosen reference bandwidth

Note 1 to entry: The maximal-noise in-band OSNR, R_{max}, is calculated as

$$R_{max} = \frac{\int_{\lambda_1}^{\lambda_2} s(\lambda) d\lambda}{B_r\ \rho_{max}} = \frac{s}{B_r\ \rho_{max}} \qquad (3)$$

where:

$s(\lambda)$	is the time-averaged signal power spectral density, not including ASE, expressed in W/nm;
s	is the total signal power, i.e. the wavelength integral of $s(\lambda)$, expressed in W;
ρ_{max}	is the maximal ASE power spectral density within the spectral range of the signal, independent of polarization, expressed in W/nm;
B_r	is the reference bandwidth expressed in nm (usually 0,1 nm if not otherwise stated);

and the integration range in nm from λ_1 to λ_2 is chosen to include the total signal spectrum.

Note 2 to entry: OSNR_{max} is usually expressed in dB as 10 log(R_{max}).

3.5
subcarrier OSNR
$OSNR_{sub}$
in-band OSNR determined for a single modulated subcarrier of a signal consisting of multiple modulated subcarriers at different wavelengths, calculated with only the signal power density of the selected subcarrier

3.6
$OSNR_{sup}$
superchannel OSNR
in-band OSNR determined by including the signal power density of all modulated subcarriers in a multiple-carrier optical signal

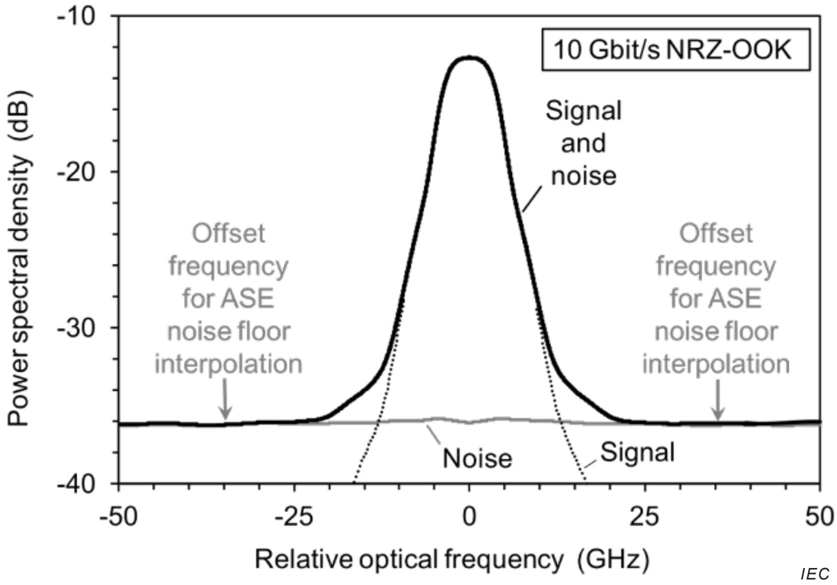
Note 1 to entry: If the signal is polarization-multiplexed, then each polarization tributary of the signal carries only a fraction of the signal power and thus, by itself, has a lower OSNR than the combined signal. This means that for the case of equal power in the two polarization tributaries, the OSNR of a polarization-multiplexed signal is 3 dB higher than that of the two components taken separately. Thus, polarization-multiplexed signals are typically assigned an OSNR value that is 3 dB higher than that for single-polarization signals of the same SNR quality, as if the total power were in a single polarization mode and only interfering with the ASE in that mode. This convention has been widely adopted by the industry, especially because it is supported by the existing measurement functionality of optical spectrum analyzer instruments.

4 Background

4.1 General

In fibre optic communication systems with in-line optical amplification, OSNR is a key parameter to assess system performance. As described in IEC 61280-2-9, OSNR is defined as the ratio of total signal power to the amplified spontaneous emission (ASE) noise power spectral density within the optical spectrum of the signal. In other words, the OSNR is a measure of the signal strength relative to the strength of the underlying ASE noise. However, this widely-used and well-established definition of OSNR assumes that the ASE noise spectrum is essentially flat across the spectrum of the transmitted signals, so that the noise power level can be characterized by a single parameter, i.e. the noise power spectral density.

An important task of measuring OSNR, therefore, is to determine the power spectral density of the ASE noise within the spectrum of the signal. The standard procedure for determining the in-band noise power spectral density is based on out-of-band ASE noise measurements, as described in IEC 61280-2-9 and illustrated in Figure 1. This procedure requires that the optical spectrum of the signal be confined to a relatively small wavelength range of the DWDM channel allocated to the signal, so that the ASE noise power level can be measured on both sides of the signal spectrum. Under the assumption that the ASE noise spectrum is essentially flat, the in-band ASE noise power spectral density can be determined by interpolation of the two noise power measurements on either side of the signal spectrum. The definition of OSNR from IEC 61280-2-9 is given in terms of this out-of-band noise measurement method. This method is especially convenient for DWDM systems because the OSNR of multiple signals can be measured simultaneously in a relatively short time. Furthermore, these measurements can be performed while the system is in service (in-service OSNR measurement).



NOTE The signal power is the integral of the power density after subtracting the ASE density. When the spectrum is measured with an optical spectrum analyzer, the resolution bandwidth is often chosen wider than the complete signal, so that the peak of the measurement trace represents this integral.

Figure 1 – Optical power spectrum composed of a modulated signal and ASE noise

However, three recent developments in optical transmission technology have now added complications to the OSNR measurement defined in IEC 61280-2-9, two of which have already been noted in Annex B of IEC 61280-2-9:2009.

4.2 Higher spectral density of signals

To increase the overall transmission capacity of fibre optic links, the transmitted signals are spaced closer together in wavelength and/or are modulated at higher symbol rates, where the latter results in broader signal spectra [3-4] [1]. Faster modulation rates and closer channel spacing often cause significant overlap of adjacent signal spectra, as illustrated in Figure 2, so that it becomes very difficult – if not impossible – to determine the ASE level between adjacent signals from a simple spectral analysis. Transmission of densely spaced DWDM signals, therefore, greatly reduces the usefulness of the interpolation method described in IEC 61280-2-9. Hence, there is a rising need for alternative methods to measure the in-band noise power spectral density (in-band OSNR measurements).

1 Numbers in square brackets refer to the Bibliography

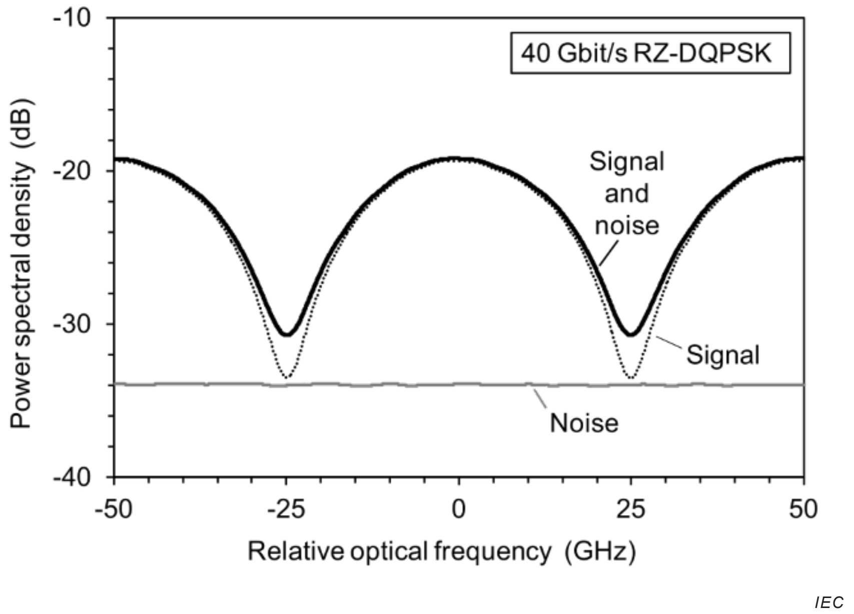


Figure 2 – Optical power spectrum of 50-GHz spaced 40 Gbit/s RZ-DQPSK signals with significant spectral overlap

4.3 Spectral filtering in wavelength-routing elements

The introduction of reconfigurable optical add-drop multiplexers (ROADM) in optical networks gives rise to spectral filtering of the transmitted signals and noise along the fibre optic link [5-6]. This filtering generally attenuates the optical power level between adjacent signal channels, as shown in Figure 3. As a result, power level measurements on either side of the signal spectrum may not be indicative of the ASE noise power spectral density at the signal wavelength. A further consequence of this filtering is that the transmitted ASE noise spectrum is no longer flat, as assumed in IEC 61280-2-9, but spectrally shaped by the transfer function of the ROADMs. Furthermore, the spectral shaping of ASE noise is usually different from the corresponding spectral shaping of the signal because noise is added at intermediate stages along the transmission link. Thus, spectral filtering in ROADMs not only greatly reduces the usefulness of the interpolation method described in IEC 61280-2-9 but also introduces substantial ambiguity in the OSNR measurement, because IEC 61280-2-9 does not define the OSNR of signals with spectrally shaped noise.

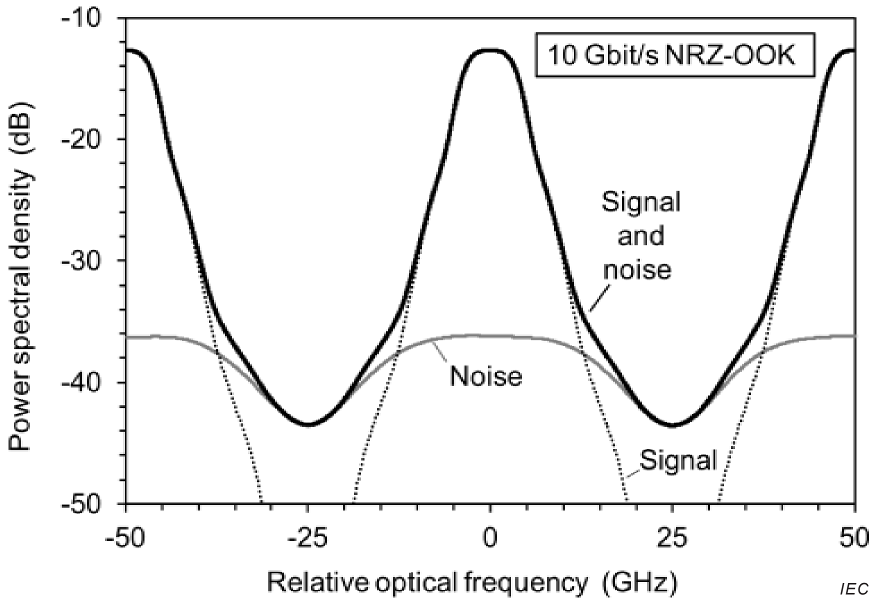


Figure 3 – Optical power spectrum of 50-GHz spaced 10 Gbit/s NRZ-OOK signals after spectral filtering in ROADMs

4.4 Transmission of signals with multiple subcarriers

To further increase the overall transmission capacity without increasing the modulation rate, signals at 100 Gbit/s and above are often composed of multiple modulated optical subcarriers [7-8], as shown in Figure 4. Since all subcarriers of any given signal are sent to the same destination (and hence do not require intermediate guard bands for wavelength routing), they can be spaced very tightly in wavelength. Since the entire spectrum of such multiple-subcarrier signals often extends over more than one 50-GHz-wide or 100-GHz-wide DWDM channel, the question arises whether the OSNR should be determined separately for each individual subcarrier or jointly for the entire multi-subcarrier signal, which is also referred to as an optical "superchannel" [7].

