UNIVERSIDAD AUTÓNOMA DE MADRID

ESCUELA POLITECNICA SUPERIOR

PROYECTO FIN DE CARRERA

Análisis del OSNR de configuraciones de enlaces de Fibra Óptica

Fabio Moliner García

Noviembre 2009

UNIVERSIDAD AUTÓNOMA DE MADRID

ESCUELA POLITECNICA SUPERIOR

MASTER THESIS

Analisis of the OSNR of Links of optical fibre

Fabio Moliner García

November 2009

Análisis del OSNR de configuraciones de enlaces de Fibra Óptica

AUTOR: Fabio Moliner García
TUTOR: Antonio Aguilar Morales

Grupo de Sistemas de Radiocomunicaciones y Comunicaciones Ópticas (GSRCO)
Dpto. de Ingeniería Informática
Escuela Politécnica Superior
Universidad Autónoma de Madrid
Noviembre 2009

Analisis of the OSNR of links of optical fibre

AUTHOR: Fabio Moliner García
TUTOR: Antonio Aguilar Morales

Grupo de Sistemas de Radiocomunicaciones y Comunicaciones Ópticas (GSRCO)
Dpto. de Ingeniería Informática
Escuela Politécnica Superior
Universidad Autónoma de Madrid
November 2009

Resumen:

En este proyecto se realiza un estudio sobre el impacto que los diferentes elementos de un enlace óptico tienen en la OSNR final (optical signal to noise ratio) al ser concatenados.

Para evaluar la calidad de un enlace de fibra óptica se suele tomar como parámetro de calidad, la tasa de error (BER) que mide los bits erróneos detectados en un determinado instante de tiempo. Por desgracia, además de ser un proceso largo, es difícil de obtenerlo con exactitud. Por ello, se recurre al cálculo de la OSNR ya que guarda una relación directa con el BER y es más fácil de calcular.

La OSNR se mide en dB y es un ratio que mide la relación señal a ruido óptico de un sistema.

Diversos factores afectan en gran manera a la OSNR de un sistema y por tanto al BER: Las características de la fibra (atenuación, dispersión cromática y PMD), las características de transmisión (formato de modulación, banda espectral, número de canales y la separación entre los mismos) y las características de los elementos de red (amplificadores y filtros ópticos) son los principales factores.

El objetivo es cuantificar su impacto para poder controlar de antemano la OSNR del sistema y así poder caracterizarlo cualitativamente .Para realizar el estudio de los distintos casos se ha usado la herramienta VPI transmisión maker.

.

Palabras clave:

OSNR, BER, Óptico, PMD, CD, VPI transmission maker

Abstract:

We present a study about the different elements which make up an optical link and the overall impact that they may have on the final OSNR when concatenated.

In order to assess the quality of any optical link transmission is common to use the bit error rate (BER) as a figure of quality. BER measures over a period of time whenever the receiver fails to detect an incoming bit correctly. Unfortunately, apart from being a long process it is hard to actually obtain accurate results. That is why; we opt for an easier solution in terms of computation which is OSNR as it is directly related to BER. OSNR is measured in dB; It is the optical signal to noise ratio of a system.

Factors of different nature strongly affect the OSNR of a system and thus, BER:
Fiber characteristics (attenuation, chromatic dispersion and PMD), transmission characteristics (modulation format, spectral band, number of channels and channel spacing) and characteristics of the elements of the network (amplifiers and optical filters) as the main players.

The aim is to quantify their impact on the global system so OSNR is known beforehand and thus the link is fully characterized. In order to perform such project, VPI transmission maker has been used as the main tool.

Keywords:

OSNR, BER, Optical, PMD, CD, VPI transmission maker

Agradecimientos

En primer lugar quisiera agradecer desde aquí a mi tutor, Antonio Aguilar, la posibilidad de hacer este proyecto con él, por su ayuda, su motivación y por estar siempre disponible para ser consultado. Así mismo, muchas gracias a Bazil Taha por ayudarme y hacerlo siempre con una gran sonrisa.

Gracias a Peter Winzer, de Alcatel-Lucent, por su valioso aporte a este proyecto en un momento clave de tanta dificultad.

Gracias a todos los compañeros de clase por estos años. Mención especial a Pablete y Luisillo por estar ahí, por ser todo en estos años, porque nos hemos reído mucho y porque de verdad creo que todavía nos queda mucho recorrido juntos.

A mis padres, por su constancia y su apoyo a lo largo no sólo en este proyecto, sino siempre; por darme todo y ser como soy. Gracias por entenderme y siempre darme los mejores consejos para cada situación. Por hacer posible los años en USA y Australia que tanto han marcado mi carrera y por tantas situaciones en las que siempre han estado allí.

A Rodri, por ser esa voz tan sabia que uno siente detrás cuando más la necesita. Gracias por ser el mejor hermano que uno puede tener. Echaré de menos el ritual característico pre-examenes con su música incluída. “A por ellos”

A Bianca, por su inestimable ayuda y su paciencia. Por aguantarme en unas situaciones nada fáciles durante este proyecto y porque a pesar de todo, la vida nos sonríe: “Remember, Have faith”.

Este proyecto va en memoria de mi abuelo, porque se quedó a falta de 3 meses para verlo realidad y sé que se hubiera sentido el hombre más orgulloso del mundo.
“Daremos un gran golpe Salaverri”

-Fabio Moliner-
Noviembre del 2009

TABLE OF CONTENTS

TABLE OF FIGURES

1

Introducción

1.1 Motivación

La comunicación y los sistemas de comunicación han ido evolucionado de forma notoria a lo largo del pasado siglo. La gran demanda de ancho de banda ha dado lugar a la aparición de nuevas tecnologías en las redes actuales para hacer frente a este problema: Desde el par de hilos trenzados, el cable coaxial ó tecnologías inalámbricas que ofrecen buena comunicación pero tienen un ancho de banda limitado y pérdidas notorias con la distancia.

Por ello la fibra óptica se modela desde los años 80 como la tecnología de transporte óptima debido a su robustez frente al ruido, su enorme ancho de banda y la posibilidad de emplear formatos de modulación a tasas binarias muy elevadas.

En éste documento se expone de manera ilustrativa el estudio llevado a cabo sobre el comportamiento de enlaces de fibra óptica cuando existen diferentes formatos de modulación, a diferentes velocidades de transmisión en presencia de filtros y amplificadores ópticos.

Dicho comportamiento es medible gracias a un parámetro significativo: BER. Éste parámetro es la tasa de error del sistema o dicho de otra manera, el número de bits recibidos incorrectamente respecto al total en un intervalo de tiempo. Ésta relación nos da una idea de la calidad y rendimiento del enlace.

Dado que la tasa de error, BER, es muy difícil de computar, se toma la alternativa de calcular un parámetro auxiliar directamente relacionado con el BER que es la OSNR (optical signal to noise ratio), un ratio que expresa la relación entre señal y ruido óptico de un enlace, y que es mucho más fácil de calcular. La OSNR se mide en decibelios (dB) y servirá para caracterizar cuantitativa y cualitativamente cualquier enlace de transmisión óptico.

Para caracterizar cada uno de los elementos de un enlace óptico y su influencia en la OSNR del sistema se introducirá el concepto de OSNR penalty, que es la diferencia de OSNR requerida para alcanzar un BER de 10^{-4} (valor umbral si se suponen técnicas de corrección de errores, FEC, en el receptor) entre la señal con camino directo (back to back) y la señal que atraviesa el enlace per sé, ambos caminos con las mismas condiciones de filtrado.

Esta diferencia en dB, nos dará una idea de cómo influyen los elementos del enlace en el rendimiento total, permitiendo saber de antemano cómo se va a comportar cualquier transmisión sobre fibra óptica y qué configuración es mejor en cada caso para poder obtener un BER deseado de 10^{-4} (Se suponen técnicas de corrección de errores)

Por último una vez caracterizados los elementos de manera individual se procederá a analizar un enlace real punto a punto y multipunto para observar dichos fenómenos.

Para llevar a cabo las pruebas, se ha hecho uso de un simulador de comunicaciones ópticas que nos ha permitido establecer los escenarios adecuados para más adelante extraer resultados. Este simulador ha sido ‘VPI Transmission Maker 8.0’ de la empresa ‘VPI systems’.

A lo largo de la memoria, se expondrán los distintos escenarios creados así como breves explicaciones teóricas sobre los factores que influyen en los mismos.

