Pollinating Innovations Through Information

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By

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Day -4

Networking with DWDM –contd.

1. what is Q-factor
2. Asynchronous sampling (voltage histogram)
3. Synchronous sampling (digital sampling scope)
4. Synchronous sampling method (single decision threshold method)
5. Synchronous sampling m et hod (dual decision threshold method)
6. System test during manufacturing
7. installation of optical networks
8. System optimization
9. Maintenance and troubleshooting
10. System monitoring
11. Calculation of Q- Factor from OSNR
12. Margin Requirements
13. Design Using Chromatic Dispersion Compensation
14. OSNR and Dispersion- Based Design
15. Effects of FWM and XPM on Long- Haul Design
16. Forward Error Correction (FEC)

What is the Q-factor ?

The Q-factor is a parameter that directly reflects the quality of a digital optical communications signal.

The higher the Q-factor , the better the quality of the optical signal.

Q-factor measurement is related to the analogue signal and in this respect differs from traditional BER tests as it gives a measure of the propagation impairments caused by-

1. Optical Noise
2. Non-linear effects,
3. Polarization effects and
4. Chromatic Dispersion.

Definition of the Q-factor

As mentioned before , the Q-factor is a measure for the *quality of the analogue signal*, which is usually defined by its SNR ratio (this is also the mathematical definition of the Q-factor).

The Q-factor is defined by the difference of the mean values of the two signal levels divided by the sum of the noise rms values (standard deviations) at the two signal levels .

This can be expressed by the following equation.

$$Q = \frac{\text{mean"1"} - \text{mean"0"}}{\text{standard deviation"1"} + \text{standard deviation"0"}}$$

The Analog representation of a digital signal on the time scale toggles between the states "0"and "1" depending on the data pattern to be sent.

To make the data stream visible however the time scale can only show a "snapshot" with a restricted number of bits as theoretically it would go to infinity .

If the data signal is triggered to the bit rate and superimposed into the same picture , the so called "eye diagram" or "eye pattern" is generated (figure 12).

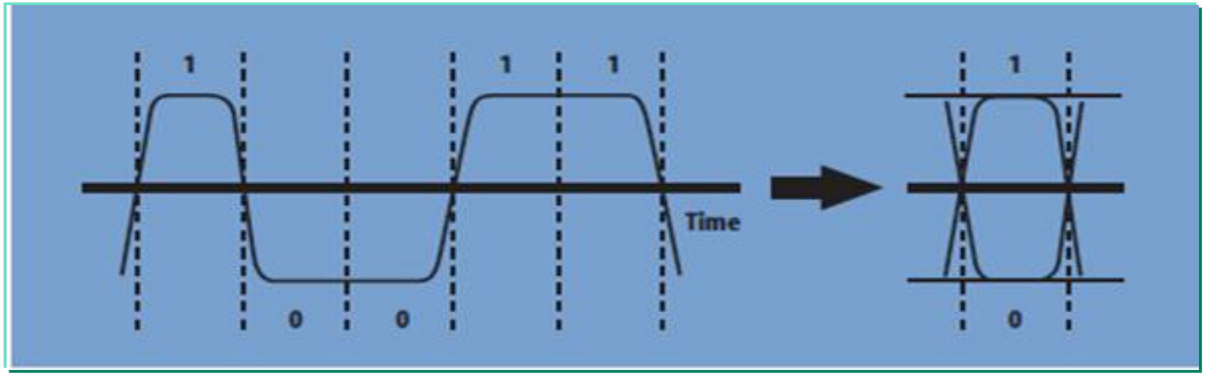


figure 12 Eye pattern generation

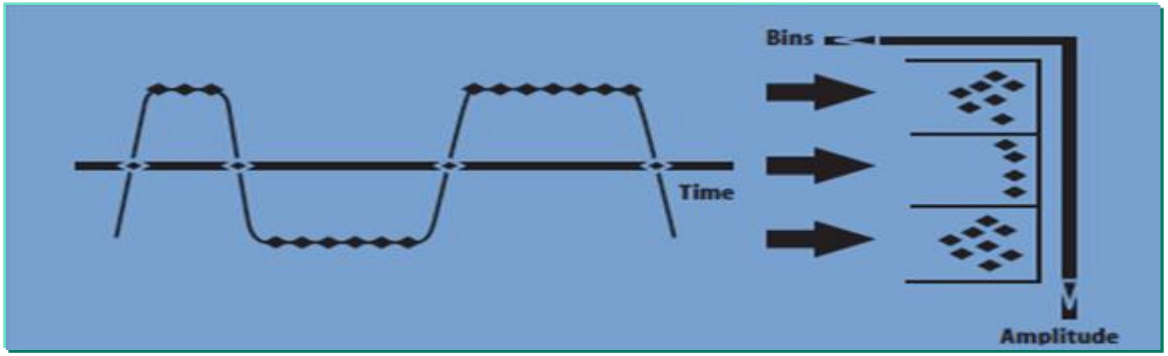


figure 13 Signal sampling into bins

As the illustrations show the signal is more likely to be at the “0”or “1”level rather than in a transient state.

The likelihood of certain signal level occurring can be described in a diagram, derived from sampling the data stream and collecting the sampling points for certain amplitude levels in bins (figure 13).

Real signals are also influenced by noise which causes the most likely amplitude levels to spread out.

The higher the sampling rate (samples per second) and smaller the bins, the more accurate the diagram generated by this method.

Assuming an infinitely high sampling rate and small bin size, the filling level of the bins can be normalized and represented by a single curve (figure 14).

The normalized curve is known as the Probability Density Function (PDF).

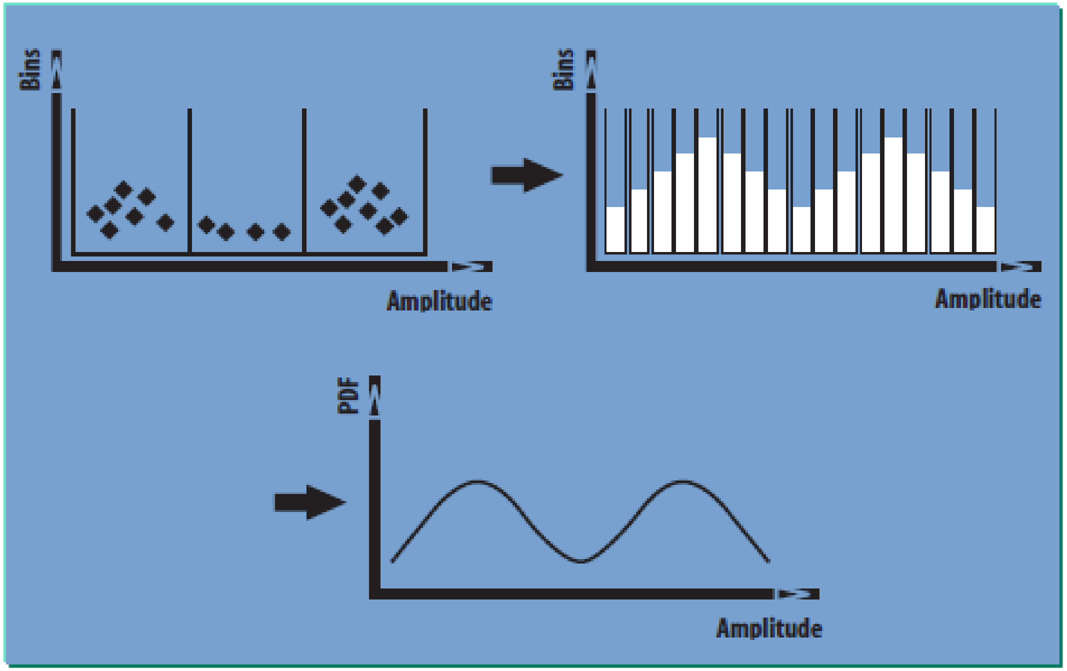
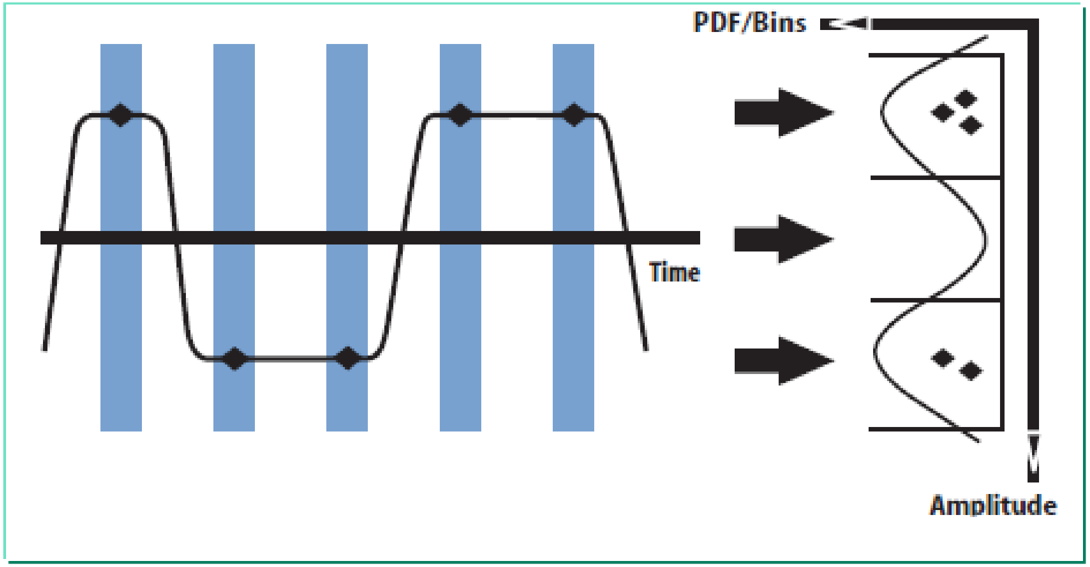


figure 14 Deriving the PDF from the bins

Only the sample values at the detection time are of importance when detecting a binary signal.

A PDF can be derived from the “bin "method – but only for detection samples (figure 15).

Deriving the PDF from detection point samples



It can be assumed that the PDF deriving from the “bin "method is the sum of two separate PDFs representing the two binary states “0”and “1”. Each binary state has a Gaussian distribution known as a “bell curve”

The signal distributions show the two most likely or mean values which are related to the binary “0”and binary “1”levels (figure 16).

As the real signal is affected by noise it shows slight deviations from the most likely amplitude values.

The spreading through noise power is called standard deviation.

The more noise a signal level contains, the broader the standard deviation.

The mean value is often denoted as µ and the standard deviation as s in mathematical equations.

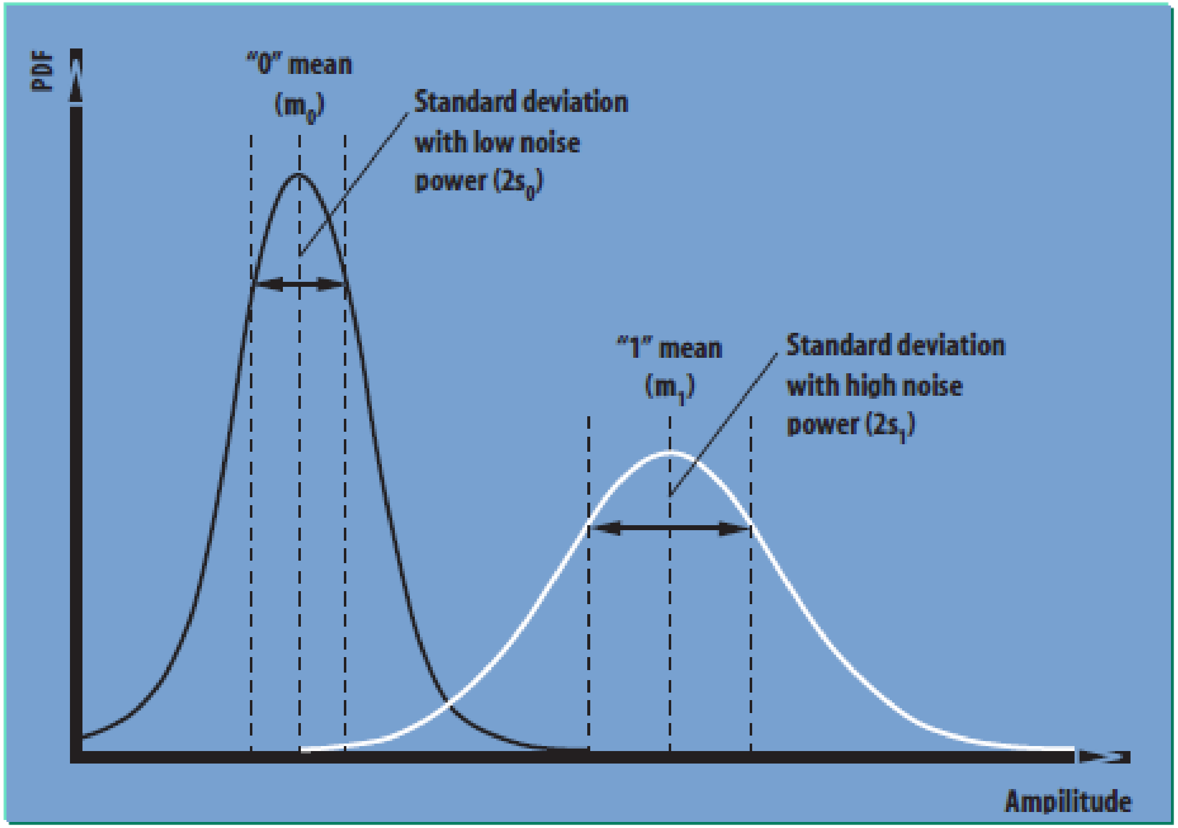


figure 16 PDF with Gaussian distributions

To determine whether a binary “0”or “1”has been sent,one must first ascertain whether the signal is on the “0”level or “1”level.

The threshold level for decision lies between the two mean values of the PDF shapes.

There is a small probability however of a binary level becoming distorted by noise for example and jumping over the threshold level.

In this case, the detection point will be misinterpreted.

There are two possibilities whereby a misinterpretation can be made:
– “0”is detected as “1”or
– “1”is detected as “0”

The probability of this particular type of misinterpretation is reflected in figure 17.

An optimum threshold can be found when looking for the smallest area covered, thus providing lowest probability of misinterpretation.

One could assume that the optimum threshold lies at the intersection of the two PDF shapes.

This is only true when both bell curves are identical.

Real systems however always have slightly different shapes for the two signal levels.

In this case the optimum threshold level does not necessarily cross the intersection point

The probability of misinterpretation or error probability can also be expressed as bit errors per total transmitted number of bits – the so called Bit Error Ratio or BER.

$$BER = \frac{\text{bit errors}}{\text{total number of bits}}$$

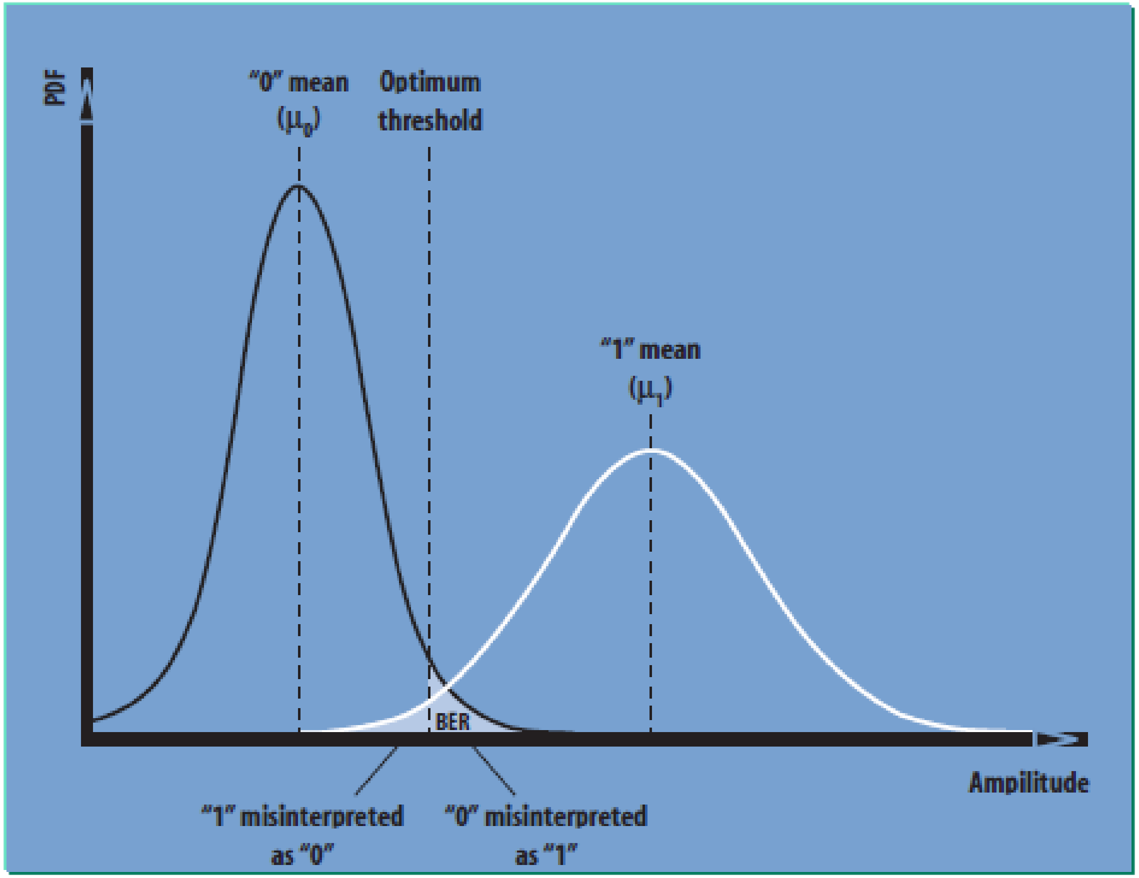


figure 17 BER in the PDF diagram

The detection of the binary level during the pulse width is not only dependent on the detection threshold but also on the detection time.