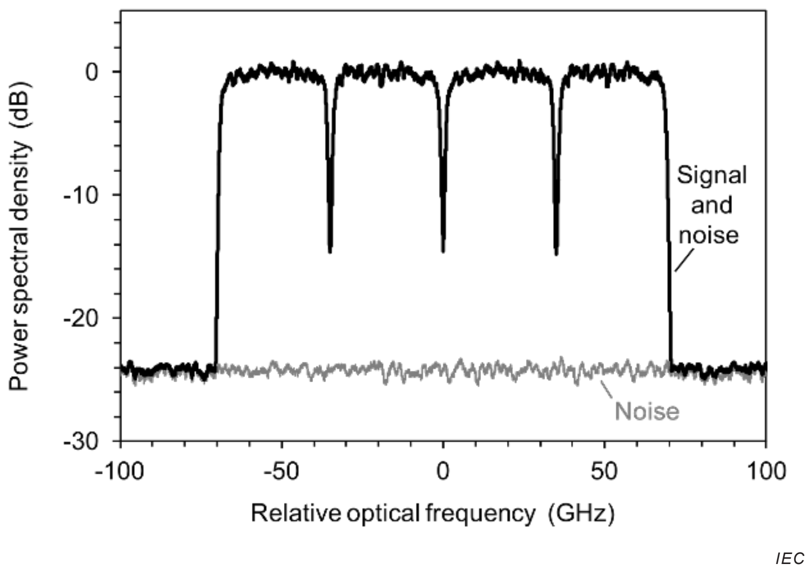


Figure 4 – Optical power spectrum of a 400 Gbit/s optical "superchannel" comprised of four very densely spaced 100 Gbit/s PM-QPSK signals

This Technical Report is intended to provide technical guidance on in-band OSNR measurements on signals that exhibit spectrally shaped noise or are composed of multiple, densely-spaced modulated sub-carriers.

5 In-band OSNR measurement with spectrally shaped noise

5.1 Measurement of in-band ASE noise

To address the technical developments described in 4.2 and 4.3, several measurement methods have been developed to directly measure the in-band ASE noise power spectrum over the entire wavelength range of the signal spectrum. These methods are commonly referred to as in-band OSNR measurements. Just like the interpolation method described in IEC 61280-2-9, these methods are based on a spectral analysis, using a conventional or slightly modified optical spectrum analyzer (OSA). However, the spectral resolution of the OSA has to be fine enough to properly resolve the spectral shape of the ASE noise as well as that of the signal.

Two typical applications where in-band OSNR is measured are performance evaluations of amplified fibre-optic links and sensitivity tests of optical receivers, where OSNR is used as a test condition. The first application usually involves systems where multiple signals are present via dense wavelength-division multiplexing (DWDM), whereas the second application may often involve only a single WDM signal. While the measurement issues for these two cases are somewhat different, both are influenced by technological developments in optical networks, as described below.

With conventional single-polarized signal, it is possible to distinguish the spectral components of the signal from those of the in-band ASE noise because ASE is generally depolarized, whereas the modulated signal is usually strongly polarized. Therefore, a properly orientated optical polarization filter in the input of the OSA may be used to block the highly polarized signal and to pass only the ASE noise that is polarized orthogonally to the signal. It is thus possible to measure the power spectrum of the in-band ASE noise while the system is in service and use this information to calculate the in-band OSNR [9]. This in-band OSNR measurement technique is commonly referred to as the "polarization-extinction" or "polarization-nulling" method.

The above-described polarization analysis becomes more complicated when the signal has experienced significant polarization mode dispersion (PMD) in the fibre link. Because PMD introduces wavelength-dependent variations in the state of polarization of the signal, it may not be possible to simultaneously block all spectral components of the signal. In this case, the orientation of the polarization filter may have to be readjusted for each analyzed wavelength. Moreover, large differential group delay (DGD) can partially depolarize the signal even within the resolution bandwidth of the OSA. This depolarization leads to decreased polarization extinction of the signal and, hence, overestimation of the in-band ASE noise. For example, 40 ps DGD could reduce the polarization extinction to only 99 % over a resolution bandwidth of 4 GHz, which is significant for measuring OSNR in the 20 dB range.

Methods for measuring in-band OSNR via spectral polarization analysis become ineffective (or at least substantially more complicated) when the signal is polarization-multiplexed, i.e. when it is composed of two independently modulated components at the same optical carrier frequency that are multiplexed in mutually orthogonal polarization states. Although polarization-multiplexed signals are highly polarized when measured on a time scale shorter than the symbol period, they appear to be nearly completely depolarized when measured on the much longer time scale of a typical spectral analysis. Therefore, in-band ASE noise of polarization-multiplexed signals cannot be measured with the polarization-extinction method.

Alternatively, the in-band noise spectrum of polarization-multiplexed signals can be measured when the optical signal is turned off (or blocked) at the transmitter. Obviously, this measurement cannot be performed while the system is in service. Hence, it is only an out-of-service measurement. Another disadvantage of this measurement is that the noise power level may increase significantly when the signal is absent, thus leading to an underestimation of the OSNR. In addition, this method may not work in certain ROADM networks, where the optical power and sometimes even the optical spectrum of the transmitted signals are continuously analyzed by optical channel monitors (OCMs). If an OCM does not detect a valid signal in a DWDM channel, it instructs the associated ROADM to block any light transmission through this channel so as to avoid unnecessary propagation of ASE noise through the network. In this case, one cannot measure the accumulated ASE noise in the absence of the signal.

5.2 In-band OSNR definitions

5.2.1 Background

Traditionally, OSNR has been defined as the ratio of the total signal power to a single value of the ASE noise power spectral density rather than a noise power spectrum. This definition is appropriate for white ASE noise, i.e. for noise that does not exhibit significant wavelength dependence within the bandwidth of the signal. However, if the ASE noise spectrum is shaped through tight optical filtering (e.g. in ROADM networks), it cannot be fully characterized by a single power spectral density value. Thus, it remains unclear in the conventional definition of OSNR which value one should use for the power spectral density of the ASE noise. A new definition of in-band OSNR, therefore, should specifically address all cases where the ASE spectral power density varies significantly with wavelength over the width of the signal spectrum or DWDM channel.

Furthermore, OSNR should be a reliable measure of the waveform degradation introduced in the received electrical signal by in-band ASE noise. Hence, it should reflect the fact that spectrally filtered ASE noise generally causes less waveform distortion than spectrally unfiltered ASE noise.

Noise-induced waveform degradation is predominantly caused by signal-ASE beat noise and, hence, depends on the amplitudes of the signal and the ASE [1]. In the frequency domain, the signal-ASE beat noise may be viewed as resulting from the beating of each frequency component in the signal spectrum with certain frequency components in the ASE spectrum. More precisely, in a broadband optical receiver with electrical bandwidth B_{el}, each signal component at frequency ν interferes with all ASE components in the frequency range between $\nu - B_{\text{el}}$ and $\nu + B_{\text{el}}$. The total signal-ASE beat noise thus depends on the shape of the ASE noise spectrum as well as on the shape of the signal spectrum. A given level of ASE noise near the edges of the signal spectrum usually causes less waveform degradation than an equal level near the centre of the spectrum. Consequently, spectrally filtered ASE noise generally causes less waveform degradation than unfiltered ASE noise.

The in-band OSNRs defined in 3.2 and 3.3 both reflect the spectral dependence of the signal-ASE beat noise, whereas the OSNR defined in 3.4, which currently is the most widely used definition, is independent of the spectral shapes of signal and ASE noise. However, in the case of flat ASE noise, all three definitions yield the same OSNR value as the conventional OSNR definition.

5.2.2 Spectrally integrated in-band OSNR

The definition of in-band OSNR in 3.2, OSNR_{int}, is based on the assumption that the noise-induced waveform distortion is approximately proportional to the ratio of the time-averaged ASE power spectral density, $\rho(\lambda)$, to the time-averaged signal power spectral density, $s(\lambda)$, at each optical frequency ν, i.e. by $\rho(\lambda)/s(\lambda)$. Consequently, the OSNR_{int} value, R_{int}, is defined as the integral of the inverse ratio $s(\lambda)/\rho(\lambda)$ over the entire wavelength range of the DWDM channel, i.e. as

$$R_{\text{int}} = \frac{1}{B_{\text{r}}} \int_{\lambda_1}^{\lambda_2} \frac{s(\lambda)}{\rho(\lambda)} d\lambda \cong \frac{1}{\tilde{B}_{\text{r}}} \int_{\nu_1}^{\nu_2} \frac{s(\nu)}{\rho(\nu)} d\nu \tag{4}$$

where the result is essentially independent of whether the integration is performed with respect to wavelength λ or optical frequency ν. An important feature of this definition is that the value of R_{int} does not change, at least in theory, when signal and noise spectra are reshaped simultaneously by a single optical filter, as can be seen from the equality

$$R_{\text{int}} = \frac{1}{B_{\text{r}}}\int_{\lambda_1}^{\lambda_2} \frac{s(\lambda)}{\rho(\lambda)} d\lambda = \frac{1}{B_{\text{r}}}\int_{\lambda_1}^{\lambda_2} \frac{s(\lambda)\cdot F(\lambda)}{\rho(\lambda)\cdot F(\lambda)} d\lambda \tag{5}$$

wherein $F(\lambda)$ denotes the transfer function of the optical filter. In practice, the values of R_{int} measured before and after simultaneous filtering of signal and noise may depend on the dynamic range of the OSA, the wavelength range of integration, and the spectral resolution of the OSA, as explained in Clause 6.

5.2.3 In-band OSNR from averaged noise power spectral density

The in-band OSNR defined in 3.3, OSNR_{avg}, is similar to the conventional definition of OSNR, except that it uses a spectrally averaged value for the noise power density. The OSNR_{avg} value, R_{avg}, is defined as

$$R_{\text{avg}} = \frac{\int_{\lambda_1}^{\lambda_2} s(\lambda) d\lambda}{B_{\text{r}}\ \rho_{\text{avg}}} \tag{6}$$

wherein ρ_{avg} is obtained by averaging the ASE power spectrum, $\rho(\lambda)$, weighted with the normalized signal power spectrum, $s(\lambda)/s$:

$$\rho_{\text{avg}} = \frac{\int_{\lambda_1}^{\lambda_2} \rho(\lambda)\cdot s(\lambda) d\lambda}{\int_{\lambda_1}^{\lambda_2} s(\lambda) d\lambda} \tag{7}$$

This definition parallels a theoretical model for in-band signal-signal crosstalk in ROADM networks, which is based on the observation that the crosstalk penalty depends on the power spectral densities of the interferer and the signal, similarly to the above-described dependence of the signal-ASE beat noise [10-11]. This definition also has the advantage that the value of R_{avg} does not critically depend on the wavelength range used for noise averaging, so long as it covers the entire signal spectrum. However, this definition yields a different OSNR_{avg} value after signal and noise are spectrally reshaped simultaneously by the same filter.