1.2 Objetivos

Como se expone más adelante, nos encontramos en un momento en el que
Las redes evolucionan de forma muy rápida. La demanda de tráfico está aumentando de tal modo que pronto se requerirá algún tipo de actuación que sería o renovar la planta de Cable con fibras de características mejoradas o la utilización de nuevos formatos de Transmisión manteniendo la planta existente, ya que los formatos actuales de modulación en intensidad Y NRZ no son válidos para velocidades de transmisión más altas sobre fibras ópticas instaladas en la planta existente.

Si se quiere transmitir a muy altas velocidades con la planta de fibra actual seguramente haya que invertir más en equipamiento.[5] Otra opción sería renovar, parte o la totalidad de la fibra actual con objeto de mejorar las prestaciones.

Por todo ello, este proyecto nace con la idea de poder caracterizar el rendimiento de enlaces de fibra óptica de antemano y saber qué decisión tomar en cuanto a la inversión requerida.

Como se puede observar, es un problema que implica muchos factores. A lo largo de este estudio se ha tratado de estudiar cada uno de ellos por separado y ver cuál es su aportación en un enlace real.

El objetivo que se persigue con el presente proyecto es el de **analizar los efectos que producen los diferentes subsistemas (transmisor, fibra, amplificador, OADM, receptor) en las prestaciones (alcance máximo)** que se puede conseguir en un enlace de comunicación sobre **transmisión todo-óptica**. Para ello se usará la OSNR (y de ahí se obtiene el BER) como parámetro de calidad para evaluar las prestaciones de un enlace

Con este fin, se analizará el efecto conjunto de los siguientes factores:

- **Características del transmisor:** formatos de modulación DPSK y DQPSK.

- **Características de la/s fibra/s que atraviesa el enlace óptico**: atenuación, dispersión cromática y dispersión por el modo de polarización.

- **Características de los amplificadores ópticos:** Figura de ruido y potencia de saturación para evitar efectos no lineales.

- **Características y número de nodos atravesados**: ROADM en cascada.

- **Características del receptor**: sensibilidad y capacidad de corrección de errores (técnicas FEC).

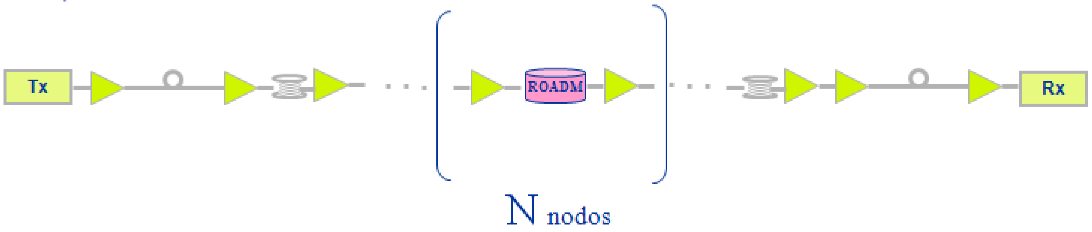


Figure 1. Esquema de los enlaces

A partir de la caracterización de los elementos del nodo y de la red, el resultado del estudio llevará a la elaboración de gráficas parametrizadas que permitan evaluar las prestaciones de la red para un diseño óptimo de la misma

1.3 Organización de la Memoria

La memoria está estructurada en 10 capítulos los cuales se detallan a continuación:

- **Capítulo 1:** *Introducción, objetivos y organización de la memoria*.
- **Capítulo 2:** *Estado del Arte*, donde se ponen de manifiesto el estado de las redes actuales y su evolución. Se exponen también, las posibles soluciones al crecimiento de la red
- **Capítulo 3:** *Rendimiento del Sistema*, donde se introducen los parámetros de calidad de un sistema: BER y OSNR
- **Capítulo 4:** *Dispersión en la Fibra*, donde se explican uno de los factores que afectan a la OSNR.
- **Capítulo 5:** *Amplificadores ópticos*, donde se explica otro factor limitante en la OSNR.
- **Capítulo 6:** *Filtros ópticos (ROADM).* Aquí se explica la función de estos elementos y cómo afectan a la OSNR
- **Capítulo 7:** *Formatos de Modulación*, donde se introducen y se detallan los 2 formatos de modulación que se usarán en las simulaciones: DPSK y DQPSK; que afectan a su vez también a la OSNR final.
- **Capítulo 8:** *VPI transmisión maker.* Aquí se introduce el paquete software utilizado para las simulaciones evaluándose sus prestaciones y posibilidades
- **Capítulo 9:** *Integración, pruebas y resultados*. En este capítulo se aborda el plan de simulación y a continuación se muestran los resultados obtenidos en las siguientes pruebas
- **Capítulo 10:** *Conclusiones y líneas abiertas de investigación.*. Finalmente aquí se expresan las conclusiones formuladas a partir del análisis de los resultados obtenidos y se hace una valoración crítica de cual podría ser el trabajo futuro a acometer.

- ***Anexo***: Donde se encuentra el glosario, presupuesto, bibliografía y pliego de condiciones.

1

Introduction

1.1 Motivation

Communication and Communications Systems have evolved notoriously throughout past Century. The increasing demand for bandwidth has lead to new technologies in the present networks. From the twisting pair, to the coaxial cable or Wi-Fi technologies which offer good performances but have great losses through the distance

Due to that, Optical fibre arises in early 80`s as a robust technology, due to its strength towards noise, its big bandwidth and the possibility to carry multiple modulation formats over a fibre at a different bit rates.

In this paper, we expose the study carried out about the behaviour of optical fibre in presence of different modulation formats, with different bit rates, taking into account the presence of filters or optical amplifiers. Such behaviour is measurable thanks to an important parameter: BER.

This parameter is the bit error rate of a system, or rather, the number of incoming bits detected wrongly over an interval of time. This relationship gives an idea of how good the link is and what type of performance it is offering to us.

Because BER is very hard to compute, we take a different strategy, and we solve for a different parameter: OSNR (optical signal to noise ratio), which is much easier to operate with and to be obtained. OSNR is measured in decibels (dB) and it will allow us to characterize any optical link in terms of performance.

In order to fully describe each of the elements within an optical link and its influence over the whole system's OSNR. The concept of OSNR penalty shall be introduced. It measures the difference of required OSNR to reach a BER of 10^{-4} (threshold value, if FEC techniques are employed) between the back-to-back path and the path with the elements under study. Both paths presenting the same filtering conditions.

Such difference in dB will give us an idea of how the elements along the path influence on the total performance, knowing beforehand how any optical link will behave and which configuration is best in order to obtain a BER of 10^{-4}

Lastly, once each individual element is analysed and fully characterised, we will proceed to analyse a real P2P link and a point to multipoint link.

In order to carry out the simulations, we shall use an optical communications simulator, which will make things easy to be set up. Such simulator is called "VPI Transmission Maker 8.0" from VPI systems

Throughout this paper, we will show the different settings and scenarios as well as some theoretical explanations about all present factors.

1.2 Goals

As it will be shown next, we find ourselves in a moment where networks are evolving quite fast. The demand for bandwidth is growing so much that soon some actions will be required to undertake. Either changing the actual infrastructure of fiber with renew and improved fibers or using new modulation formats keeping the current infrastructure, because the current modulation formats such as NRZ are no longer valid for higher bit rates over the current fibers.

If higher bit rates want to be achieved with the current infrastructure probably we should invest more on equipment. Another option is renew, part of the whole infrastructure in order to achieve better performance.

Therefore, this project arises with the idea of characterizing the performance of optical links in order to take beforehand wiser solutions in terms of investment.

As it can be observed, this issue can be broken up into many factors. Throughout this paper we will treat each factor as an individual and we will see how dependant a real scenario is on each factor.

The ultimate goal pursued with this thesis is to **analyse the effects of the different subsystems (transmitter, fibre, amplifier, OADM and receiver) over the whole performance (maximum reach (km))** that it can be reached through a communication link using **optical transmission.** In order to realize this, we will use OSNR (and from there BER will be obtained, as a quality-parameter to evaluate the performance of any link

With such intention, we will analyse the whole effect of the following factors:

- **Transmitter characteristics**: Modulation formats (DPSK and DQPSK)
- **Optical Fibre characteristics**: attenuation, chromatic dispersion and polarization mode dispersion
- **Amplifier characteristics**: Noise figure and Saturation Power to avoid non-linear effects
- **Number of spans**: OADM connected in cascade
- **Receiver characteristics**: Sensitivity and FEC techniques

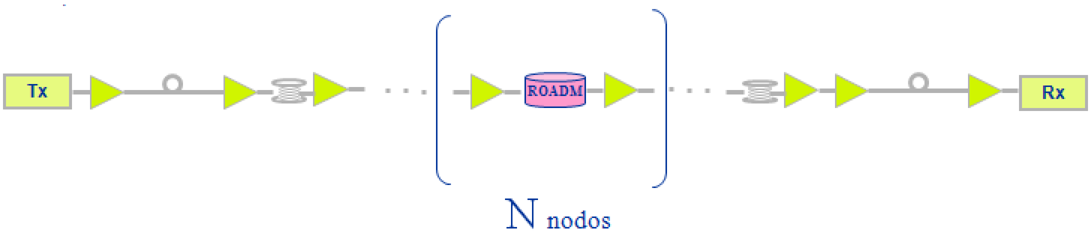


Figure 2. Schema of the links

From the study of the elements of each node and the whole network, results will be accordingly graphed so the performance of the network can be analysed for an optimum design of such.