The detection time is often expressed as sampling phase.

This comes from the definition of the pulse width in radians.

The pulse width itself may be defined to cover the range from 0 to 2 (see in figure 18).

The centre of the eye opening provides optimal conditions for the detection of the binary signal and is defined as the sampling phase with the highest vertical eye opening (figure 18).

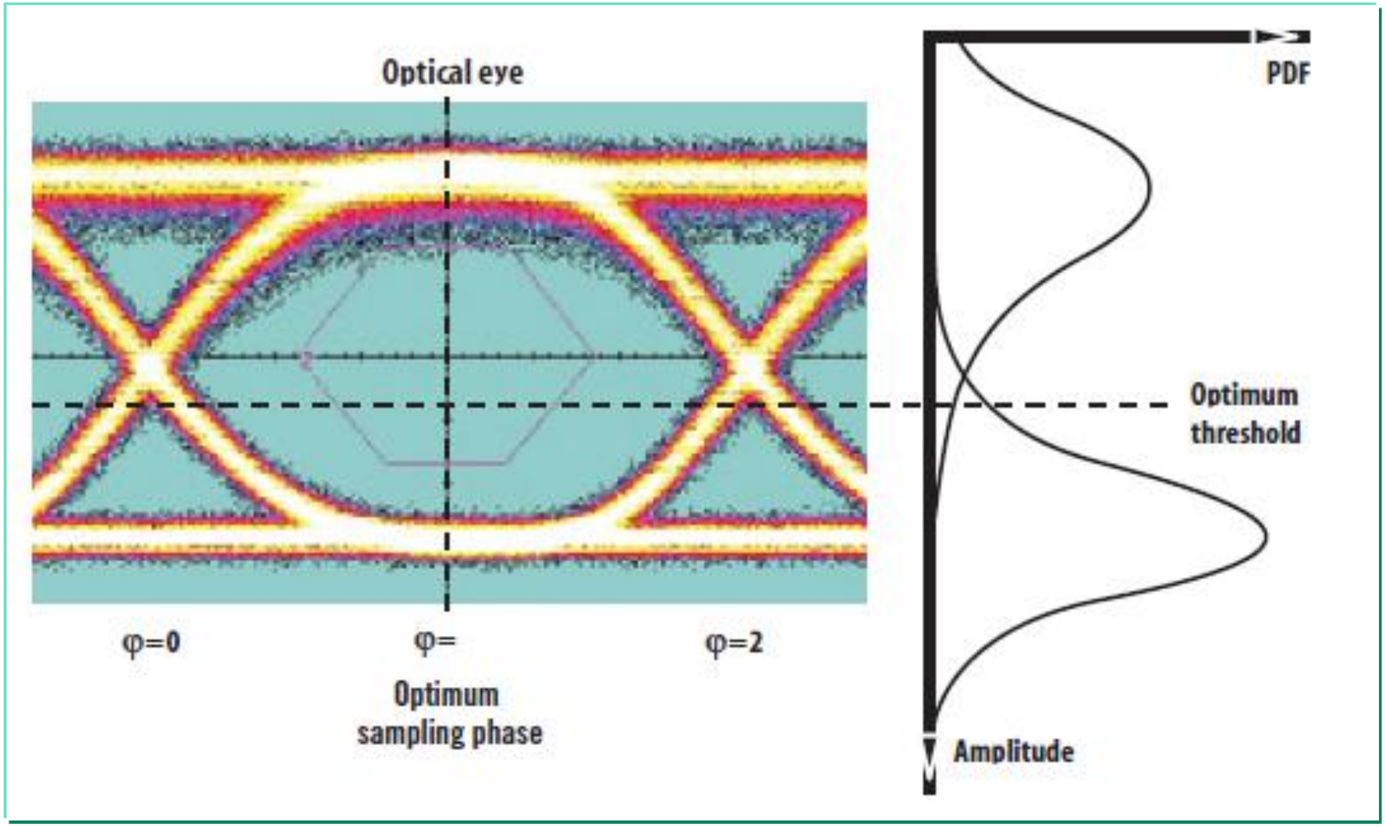


figure 18 Optical eye with optimum detection point

Assuming that the signal distributions are Gaussian,

The Q-factor can also be expressed as BER and vice versa.

Let’s go back to the initial definition of the Q-factor to understand how it relates to the BER.

The difference in the mean values produces the vertical eye opening.

The higher the difference , the better the BER will be as the two bell curves drift away from each other and have less overlap .

This difference is divided by the sum of the noise distributions which are represented by the width of the bell curves.

Increases in noise result in more overlap in the two bell curves resulting in a higher BER.

There are two fundamental methods for determining the Q-factor:

1. The Histogram method and
2. The Pseudo-BER method.

Though the processes behind each method differ, the intention of them is to estimate the BER for the optimum threshold which is directly related to the Q-factor.

The Histogram method samples the signal and collects the sampling points into bins .

The Pseudo-BER method determines the BER for different threshold levels representing different areas under the PDF curve.

With the BERs at different threshold levels, an extrapolation can be made for the estimated BER at the optimum threshold.

Fundamental method	Sampling	Description
Histogram method	Asynchronous	Voltage histogram
	Synchronous	Digital sampling scope
Pseudo-BER method	Synchronous	Single threshold method
	Synchronous	Dual threshold method

Table 1 Methods to determine Q

Asynchronous sampling (voltage histogram) – All the amplitude values of the eye diagram (including the amplitude values of the transient regions) are sampled asynchronously resulting in a histogram representing the PDF of the complete signal including the transient regions (figure 19).

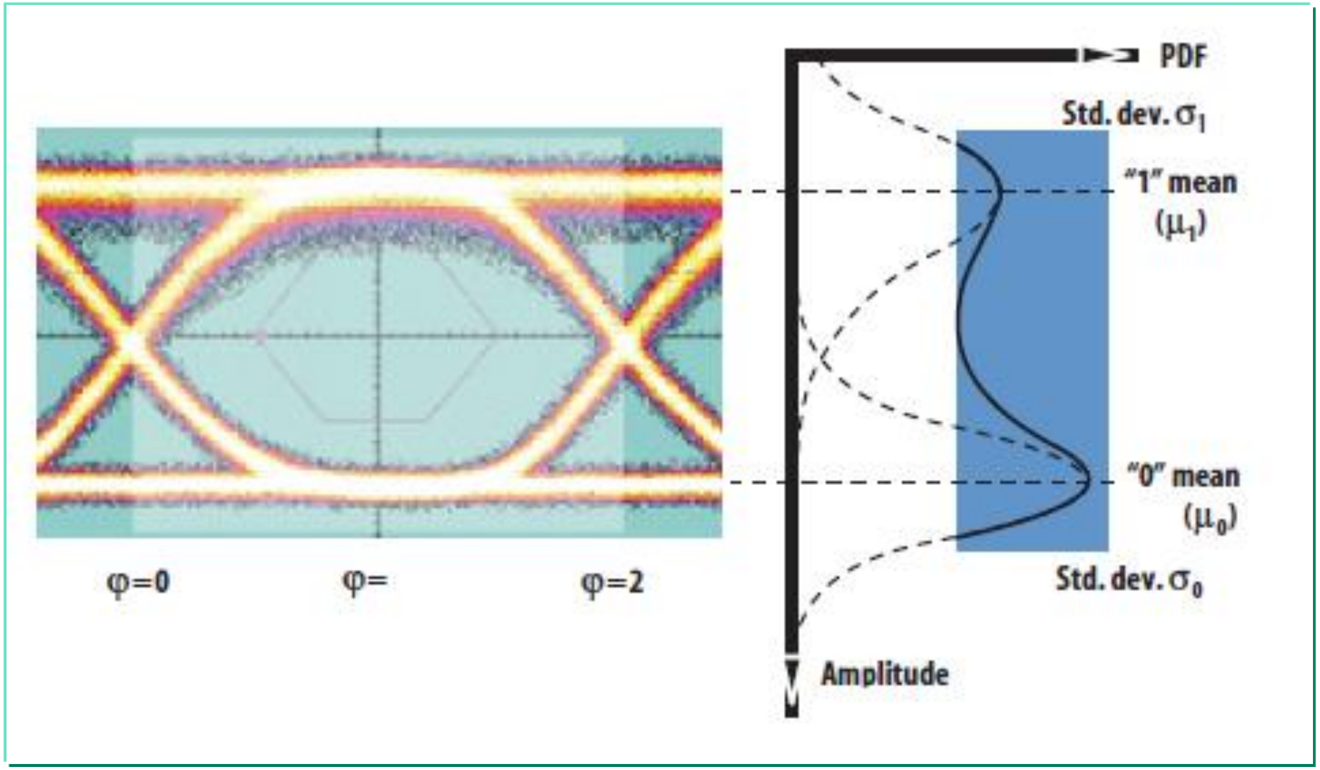


figure 19 Asynchronous sampling

The main objective in acquiring an evaluation of the performance is to determine the PDF of the optimum sampling phase which would be (in this particular case).

The contribution of the transient regions to the overall PDF is to “hide "the PDF of the sampling phase.

The transient region samples fill up the centre between the two means.

Two possible solutions for correction are the “cut and flip "or the “cut and delete "methods (figure 20).

The idea behind this is that the histogram’s edges are influenced only by the noise distributions but not by the transient.

In the first case, the edges representing noise distributions are flipped inside to get a more appropriate model of the PDF.

In the second case, the centre (which is affected by the transient samples) is omitted leaving the edges for evaluation.

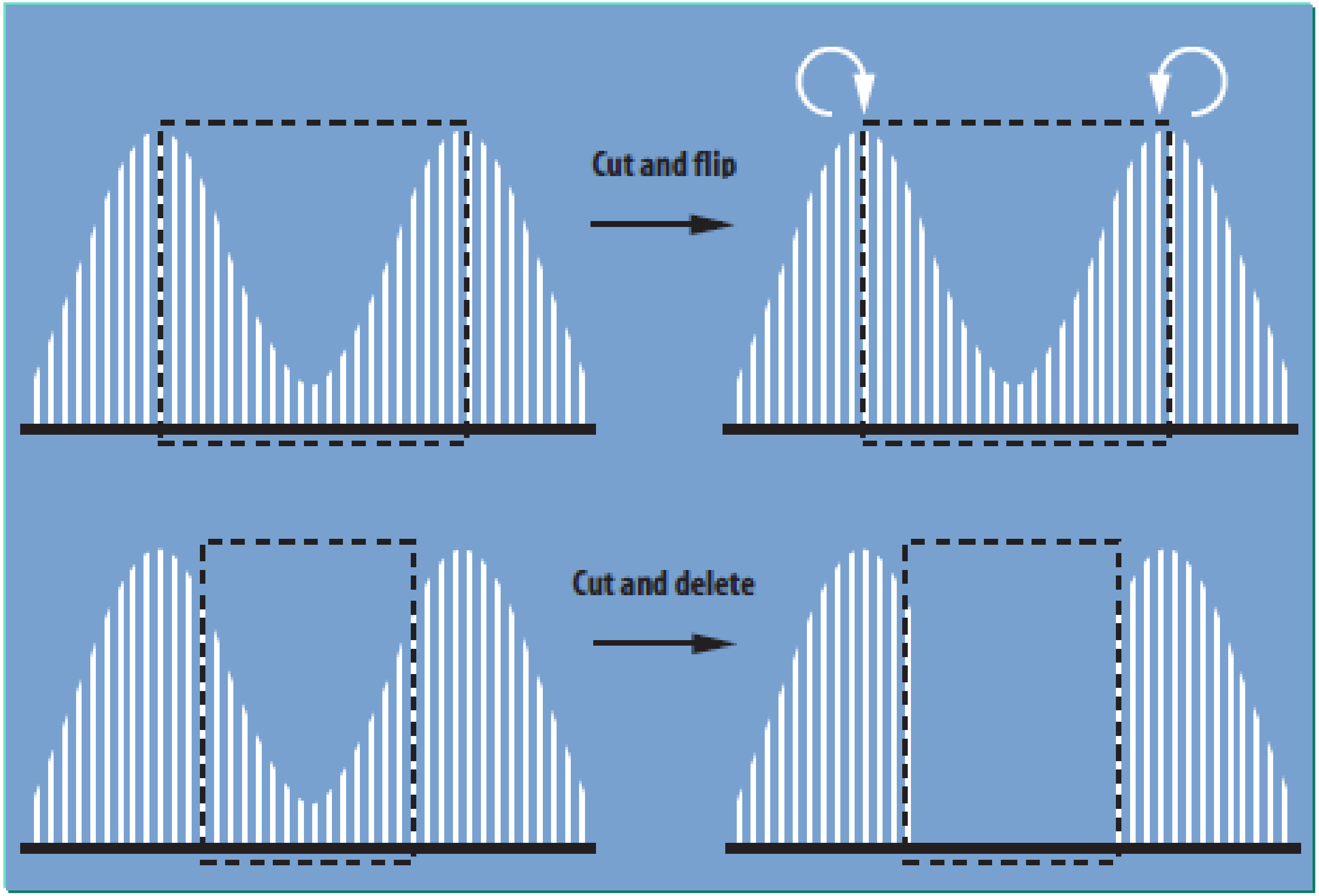


figure 20 “Cut and flip” and “cut and delete” method

Asynchronous Sampling-contd.

The characteristics of the asynchronous sampling method make it very difficult to fit the Gaussian functions to the measurement results which are necessary for the BER Calculation .

The BER calculation for the signal will not give a high accuracy for the optimum sampling phase as the PDF needs to be prepared to provide a better estimation.

Until now , the exact estimation of the Q-factor from the asynchronous sampling histogram could not be accurately proved .

Although this technique has restrictions for performance monitoring ,it remains a very powerful tool for detecting small signal degradations.

Synchronous sampling (digital sampling scope) –

The main restriction of asynchronous sampling is that the transient regions affect the result.

To overcome this restriction and gain higher accuracy, synchronous sampling must be performed.

Synchronous sampling needs a clock recovery and is therefore more complex.

The Sampling phase is locked to the optimum phase and can therefore give a more accurate result of the BER estimation.

Synchronous sampling concentrates more on the detection phase rather than the whole signal (figure 21).