5.2.4 In-band OSNR from maximal noise power spectral density

The most-widely used definition for in-band OSNR thus far is OSNR_{max} as defined in 3.4. It is almost identical to the conventional OSNR definition in IEC 61280-2-9, except that it explicitly specifies to use the maximal value of ASE power spectral density, ρ_{max}, for the OSNR_{max} calculation (which is usually found near the centre of the signal spectrum). The OSNR_{max} value, R_{max}, is defined as

$$R_{\text{max}} = \frac{\int_{\lambda_1}^{\lambda_2} s(\lambda) d\lambda}{B_{\text{r}}\ \rho_{\text{max}}} \tag{8}$$

In contrast to OSNR_{int} and OSNR_{avg}, the OSNR_{max} values calculated from Equation (8) are agnostic to the spectral shape of the ASE noise. Thus, a signal with spectrally filtered ASE noise exhibits the same $OSNR_{max}$ value as an identical signal with spectrally flat ASE noise. It is therefore not surprising that $OSNR_{max}$ is less sensitive to the spectral resolution of the OSA than $OSNR_{int}$ and $OSNR_{avg}$. It should also be noted that the $OSNR_{max}$ value always decreases after spectral filtering because of spectral clipping of $s(\lambda)$, independently of how much ASE noise has been removed from the signal.

5.2.5 In-band OSNR for individual optical subcarriers

When a multitude of modulated optical subcarriers is transmitted in an optical “superchannel”, it may be useful to determine the in-band OSNR individually for each modulated subcarrier. The subcarrier OSNR defined in 3.5, $OSNR_{sub}$, is of particular interest when the transmission performance of a single modulated subcarrier is to be compared to that of a conventional single-carrier optical signal at the same data rate, which is often the case when the various subcarriers of given a superchannel are encoded with independent data.

The $OSNR_{sub}$, value may be determined by using one of the three in-band OSNR definitions described above, i.e. $OSNR_{int}$, $OSNR_{avg}$ or $OSNR_{max}$, where the same definition shall be applied to all subcarriers. The wavelength integration ranges in R_{int}, R_{avg} or R_{max}, i.e. λ_1 and λ_2, shall be adjusted so that they include only the spectral width of the subcarrier to be measured. Particular care shall be taken when measuring the signal power of the modulated subcarrier, so as not to include signal power of neighbouring subcarriers. In case of very densely spaced subcarriers, as illustrated in the example of Figure 4 above, the accuracy of the subcarrier power measurement may be limited by the spectral resolution of the OSA, which should be high enough to avoid undesired crosstalk from neighbouring subcarriers.

However, $OSNR_{sub}$ is of considerably less interest when the various subcarriers transmit a single contiguous data stream, for example when two modulated subcarriers each transmit 50 Gbit/s of a contiguous 100 Gbit/s signal. In this case, one may want to compare the OSNR of the entire two-carrier signal to that of another single-carrier or multiple-carrier 100 Gbit/s signal, using the channel or superchannel in-band OSNR, $OSNR_{sup}$, defined in 3.6. The $OSNR_{sup}$ value shall be determined by adjusting the wavelength integration ranges for R_{int}, R_{avg} or R_{max} so that they encompass the signal spectra of both modulated subcarriers. In case of a flat ASE noise spectrum and equal signal powers in all modulated subcarriers, the value of $OSNR_{sup}$ is equal to N times the value of $OSNR_{sub}$, where N is the total number of subcarriers in the superchannel.

5.3 Spectral shaping of ASE noise

5.3.1 General

The necessity of measuring in-band OSNR with a wavelength resolution finer than the signal width raises issues for the definition of OSNR, since the measured result may depend on the chosen resolution. This complication is considered here within the framework of some case examples explained in 5.3.2 to 5.3.4.

5.3.2 Case (a): ASE noise shaped outside of the signal spectrum

The simplest example of a signal with shaped ASE noise is often encountered in optical receiver testing, where white noise from a broadband ASE source is mixed with the transmitted signal immediately before the receiver to emulate various OSNR levels during receiver sensitivity tests. These tests generally require spectral filtering of the ASE noise before the receiver to avoid excessively large background noise due to ASE-ASE beat noise. The width of this filter is usually chosen so as to not affect the shape of the signal spectrum. Hence, the ASE noise spectrum remains flat within the signal spectral width but is shaped outside of the signal spectrum, as illustrated in Figure 5 for the example of a 10 Gbit/s NRZ-OOK signal.

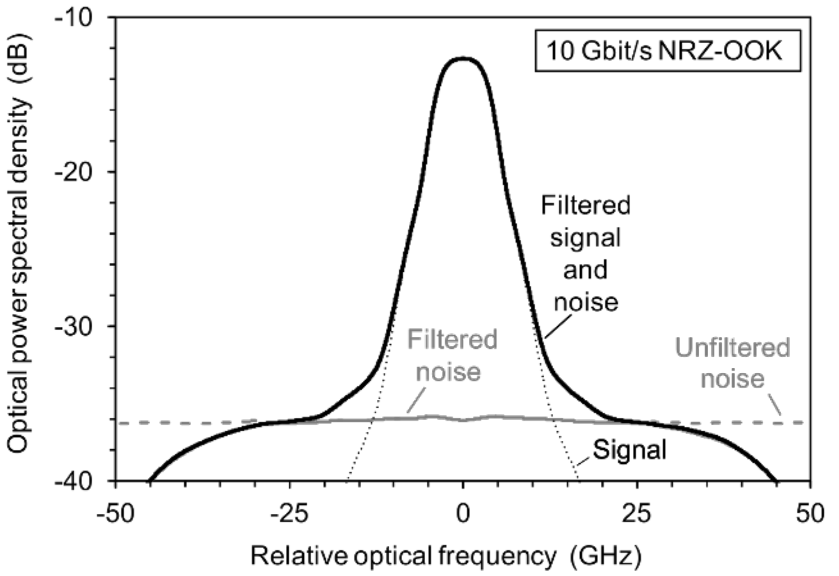


Figure 5 – Power spectral density of a 10 Gbit/s signal with ASE noise that has been shaped by a relatively broad optical filter

To determine the OSNR *after* filtering, it may be necessary to measure the in-band noise floor. However, since the in-band noise spectrum is essentially flat, the three in-band OSNR definitions $OSNR_{int}$, $OSNR_{avg}$ and $OSNR_{max}$ yield the same value, i.e. $R_{int} = R_{avg} = R_{max}$. It should be noted that this value is identical to the OSNR value measured *before* filtering (which may be measured, for example, with the interpolation method described in IEC 61280-2-9).

5.3.3 Case (b): ASE noise shaped within the signal spectrum

The situation becomes more complex when the bandwidth of the optical filter in case (a) is so narrow that both the signal and ASE spectra are reshaped, which is often the case when the performance of a receiver for broadband 40 Gbit/s or 100 Gbit/s signals is tested with a 50-GHz (or narrower) wavelength demultiplexer before the receiver. As illustrated in Figure 6, for the example of a 43 Gbit/s RZ-DQPSK signal, such narrow-band wavelength filtering significantly attenuates the edges of the signal spectrum, thus reducing the total signal power. It also reshapes the ASE noise spectrum in such a way that it is no longer flat within the bandwidth of the filtered signal.

In this case, the in-band OSNR definitions in 3.2 to 3.4 generally yield different results. The lowest (i.e. most conservative) OSNR value is obtained from $OSNR_{max}$, which accounts for the decrease in signal power but completely ignores the spectral clipping of the ASE noise because it uses the noise power spectral density at the centre of the signal (which is not affected by filtering). In contrast, $OSNR_{int}$ always yields the highest OSNR value because it offsets the wavelength-dependent attenuation of the signal by a corresponding wavelength-dependent attenuation of the ASE noise, which are identical in this case. In fact, $OSNR_{int}$ defined in 3.2 is independent of the filter bandwidth and, therefore, gives the same OSNR value before and after filtering, just like in case (a). This is illustrated in Figure 7, which displays the OSNR values R_{int}, R_{avg} and R_{max} calculated for a 43 Gbit/s RZ-DQPSK signal as a function of filter bandwidth. Whereas R_{int} stays constant at the original value of 20 dB, R_{avg} and R_{max} decrease monotonically with decreasing filter bandwidth, with R_{avg} being always larger than R_{max}. Thus, it is this case that gives the clearest support for the in-band OSNR definition $OSNR_{int}$ in 3.2. However, for filters with moderate bandwidth, the difference between the three OSNR values may be small compared to other sources of measurement uncertainty and to the practical requirements of the measurement.

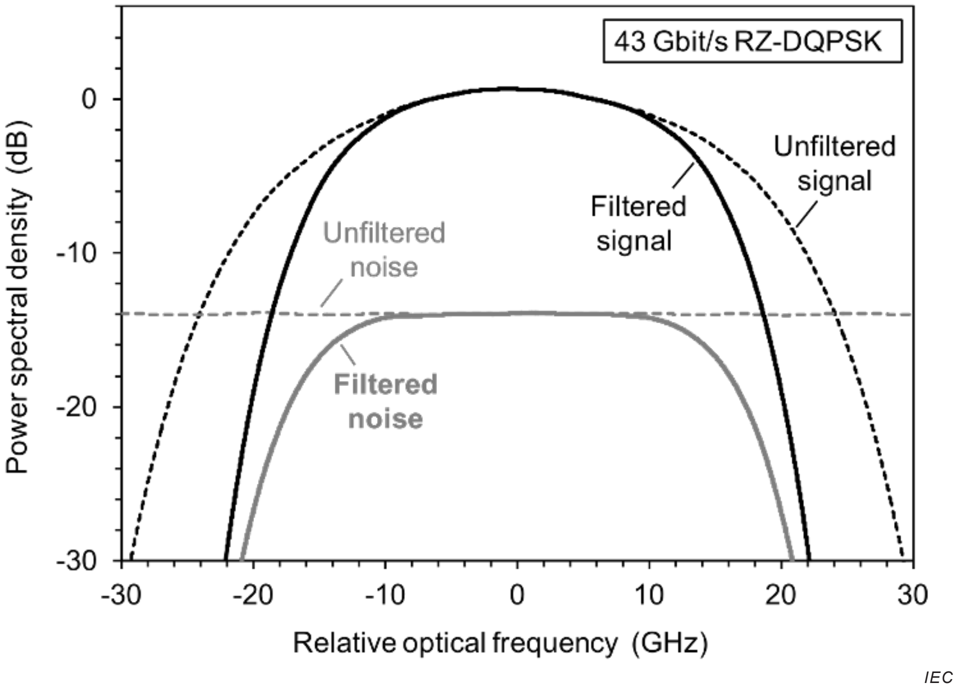
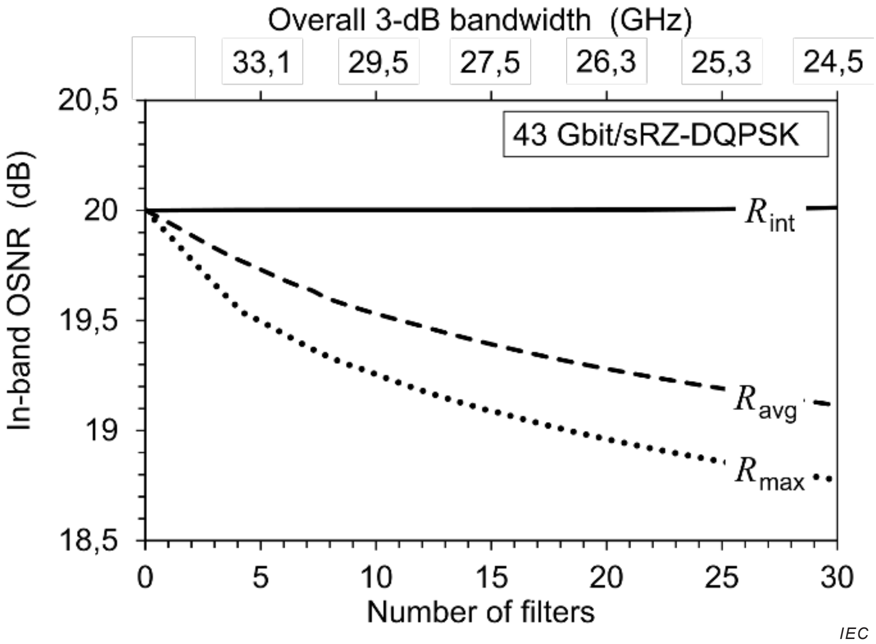