1.3 Report Outline

The paper is made up of 10 chapters as shown next:

- **Chapter 1**: *Introduction, goals and paper content*
- **Chapter 2**: *State of Art*, where we explain the state of the current networks and its possible evolution. We show as well, the possible solutions towards facing the current network growing
- **Chapter 3**: *System Performance*: Key parameters will be introduced: BER and OSNR
- **Chapter 4**: *Dispersion over the fibre*. We will explain how this factor affects OSNR
- **Chapter 5**: *Amplifiers*. It will be explained how this factor affects OSNR
- **Chapter 6**: *Optical Filters (ROADM).* It will be explained how they work and how they affect the OSNR
- **Chapter 7**: *Modulation Formats*, where the 2 modulation formats used along the whole process will be introduced: DPSK and DQPSK
- **Chapter 8**: *VPI transmission Maker*, here, the software used is introduced and presented.
- **Chapter 9**: *Tests and Results*, we come up with the simulation plan and the results obtained
- **Chapter 10**: *Conclusions and open issues*: Finally, we draw up our conclusions obtained from the previous work on chapter 9 and we make a possible list of the tasks which could be done on the future

- **Appendix**: Contains the Legal conditions of the document, glossary, budget and bibliography.

2

State of Art

2.1 Current Needs

Nowadays, providing user services such as “triple play” (phone, video and data) including High definition, require a great amount of bandwidth on the different segments of a network (access and transport). On the business side (public and private networks) a great amount of bandwidth is needed in order to comply with their actual needs.

In the access network, the goal is to offer each user as much as bandwidth they require trying to avoid the undesirable “bottleneck” on the process of carrying data from homes to the Service Node [5]. On a recent study provided by the Amsterdam Internet Exchange (AMS-IX) on 2007, it was shown that on that area there were appearing already peaks of 305 Gb/s at some periods of the day.

Trying to provide all the commented services, its great bandwidth and its frequent use provokes a very high internet traffic which it is expect to keep growing exponentially on the upcoming years[1]:.

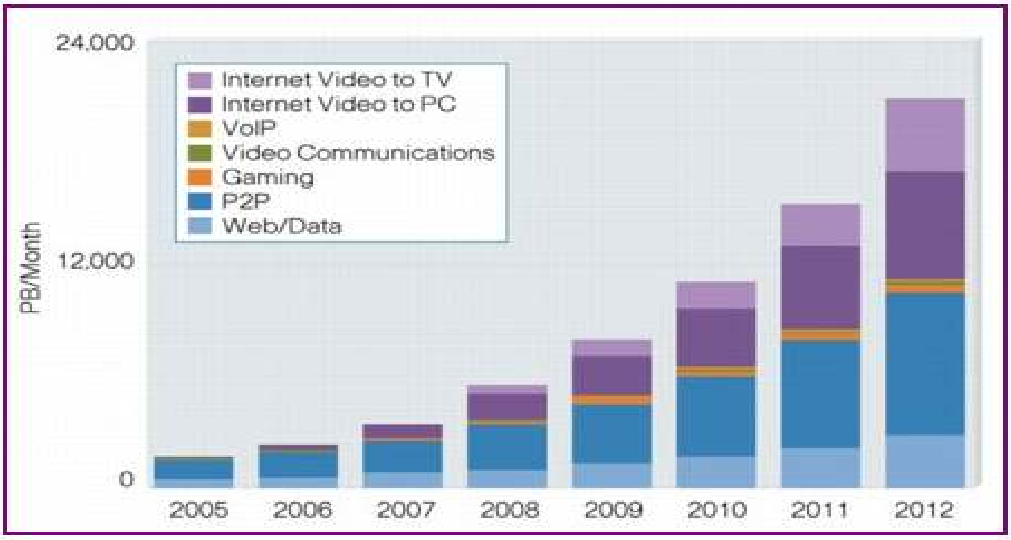


Figure 3. Expected evolution of Internet traffic (2005-2012)

According to a study conducted by Cisco Systems, 90% of the internet traffic will be video streaming. This includes video on demand, peer to peer traffic and any sort of video through the internet. All these factors sum up to make up to 50% of the internet traffic on a house.

In order to cope with all these new services providing the highest quality possible to each user, it is needed a network with higher bandwidth over an infrastructure with both mobile and fixed accesses. The total traffic must be sliced among the different areas: Local, metropolitan, national and international.

[5]In order to fulfil the demand, new access technologies have arisen like multiservice nodes (MSAN) with digital lines VDSL/VDSL2 (very high speed digital subscriber Line), optical passive networks (PON) o mobile technologies such as HSPA (high speed packet access), WIMAX (worldwide interoperability for microwave access) or in a long term LTE (long term evolution) which will allow an upstream speed of 30 Mb/s and downstream of 100 Mb/s.
With such a new revolution of services and technologies, it is necessary a transformation on the transport network so new traffic can be added.

This backbone network needs transmission links of a very high speed. These requisites are fulfilled by DWDM systems with optical fibres working at 40 Gb/s or 100 Gb/s on a per channel basis.

This combination results in a network more simple and less complex able to carry all that traffic.

2.2 Possible Solutions

As it has been commented previously in order to transport these new services, we need to reach high bit rates, which means raising each optical channel capacity via SDH/SONET at speeds of 40 Gb/s or going up to an improved version of Ethernet reaching 100 Gb/s.

It has been already proved, that data can be carried at 100 Gb/s through wavelengths across large distances, but in any case the big expenditure is not based on the technology WDM itself but on the switching devices (technologies such as packet-based or circuit based). Approximately 50 to 80% of the traffic on a sole node is just transit traffic resulting on an efficient less arquitecture when data is increased.

[21]A promising option to reduce the total expenditure is to come up with optical technologies or Ethernet specially when dealing with high bit rates (100 Gb/s). The overall result would be a network on which most of the traffic is carried instead of routed, allowing future traffic optimization.

In comparison to 10 Gb/s, transport at 100 Gb/s needs higher OSNR in order to keep having the same quality on reception if using the same transmission techniques. Another problem is chromatic dispersion on fibre (10 times higher) or polarization mode dispersion (100 times higher).

The technical criteria to have a successful transmission over 100 Gb/s is to take care of the OSNR, spectral efficiency and dispersion. The next sequence of processes would give us similar results than the ones at 10 Gb/s but for 100 Gb/s in this case:

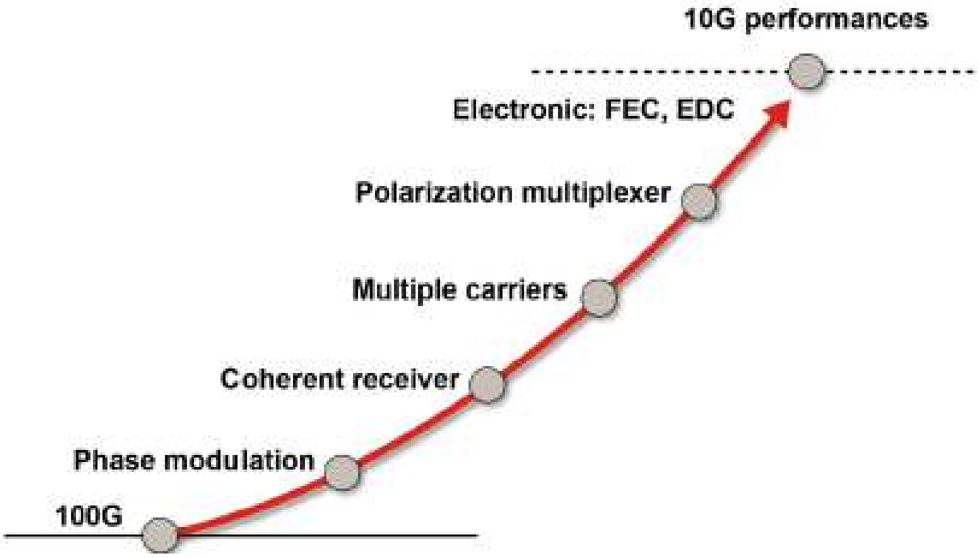


Figure 4. Process to obtain optimal performance at 100 Gbps

Depending on network topology, there will always be a trade-off between cost and performance which will drive to having more than one possible solution

Another solution could be the use of inverse-multiplexing, which means breaking the signal of 100 Gb/s into signals of lower speed in parallel, so maximum reach is higher. Routers can drive the different wavelengths to the same direction; otherwise there would be serious problems of delay.