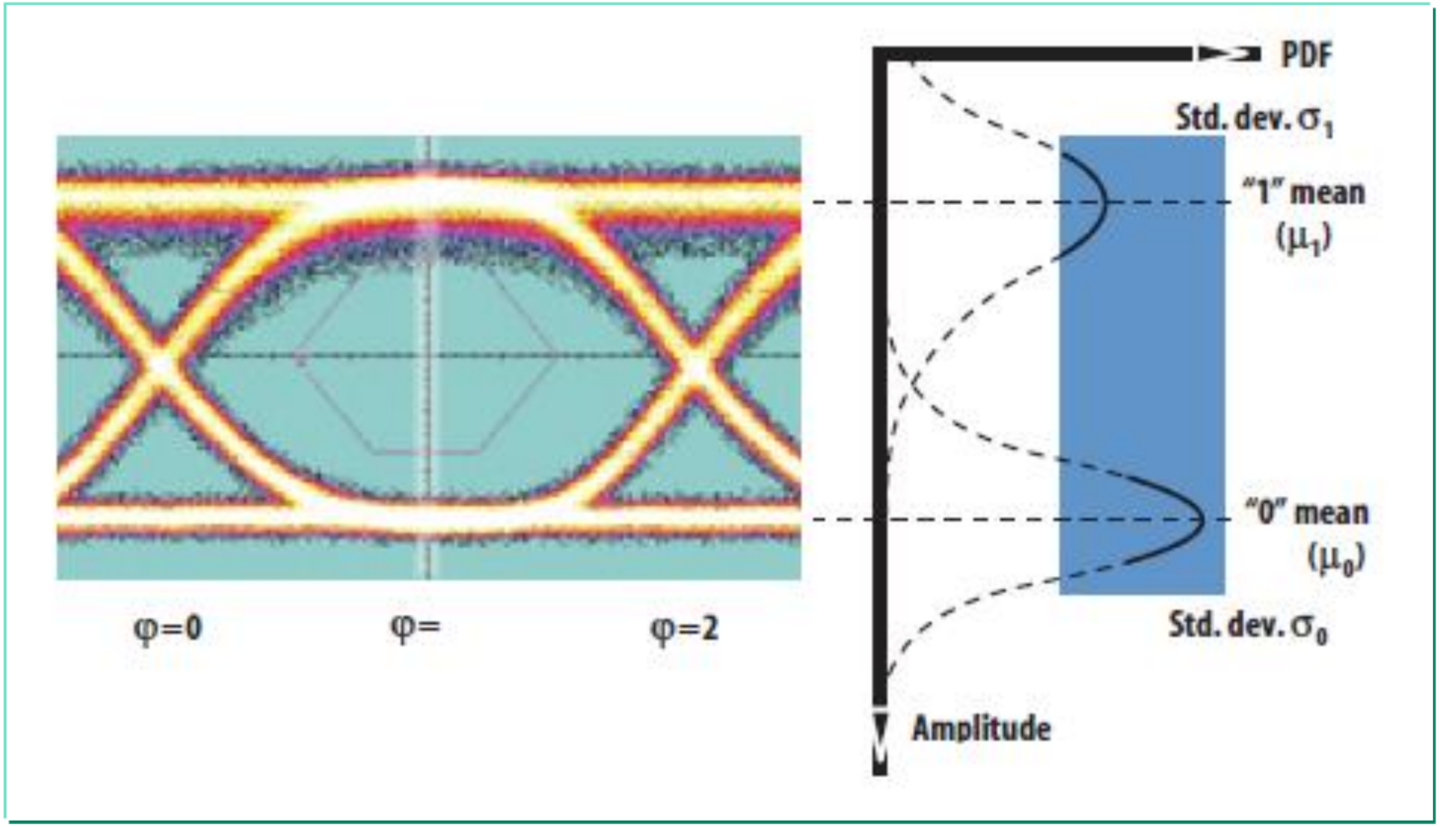


figure 21 Synchronous sampling histogram method

One disadvantage of this method is that the digital sampling scopes used often do not have the sampling rate needed for Q-factor measurements.

A Typical sampling rate would be 100,000 samples per second.

Assuming a 10 Gbps signal (10,000,000,000 bits per second) is received , only one bit out of 100,000 would be sampled.

An additional disadvantage is that due to the low statistical probability of a sample being affected during measurement occurring at the tail of the Gaussian function , the samples tend to be concentrated at the “0”and “1”levels.

This gives a good estimation around the mean values of the two Gaussian distribution functions although the estimation of the correct standard deviations and hence the bell curve is difficult to determine .

The shape of the bell curve however contributes greatly to the BER estimation as the evaluation takes place mostly at the tail of the bell curve.

Although this method gives a higher degree of accuracy than the asynchronous histogram method , it is still not very accurate and mostly shows lower Q- factor values (higher BER).

Synchronous sampling method (single decision threshold method) –

Rather than taking the histogram to determine the shape of the PDF (and thus the estimated BER),

BER measurements at different decision threshold levels can be taken to extrapolate the estimated BER.

The BER measurement method described in ITU-T standards can be time consuming given that the measurement time must fulfil the requirement of a certain statistical confidence.

By taking decision threshold levels which are correlated to BERs of 10-4 to 10-8,the measurement can be completed much quicker (table 2).

Assuming the distribution of the PDFs are Gaussian , the BER of the optimum threshold level can be evaluated giving an estimated BER as opposed to an actual measured value.

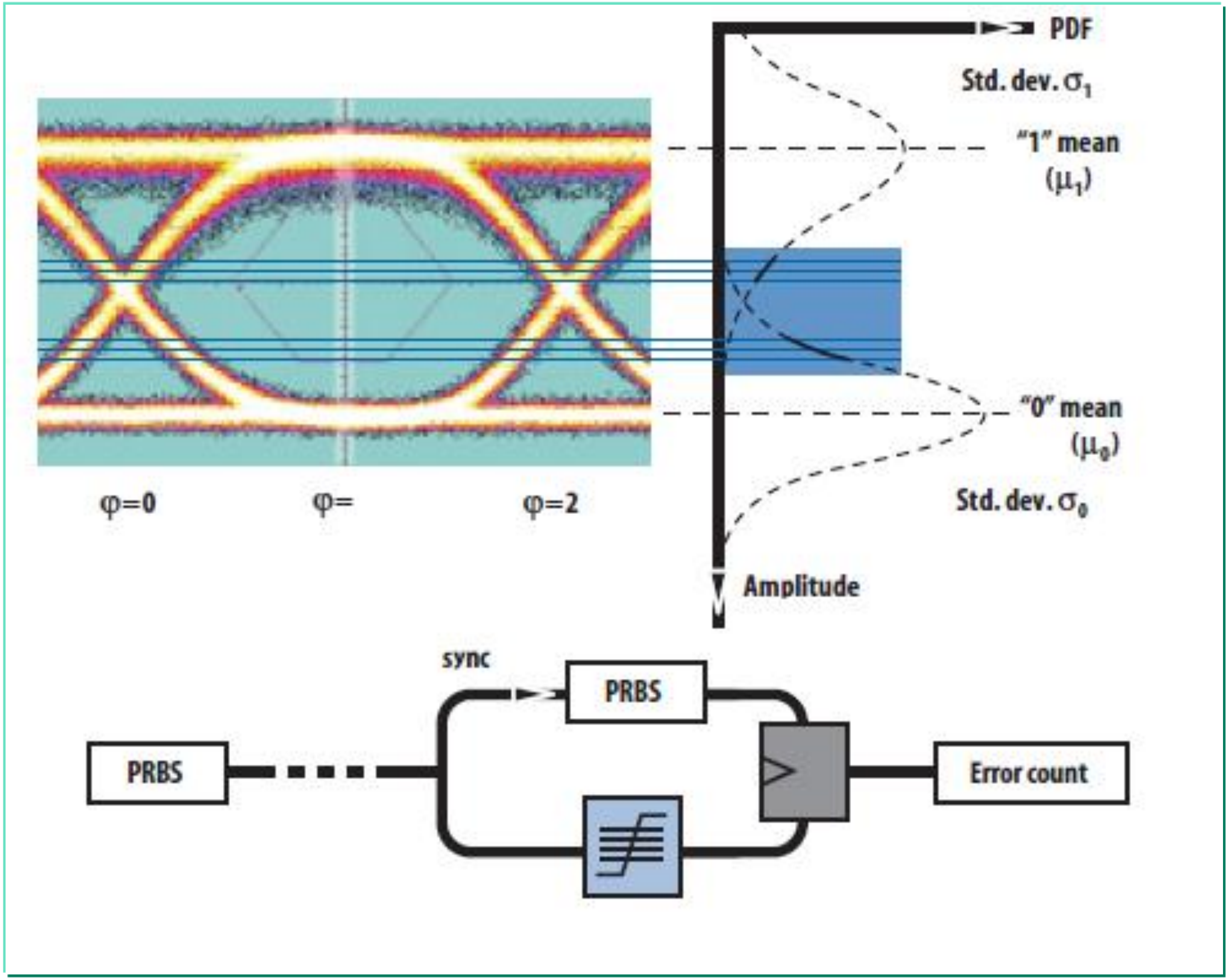
BER	10^{-4}	10^{-8}	10^{-14}	10^{-15}	10^{-16}	10^{-18}	10^{-20}
STM-16/ OC-48	0.004 ms	0.04 s	11 h	6 days	46 days	13 y	1268 y
STM-64/ OC-192	0.001 ms	0.01 s	3 h	28 h	12 days	3 y	317 y

table 2 Time for one error to occur at different bit rates

By using the Pseudo-BER method, the number of samples is the same as those given by the bit rate.

For example, a 10 Gbps signal results in 10,000,000,000 samples per second,which when compared to a sampling scope gives a much higher rate.

figure 22 Single decision threshold method


PDF
Std. dev. σ1
"1" mean
(μ1)
"0" mean
(μ0)
Std. dev. σ0
Amplitude
φ=0
φ=
φ=2
sync
PRBS
PRBS
Error count

The principle block diagram shows how the single decision threshold method works (figure 22).

On the transmitter side a known data pattern which can be realized by a Pseudo-Random Binary Sequence (PRBS) is sent.

On the receiver side the signal is detected with variable decision threshold levels.

A Second path is required to provide the known data pattern (PRBS) as a reference signal.

The detected signal and the reference signal are compared with each other to identify the bit errors.

The errors are then counted over a certain time frame to determine the BER.

This process is repeated at different threshold levels.

Once the BERs have been measured, an extrapolation can be made for the optimum decision threshold level.

The different threshold levels also allow a better evaluation at the tail of the PDF as the area investigated is much closer to the tail than it is with the histogram method.

This results in a better fitting of the Gaussian curve and in turn a higher confidence and accuracy of the BER estimation at the optimum detection point.

A BER estimation with this method may be completed in just under 1 minute.

Synchronous sampling method (dual decision threshold method) –

The single decision threshold method is based on the traditional BER testing with a known bit pattern (PRBS).

This of course has the drawback that the single decision threshold method can only be performed in out-of-service mode.

To overcome this disadvantage the dual decision threshold method is applied.

The receiver has two signal paths, one set to the assumed optimum threshold (used as reference path or signal),the other operating with variable decision threshold levels (figure 23).

The two paths are compared to count bit errors thus making the known data pattern at the receiver side obsolete.

Being independent of the bit rate and a specific test pattern, this method clearly shows its benefits as an in-service performance measurement.

If not otherwise stated, the Q-factor measurement always refers to the synchronous sampling method with dual decision threshold in this pocket guide.

The results of the Q-factor measurement can be graphically displayed in a diagram with the x-axis representing the threshold level and the y-axis representing the BER (error count with regard to the reference threshold level and estimated BER).

Each threshold level generates a data point in the range of 10-4 to 10-8 in order to receive short measurement time.

An extrapolation using the measured BERs (light area in figure 24) allows for an estimation of the BER of the optimum threshold level (Q-factor point in figure 24).

The estimated BER can be expressed as Q-factor.

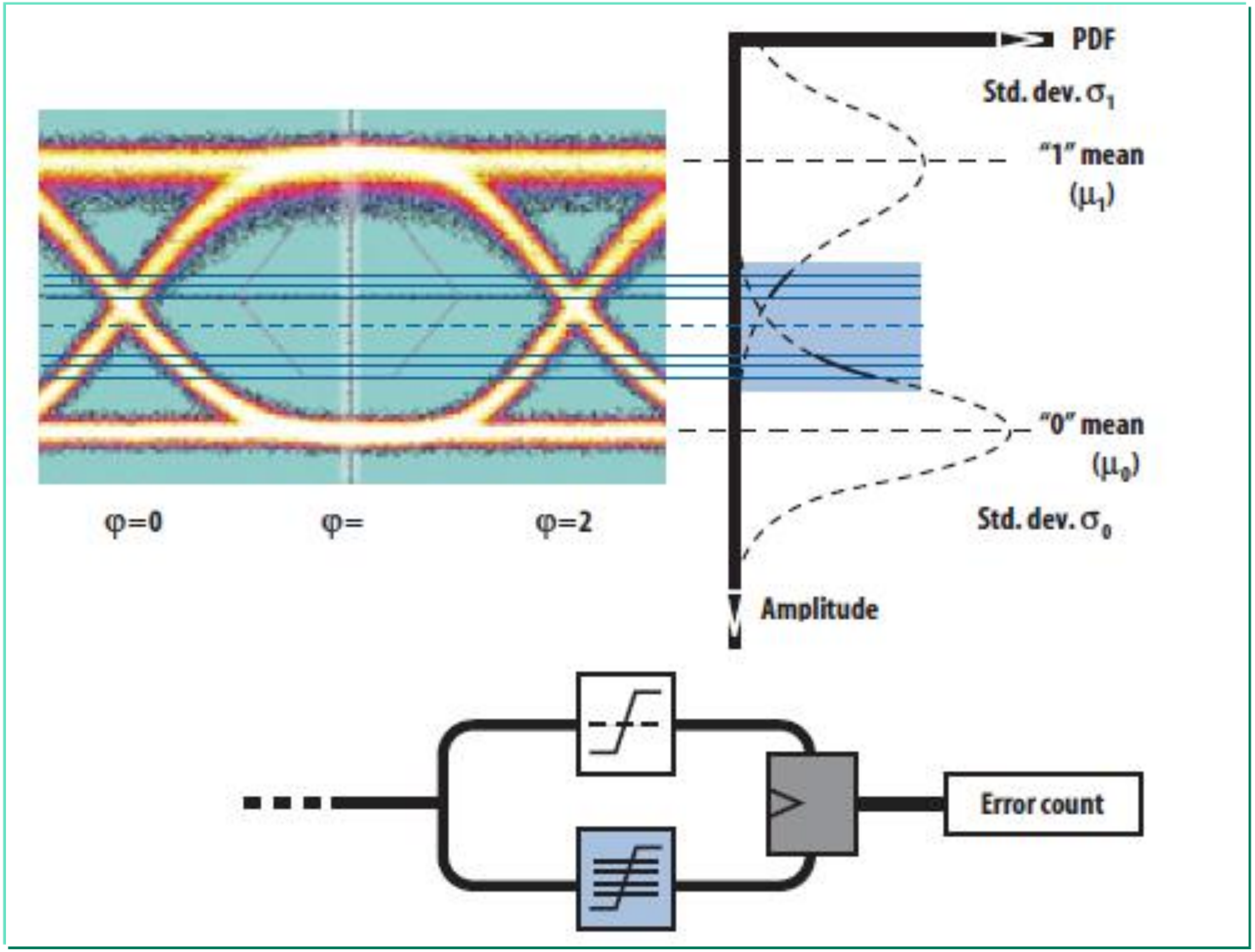


figure 23 Dual decision threshold method

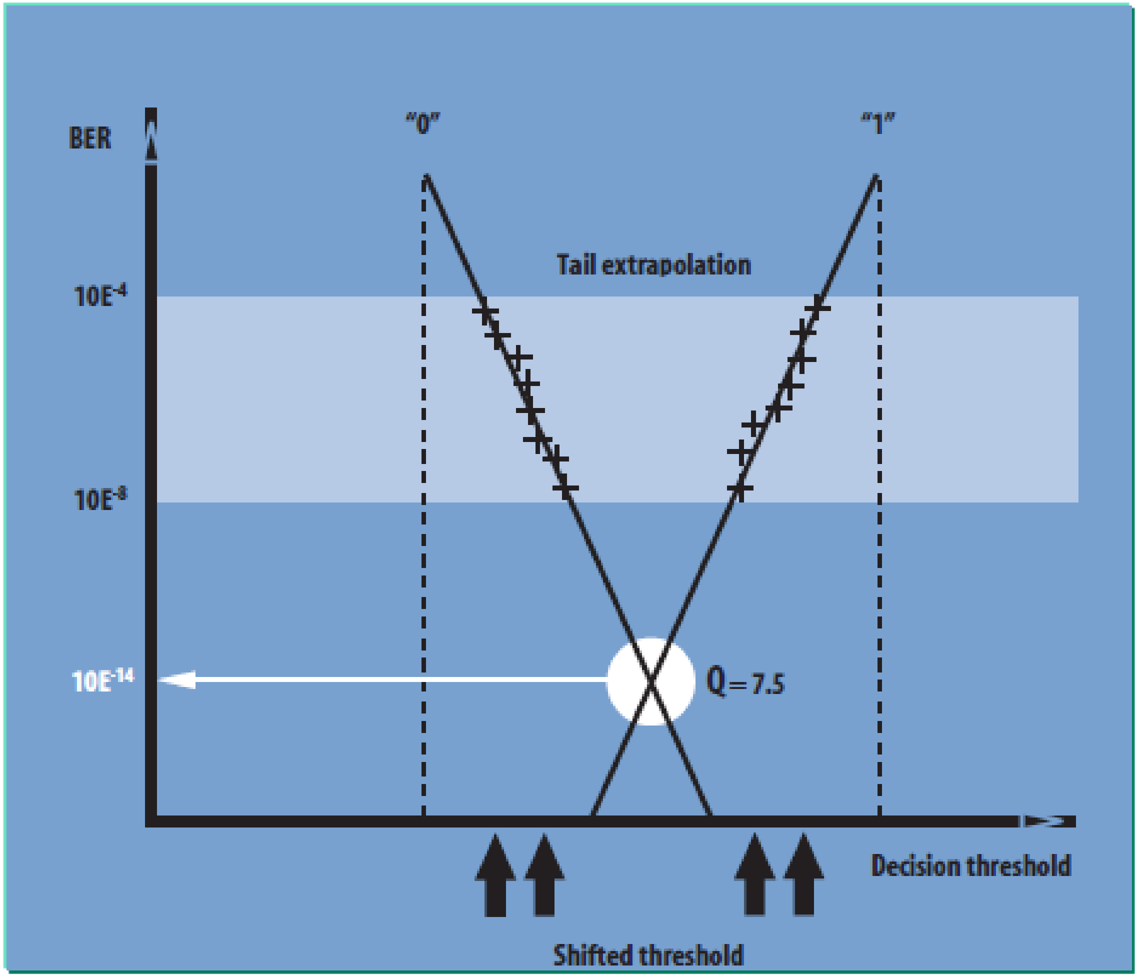


figure 24 Q-factor extrapolation

Q-factor applications

1. Manufacturing - system components must be checked after Manufacturing.

2. Installation - functionality of equipment set up at network operator sites must be verified.

3. Optimization - systems currently in operation must be optimized for best system performance.

4. Maintenance and Troubleshooting- covering tasks where the Q-factor meter can be used as a measuring tool.

5. Monitoring - Q-factor can show the smallest of signal degradations.

During manufacturing a final system test must be performed in order to verify the technical specifications of systems.