Figure 6 – Power spectral densities of a broadband 40 Gbit/s signal and ASE noise which have been shaped by the same filter



NOTE In this simulation, the effective filter bandwidth is varied by cascading several identical filters, each having a third-order super-Gaussian transmission function with a 3-dB bandwidth of 43 GHz (same as the ROADM filters in Figure 9).

Figure 7 – Variation of the in-band OSNR values R_{int}, R_{avg} and R_{max} versus filter bandwidth for the signal shown in Figure 6

5.3.4 Case (c): ASE noise shaping in a ROADM network

A signal that passes through multiple spectral filters with intermediate amplification, like in a network with ROADMs, results in different spectral shaping for the signal, which passes all filters, and the ASE, which is generated between the filter stages and hence, in part, passes through fewer filter stages. Generally, this distributed filtering of the noise produces a broader ASE spectrum than if all filters were placed directly before the receiver, as illustrated in Figure 8. In this sense, it is an intermediate case between (a) and (b), which were both well described by $OSNR_{int}$ defined in 3.2.

The graph in Figure 9 displays the OSNR values R_{int}, R_{avg} and R_{max} calculated for a 43 Gb/s RZ-DQPSK signal as a function of the number of 50-GHz filters/ROADMs, where it is assumed that ASE noise is added in equal portions between filters and that it always adds up to the same total amount. In this case, all three OSNR values decrease with increasing number of filters (i.e. with decreasing overall filter bandwidth). While R_{int} is always larger than R_{avg}, and R_{avg} larger than R_{max}, just like in case (b), the difference between the three curves is significantly smaller than in case (b). For comparable filtering of the signal, the spectrally integrated ratio R_{int} and the OSNR calculated from the average noise power spectral density, R_{avg}, produce lower OSNR values than in case (b), whereas the OSNR calculated from the maximal noise power spectral density at the centre, R_{max}, is identical to that in case (b), which is expected, because there is more ASE noise in the wings of the signal spectrum but the same ASE noise density in the centre. In the extreme of this case, where the in-band ASE noise is effectively flat while the signal is shaped, all three OSNR values will be lower than in case (a) because the signal has shed optical power due to spectral clipping in the filters. The actual spectral shape of the filtered signal does not impact the OSNR value, only the total signal power, when the ASE noise is flat.

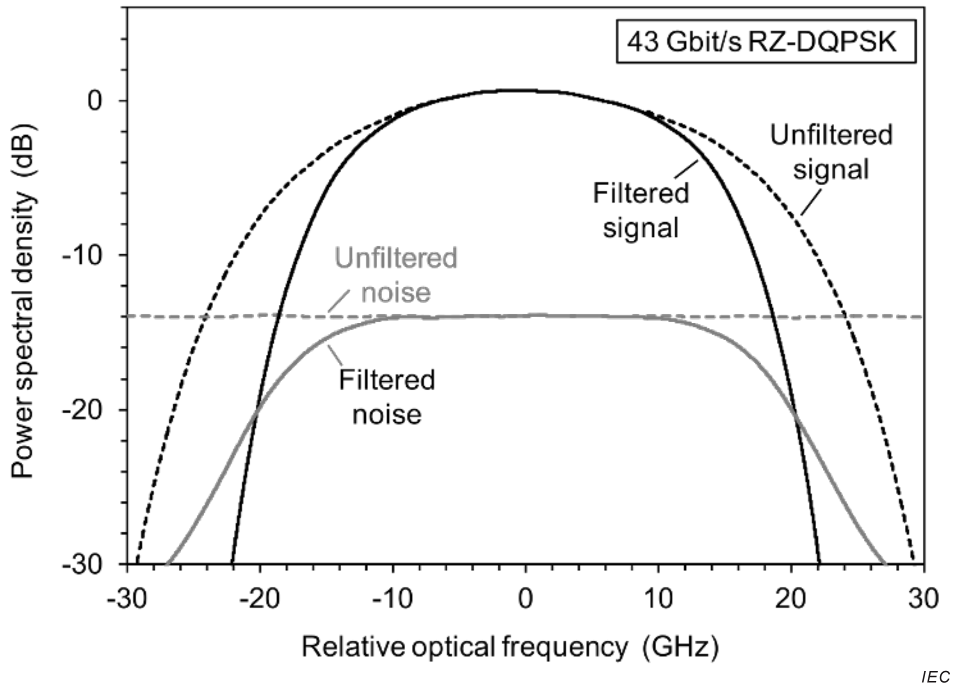
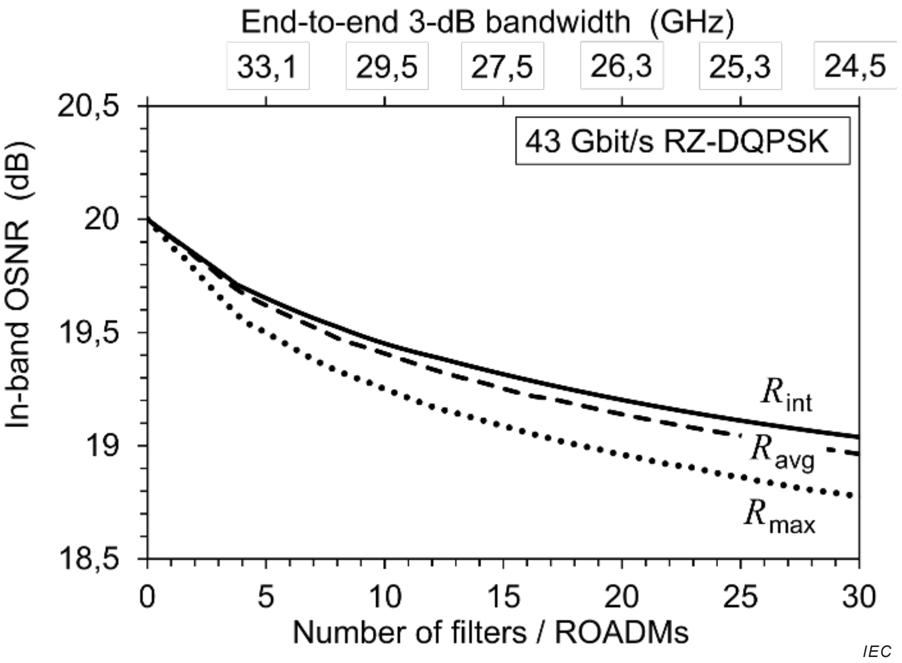


Figure 8 – Optical power density spectra of signal and ASE noise after filtering in a ROADM network with intermediate amplification



NOTE In this simulation, each ROADM filter exhibits a third-order super-Gaussian transmission function with a 3-dB bandwidth of 43 GHz, and the ASE noise is added in equal portions between the ROADMs.

Figure 9 – Variation of the in-band OSNR values R_{int}, R_{avg} and R_{max} versus number of filters for the signal shown in Figure 8

Considering these cases, it is seen that the three in-band OSNR definitions $OSNR_{int}$, $OSNR_{avg}$ and $OSNR_{max}$ yield identical or at least very similar results in cases (a) and (c), whereas they may produce substantially different results in case (b), with $OSNR_{max}$ providing the most conservative and $OSNR_{int}$ the highest value. However, in most practical applications, the filter bandwidth in case (b) is similar to the spectral width of the signal, so the differences between $OSNR_{int}$, $OSNR_{avg}$, and $OSNR_{max}$ are relatively small and even comparable to other measurement uncertainties.

It should be pointed out that the results presented in Figures 7 and 9 were calculated under the assumption that the signal and noise spectra are measured with an ideal instrument, having unlimited dynamic range and infinitely small spectral resolution. It turns out, however, that the values of $OSNR_{int}$ and $OSNR_{avg}$ depend substantially on the spectral resolution of the measurement equipment as discussed in Clause 6, and, furthermore, that the value of $OSNR_{int}$ depends on the dynamic range of the instrument, especially in case (b). In practical measurements, therefore, where dynamic range and spectral resolution are limited, the three in-band OSNR values R_{int}, R_{avg} and R_{max} can differ from those shown in Figures 7 and 9.

6 Guidelines for using the definitions

6.1 General

It is the intention of this part of IEC 61282 to provide a mathematical definition of OSNR and not to prescribe a measurement method. It is recognized that practical methods will likely provide approximations of this parameter based on assumptions appropriate to the use case, such as the shape of the ASE, the degree of polarization and the width of the signal. The impact of these assumptions should be estimated as contributions to the uncertainty, just like that due to uncertainty in noise equivalent bandwidth and dynamic range in the method of IEC 61280-2-9.

An important point for realizing accurate OSNR measurements is that the raw measurement of signal power is likely to include a contribution of ASE. Especially for lower OSNR values, it is important to correct the signal power for this contribution, which is usually estimated from the ASE measurement part of the procedure. The accuracy of this estimate is also often based on the validity of the assumption that the ASE is depolarized.

The reference bandwidth for the noise power is most commonly chosen as B_r = 0,1 nm. If, for example, a wider bandwidth like B_r = 1 nm is chosen, then the OSNR value is 10 dB lower. The reference bandwidth can also be expressed in frequency instead of wavelength.

6.2 Wavelength integration range

The choice of integration range for determining the signal power

$$s = \int_{\lambda_1}^{\lambda_2} s(\lambda)\, d\lambda \tag{9}$$

in R_{avg} and R_{max} (3.3 and 3.4) is subject to the same considerations discussed in IEC 61280-2-9: care shall be taken to integrate the complete spectral width of the signal, which increases with the modulation rate of the signal. For example, a wavelength range of at least 0,2 nm (or about 25 GHz) should be used for 10 Gbit/s NRZ-OOK signals in order to measure signal power within 0,1 dB uncertainty. This range scales with the modulation rate and varies with the modulation format. For spectrally broadband signals like the 43 Gbit/s RZ-DQPSK signal shown in Figure 6, the integration range should be around 0,4 nm, i.e. the entire width of a 50-GHz wide DWDM channel. Using a wider integration range than necessary is not an issue for the calculation of the signal power, but care is needed to assure that only the intended signal is included in the calculation. For DWDM signals, this generally limits the maximal integration range to the bandwidth of the DWDM channel.