Another possible solution more “elegant” is carrying the signals on their original format minimizing the use of the network in order to do so, in this way the routing process gets simplified and more efficient. The main drawback on doing so is a more complex engineering design which requires an optical network more complex, but it is the option that really solves for bottlenecks and easers the routing process.

3

System Performance

3.1 Bit Error Rate

During the transmission of data through an optical channel, the receiver should be able to receive individual bits without errors. Errors occur when a receiver fails to detect an incoming bit correctly. Causes for errors generally come from impairments that are associated with the transmission channel. A receiver fails to detect a bit correctly when it detects a 1 bit for a 0 bit that is transmitted or a 0 bit when a 1 bit is transmitted. The receiver is also bit-rate sensitive.

For different bit rates, a receiver has different magnitudes of errors; therefore, BER is a figure of quality in an optical network. Typically, optical end systems should have a BER of 10^{-9} to 10^{-12}; in other words, for every 10^9 bits transmitted, one corrupted bit is allowed**.**

Mathematically speaking, BER is the sum of probabilities, such that when a 0 bit is transmitted, a 1 bit is received; when a 1 bit is transmitted, a 0 bit is received. This summation of these conditional probabilities gives the BER of the system statistically. This probability can be described as:

BER= P(1)P(0 received for 1 transmitted) + P(0)P(1 received for 0 transmitted)

Where P(0)= probability of a zero bit transmitted= 1/2 and P(1)= probability of a 1 bit transmitted=1/2. P(0/1) and P(1/0) depend on the distribution of the current over time while detecting the signal.

In other words, the probability density of the noise associated with the system affects the final waveform of the current. That is, if you consider noise as being superimposed on the signal, this superimposed waveform is what determines how many wrong decisions were made at the receiver.

This can be outlined by the following figures, first the original signal:

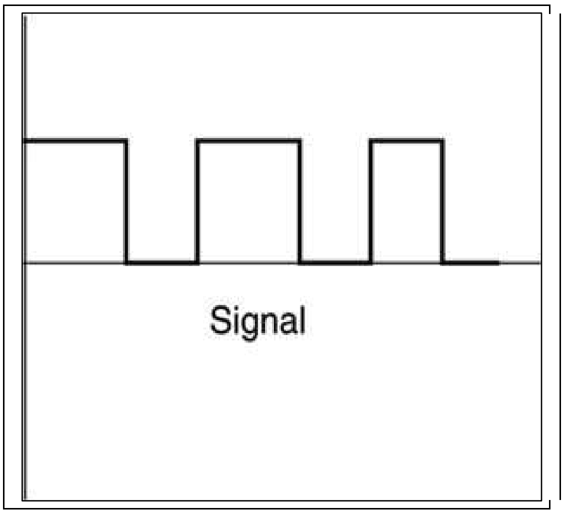


Figure 5.Original Signal

Then, the noise distribution:

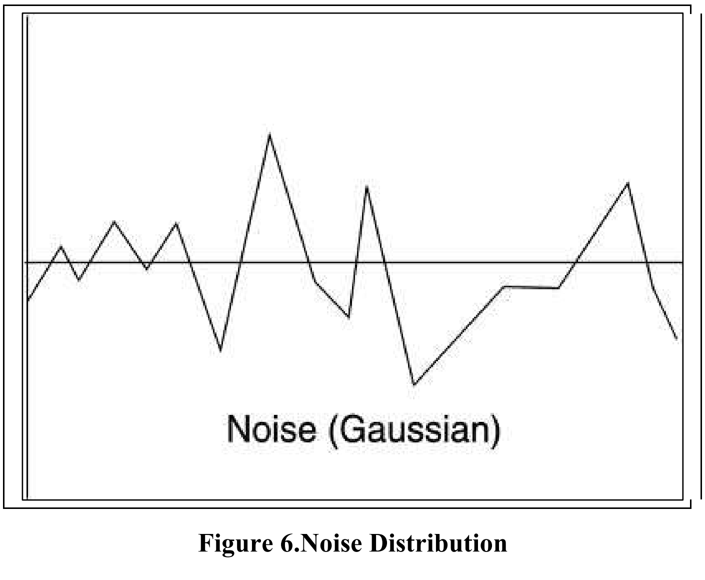


Figure 6.Noise Distribution

And then the final signal:

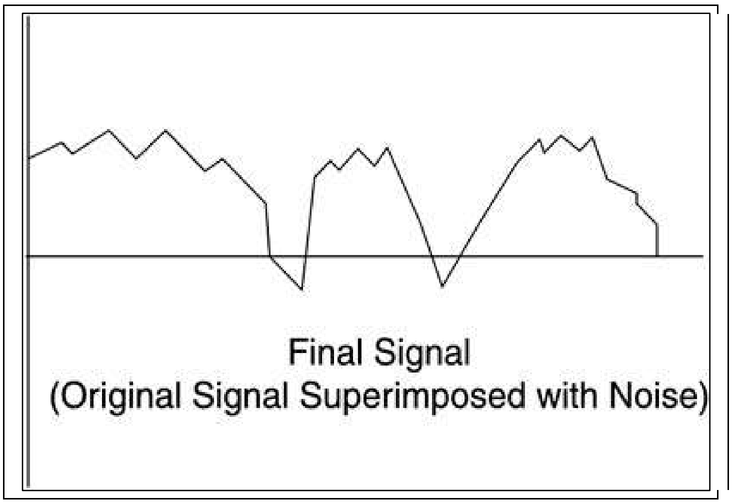


Figure 7.Final Signal

3.1.1 Error Function and its relationship to BER:

[1]The distribution function of a Gaussian distribution is shown as:

$$f(x) = \int_{-\alpha}^{x} \frac{e^{-x^2/2\sigma^2}}{\sqrt{2\pi\sigma^2}} dx$$

This integral can be mapped to error function (erf) which is defined as:

$$\operatorname{erf} K \equiv \frac{2}{\sqrt{\pi}} \int_{0}^{k} e^{-k^2} du$$

$$\operatorname{erf}(0) = 0 \quad \operatorname{erf}(\infty) = 1$$

After few calculations (please see DWDM Cisco Book for more details) we get to the expression:

$$BER = \frac{1}{2} erfc\left(\frac{Q}{\sqrt{2}}\right)$$

Where Q, is the Q factor of the system. The Q-factor is defined as the electrical Signal to noise ratio of a digital transmission and indicates the minimum *electrical SNR* required to obtain a specific BER for a given signal. The following figure illustrates the concept [11]:

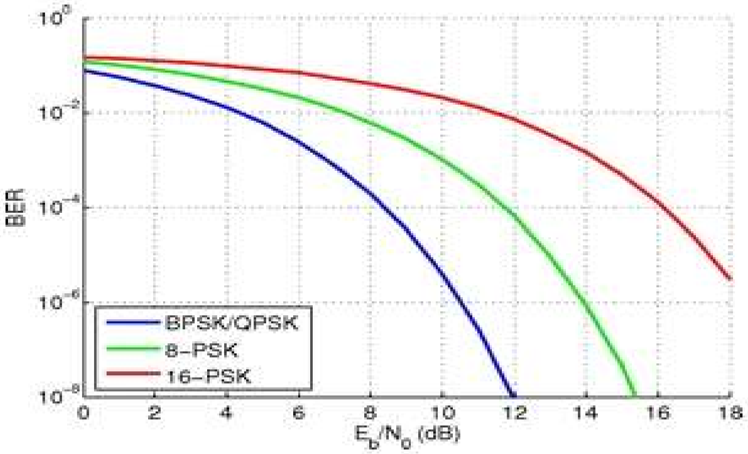
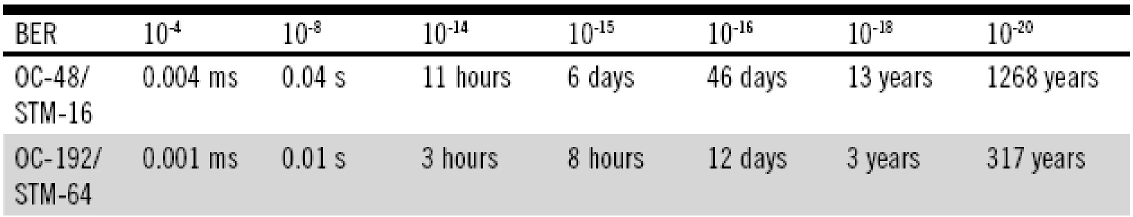


Figure 8. The Relationship of Q to BER

As we have seen BER is a magnitude which indicates the performance of the system, but it is indeed very difficult to simulate or calculate.