DWDM implies multi-channel systems of which every channel must be thoroughly checked.

Systems able to handle 40 or 80 channels are common with some higher channel systems currently emerging in the market place.

BER performance of better than 10-12 is a common requirement, though this can be a time consuming task especially for multi-channel systems.

Assuming a single 10 Gbps channel needs to stand the requirement for a BER of better than 10-13,the test time is 28 hours to get a statistically correct result.

With DWDM systems able to carry up to 100 channels, the overall test time will be in a range where it is no longer economical to apply this kind of test method.

Twenty-eight hours multiplied by 100 channels results in a testing time of approximately four months.

An alternative option is to apply new test methods which do not allow direct proof of the performance but deliver a performance estimation with a high degree of confidence.

The Q-factor method is an ideal solution for this (figure 25).

The fast BER estimation checks all system channels quickly, thus lowering test time and costs.

Typically an “out-of-servicec”application,factory calibration and optimization can now be performed efficiently and economically especially in multi-channel-systems.

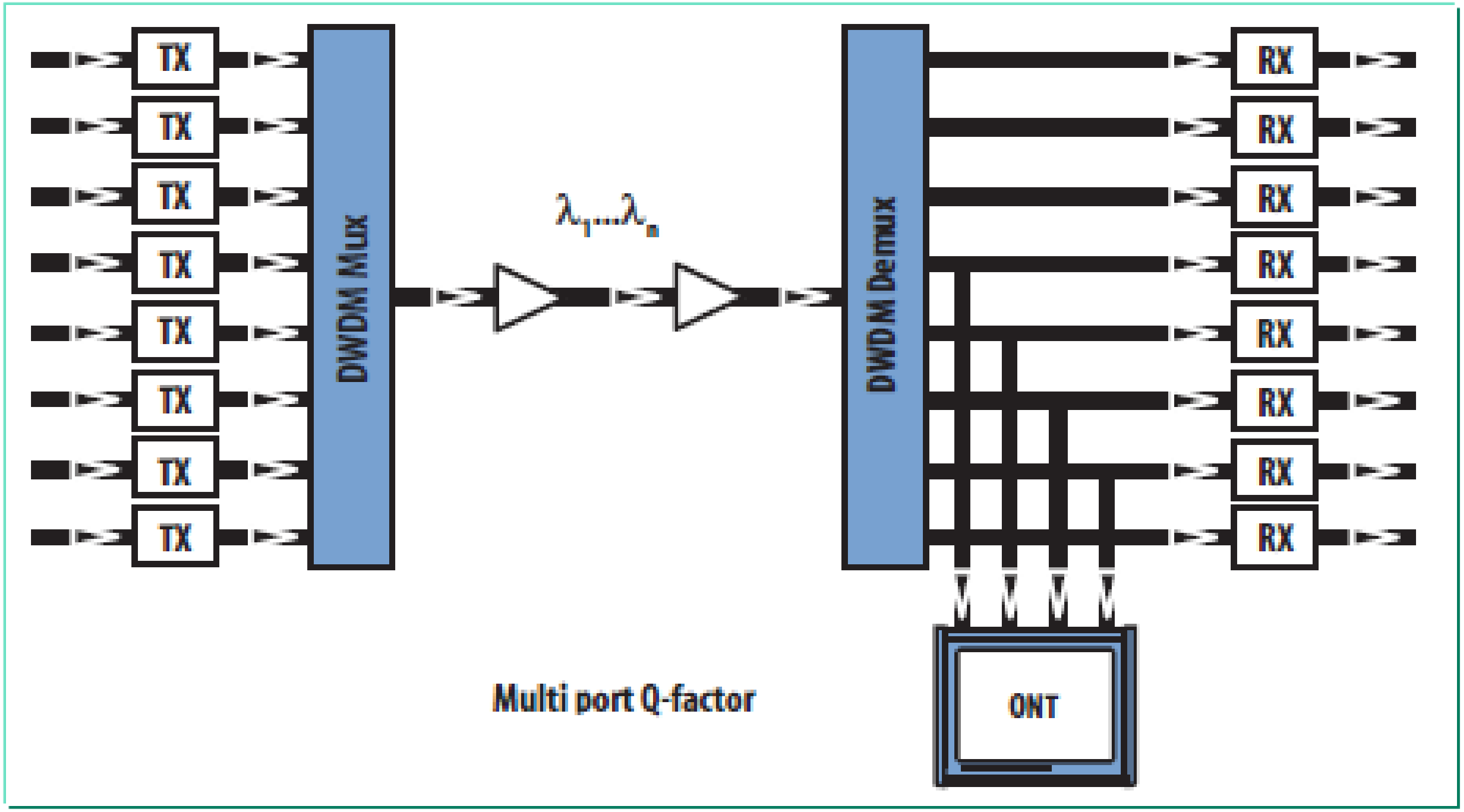


figure 25 System test during manufacturing

Another "out-of service "application in which the Q-factor can be utilized is during installation of optical networks at a network operator's site (figure 26).

Here the Q-factor measurement allows for the functional verification of the optical network elements.

Typical questions arising at installation include:

Question :

– Has the installation of the subsystem been successfully completed?

– Will the performance of a subsystem be good enough to support the overall performance requirements?

– Are there certain parts or components of the system which could be problematic?

Answer :

The Q-factor meter allows a fast BER estimation during installation to answer these questions.

Time consuming traditional BER tests can be avoided before final commissioning.

An Optical Spectrum Analyzer (OSA) can also be used to monitor various parameters such as power, (OSNR) and wavelength.

It should be noted that the Q-factor does not replace the final commissioning with a BER tester to determine the overall QoS.

For final commissioning the whole link needs to be seen as a Device Under Test (DUT) (including system transmitter and system receiver).

The system transmitter is then replaced by a pattern generator and the output of the system receiver fed into a BER tester.

ITU-T considers this the only test method valid today to determine the QoS of a digital channel.

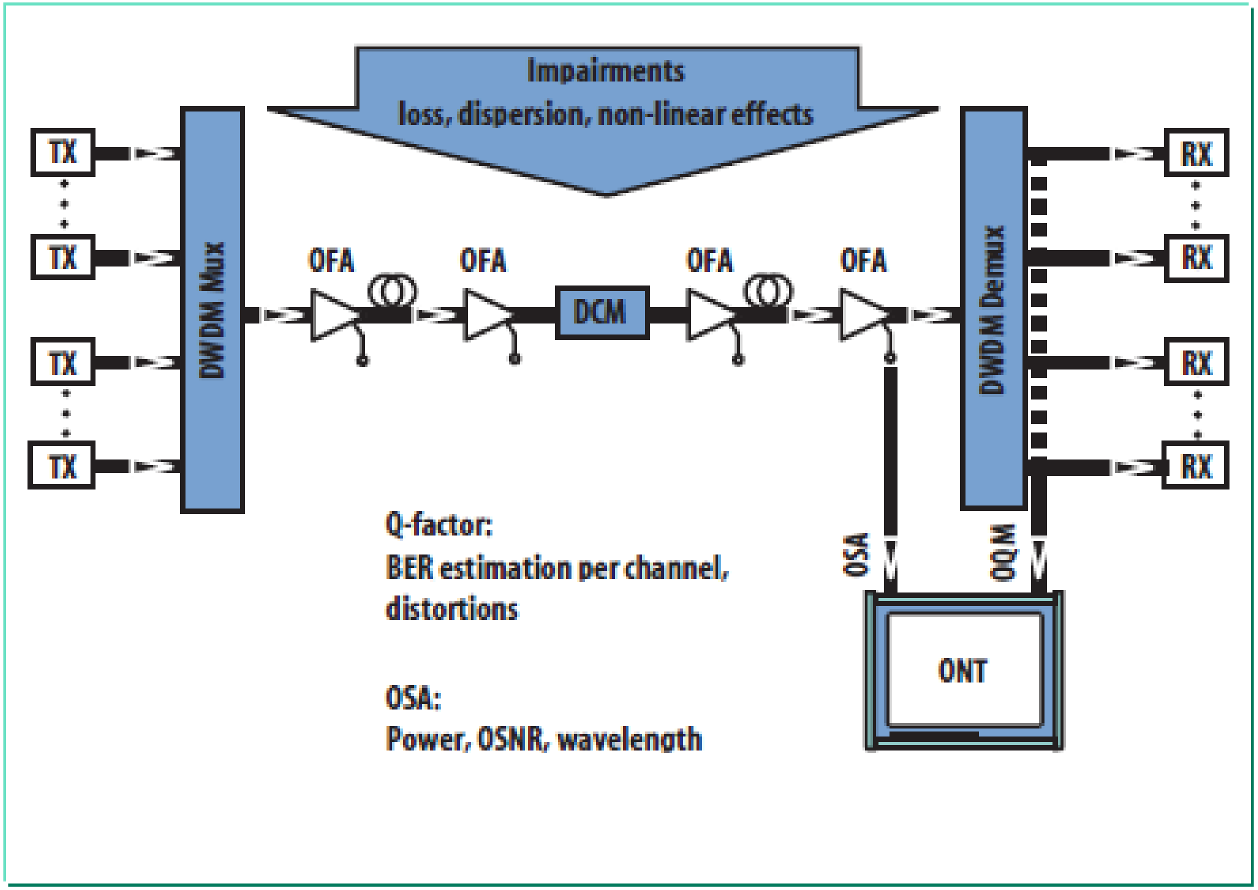


figure 26 Possible setup during installation

Installed systems include components which can be adjusted for optimum performance.

Although this is part of the installation process, it may also be a factor to be resolved during operation.

A common question at this stage:

Question

– Have the system parameters such as channel power level and chromatic dispersion been adjusted for optimum performance?

Answer

The Q-factor meter allows direct monitoring of the performance as it provides fast BER estimation.

System optimization can be easily achieved through the adjustment of network elements with results which can be seen immediately (figure 27).

The proper settings for Optical Fiber Amplifier (OFA) output levels for example can be checked very quickly as the settings have a direct impact on signal quality.

A significant advantage with the Q-factor meter is that it also operates in the in-service mode when the appropriate tap points are provided.

This is made possible as the Q-factor meter is independent of bit rate and data format.

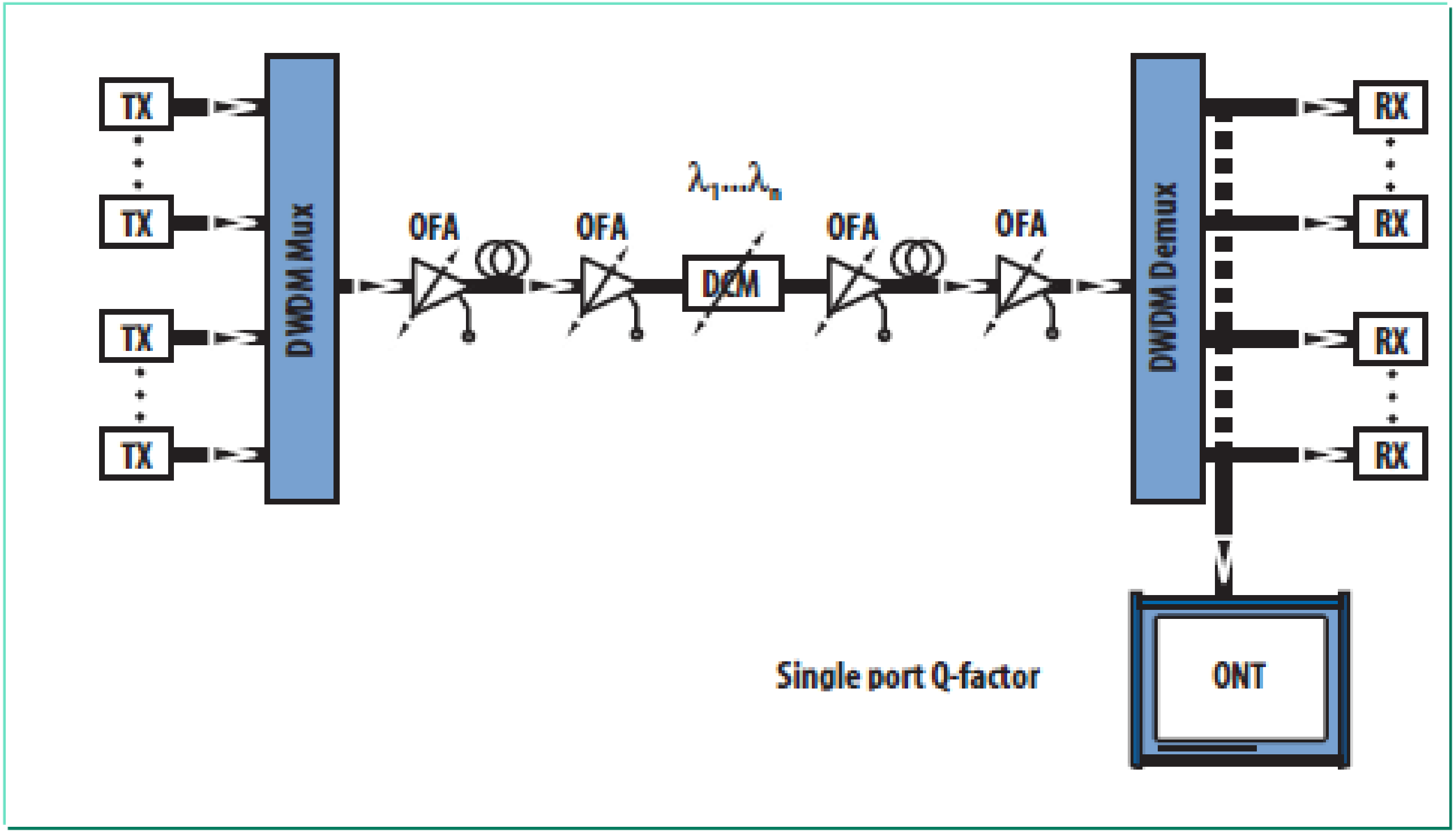


figure 27 Q-factor used for system optimization

During maintenance and troubleshooting one of the main objectives is to gather as much information as possible on the system in-service .

To take the system out-of-service costs time and money.

A performance estimation with a Q-factor meter is therefore an ideal solution.

Tapped signals provided in systems allow for these measurements to be made.