The integration range for the spectrally weighted noise density $s(\lambda) \cdot \rho(\lambda)$ in R_{avg} (3.2) shall be identical to the one used for the integration of the signal power.

For the signal-to-noise ratio $s(\lambda)/\rho(\lambda)$ in R_{int} (3.2), the integration range should ideally extend over the entire spectral width of the *unfiltered* signal, which may be significantly wider than that of the *filtered* signal. This is especially important for receiver testing with narrowband optical filters/demultiplexers, as described in case (b) of 5.3. For signals that have been spectrally filtered in ROADM networks, as in case (c) of 5.3, it is usually sufficient to integrate $s(\lambda)/\rho(\lambda)$ over the spectral width of the *filtered* signal, as is evident from the curves displayed in Figure 10.

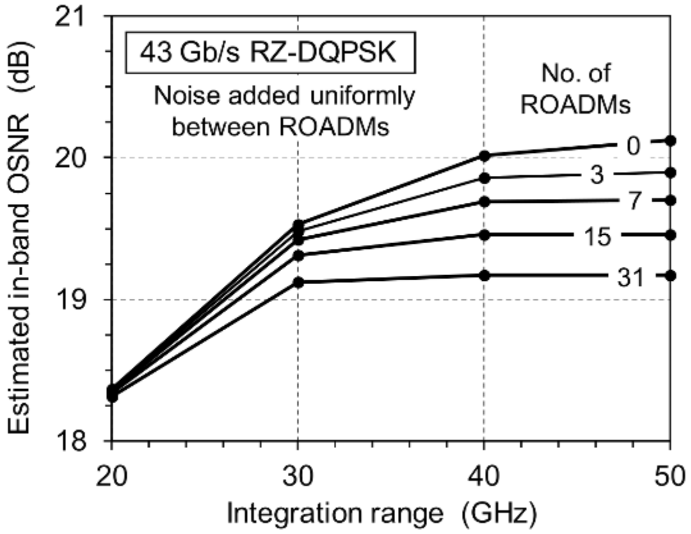
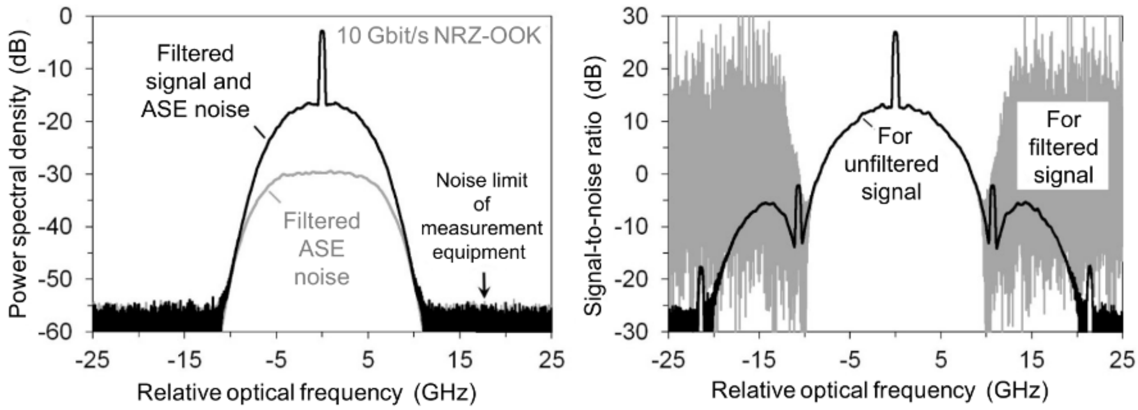


Figure 10 – Impact of integration range on R_{int} for 43 Gbit/s RZ-DPSK signals in a ROADM network

However, integration should be avoided at wavelengths where both signal and ASE are so strongly filtered that they are below the sensitivity-limited detection threshold of the measurement equipment, because this may cause significant overestimation of the signal-to-noise ratio, especially at low OSNR values. The impact of measurement-induced noise on $s(\lambda)/\rho(\lambda)$ is illustrated in Figure 11 for the example of a strongly filtered 10 Gbit/s NRZ-OOK signal with 15 dB OSNR.



The left diagram displays the noise and signal spectra after filtering as measured with a high-resolution OSA, and the right diagram compares the resulting signal-to-noise ratio $s(\nu)/\rho(\nu)$ of the filtered (grey curve) and unfiltered signal (black curve). To avoid overestimation of R_{int}, the integration range for the signal-to-noise ratio $s(\nu)/\rho(\nu)$ of the filtered signal should be limited to the frequency interval between -10 and +10 GHz because outside of this range, the mean value of the filtered $s(\nu)/\rho(\nu)$ becomes significantly larger than that of the unfiltered $s(\nu)/\rho(\nu)$.

Figure 11 – Impact of instrument noise on $s(\nu)/\rho(\nu)$ for strongly filtered 10 Gbit/s NRZ-OOK signals

In practice, therefore, the integration range of $s(\lambda)/\rho(\lambda)$ should be limited to wavelengths where the filtered signal exhibits significant optical power. This can be accomplished, for example, by terminating the integration at wavelengths where the signal power spectral density drops below a certain threshold, for example 0,1 % to 1 % of the peak power density (note that while this threshold is usually appropriate for signals that do not exhibit narrow peaks in their spectrum, it may be too high for signals with large discrete frequency components, such as the residual optical carrier in the 10 Gbit/s NRZ-OOK spectrum of

Figure 10). For spectrally broadband signals with symbol rates above 20 GBd, the DWDM channel bandwidth can often serve as a proper and easy-to-implement bound for the integration range, as long as the noise is not too strongly filtered. Strong shaping from ROADM filtering, however, can reduce the power densities to sensitivity limits within the nominal bandwidth, as illustrated in Figure 8.

Such issues do not exist for the calculation of the average noise spectral density in R_{avg} (3.3), where the integration range of $s(\lambda) \cdot \rho(\lambda)$ is inherently limited by the width of the signal spectrum.

6.3 Spectral resolution

When both signal and ASE noise are spectrally shaped, it is important that their spectra are measured with sufficient accuracy, which usually requires an instrument whose resolution is much finer than the width of the noise and signal spectra. This is an important difference to OSNR measurements based on out-of-band ASE noise (IEC 61280-2-9), where it is often possible to choose the resolution bandwidth of the OSA wider than the signal spectrum, so that the peak of the measured spectrum represents the integrated signal power (Figure 1). Signals that are depolarized by high PMD may also require high spectral resolution, as explained in 5.1.

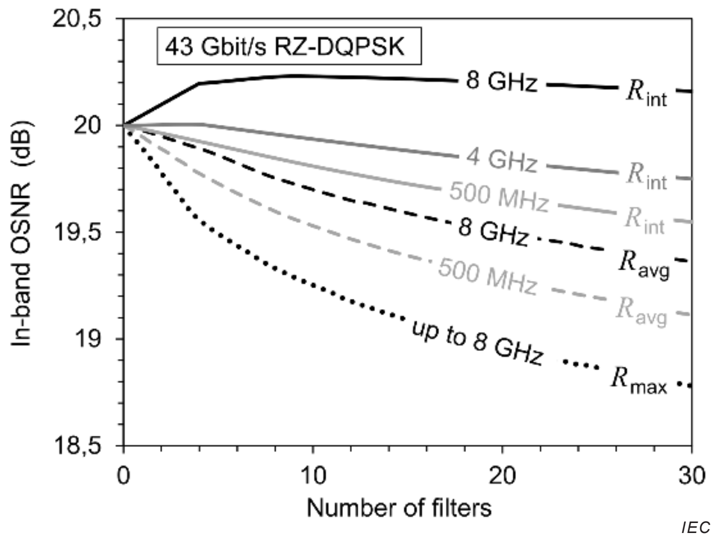
It turns out that $OSNR_{int}$ in 3.2 is more sensitive to the spectral resolution of the measurement than $OSNR_{avg}$ and $OSNR_{max}$. Since the measured spectra are generally broader than the actual spectra due to the instrument's finite spectral resolution, the shapes of the *measured* signal and noise spectra may be significantly different from those of the *actual* spectra, especially near the edges of the spectra. This can be shown by expressing the measured power spectral densities as $s_{meas}(\lambda) = s(\lambda) \otimes T(\lambda)$ and $\rho_{meas}(\lambda) = \rho(\lambda) \otimes T(\lambda)$, respectively, where $T(\lambda)$ denotes the transfer function of the OSA and $\otimes$ the convolution of the spectrum with $T(\lambda)$. Thus, the measured signal-to-noise ratio $s_{meas}(\lambda)/\rho_{meas}(\lambda)$ may be different from the actual ratio $s(\lambda)/\rho(\lambda)$, especially after strong filtering, so that in general

$$\int_{\lambda_1}^{\lambda_2} \frac{s(\lambda) \otimes T(\lambda)}{\rho(\lambda) \otimes T(\lambda)} d\lambda \neq \int_{\lambda_1}^{\lambda_2} \frac{[s(\lambda) \cdot F(\lambda)] \otimes T(\lambda)}{[\rho(\lambda) \cdot F(\lambda)] \otimes T(\lambda)} d\lambda \qquad (9)$$

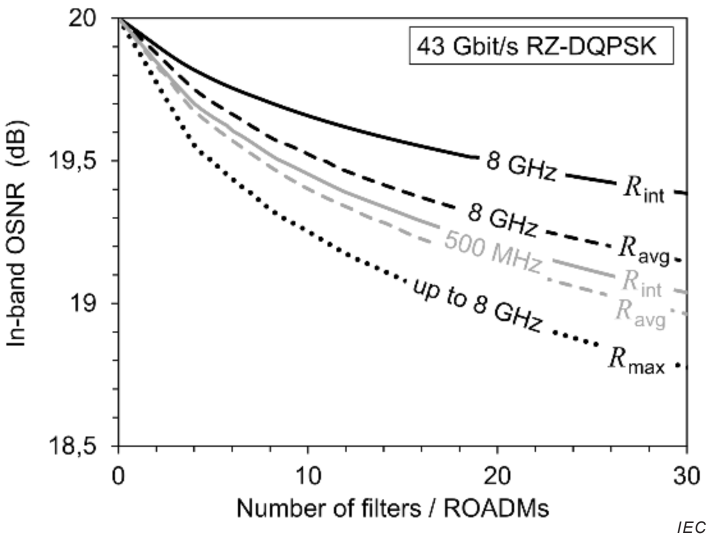
and Equation (5) is no longer valid. Since the difference between $s_{meas}(\lambda)/\rho_{meas}(\lambda)$ and $s(\lambda)/\rho(\lambda)$ is largest near the edges of the signal spectrum, the difference between the two terms in Equation (9) can be reduced by limiting the integration of $s_{meas}(\lambda)/\rho_{meas}(\lambda)$ to the wavelength range where significant signal power is detected (as described in 6.2). Similarly, it can be shown that the average noise power density ρ_{avg} in R_{avg} is sensitive to the spectral resolution of the OSA because, in general

$$\int_{\lambda_1}^{\lambda_2} \rho(\lambda) \cdot s(\lambda) d\lambda \neq \int_{\lambda_1}^{\lambda_2} [\rho(\lambda) \otimes T(\lambda)] \cdot [s(\lambda) \otimes T(\lambda)] d\lambda \qquad (10)$$

In contrast, the maximal noise power density ρ_{max} in R_{max} (3.4) is much less sensitive to the spectral resolution of the instrument, even if the filtering is fairly strong. The dependence of R_{int}, R_{avg} and R_{max} on the spectral resolution of the measurement is illustrated in Figure 12 for the case of strongly filtered 43 Gbit/s RZ-DQPSK signals and in Figure 13 for the case of strongly filtered 10 Gbit/s NRZ-OOK signals.