The following table shows the required time for an error to occur at different bit rates [18]:



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

Figure 9. Time for an error to occur

For a given design at a BER (such as 10^{-16} and a line rate of 9.6 Gbps/OC-192), the network would have one error in approximately 12 days. It would take 1200 days to record a steady state BER value. That is why BER calculations are quite difficult. On the other hand, Q-factor analysis is comparatively easy to obtain fortunately. And it can be obtained from OSNR.

3.2 OSNR: Optical signal to noise ratio

Optical Signal to Noise Ratio (OSNR)[dB] is the measure of the ratio of signal power to noise power in an optical channel normalized to 0.1-nm spectral window:

$$OSNR = 10dB \cdot Log_{10}\left(\frac{S}{N}\right)$$

Where,

- "S" represents the (linear) optical power of the signal and
- "N" the (linear) optical noise power (band-limited)

This is one of the multiple definitions which can be found in the literature, as many of them try to describe OSNR as a function of different parameters (Noise Figure, Span Length…etc) . Normally, it is found specifying the type of noise: ASE Noise (Noise coming from Amplifiers mainly and other sources), Thus:

OSNR[dB] =10 log (S /ASE Noise)

The OSNR is the most important parameter that is associated with a given optical signal. It is a measurable quantity for a given network, and it can be calculated from the given system parameters. It suggests a degree of impairment when the optical signal is carried by an optical transmission system that includes optical amplifiers.
Commonly, the signal quality is expressed by the required OSNR in front of the receiver. (Signal degradation is expressed by the OSNR penalty)

It is the keystone of this project and indeed the parameter that will be devoted most of our time on the simulations. As its calculation, allows us to obtain BER in an easy manner.

The logarithmic value of Q in dB is related to the OSNR by

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

Where:

- Bo is the optical bandwidth of the end device (photo detector)
- Bc is the electrical bandwidth of the receiver filter.

Thus, Q(dB) can be described as:

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

For Practical Designs OSNR (dB) > Q (dB) by at least 1-2 dB. 2 dB approximately when designing a high bit-rate system. It needs to be taken into account that if Bo> Bc, Q(dB)> OSNR (dB). This fact rarely happens.

The following figure illustrates the increase in OSNR corresponding to a variation of the Q-factor equal to 2 dB[1]:

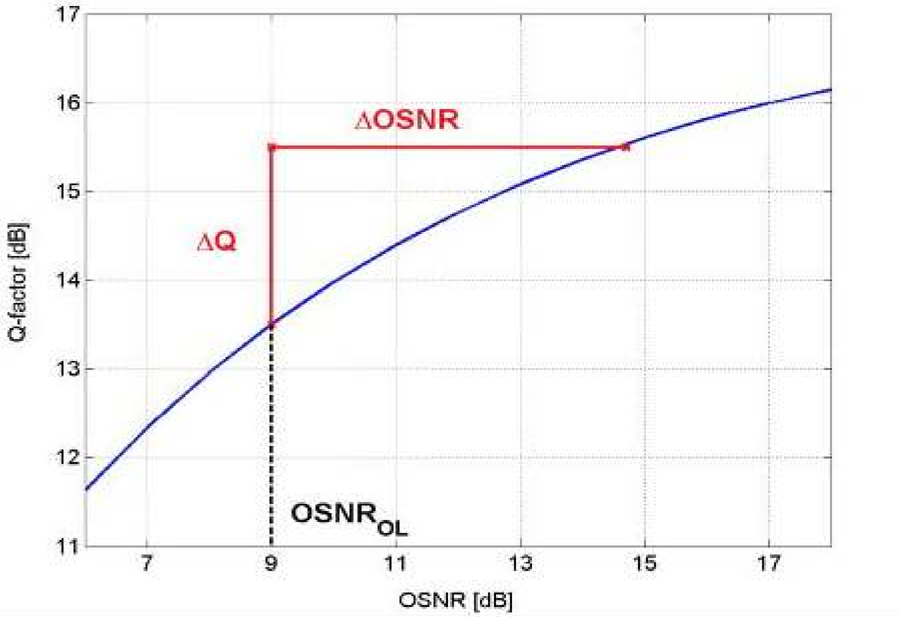


Figure 10.Q vs. OSNR

The slope of the Q-factor (BER error function) curve versus OSNR or Rx power determines how a BER increase could be recovered with an increase of OSNR, power, or both depending on the case... In general, the scale factors are two values (one in OSNR and one in power).

3.3 BER vs. OSNR

[3] As it has been shown in the previous section The BER (Bit Error Ratio) is a fundamental quality measure for digital communications.
Whereas a study of the BER versus Power is good to characterize the reception of weak, unamplified digital optical signals, the study of BER versus OSNR is good to characterize the reception of strong, amplified optical signals. Once a signal has been degraded to a certain level of OSNR, the BER for a certain receiver design cannot
Be improved regardless of signal strength. Thus, in the design of an amplified digital transmission system, the final, delivered OSNR becomes a major issue and concern.
It is then a question of whether the receiver can produce an adequate BER from that OSNR.

However on trying to compute OSNR, the following factors that somehow affect OSNR need to be known and taken care of, and therefore the global performance of the network

3.3.1 Factors Affecting OSNR

- **Modulation Format**: DQPSK and DPSK
- **Velocity of Transmission**: For the tests, 40 Gb/s and 100 Gb/s
- **Power**: The output power from the amplifier (nonlinear effects if too high)
- **Dispersion in the Optical Fibre**: Polarization Mode Dispersion (PMD) and Chromatic Dispersion (CD)
- **Optical Amplifiers**: Noise Figure linked to ASE noise
- **Resolution Bandwidth**: Bandwidth that measures the NF, usually set to 12.5Ghz (0.1nm)
- **Channel Spacing**: For multi-channel purposes it is important. Out of the scope of this thesis.
- **Receiver Filter**: Optical Bandwidth and Electrical Bandwidth of the end device (set by default). It will not vary within the context of this thesis.

4

Dispersion in Optical Fibre

4.1 Dispersion: Definition and Types

[1] The velocity of propagation of light depends on wavelength. The degradation of light waves is caused by the various spectral components present within the wave, each travelling at its own velocity. This phenomenon is called *dispersion*. Several types of dispersion exist, two of which include chromatic dispersion and polarization mode dispersion (PMD). Chromatic dispersion is common at all bit rates. PMD is comparatively effective only at high bit rates. Waveguide and material dispersion are forms of chromatic dispersion, whereas PMD is a measure of differential group delay of the different polarization profiles of the optical signal.

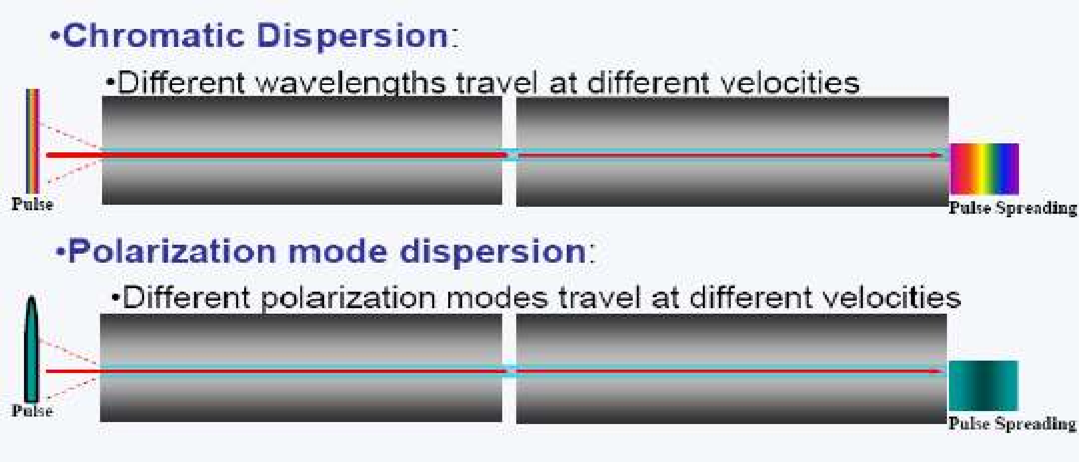


Figure 11.CD vs. PMD

Too much dispersion on a system will lead to a system penalty and poor QoS, however very little dispersion or none in DWDM systems leads to system impairments from fibre non-linearities such as Four Wave Mixing (FWM) which is an undesirable effect.