Questions raised relating to these measurement tasks include:

Question

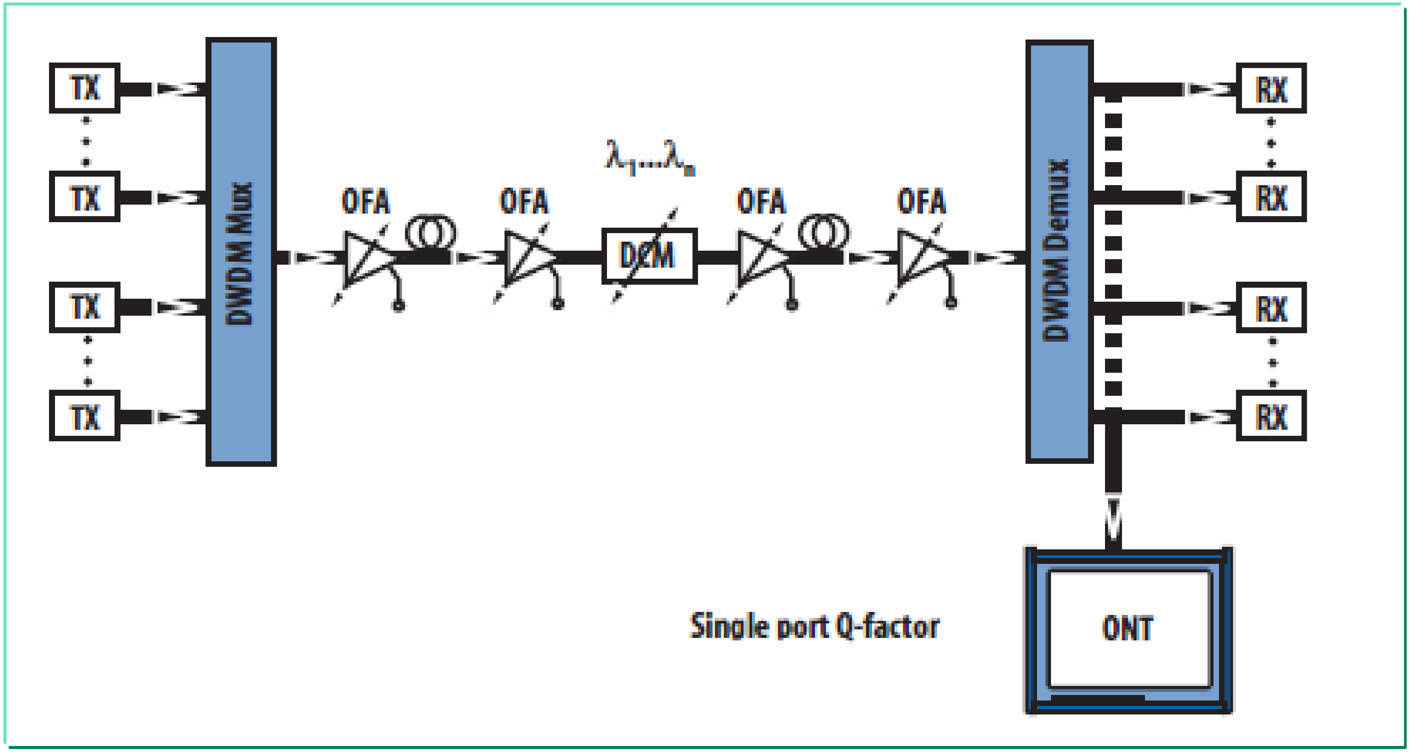
1. Are there system degradations which make it necessary to switch to an alternative transmission path?

2. Are there crosstalk or non-linear effects present due to added channels during a system upgrade?

Answer

To bring the system back to the guaranteed QoS it is necessary to have the right tools for fault identification and location.

The Q-factor meter can be used for maintenance as well as for troubleshooting to view when and where a system degradation might occur (figure 28).



Q-factor used for system optimization

To check the system performance over a certain period of time or within specific time intervals, monitoring needs to be performed. Monitoring may also imply that the user handles equipment remotely from a central location such as a Network Operations Center (NOC) for example (figure 29).

Typical questions which arise include:

Question

1. Is it possible to perform monitoring as preventive maintenance in an in-service mode?

2. Can system degradations be identified during preventive maintenance monitoring which is independent of bit rate and protocols used (for example SDH with and without digital wrappers, ATM,IP,etc.)?

Answer

Monitoring is possible when tapped signals are provided by the system.

Pre-maintenance monitoring shows even small degradations in QoS and the network operator can react quickly to this.

Degradation effects can occur through aging and mechanical stress.

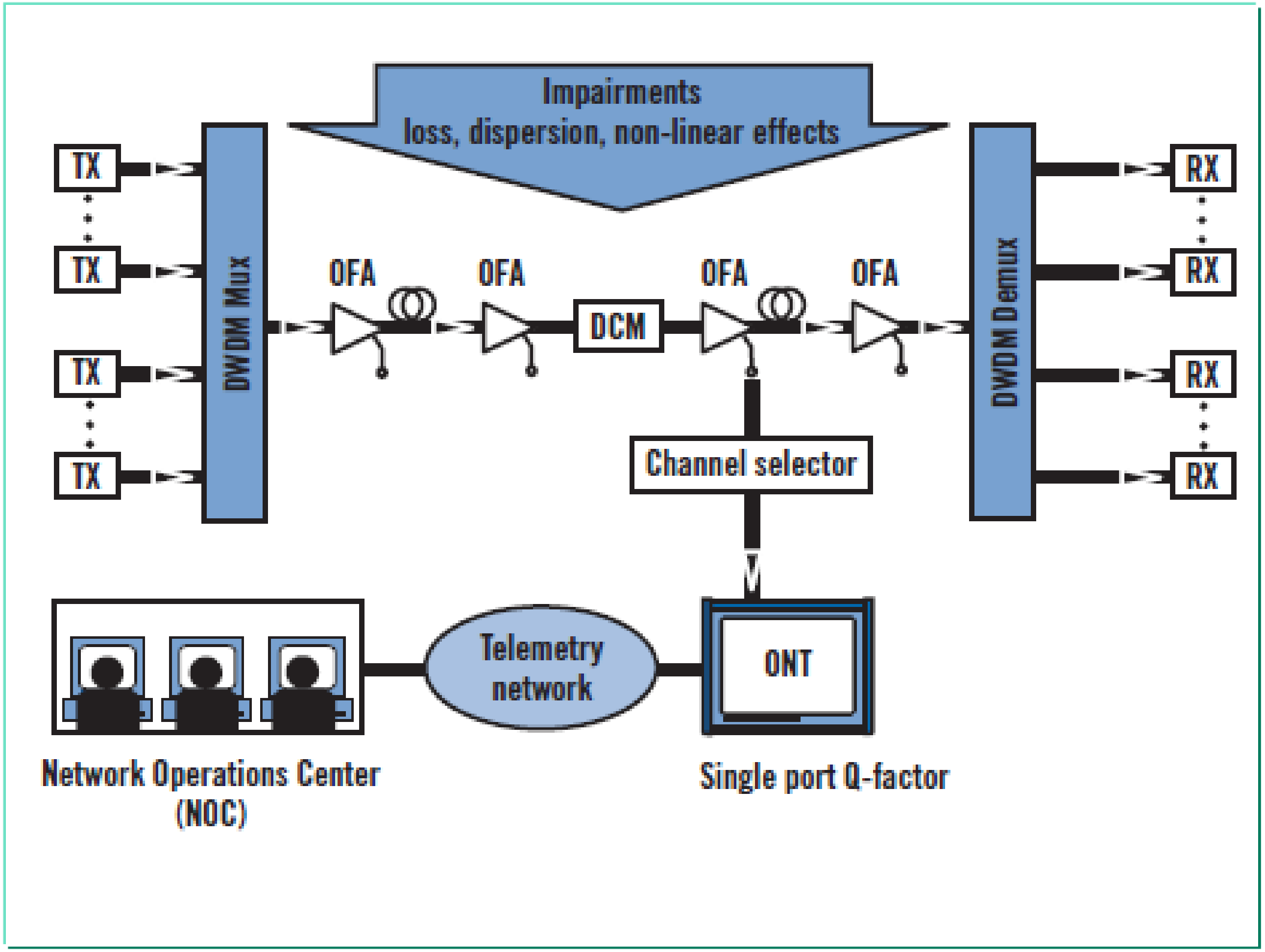


figure 29 Setup of ONT with Q-factor during system monitoring

Q-Factor : is a measure of noise in a pulse.

It is a function of the OSNR, which provides a qualitative description of the receiver performance.

The Q-factor suggests the minimum (SNR) required to obtain a specific BER for a given signal.

OSNR is measured in decibels.

Note : The higher the bit rate, the higher the OSNR ratio required.

For OC-192 transmissions, the OSNR should be at least 27 to 31 dB compared to 18 to 21 dB for OC-48.

The OSNR is the most important parameter that is associated with a given optical signal.

It is a measurable (practical) quantity for a given network, and it can be calculated from the given system parameters.

The logarithmic value of Q (in dB) is related to the OSNR by following Equation :

In the Equation, B_0 is the optical bandwidth of the end device(Photo-detector) , and B_c is the Electrical bandwidth of the receiver filter.

Therefore, Q (in dB) is shown as-

$$Q_{dB} = 20\log\sqrt{OSNR}\sqrt{\frac{B_0}{B_c}}$$

$$Q_{dB} = OSNR + 10\log\frac{B_0}{B_c}$$

In other words, Q is somewhat proportional to the OSNR.

Generally, noise calculations are performed by optical spectrum analyzers (OSAs) or sampling oscilloscopes, and these measurements are carried over a particular measuring range of B_m.

Typically, B_m is approximately 0.1 nm or 12.5 GHz for a given OSA.

From Equation showing Q in dB in terms of OSNR, it can be understood that if $B_0 < B_c$, then OSNR (dB)> Q (dB).

For practical designs OSNR(dB) > Q(dB), by at least 1–2 dB.

Typically, while designing a high-bit rate system, the margin at the receiver is approximately 2 dB, such that Q is about 2 dB smaller than OSNR (dB).

The Q factor provides a qualitative description of the receiver performance because it is a function of the signal to noise ratio (optical).

The Q-factor suggests the minimum SNR required to obtain a specific BER for a given signal.

The higher the Q factor of the signal, the lower the BER will be. (BER is improved with the Q Factor) .

The Q-factor meter is a tool which can be used during:

– Manufacturing for system test
– Installation for a fast BER estimation (BER prequalification)
– Installation and operation for system optimization
– Maintenance, troubleshooting and monitoring.

The Q-factor meter estimates the BER for optimum threshold level and sampling phase in less than 1 minute , making the Q-factor measurement faster than traditional BER testing.

The Q-factor measurement is independent of bit rate and data format and as such is a "universal tool" in systems carrying different bit rates and protocols.

As DWDM systems are transparent for different data formats the Q-factor meter is an ideal solution.

In addition to this , the Q-factor does not require a known bit pattern to be sent thus allowing in-service monitoring when appropriate tapped signals are provided.

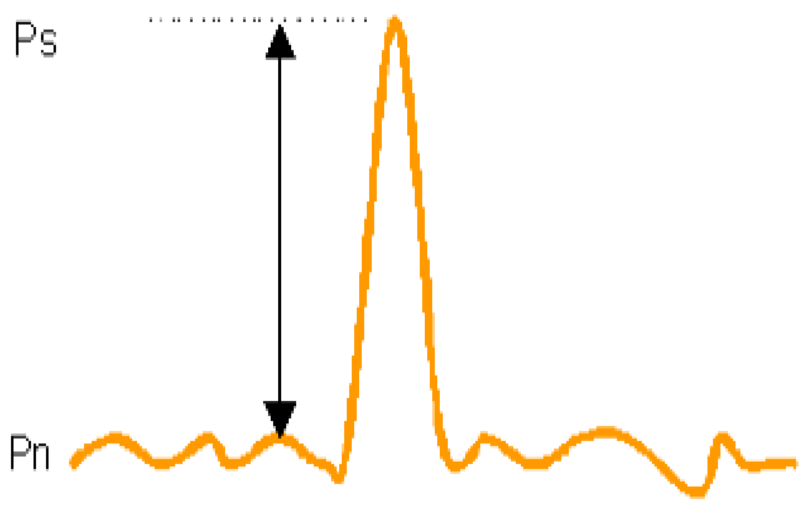
Figure-31, OSNR shows the ratio of power in the signal to the noise that is with the signal.

Better OSR is indicated by High Numbers.

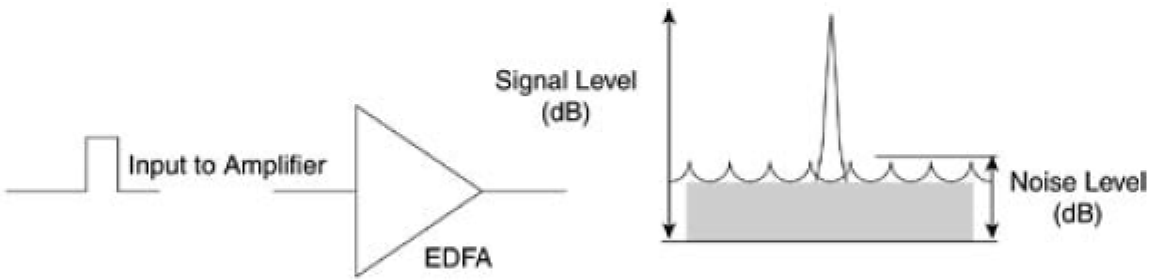
In most cases, the OSNR of 10 dB or better is needed for error-free operation.

“P n” is the power level of the noise and “P s” is the power level of the signal.

$$(OSNR = 10\log_{10}(P_s/P_n).$$

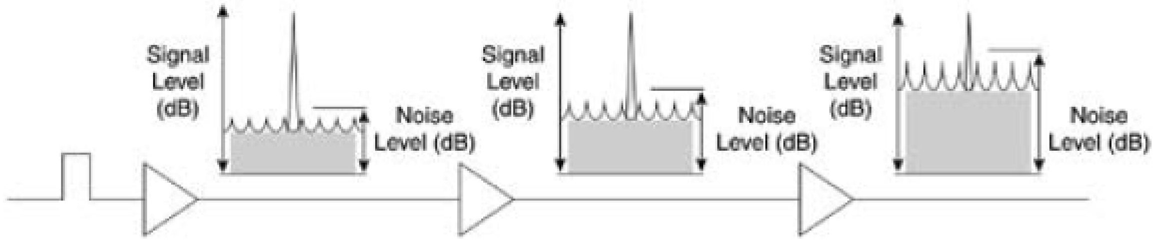


Single Stage Amplifier and Noise Associated with Signal



The noise is random in nature, and it is accumulated at each amplification stage. Refer to Figure

Noise Accumulation Resulting from Multistage Amplification



Amplifier noise is a severe problem in system design.

A figure of merit here is the optical signal to- noise ratio (OSNR) requirement of the system.

The OSNR specifies the ratio of the net signal power to the net noise power where it is a ratio of two powers;

Therefore, if a signal and noise are both amplified, system OSNR still tells the quality of the signal by calculating this ratio.

System design based on OSNR is an important fundamental design tool.

NOTE : OSNR is not just limited to optical amplifier-based networks. Other active and passive devices can also add noise and create an OSNR-limited system design problem.

Active devices such as lasers and amplifiers add noise while Passive devices such as taps and the fiber can add components of noise.

In the calculation of system design, optical amplifier noise is considered the predominant source for OSNR penalty and degradation.

Symptom	Loss Margin
Fiber dispersion	1 dB
SPM margin	0.5 dB
XPM margin	0.5 dB
DCU compensation	6 dB
FWM	0.5 dB
SRS/SBS	0.5 dB
PDL	0.3 dB
PMD	0.5 dB
Amplifier gain tilt (due to nonflat gain spectra)	3.0 dB
Receiver sensitivity tilt (wavelength dependence of PMD)	0.5 dB
Transmitter chirp	0.5 dB
AWG cross-talk	0.2 dB
Fiber connectors	0.5 dB

The above table presents margin requirements for a good design where these margins adhere to variations in optical signal budgeting issues, especially on a dynamic level.

The margins are generally chosen by evaluating a set of readings that represent the pseudo-population of a number of discrete events governing the entire sample space of optical signal design.

Suppose if we consider the multimode WDM link, the main component of the system loss is apart from attenuation , is the loss associated with the various subsystems, consists of multiple nodes, each equipped with a variety of components, then the loss due to each component is high, resulting in a severe penalty for system design.