(a)



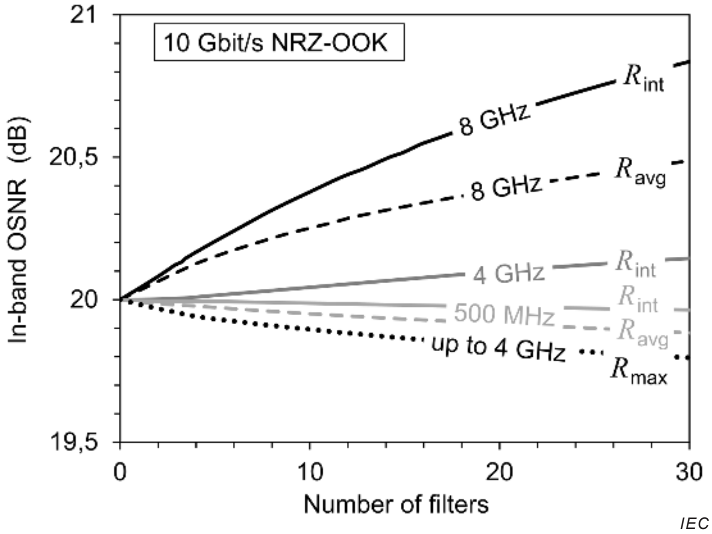
(b)

NOTE The upper diagram (a) displays simulated in-band OSNR values for the same case shown in Figure 7, when signal and noise spectra are measured with spectral resolutions of 500 MHz (light grey curves), 4 GHz (dark grey curve), and 8 GHz (black curves); while the lower diagram (b) displays simulated in-band OSNR values for the case shown in Figure 9, when measured with spectral resolutions of 500 MHz and 8 GHz. The wavelength integration range for R_{max} and R_{avg} extends over the entire width of the 50-GHz DWDM channel, whereas for R_{int}, it is limited to the range where the signal power density is larger than 1 % of the peak power density.

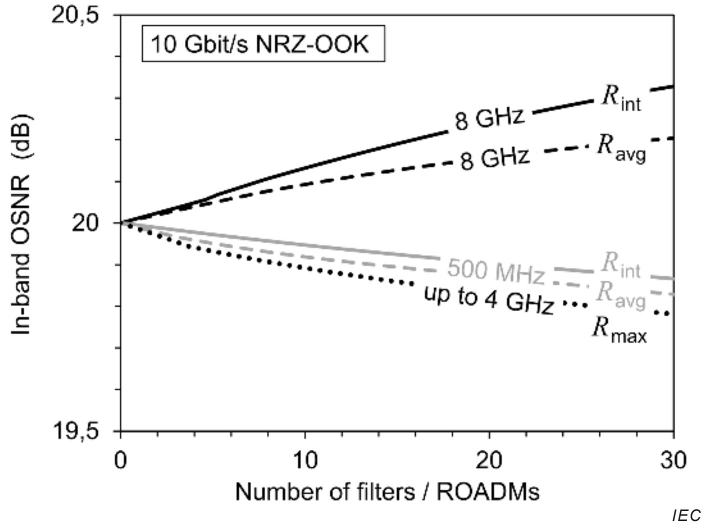
Figure 12 – Dependence of in-band OSNR on spectral resolution for 43 Gbit/s RZ-DQPSK signals

For the spectrally broadband 43 Gbit/s RZ-DQPSK signal, a moderate spectral resolution of 8 GHz (or equivalently 0,064 nm), which is not uncommon for field-deployable instruments, can cause overestimation of R_{int} (up to 0,25 dB in Figure 12 (a)), which may be small compared to other sources of measurement uncertainty. By contrast, R_{max} is essentially insensitive to the spectral resolution of the instrument up to about 8 GHz resolution. Note that in Figure 12, the integration range for $s(\lambda)/\rho(\lambda)$ is limited to those wavelengths where the signal power spectral density is larger than 1 % of the peak power density. As a result, the value of R_{int} – as measured with a high-resolution instrument – does not remain constant when signal and noise experience the same spectral attenuation (Figure 7), but rather decreases with decreasing filter bandwidth, as shown in Figure 12 (a). Limiting the wavelength integration range for $s(\lambda)/\rho(\lambda)$ thus offsets the overestimation of in R_{int} caused by insufficient spectral resolution.

Stronger dependence on spectral resolution is observed for the 10 Gbit/s NRZ-OOK signals in Figure 13, which have a narrower spectrum than the 40 Gbit/s signals in Figure 12 and which pass through significantly narrower filters. In Figure 13, the integration range for $s(\lambda)/\rho(\lambda)$ is limited to those wavelengths where the signal power density is larger than 0,1 % of the peak power density.



(a)



(b)

NOTE The two diagrams display the in-band OSNR values calculated for a 10 Gb/s NRZ-OOK signal when measured with spectral resolutions of 500 MHz (light grey curves), 4 GHz (dark grey curve), and 8 GHz (black curves). The upper diagram (a) represents the case where signal and white ASE noise pass through the same cascade of identical filters, whereas the lower diagram (b) represents the case of distributed filtering in a ROADM network. In either case, each filter/ROADM has a second-order super-Gaussian transfer function with a 3-dB bandwidth of 30 GHz. The wavelength integration for R_{int} is limited to the range where the signal power density is larger than 0,1 % of the peak power density.

Figure 13 – Dependence of in-band OSNR on spectral resolution for 10 Gbit/s NRZ-OOK signals

Simulations in Clause 7 compare OSNR penalties calculated from the three in-band OSNR definitions.

7 In-band OSNR penalties of filtered signals

7.1 Scope of simulations

Strong optical filtering can give rise to significant signal distortions and, therefore, impair the end-to-end transmission quality. These impairments are often characterized by an OSNR penalty, which is the ratio of the OSNR required to receive the *unfiltered* signal at a given bit-error rate (BER) to the OSNR required to receive the *filtered* signal at the same BER. In the case of spectrally shaped ASE noise, the OSNR values before and after filtering should be determined using either $OSNR_{int}$, $OSNR_{avg}$, or $OSNR_{max}$. Since these three definitions generally yield different OSNR values, depending on the amount of filtering and use case, it can be expected that the resulting OSNR penalties also vary significantly.

The numerical simulations presented below compare OSNR penalties for strongly filtered signals, which are calculated using the three in-band OSNR definitions in 3.2 to 3.4. As representative examples, simulations have been performed for following widely used modulation formats:

i) Conventional 10 Gbits NRZ-OOK with intensity-envelope detection,

ii) Non-coherently, differentially detected 43 Gbit/s RZ-DQPSK, and

iii) Coherently detected 128 Gbit/s polarization multiplexed (PM) NRZ-QPSK.

All signals are launched into a 50-GHz wide DWDM channel and subsequently pass through a varying number of 50-GHz ROADM filters. Since ROADM nodes may be distributed differently and unevenly along different transmission links, the shape of ASE noise spectrum may vary widely from link to link, even if the number of ROADMs is the same. Since it would be difficult to investigate all possible scenarios, the simulations were limited to three special cases, as depicted in Figure 14:

a) Strongly filtered signal with spectrally flat ASE noise

   This extreme case is simulated by first passing the signal through N ROADMs and then adding flat ASE noise before analyzing the OSNR of the signal. This arrangement is very similar to the one considered in case (a) of 5.3.

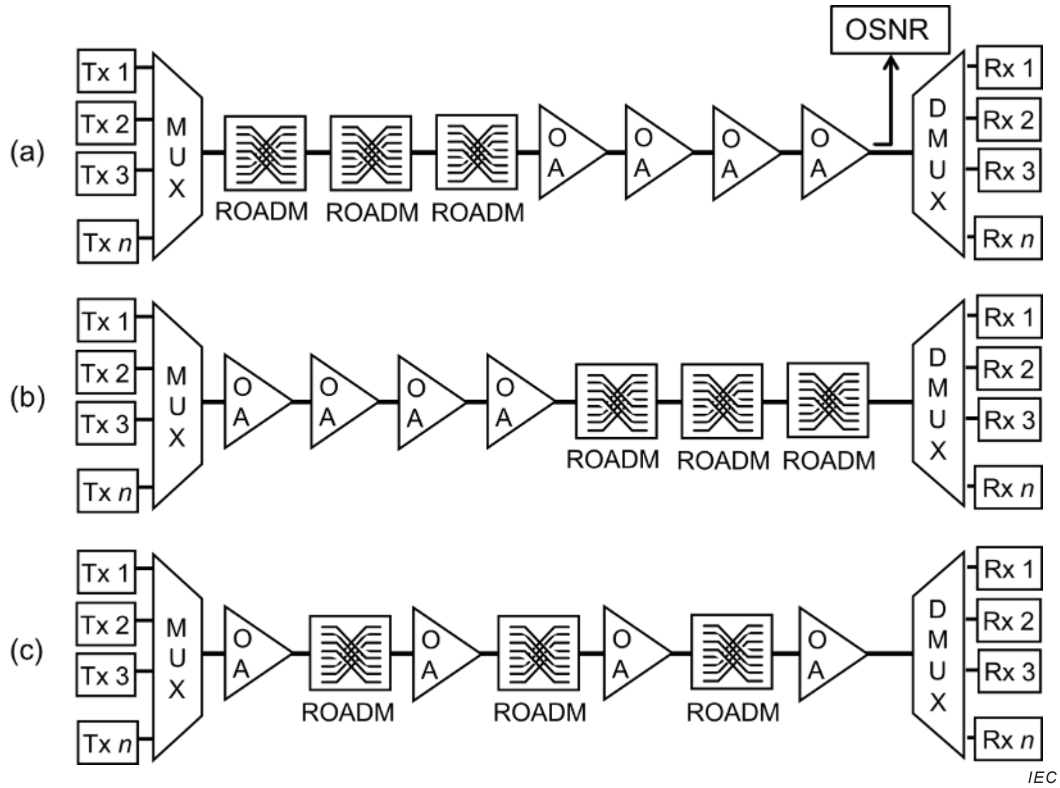
b) Strongly filtered signal with equally filtered ASE noise

   This extreme case is simulated by first adding flat ASE noise to the signal and then passing signal and noise through N cascaded ROADMs before analyzing the OSNR of the signal. This arrangement is very similar to the one considered in case (b) of 5.3.

c) Strongly filtered signal with uniformly added and filtered ASE noise

   This intermediate case is simulated by adding the same amount of flat ASE noise to the signal after each pass through one of the N cascaded ROADMs. This arrangement is identical to the one considered in case (c) of 5.3.