The following two sections cover with more detail each one of the two types of dispersion and how they can be treated or compensated.

4.2 Polarization mode Dispersion

[1] The fibre is not truly a cylindrical waveguide, but it can be best described as an imperfect cylinder with physical dimensions that are not perfectly constant. The mechanical stress exerted upon the fibre as well as the imperfections resulting from the manufacturing process are the reasons for the variations in the cylindrical geometry. This variation also leads to a phenomenon called birefringence whereby a fibre that acquires birefringence causes a propagating pulse to loose the balance between the polarization components.
This leads to a stage where different polarization components travel at different velocities creating pulse-spread, and this spread is PMD.

The degree of birefringence (Bire) is calculated as the difference between the indexes of the polarization component (now termed mode indexes) due to the different magnitude of these components, gaining different modal properties. This can be visualized as the two discrete orthogonal polarization states as two separate modes. Bire (degree of birefringence or just birefringence) is a time-varying phenomenon that carries a state of random polarization of the induced pulse.

[10] There are different manifestations of PMD depending on the view taken.
In the frequency domain view one sees, for a fixed input polarization, a change with frequency w of the output polarization. In the time domain one observes a mean time delay of a pulse traversing the fibre which is a function of the polarization of the input pulse. The two phenomena are intimately connected.
There exist special orthogonal pairs of polarization at the input and the output of the fibre called the PSPs. Light launched in a PSP does not change polarization at the output to first order in w. These PSPs have group delays, tg, which are the maximum And minimum mean time delays of the time domain view.
The difference between these two delays is called the DGD (differential group delay).

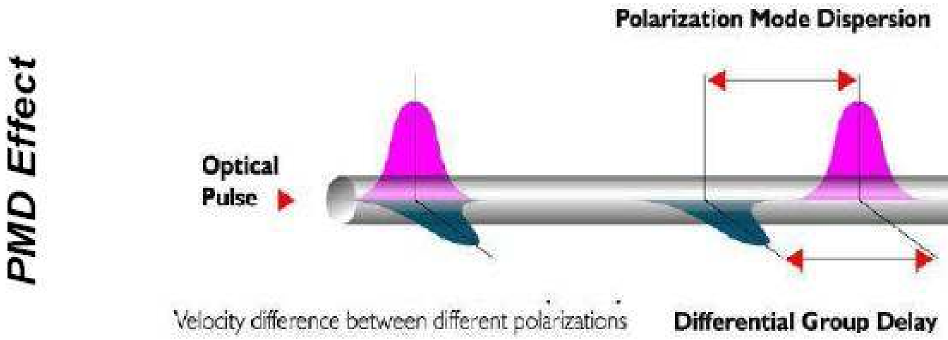


Figure 12.PMD effect

Figure 12 shows PMD resulting from the effects of a fibre acquiring birefringence and the energy transfer between the two polarized modes, leading to pulse spread.

It has been shown that for an optical bandwidth relatively small, the global effect can be described as a spread of the optical pulse in 2 optical pulses in the output with two different polarization states. This effect is commonly known as first order PMD.

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

The following figure shows the heuristics that create PMD in high bit-rate systems:

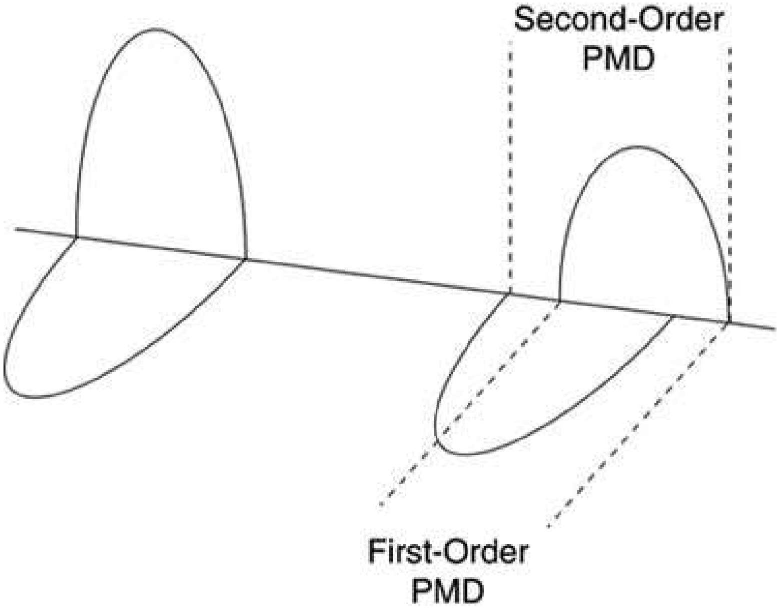


Figure 13.First order PMD vs. Second order PMD

A measure of PMD is commonly the DGD, described before as the time difference in multiple spectral components (at multiple speeds) over a given length of fibre. The polarization axes are no longer joint, and the separation increases as the pulse is Transmitted through a fibre. The difference is somewhat proportional to the DGD. Therefore, DGD can be accurately used as a measure of PMD for a given system:

$$\textbf{DGD (ps)= (PMD Coefficient) * (Length)}^{1/2}$$

Where PMD coefficient is the Group Delay over Length and usually lies between 0.5 and 2 ps/km.

PMD has to be taken care of because if it is too high it can introduce a power penalty measurable by the following equation:

$$\varepsilon \cong \frac{A\Delta \tau^{2}\gamma (1-\gamma)}{T^{2}}$$

Where A: is a parameter depending upon the shape of the impulse and receiver characteristics. $\Delta\tau$ is the DGD, γ is the power spread between modes ($0< \gamma<1$) and T is the bandwidth at half the impulse's peak amplitude.

Using the DGD equation, Let us consider a numerical example:

- PMD coefficient: 2ps/km
- Distance under consideration: 400 km:

DGD =2ps * $400^{(1/2)}$ = 40 ps.

This value of DGD at low bit rates it is not an issue but in 10Gpbs and 40Gbps systems, a DGD of this magnitude severely degrades the performance of the system, introducing an OSNR penalty which results in a fuzzy eye-diagram creating more BER:

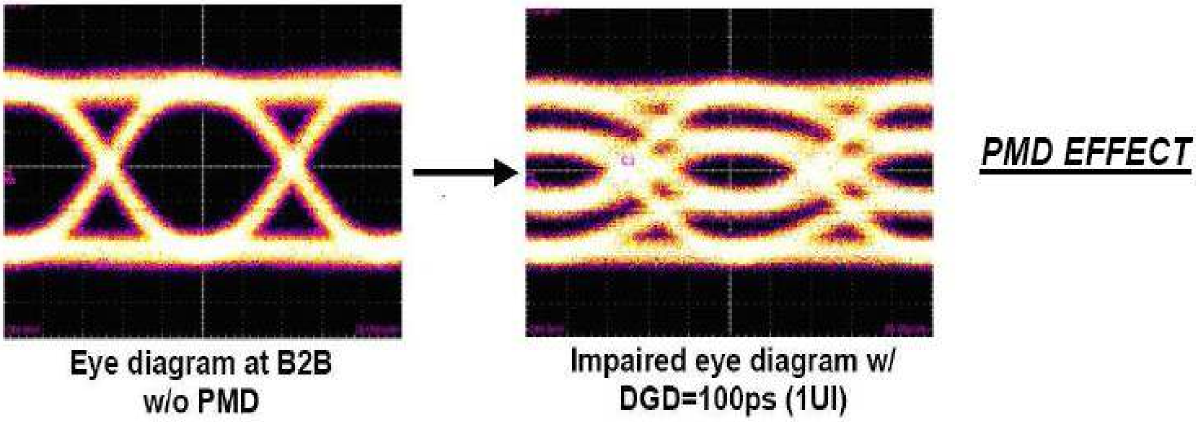


Figure 14.Effect of Polarization Mode Dispersion

In modern WDM systems working at high data rates, this parameter is of extreme importance and therefore it will have to be compensated or diminished with better performance fibres with lower PMD coefficients.