A Typical WDM node might have a full optical multiplex section (OMS) that consists of arrayed waveguides (AWGs) and a switching matrix.

A Typical grating-based AWG has a **5 dB loss** (insertion loss) associated with it.

An Optical signal that is passing through a node with two such AWGs (multiplexer and Demultiplexers section) is typically subject to 10 dB loss in addition to the switching fabric loss.

An estimate of the loss can be understood with the following Example :-

Consider two nodes, each equipped with AWGs (loss = 5 dB) and switching fabric (loss = 3dB) in addition to connector loss (2 dB).

If they are separated by 50 km of SMF (a = 0.2 dB/km), the total attenuation due to transmission is 10 dB (.2 x 50). However, at each node, the loss is 5 + 5+ 3 + 2, or 15 dB. In other words, the nodal losses can be higher as in comparison to transmission losses.

This affects system designs and OSNR as well.

The effect is indirect in the sense that output power from a node is affected due to such losses, which further affects OSNR.

Component	Insertion Loss	Wavelength-Dependent Loss	Polarization-Dependent Loss	Cross-TalkNF
Multiplexer Demultiplex (AWG)	5 dB	< 1 dB	0.1 dB	–40 dB
Optical 2 x 2 add-drop switch	1.2 dB	< 0.2 dB	0.1 dB	–40 dBm
Coupler (2 x 2) passive	3 dB	-	-	-
Filter-Thin-film	1 dB	0.1 dB	-	–40 dBm
Filter- AOTF/MZI	1 dB	0.1 dB	-	–35 dBm
Interleaver	2–3 dB	-	-	-
Optical cross-connect (OXC) Port to port	3 dB typical without AWG loss	< 0.4 dB	0.1 dB	–40 dBm

Insertion Loss and Other Losses for 1550 nm Operation

There is a need to place dispersion compensation units (DCUs) at different positions in a network in order to compensate the total accumulated dispersion for a travelling pulse greater than the maximum allowable dispersion where the system cannot function because of tremendous ISI or just pure pulse spread in a chromatic dispersion-limited system .

Therefore, we need to place dispersion compensation units (DCUs) at different positions in a network.

some of the dispersion-compensating schemes, such as dispersion shifted fibers and FBGs, which are the most common.

we should use dispersion maps to effectively design a system for a high bit rate WDM link.

Dispersion maps are two-dimensional maps that plot the accumulated dispersion versus the length of transmission and help designers tell where to place dispersion compensators in a network.

Accumulated dispersion is calculated by multiplying the fiber and the laser dispersion specifications for a given bit rate with respect to the length of the fiber.

For example, an SMF fiber's typical value of dispersion is 16 ps/nm-km, which means that for every traversed kilometre of SMF fiber, a pulse at 10 Gbps (100 ps pulse width) spreads for about 16 ps from its mean.

Ensure that the accumulated pulse spread across 'x' km is less than the maximum dispersion limit (which might be 1600 ps/km-nm for a 10 Gbps signal).

Hence, it is obvious that the signal can travel 16x = 1600 km (if x = 100) of SMF fiber at a 10 Gbps bit rate.

It is important to note that as the signal traverses a greater distance, the accumulated dispersion also increases.

For a given bit rate and at a given operating wavelength (or operating band), the maximum allowable accumulated dispersion is given by a standard specification.

At no point in the dispersion map should the value of the curve go higher than the dispersion tolerance limit.

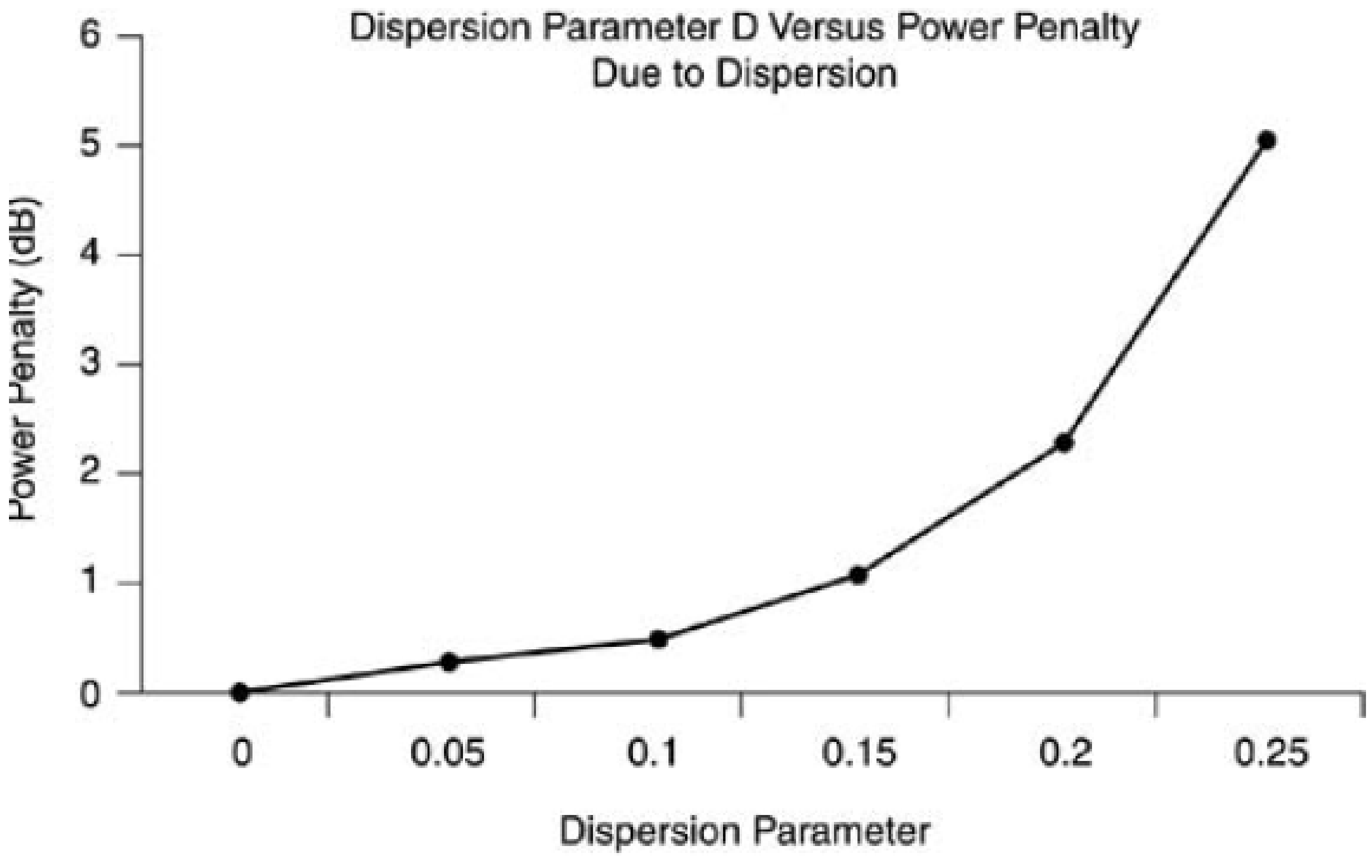
Note that the dispersion parameters depend on many factors. ie.

- the bit rate (which gives the pulse width)
- the length of the fiber,
- the basic dispersion parameter, and
- the spectral width of the laser, which qualitatively provides the amount of dispersion induced (GVD).

An interesting speculation is that of the variation of power penalty for dispersion-limited systems as a function of the dispersion parameter D, which is derived from the specification of the basic fiber.

D can be considered a balancing component between the bit rate, the length of the fiber, and the width of the spectral source that emits the pulse.

Refer to Figure.



Variation of Dispersion Parameter D with Power Penalty

Two techniques—pre-compensation and post-compensation can compensate dispersion using any of these methods.

As the name implies, *pre-compensation means compensating for dispersion* before the signal is induced in the system.

This is a technique of compressing the pulse in advance with DCUs; it takes care of the accumulated dispersion in advance.

In contrast, post-compensation uses compensating equipment that is placed at the end of a fiber.

In pre-compensation, we can place the DCU after the post line amplifier.

Such units have loops of fiber with dispersion profile opposite to that of the transmission fiber.

For example, a transmission fiber would have dispersion parameter of 16 ps/nm-km.

A DCU could hypothetically be made to have a dispersion profile of – ~ 50 ps/nm-km.

The signal passes through such fiber spools (DCU) and the pulse is pre-compensated.

Conversely, with post-compensation techniques, the DCU modules are placed before the preline amplifier, as shown in Figure and Table shows the dispersion parameter D for different kinds of fiber at 1550 nm.

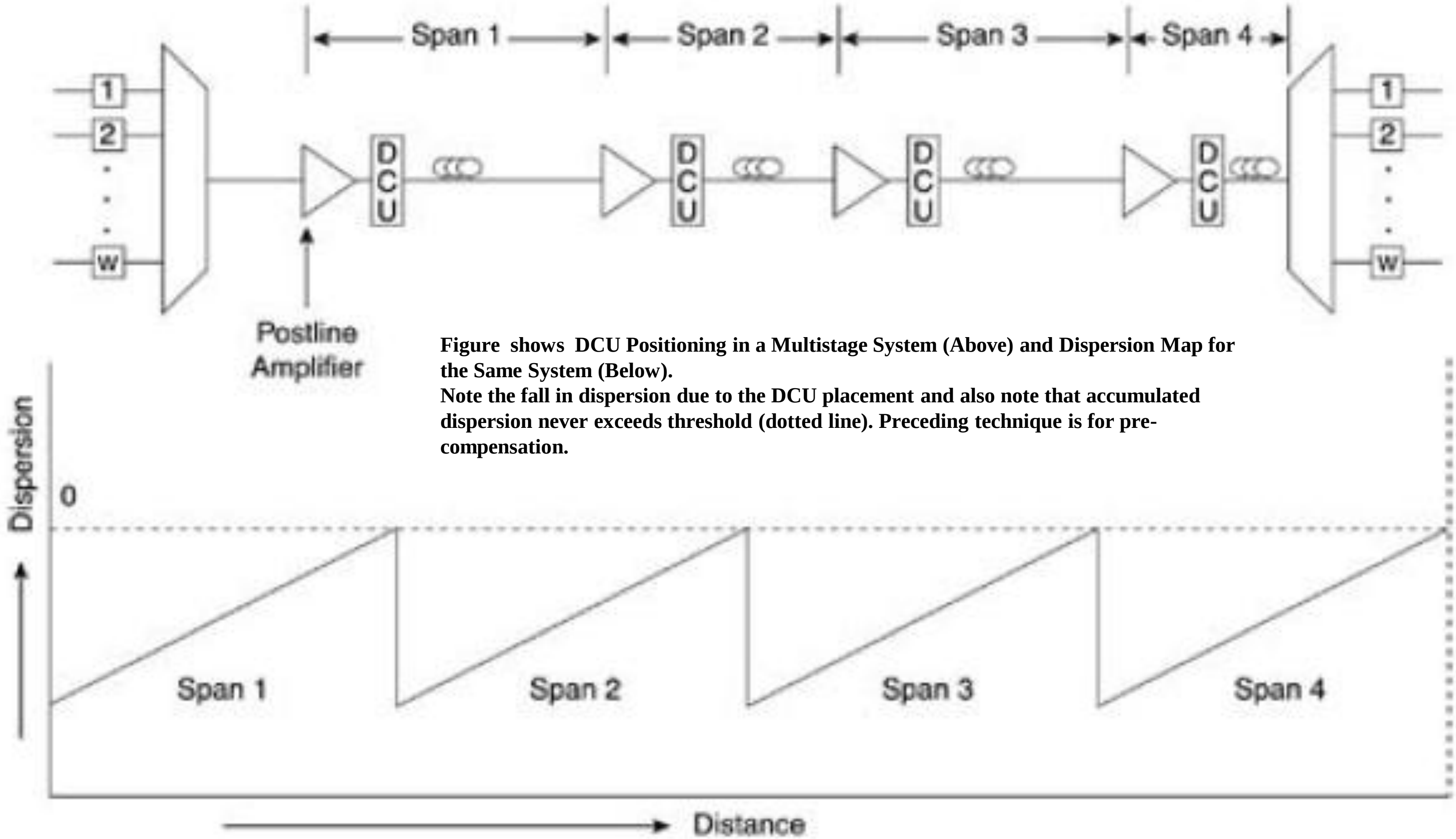


Figure shows DCU Positioning in a Multistage System (Above) and Dispersion Map for the Same System (Below).
Note the fall in dispersion due to the DCU placement and also note that accumulated dispersion never exceeds threshold (dotted line). Preceding technique is for pre-compensation.

Table Dispersion Parameter D

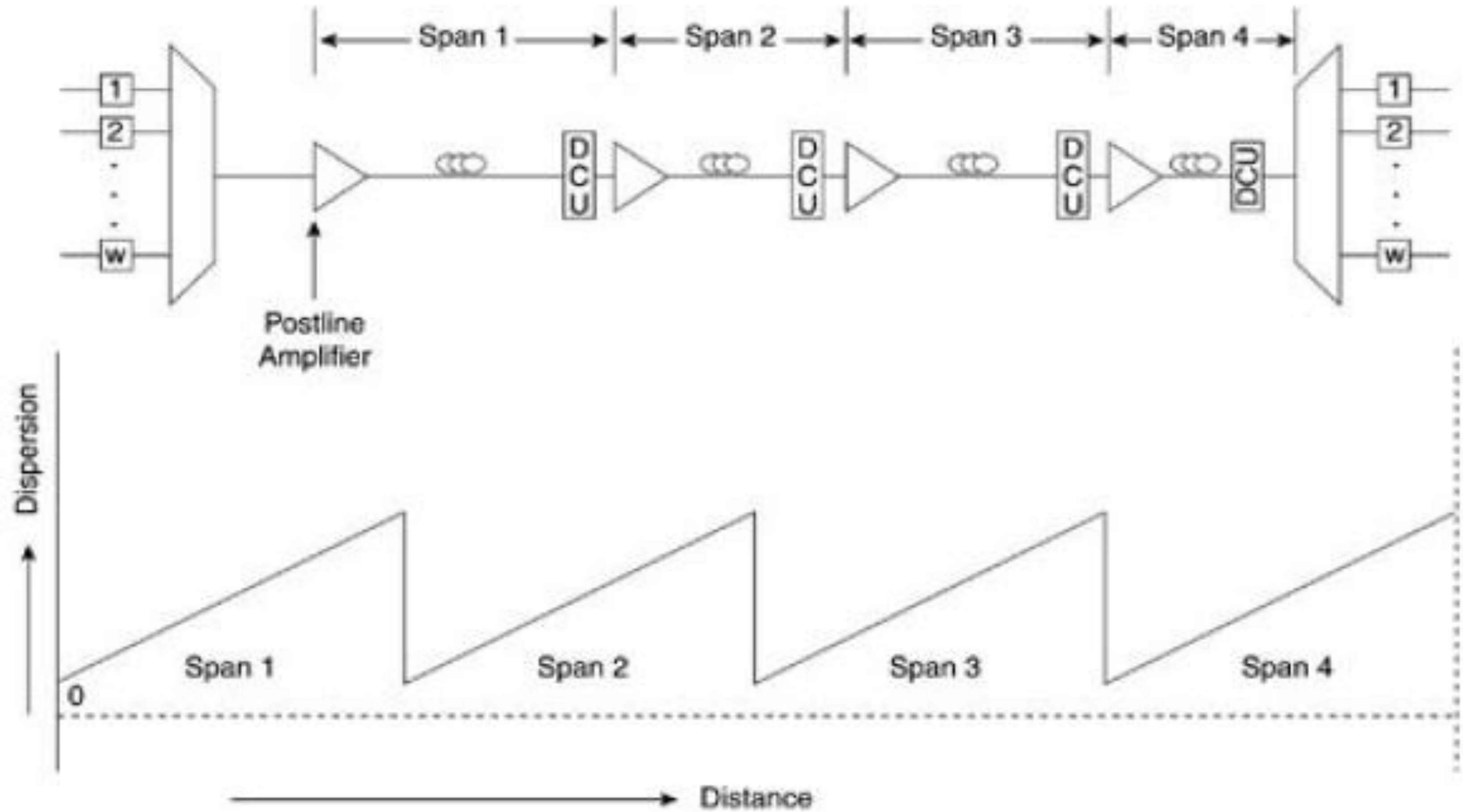
Fiber Type	Normal Dispersion at 1550 nm Measured in ps/nm-km
Single mode fiber (SMF)	17
E-Large Effective area fiber (ELEAF)	4
TrueWave RS (TW-RS)	4.2
Dispersion shifted fiber (DSF)	-0.33

A serious loss (attenuation) occurs when DCUs are added due to a coupling difference between transmission fiber and the DCU.