In all three cases, the signal passes through the same number of ROADMs, and hence exhibits the same spectral shape, whereas the ASE noise is filtered differently and thus exhibits different spectral shapes. The total amount of added ASE noise is adjusted so that it would be the same in all three cases if the filters were absent. Three identical signals are multiplexed into adjacent DWDM channels at the launch site, using a ROADM-like wavelength multiplexer, and demultiplexed at the receiver site using an identical device in reverse. The OSNR is always analyzed *before* the wavelength demultiplexer, which is needed for proper reception and BER counting. Therefore, the wavelength multiplexer is not included in the number of ROADM filters.



Key

Tx	optical transmitter
Rx	optical receiver
OA	optical amplifier
MUX	WDM multiplexer
DMUX	WDM demultiplexer
ROADM	reconfigurable optical add-drop multiplexer

Figure 14 – ROADM filter arrangements for OSNR penalty simulations

For the spectrally broadband 43 Gbit/s RZ-DQPSK and 128 PM NRZ-QPSK signals, the transmission window of each ROADM is a third-order super-Gaussian function with a 3-dB bandwidth of 43 GHz [6]; whereas for the spectrally narrower 10 Gbit/s NRZ-OOK signal, it is a narrower, second-order super-Gaussian function with a 3-dB bandwidth of 30 GHz. The minimal OSNR for signal reception with 10^{-3} BER is determined by interpolation of the BER measured at various OSNR levels, where the in-band OSNR is determined for each of the three definitions $OSNR_{int}$, $OSNR_{avg}$, and $OSNR_{max}$.

7.2 Results for 43 Gbit/s RZ-DQPSK

Figure 15 summarizes the results for 43 Gbit/s RZ-DQPSK signals. The three graphs display the in-band OSNR values R_{max}, R_{avg} and R_{int} required for 10^{-3} BER as a function of the number of ROADM filters for the three arrangements described above. Results are shown for spectral resolutions of 500 MHz, 8 GHz and 16 GHz. The wavelength integration range for R_{max} and R_{avg} is 50 GHz (i.e. the entire width of the DWDM channel), whereas the integration for R_{int} is limited to the range where the signal power density is larger than 1 % of the peak power density at the centre of the spectrum.

When $OSNR_{max}$ is used to characterize the signal's in-band OSNR, the three curves corresponding to the different filter arrangements diverge quite rapidly as the number of filters increases. As one would expect, the required $OSNR_{max}$ is lowest in case (b), where signal and noise pass through the same number of filters, so that the noise spectrum is narrowest.

On the other hand, the required $OSNR_{max}$ is highest in case (a), when flat noise added to the filtered signal, so that the noise spectrum is widest. Not surprisingly, when noise is added uniformly between the filters, as in case (c), the required $OSNR_{max}$ is intermediate between those of cases (a) and (b).

NOTE 1 The decrease of the required $OSNR_{max}$ value in case (b) with increasing number of filters (i.e. the negative filtering penalty) can be explained by the fact that RZ-DQPSK signals (just like other RZ-formatted signals) are fairly tolerant to spectral filtering. Although there is always signal distortion due to spectral filtering, however small, the resulting OSNR penalty in case (b) is significantly lower than the decrease in OSNR due to total signal power loss caused by spectral clipping, which is about 1,1 dB after 24 ROADM filters.

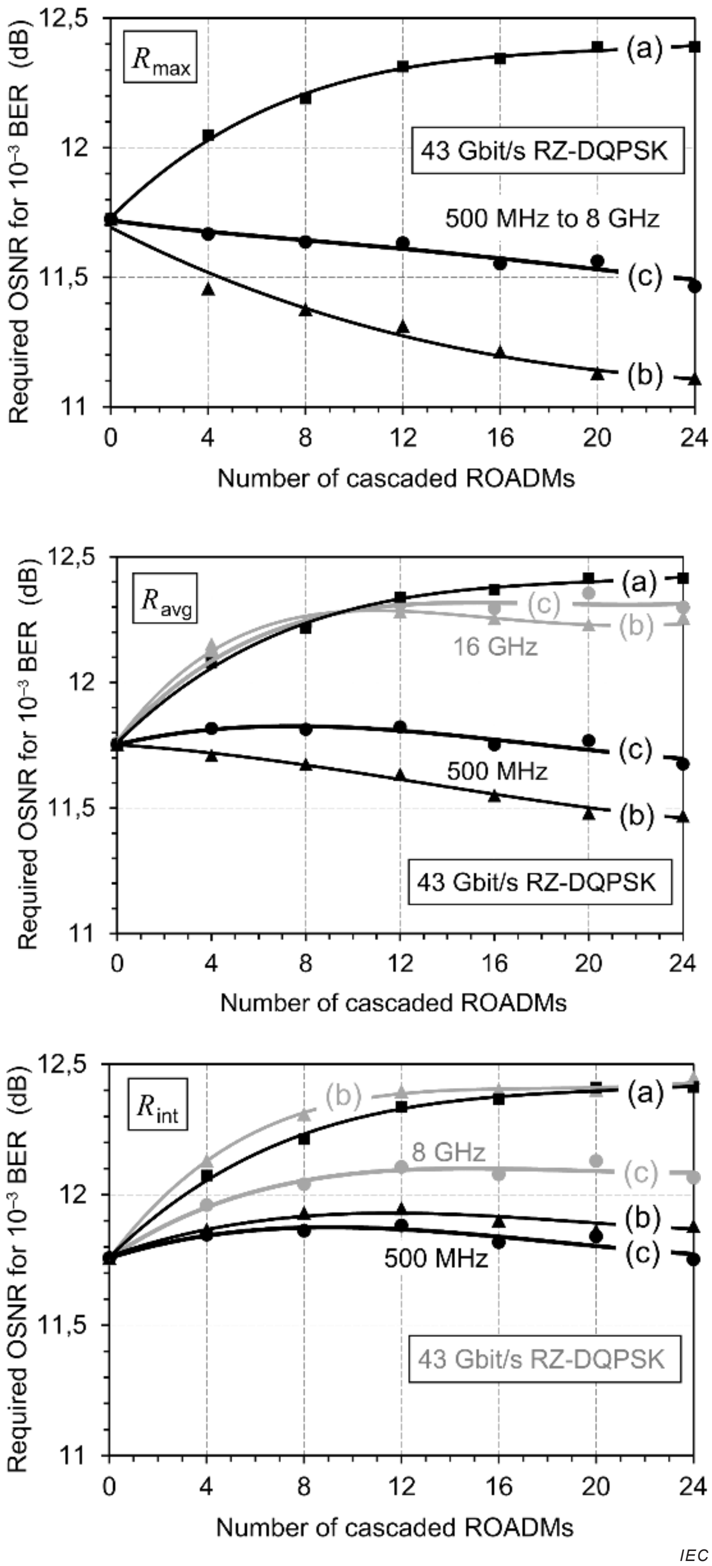
Since $OSNR_{max}$ is agnostic to the shape of the noise spectrum, the difference between the three curves directly reveals the adverse effect of in-band ASE noise near the edges of the spectrum. After 24 ROADMs, the $OSNR_{max}$ difference between the extreme cases (a) and (b) reaches 1,3 dB. Consequently, when the OSNR penalties resulting from spectral filtering are investigated using arrangement (a) of Figure 14, the results can be significantly higher than in the more realistic case (c). It would thus be desirable to use an in-band OSNR definition for which the penalty results are fairly independent of the filter arrangement.

Indeed, the difference between the three curves is significantly smaller when the signal's in-band OSNR is characterized by $OSNR_{avg}$ or $OSNR_{int}$, as can be seen in the two lower graphs of Figure 15. With $OSNR_{avg}$, the required OSNR again is lowest in case (b) and highest in case (a), whereas in case (c) it is somewhere between those of cases (a) and (b). With $OSNR_{int}$, on the other hand, the required OSNR is lowest in case (c) followed by (b) and (a). This partial reversal of the OSNR penalty ranking arises from the fact that the value of R_{int} tends to be larger in case (b) than in case (c), as is clearly illustrated in Figure 12.

Since the values of R_{avg} and R_{int} depend on the spectral resolution of the measurement, especially in cases (b) and (c), the difference between the three curves varies with the spectral resolution. The difference is largest for the finest resolution of 500 MHz and deceases for coarser resolutions up to 8 GHz and 16 GHz, respectively. At 16 GHz resolution, the three curves for R_{avg} trace one another very closely with a maximal difference of less than 0,25 dB. At even coarser resolutions, the differences between the three curves increase again.

NOTE 2 The close proximity of the three curves at 16 GHz resolution is in good agreement with the spectral signal-ASE interference model described in 5.2, which stipulates that in a receiver with electrical bandwidth B_{el}, each signal component at frequency ν interferes with all ASE components in the frequency range between $\nu - B_{el}$ and $\nu + B_{el}$. Since $B_{el} \approx 16$ GHz in the 21,5 GBd RZ-DQPSK receiver, the total power of the signal-ASE interference is approximately given by the spectrally weighted average noise power density when signal and noise spectra are broadened by a 16-GHz wide transfer function of the instrument.

Similarly, the three curves for R_{int} trace one another closely at 8 GHz resolution, with a maximal difference of about 0,3 dB. When measured with coarser spectral resolution, for example with 16 GHz, the OSNRs required for signals with strongly filtered ASE noise (case (b)) and with uniformly added ASE noise (case (c)) become substantially larger than the one required for signals with flat ASE noise (case (a)), yielding a complete reversal of the OSNR penalty ranking.