4.2.1 Compensation of PMD

[10] Unlike chromatic dispersion, statistical dimension of PMD is due to the variations in time of the external stress on the fiber. In transmission systems, there is no guarantee of the maximum penalty due to PMD. That is why it gets a difficult task to compensate this effect apart from the costly solutions offered.

The principle of operation of a PMD compensator is to reduce the total PMD of the fiber line plus that in the compensator. Figure 15 shows the basic scheme of a PMD compensator. It consists of one fixed highly birefringent element (polarization maintaining fiber), polarization controller to orient the axis of the counteractive elements and control algorithm with control circuits

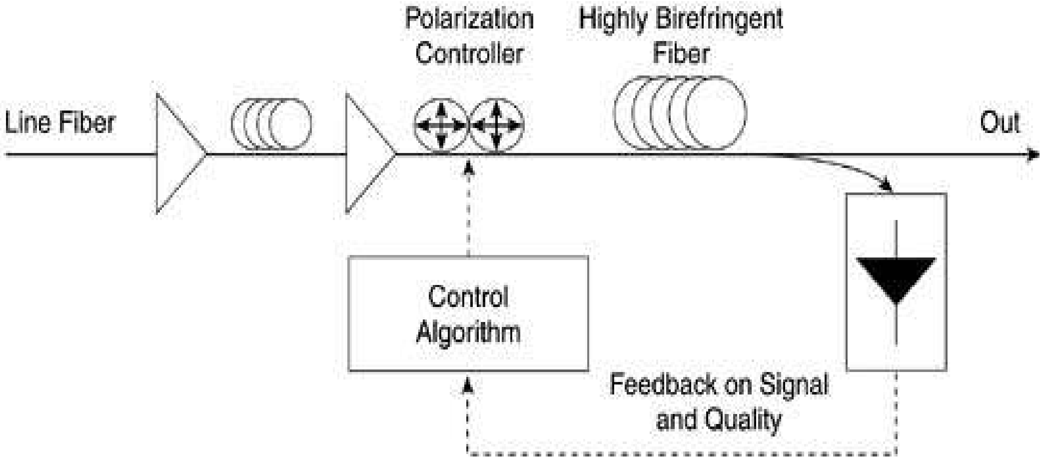


Figure 15.PMD compensation scheme

The control algorithm is in a tracking mode and operates in blind mode-PMD conditions are not dynamically controlled; Control algorithm has to keep track of local optimum feedback signals. This is the main limitation of the compensator.

The aim of this section is to introduce a possible technique, but it is out of the scope to implement it due to the lack of such module in VPI Transmission maker. Thus, we shall be careful when dealing with PMD, for our simulation we will try to work efficiently with optical fibres with low PMD coefficients. That is our only way to counteract this undesirable effect.

4.3 Chromatic Dispersion

[2]Chromatic dispersion is a broadening of the input signal as it travels down the length of the fibre. The concept to consider when talking about chromatic dispersion (CD) should be optical phase. It is important to mention optical phase before any explanations of CD or group delay because of their mathematical relationship. Group delay is defined as the first derivative of optical phase with respect to optical frequency. Chromatic dispersion is the second derivative of optical phase with respect to optical frequency. These quantities are represented as follows [19]:

$$Group\ Delay = \frac{\partial \phi}{\partial \omega} \qquad\qquad Chromatic\ Dispersion = \frac{\partial^2 \phi}{\partial \omega^2}$$

$$where\ \phi = optical\ \ phase\ and\ \omega = optical\ \ frequency\ .$$

[22]Chromatic dispersion consists of both material dispersion and waveguide dispersion as illustrated in Figure 16.

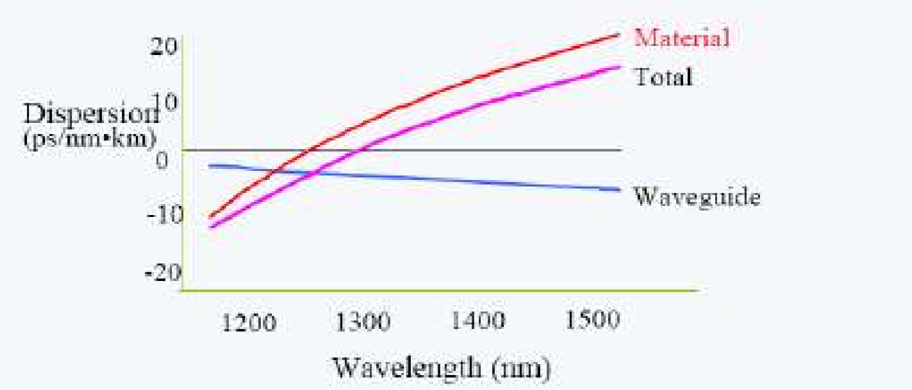


Figure 16.Material Dispersion and Waveguide Dispersion

Both of these phenomena happen due to a finite spectral width of all optical signals, And different spectral components will propagate at different speeds along the length of The fibre.

- One cause of this velocity difference is that the index of refraction of the fibre Core is different for different wavelengths. This is called *material dispersion* and it is the dominant source of chromatic dispersion in single-mode fibres.

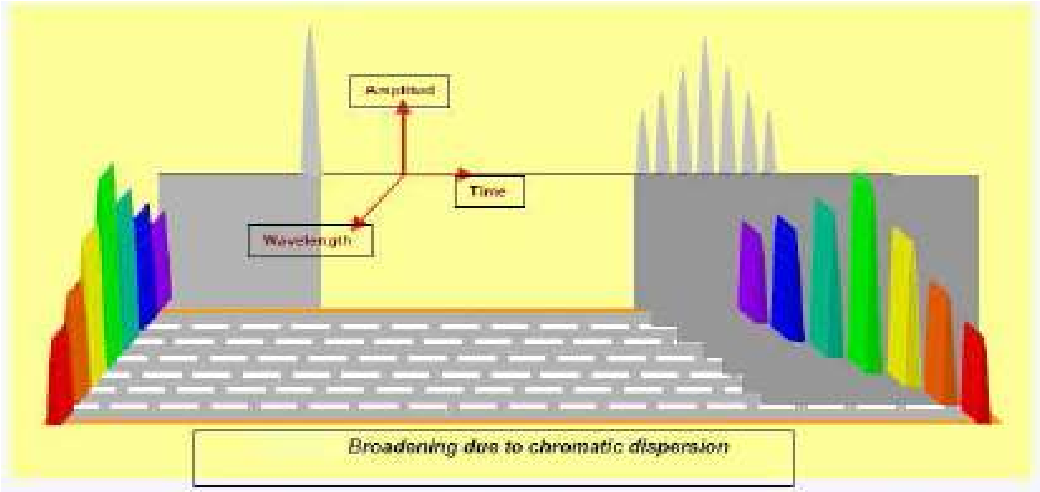


Figure 17.Broadening due to Chromatic Dispersion

In a positive dispersion fibre, short (blue) wavelengths arrive before long (red) wavelengths. Because laser light sources are not monochromatic, pulse spreading occurs.

Another cause of dispersion is that the cross-sectional distribution of light within the fibre also changes for different wavelengths. Shorter wavelengths are more completely confined to the fibre core, while a larger portion of the optical power at longer wavelengths propagates in the cladding. Since the index of the core is greater than the index of the cladding, this difference in spatial distribution causes a change in propagation velocity. This phenomenon is known as *waveguide dispersion*.

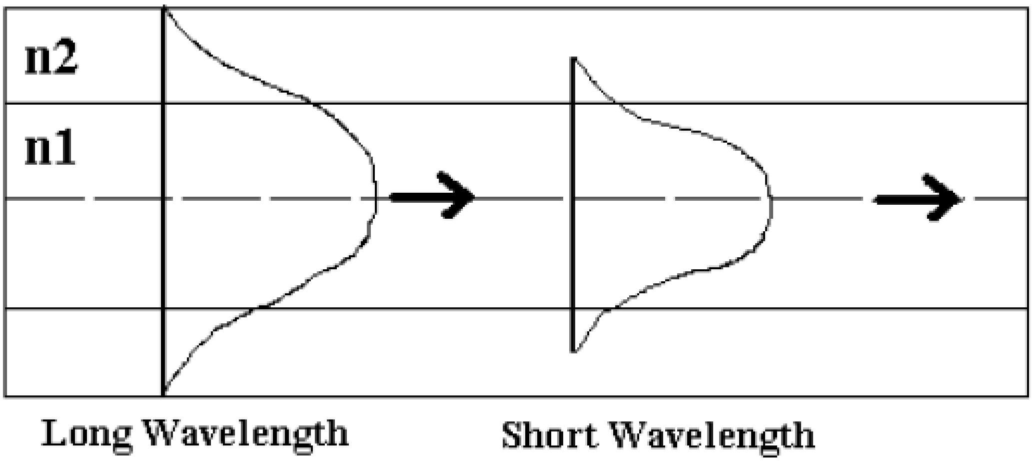


Figure 18.Waveguide Dispersion

In Waveguide Dispersion different wavelengths will experience different effective refractive indices.