Moreover, different dispersion profiles result in a phase mismatch, which prevents FWM from happening.

This is one advantage of DCU in limiting the effects of nonlinearity.

Referring to the Figures from Pre compensation above and Post-compensation below as :



Dispersion Maps for Post-compensation Scheme

While designing the network, it is important to keep in mind for OSNR & Dispersion limitations.

It is possible to compensate for dispersion to a great extent.

However, OSNR compensation needs 3R (O-E-O) regeneration, which is expensive.

In other words, OSNR compensation is almost impossible for multichannel WDM systems.

Hence, designing a WDM link, it is imperative to first consider OSNR's limitations which means that OSNR based design at the final stage (at the receiver) is in conformity with the OSNR with good BER thus by guaranteeing the BER requirement that is essential for **generating revenue**.

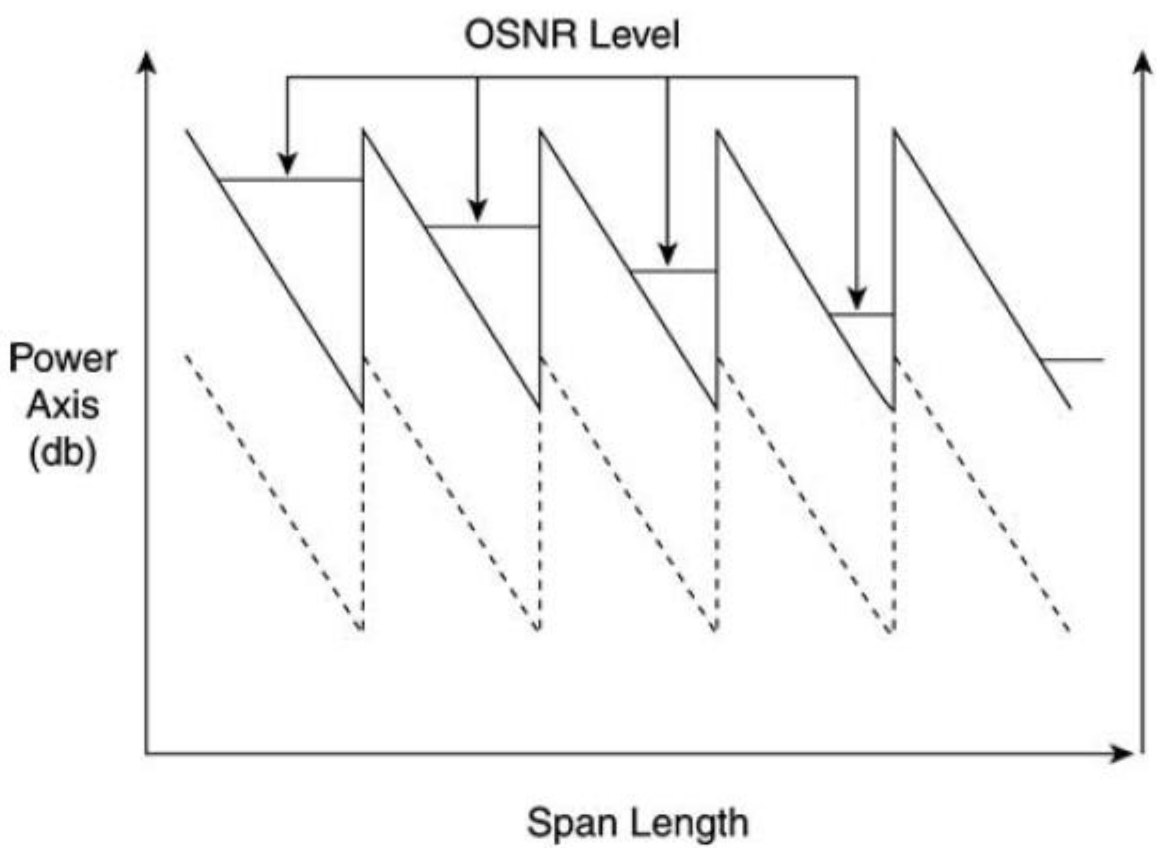
Following OSNR-based design, dispersion is the next issue to compensate from a design perspective.

Dispersion-compensating units are readily available, but an important issue is where to place them.

Various algorithms have been suggested depending on the network topology, the transmission length, and the bit rates.

For most designs, optimization placements have to be done on a span (per length) basis.

OSNR map that carefully disseminates the optical signal level and the noise level as the signal passes through each amplification stage.



OSNR Levels in Terms of Signal and Noise Power Levels for Multistage WDM Transmission

Frequency Chirp :

When pulses are generated at the transmitted end, intensity modulation causes phase modulation due to the carrier-induced change in the refractive index.

This change is inherently due to the laser line width.

Such optical pulses with a time-dependent phase shift are called *chirped pulses*.

The optical spectrum is broadened due to this chirp.

Theoretically, the chirp induced power penalty is difficult to calculate, but it can be approximated to a 0.5 dB margin in system design.

PMD is not an issue at **low bit rates** as it becomes a dominant issue at bit rates in excess of 5 Gbps.

PMD is inherently caused by the asymmetry of the fiber which adds to a property called *birefringence, such that the two principle degenerate modes (polarization modes* Ex and Ey) are subject to walkover effect.

Due to this walkover effect, the modes are not coupled to each other, which in turn causes the pulse to spread in time.

The main type of PMD considered is second-order PMD, which essentially originates from dispersion due to wavelength dependence of the signal as well as the spectral width of the signal.

The PMD in a Pulse

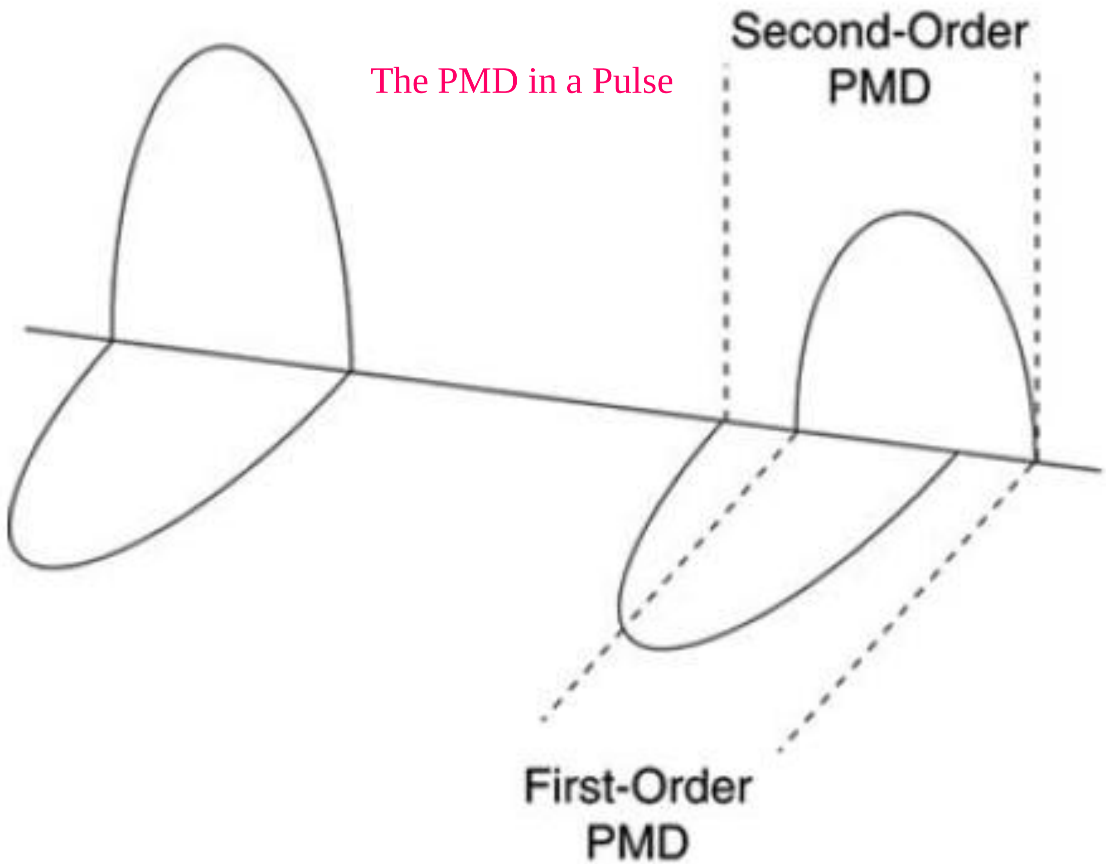


Figure shows the heuristics that create PMD in high bit-rate systems.

A measure of PMD is the differential group delay (DGD), which can simply be visualized as the time difference in multiple spectral components (at multiple speeds) over a given length of fiber.

The polarization axes are no longer joint, and the separation increases as the pulse is transmitted through a fiber.

The difference is somewhat proportional to the DGD.

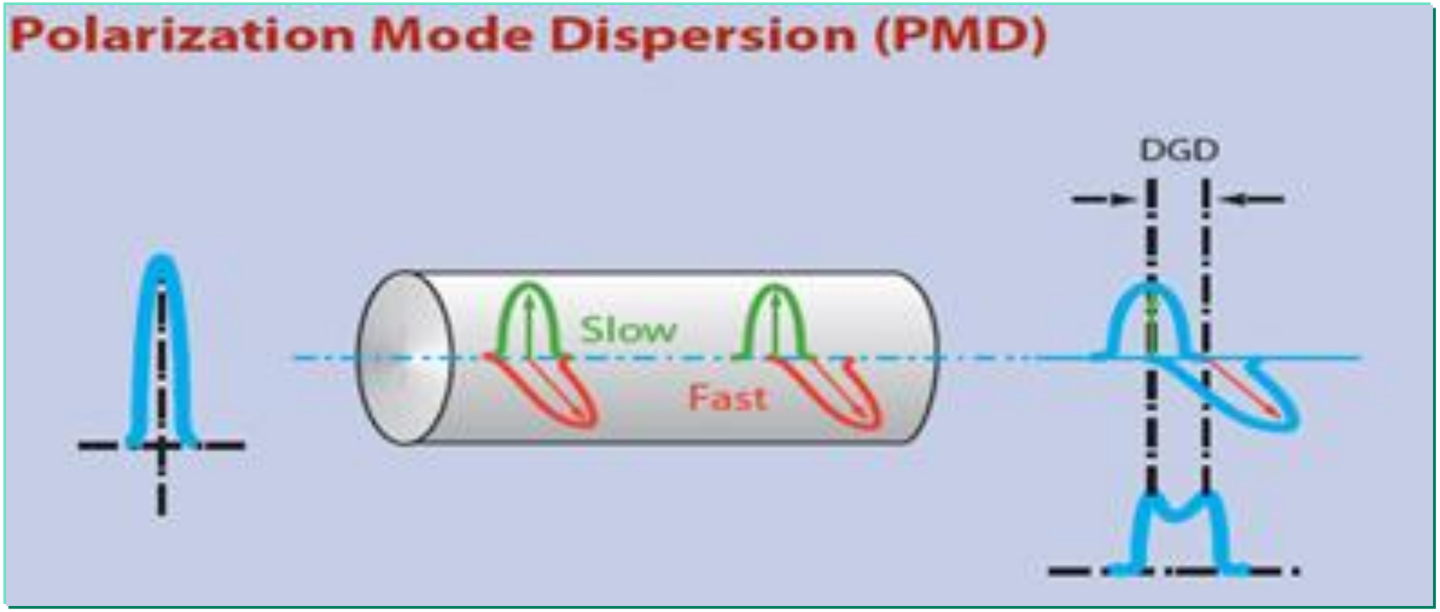
Therefore, DGD can be accurately used as a measure of PMD for a given system.

Moreover, PMD for a given fiber is defined as the mean of DGD.

Note-

Birefringence causes one polarization mode to travel faster than the other, resulting in a difference in the propagation time called the *differential group delay (DGD)*.

DGD is the unit that is used to describe PMD and typically measured in picoseconds.


Polarization Mode Dispersion (PMD)
DGD
Slow
Fast

PMD refers to the effect when different polarization modes (fast axis and slow axis) of a signal statistically travel at different velocities due to fiber imperfections.

The Time difference is called Differential Group Delay (DGD).

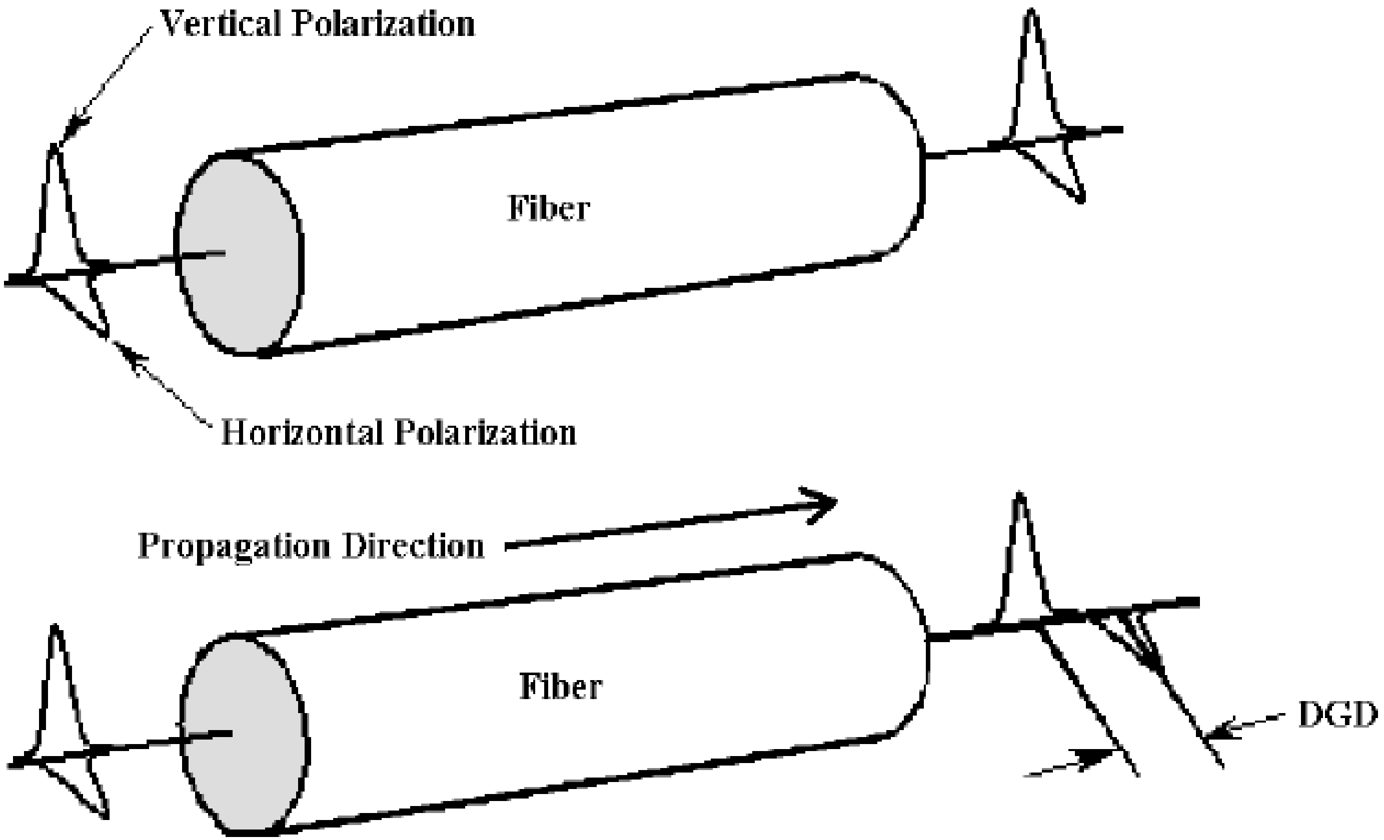
Effects:

1. **Decrease of peak power**
2. **Distortion of pulse shape and**
3. **Bit errors.**

Solutions:

1. **lay fiber carefully** (no stress)
2. **Use new fiber with low PMD values**
3. **Exact fiber Geometry.**

There is no PMD in a "perfect" fiber (top). Real optical fibers have some core assymetries which results in DGD (bottom).



The mean DGD can be calculated from Equation 4-26.