Key

BER Bit-error rate

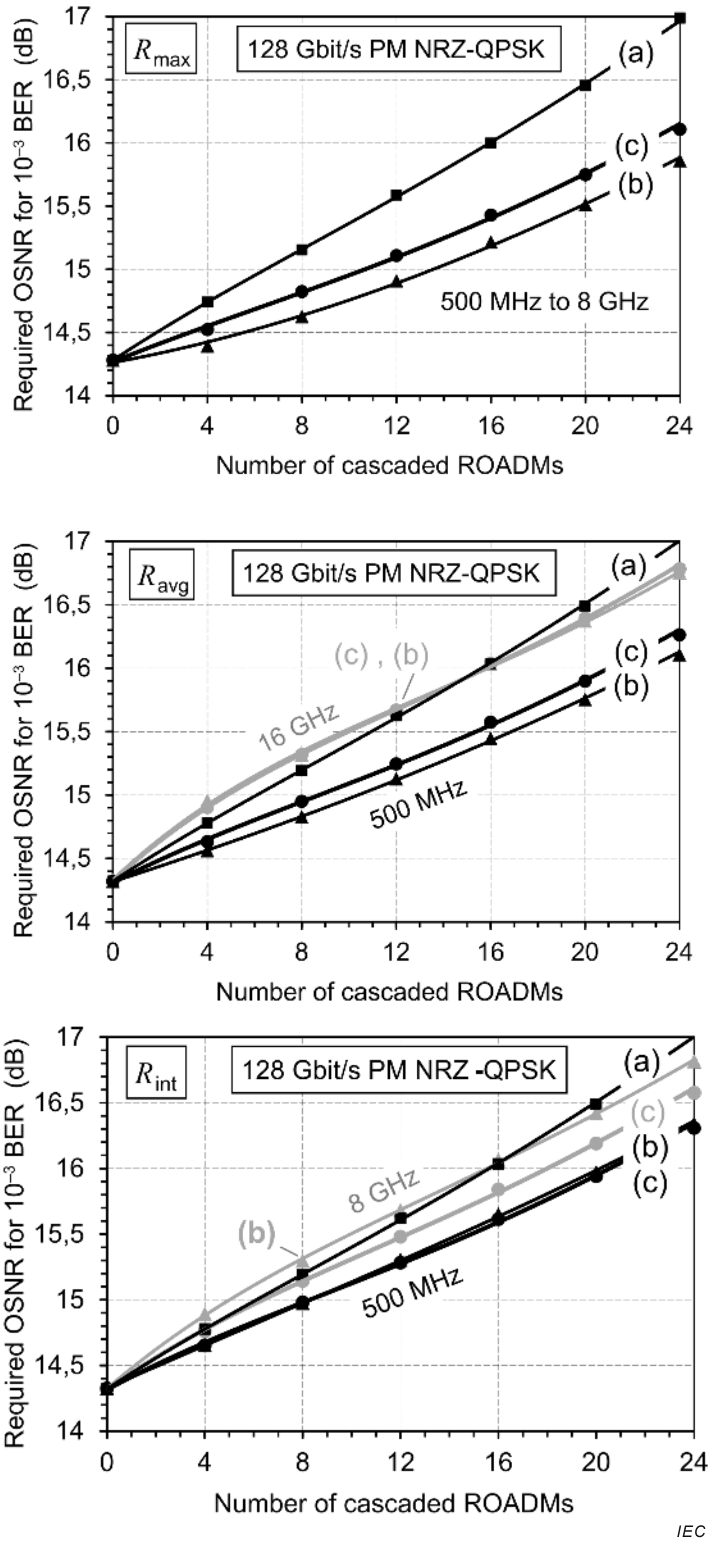
(a) For flat ASE noise added *after* spectral filtering of signal

(b) For flat ASE noise added *before* spectral filtering of signal

(c) Flat ASE noise added *uniformly* between ROADM nodes

500 MHz to 16 GHz Spectral resolution of measurement

Figure 15 – In-band OSNR penalties for filtered 43 Gbit/s RZ-DQPSK signals



Key

BER Bit-error rate

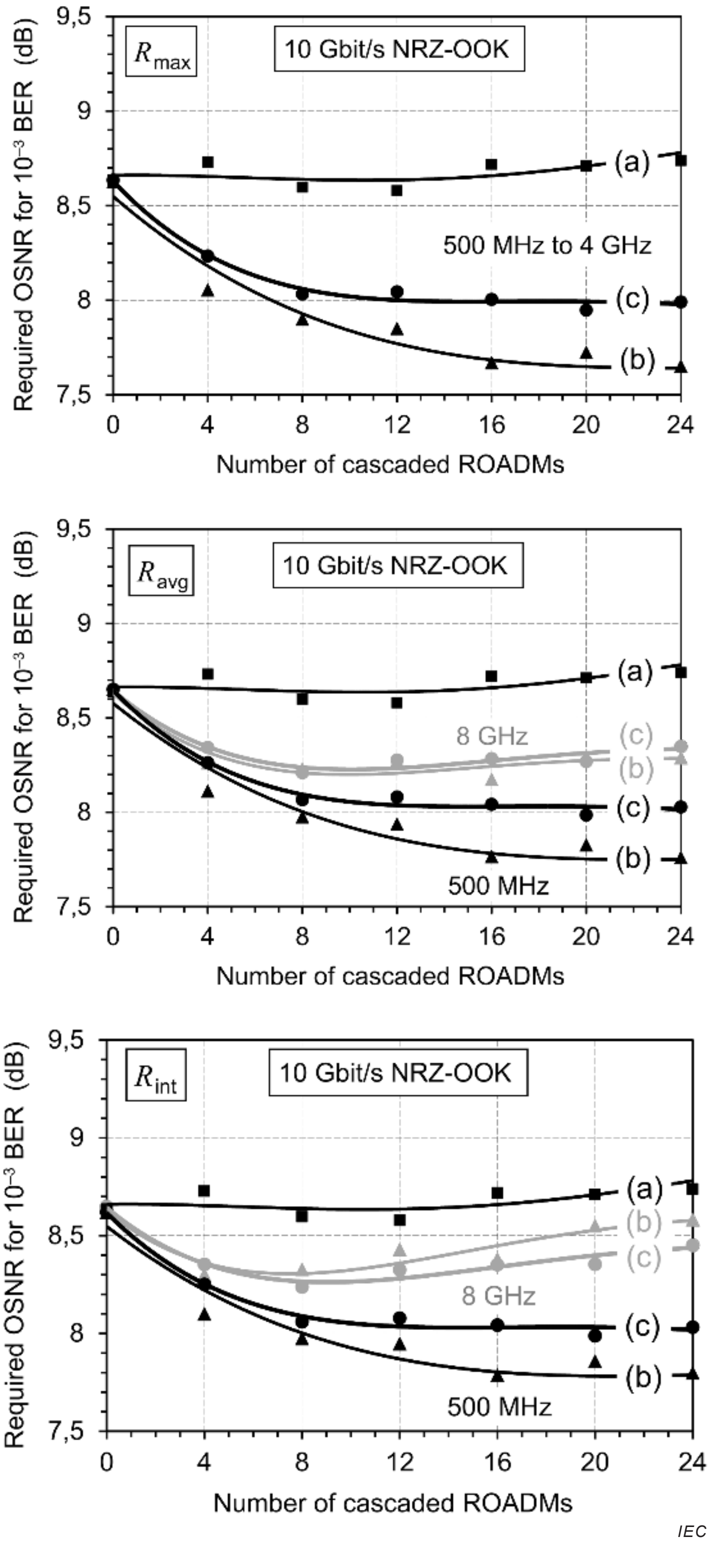
(a) For flat ASE noise added *after* spectral filtering of signal

(b) For flat ASE noise added *before* spectral filtering of signal

(c) Flat ASE noise added *uniformly* between ROADM nodes

500 MHz to 16 GHz Spectral resolution of measurement

Figure 16 – In-band OSNR penalties for filtered 128 Gbit/s PM NRZ-QPSK signals



Key

BER Bit-error rate

(a) For flat ASE noise added *after* spectral filtering of signal

(b) For flat ASE noise added *before* spectral filtering of signal

(c) Flat ASE noise added *uniformly* between ROADM nodes

500 MHz to 16 GHz Spectral resolution of measurement

Figure 17 – In-band OSNR penalties for filtered 10 Gbit/s NRZ-OOK signals

7.3 Results for 128 Gbit/s PM NRZ-QPSK

Figure 16 summarizes the results for coherently detected 128 Gbit/s polarization-multiplexed NRZ-QPSK signals. Again, the three graphs display the in-band OSNR values R_{max}, R_{avg} and R_{int} required for 10^{-3} BER as a function of the number of ROADM filters for the three different filter arrangements. Results are shown for spectral resolutions of 500 MHz, 8 GHz and 16 GHz, and the wavelength integration range for R_{max} and R_{avg} is 50 GHz, whereas for R_{int} it is limited to the range where the signal power density is larger than 1 % of the peak power density.

Aside from the fact that the OSNR penalties rise much more rapidly with increasing number of ROADM filters, the results are otherwise very similar to those obtained for the 43 Gbit/sRZ-DQPSK signal: when using R_{max} or R_{avg}, the required OSNR is lowest in case (b), followed by case (c), and it is highest in case (a), whereas with R_{int} the required OSNR is lowest in case (c), followed by (b) and (a).

NOTE The relatively steep increase of the required OSNR with increasing number of filters is typical for NRZ-formatted signals, which are less tolerant to spectral filtering than RZ-formatted signals. Another contributing factor is the higher symbol rate of the signal, which is 32 GBd for the 128 Gbit/s signal versus 21,5 GBd for the 43 Gbit/s signal.

Despite the steeper OSNR penalties, the differences between the three curves are about the same as for the 43 Gbit/s signal in Figure 15. The differences are largest for R_{max} and significantly smaller for R_{avg} and R_{int}. When measured with 16 GHz resolution, the three curves for R_{avg} trace one another very closely, with a maximal difference of less than 0,25 dB. Likewise, the three curves for R_{int} trace one another closely at a spectral resolution of 8 GHz resolution, with a maximal difference of about 0,4 dB.

7.4 Results for 10 Gbit/s NRZ-OOK

Figure 17 summarizes the results for conventional 10 Gbit/s NRZ-OOK signals. Again, the three graphs display the in-band OSNR values R_{max}, R_{avg} and R_{int} required for 10^{-3} BER as a function of the number of ROADM filters for the three different filter arrangements. Results are shown for spectral resolutions of 500 MHz and 8 GHz only. The wavelength integration for R_{int} it is limited here to the range where the signal power density is larger than 0,1 % of the peak power density.

The filtering penalties for the 10 Gbit/s signal are much smaller than for the other two signals because of the substantially narrower signal spectrum. Otherwise, the results are quantitatively similar to those obtained for the 43 Gbit/s RZ-DQPSK and 128 Gbit/s PM NRZ-QPSK signals: when using R_{max} or R_{avg}, the required OSNR is lowest in case (b), followed by case (c), and it is highest in case (a). For R_{int}, the required OSNR is lowest in case (c) when measured with a coarse resolution of 8 GHz, whereas the lowest OSNR is required in case (b), followed by (b) and (a).

When measured with 8 GHz resolution, the three curves for R_{avg} trace one another more closely with a maximal difference of less than 0,5 dB, and likewise, the three curves for R_{int} are found to be very closely spaced, with a maximal difference of about 0,4 dB.

7.5 Observations

Considering the simulation results presented above, it is seen that the in-band definitions $OSNR_{int}$ and $OSNR_{avg}$ consistently produce OSNR values (and OSNR penalties) for the three filter arrangements (a) through (c) that differ significantly less than those obtained from the presently used $OSNR_{max}$. In the practical case of distributed filtering (case (c)) and for spectral resolutions up to about 8 GHz, $OSNR_{int}$ and $OSNR_{avg}$ produce very similar results (less than 0,25 dB difference).

However, the measured OSNR values for signals with spectrally shaped in-band ASE noise (cases (b) and (c)) depend on the spectral resolution of the OSA and, thus, may vary in practical applications when different measurement equipment is used. Furthermore for the special case (b), $OSNR_{int}$ is more sensitive to spectral resolution than $OSNR_{avg}$ and the integration range for $OSNR_{int}$ needs to be limited to wavelengths where the signal power is significant, whereas the integration range for $OSNR_{avg}$ may extend over the entire DWDM channel.

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