Equation 4-26

$$DGD = (\text{PMD Coefficient}) \times \text{Length}^{\frac{1}{2}}$$

The typical system margin for PMD is 1 dB for general long haul, but it depends on the transmission length.

Consider a numerical example: If the PMD coefficient of the given fiber is 2 ps and the distance under consideration is 625 Km, calculate the DGD. Refer to Equation 4-27.

Equation 4-27

$$DGD = 2ps\sqrt{Km} = 2^{*}\sqrt{625} = 2^{*}25 = 50ps$$

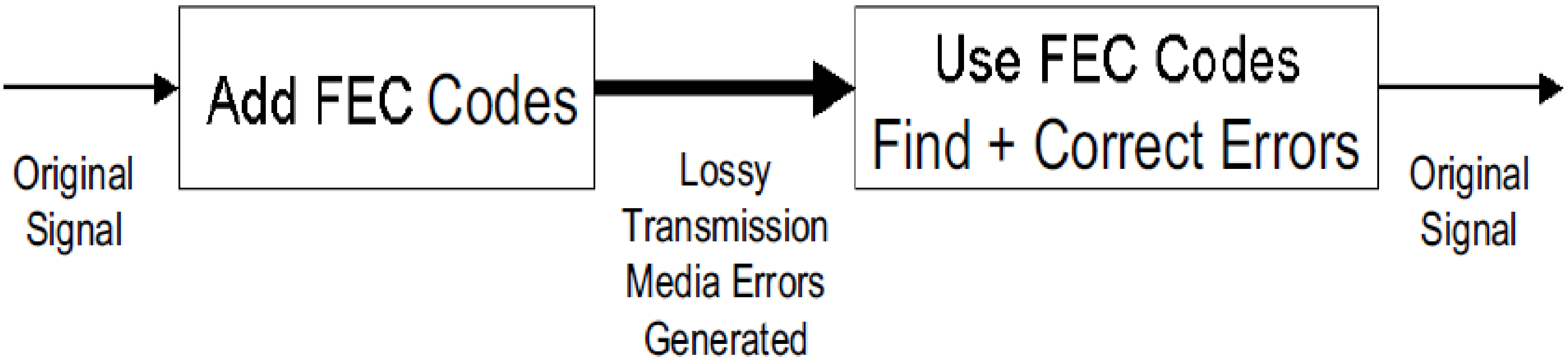
In 10 G and 40 G systems, a DGD of this magnitude degrades the performance of the system (causes more BER).

Forward Error Correction(Solution to BER) – is used to support higher capacity and longer transmission distances by improving the bit error rate (BER).

FEC makes the system more robust *in respect to* errors and the FEC code bytes are used at the end of a transmitted frame by the receiving system to find and correct errors.

Types of Forward Error Correction: The two main kinds of forward error correction (FEC) used in optical transmission are in-band and out-of-band.

In-band is sometimes called **“simple” FEC.**


Add FEC Codes
Use FEC Codes
Find + Correct Errors
Original Signal
Lossy Transmission Media Errors Generated
Original Signal

In-Band FEC

In-Band FEC is the most common method used in SONET Network Elements.

FEC bytes are carried as part of the SONET overhead.

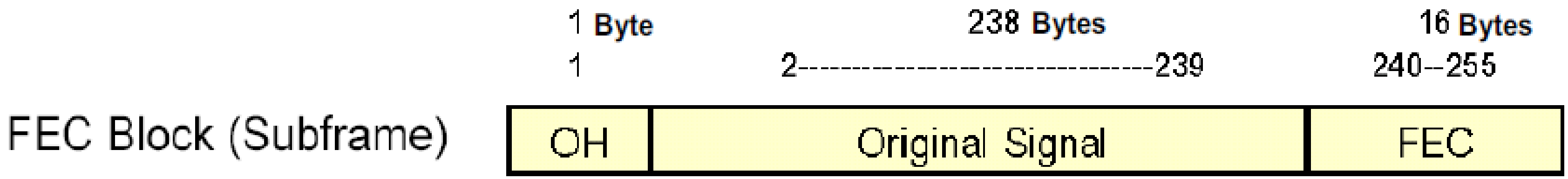
The simple FEC shown in Figure of **Forward Error Correction** is representative of In-band FEC.

Out-of-Band FEC

OOB-FEC is the type used for DWDM systems where FEC bytes are added on top of the signal to be carried shown in next fig below.

For example, adding OOB-FEC changes the signal from 9.958 Gb/s to 10.7 Gb/s for 10 Gb/s SONET transport, resulting in 6 percent overhead added outside the normal signal envelope.

OOB-FEC yields concurrent BER to BER performance.



OOB-FEC Example

- Forward Error Correction is the addition/interleaving of redundancy in a data stream allowing for correction of errors during reception of data without retransmission.
- Based on highly complex mathematical field known as sets and finite field theory.
- Provides increased gain which can be DIRECTLY applied to the optical link budget
- FEC decreases the BER.
- FEC is a bandwidth efficient solution to improving the BER.
- Allows correction without retransmission
- Allows decreased receiver cost for equivalent performance

- FEC is a coding technology widely used in communication systems.

- Using a classical block code as an example, the FEC encoder at the transmit end uses kilo bits of information as a block code.

- During the encoding, FEC adds n-k redundant check bits to the information bits, constructing an n-bit codeword.

- After the codeword is transmitted to the receive end over a channel, the FEC decoder detects and corrects bit errors during decoding – if the errors are within the correction range.
- In this manner, FEC prevents interference from channel transmission and improves the reliability of an optical communication system.

- This shows that FEC can efficiently reduce the system BER with only a small number of redundant overhead bits, thus extending the transmission distance and reducing system costs.

The FEC technology is originally used in the submarine cable system for ultra-long haul transmission.

But with the development of terrestrial optical communication system and increase of single-channel rate, the FEC will become one of the optimal choices to lower the OSNR of equipment and networking cost as well.

Note - When no FEC technology is used and the signal rate is increased to 10 Gbit/s or even higher, the transmission distance without electrical regenerators turns too short to reach a practical length.

Currently, the effective technologies available to expand capacity and extend communication distance are as follows:

- Wavelength division multiplexing (WDM)
- Erbium doped fiber amplifier (EDFA)
- High power laser
- Dispersion compensation fiber (DCF)
- Forward error correction (FEC)

FEC causes a direct improvement in system gain.

For In band FEC, the gain is around 2 dB and the gain experienced for out-of-band FEC can be expected around 6 dB.

This does show phenomenal improvement in system performance, but the FEC equipment comes at a price due to high-speed electronic circuitry involved.

Note : In today's networks, FEC is implemented using Reed-Solomon codes (RS-codes).

The bit rate enhancement due to FEC is shown in Equation 5-5.

Equation 5-5

$$\text{Bit rate}_{\text{with FEC}} = \text{Bit rate}_{\text{original}} \times 1.07 \text{ for out of band (OOB) FEC}$$

FEC with 40 Gbps Systems : Currently, the most talked about cutting-edge technology under development is 40 Gbps. So, many challenges were made to meet the 40 Gbps system

More feasible and economical.

The systems that are currently being developed are based on SONET/SDH (OC-768/STM-256) at bit rates around 39.8 Gbps and several impairments affect 40 Gbps or equivalent bit rate transmission.

Hence , forward error correction (FEC) given by the G.709 standard to alleviate this problem.

Forward error corrections (FEC) are used in long-haul transport where they help the signal to travel longer distances.

FEC adds extra bits to the signal, by increasing the bit-rate to 43 Gbps.

The constraints that are imposed by the insertion loss and polarization-dependent loss (PDL) are much higher (specification) than those for 10 Gbps systems.

Chromatic dispersion and polarization mode dispersion (PMD) need to be compensated at and above 10 Gbps speeds.

PMD compensations are expensive and challenging in 40 Gbps transmission systems.

(Impairment changes due to PMD over a short distance are unpredictable and the main issues in 40 Gbps transmission is optical impairments.

The exponential rise of these impairments beyond 10 Gbps speeds creates massive problems for 40Gbps implementation.

Note : The most persistent problem being dispersion of the optical signal.

Both chromatic (GVD) and polarization mode dispersion are severe at such speeds.
XPM and FWM too are quite limiting factors for such speeds.

For dispersion, we have to place multiple compensating sites, in the most optimized way (correct placement).

Another method to alleviate some of the issues faced by 40 Gbps communication, is by choosing the right fiber, whose zero dispersion wavelength is shifted in the operating band, creates less chromatic dispersion of the optical signal.

For polarization mode dispersion, we have to place the compensators in the right position.
Strict power budgeting takes care to some degree of nonlinear effects.)

FWM is a third-order nonlinearity in optical links that can be compared to the inter modulation distortion in standard electrical systems.

FWM is worse for equally spaced WDM systems and at high powers.

When three optical channels at frequencies ω_i, ω_j, and ω_k travel such that they are close to the zero dispersion wavelength, they intermingle to produce a fourth signal whose frequency is shown in Equation 4-24.

Equation 4-24

$$w_{ijk} = w_i \pm w_j \pm w_k$$

This "ijk" can mix with another WDM channel, causing Severe cross-talk.
For W wavelengths in a fiber, the no of FWM channels(N) produced is shown in Equation 4-25.

Equation 4-25

$$N = \frac{w^2}{2}(w-1)$$

Fig- 4-12 shows the effect of FWM in equally spaced systems and power considerations while,

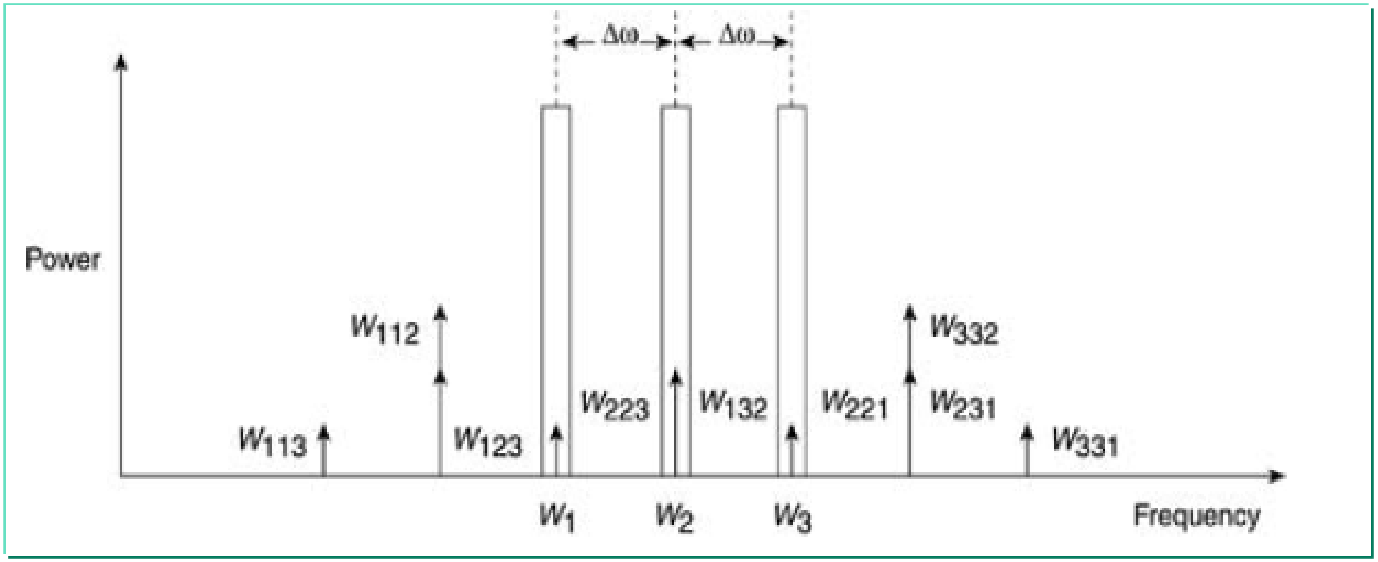


Figure 4-12. Equal Channel Spacing (Three Equally Spaced Channels Generated Nine FWM Signals, Out of Which Three Fall on Top of the Signals)

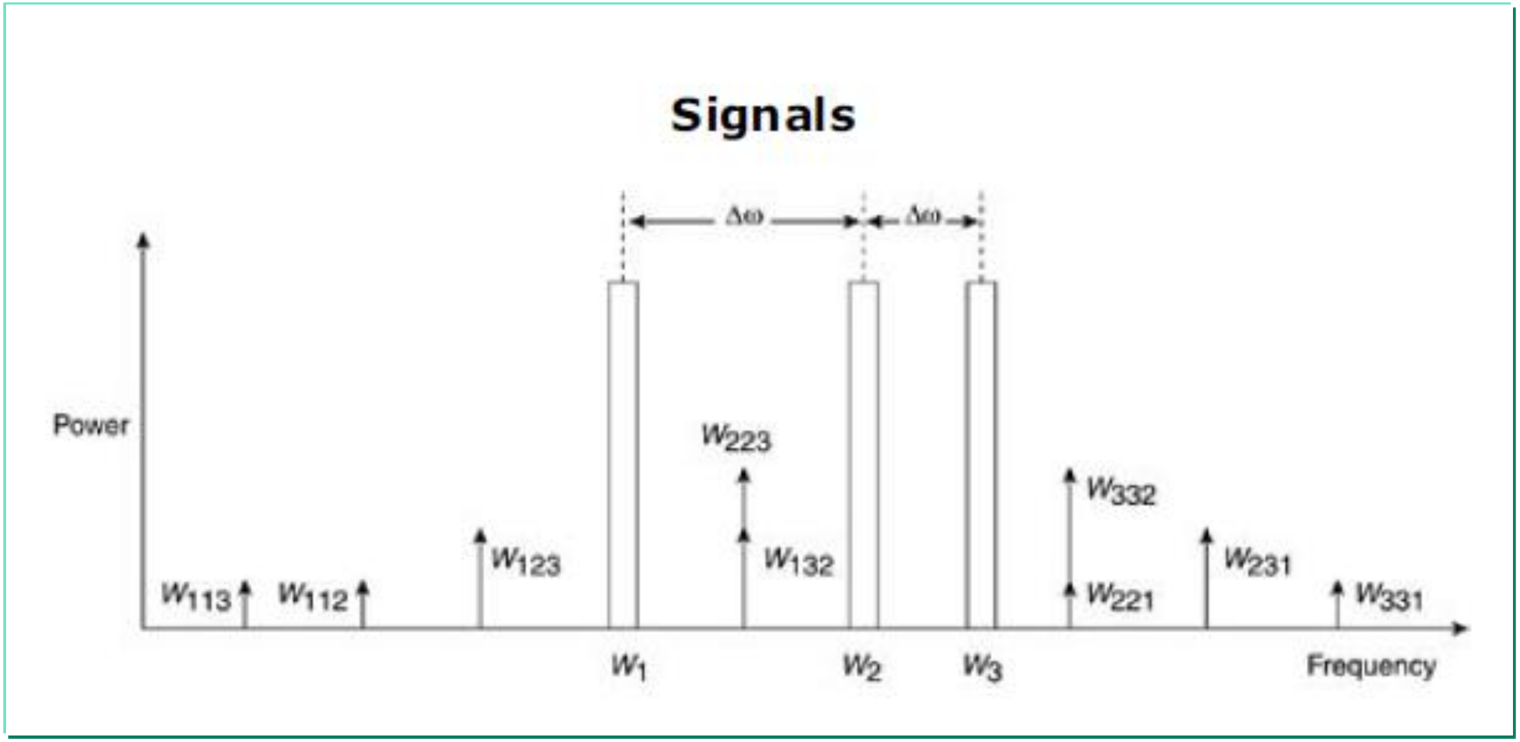


Fig-4-13 shows same considerations for Unequally spaced systems

Figure 4-13. Three Unequal Spaced Channels Generating Nine FWM Signals; None of the Generated Signals Falls on Top of the Original

The solution for minimizing FWM is to use unequal channel spacing in such a way that the generated wavelength does not interfere with the signal channel(s).

Use of NZDSF minimizes the effect of FWM.

In multichannel WDM systems, XPM causes intensity-based modulation to adjacent frequency channels.

XPM causes fluctuations in pulse propagation due to the effect of other channels.

Furthermore, if adjacent channels are travelling at the same bit rate, XPM effects are more pronounced.

One way to avoid XPM is by carefully selecting bit rates for adjacent channels that are not equal to the present channel bit rate.

When designing WDM links, we typically keep a 0.5 dB power penalty margin for both FWM and XPM.

XPM has more impact on certain types of modulation formats.

Typically, FSK and PSK have a more pronounced impact than pure NRZ and RZ coding.

Thank You

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