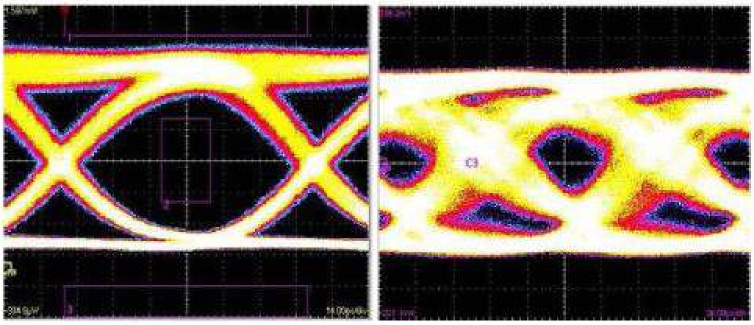
However Waveguide dispersion is relatively small compared to material dispersion. After the process followed in [5] we can arrive to the generic expression for the coefficient of Chromatic Dispersion expressed in *ps/nm*km* Where B2 stands for being the coefficient of group velocity:

$$D = -\frac{2\pi c}{\lambda^{2}}\beta_{2}$$

After the transmission across the optical fibre, the total accumulated dispersion is:

$$CD_{acumulada} = D \cdot l = \frac{\tau}{\delta\lambda} \quad [\text{ps/nm}]$$

Which introduces as it has been seen, a broadening in the impulses resulting in ISI (inter symbol interference) which results in a difficulty for distinguishing adjacent pulses in the receiver.



Eye diagram at B2B w/o dispersion

Eye diagram after 140km (2400ps/nm)

CD EFFECT

Figure 19.Effect of Chromatic Dispersion

Furthermore, it leads to a power penalty. This power penalty is measurable by the following expression:

$$Penalty_{DISP} = \frac{10\log\frac{\sigma}{\sigma_0}}{\sqrt{1+\left(D_L\frac{\sigma_\lambda}{\sigma_0}\right)^2}}$$

As it can be seen it creates a penalty resulting in degradation of the system OSNR. Thus, BER will increase.

This phenomenon will need to be compensated to diminish the impact on the system under studio.

4.3.1 Compensation of Chromatic Dispersion

[4] In a chromatic dispersion-limited system in which the total accumulated dispersion for a travelling pulse is greater than the maximum allowable dispersion, the system cannot operate properly due to the existence of tremendous ISI or just pure pulse spread. Therefore, we shall be able to place dispersion compensation units (DCUs) at different positions in a network

Because the primary aim is to keep the total dispersion at the end of the communication channel as low as possible (close to zero but not reaching it), the fiber used has to have an opposite dispersion profile as the SMF fiber (different dispersion sign) so they can cancel when concatenated.

There are two techniques to achieve such goal [1]:

- Precompensation Technique
- Postcompensation Technique

In the first one the dispersion is compensated before the signal is induced in the system:

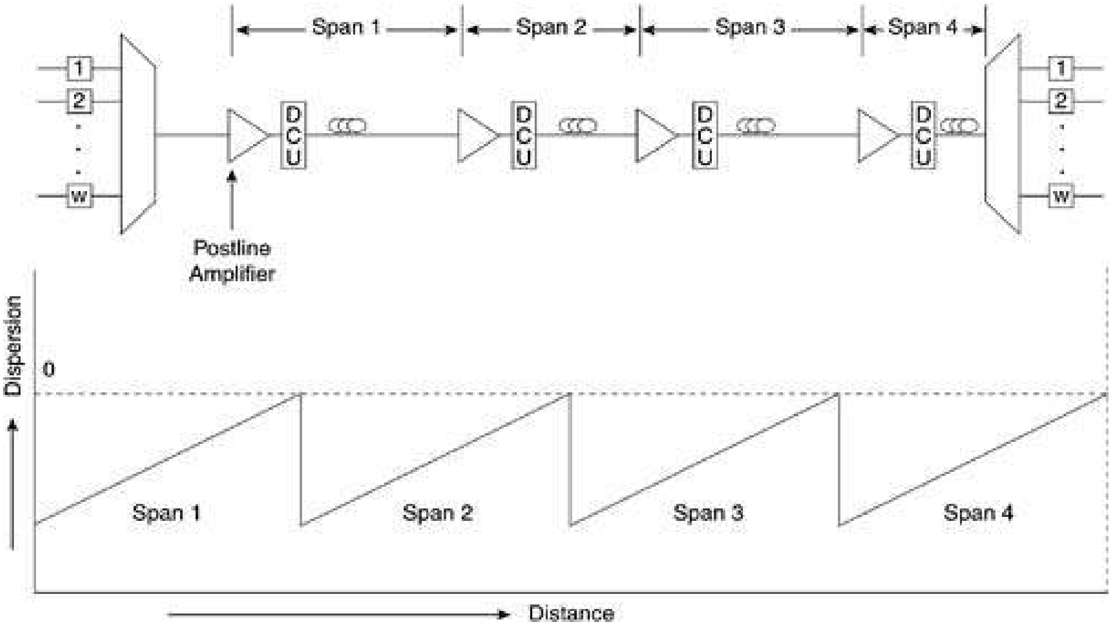


Figure 20: Dispersion Maps for Precompensation scheme

In the postcompensation technique the DCU modules are placed before the preline amplifier as shown in figure 21:

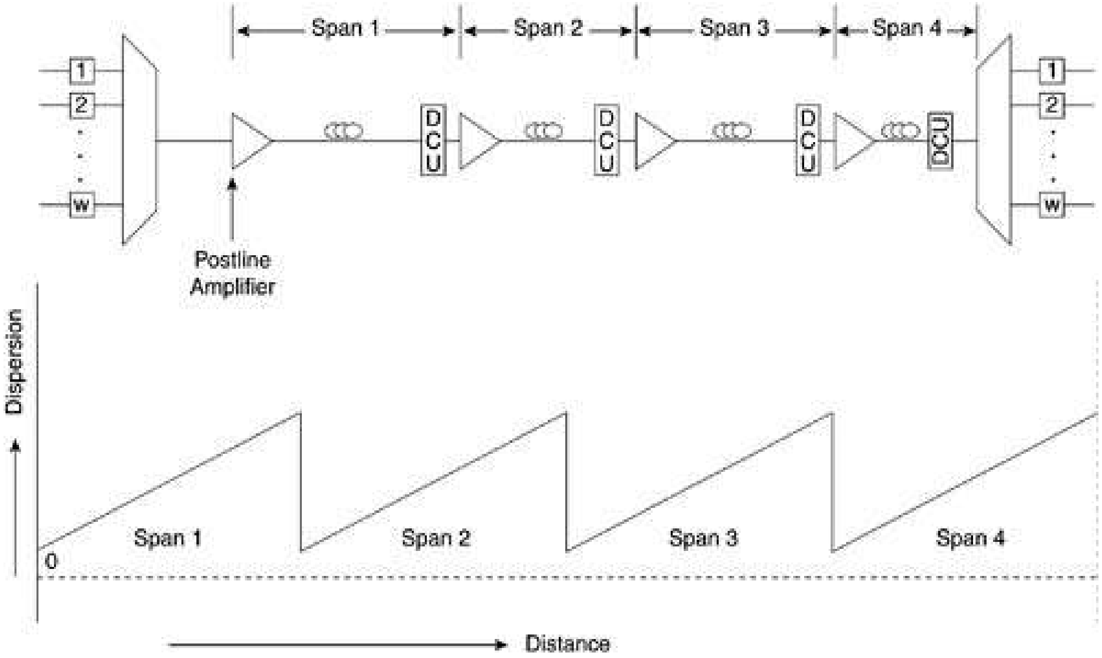


Figure 21.Dispersion Maps for postcompensation scheme

However, when adding dispersion compensating fibers (DCFs) there is a serious loss (attenuation). The attenuation parameter α for DCF fibers is much greater than the attenuation for normal single-mode fibers (SMFs). It is typically as high as 0.5-0.8 dB/km in contrast to 0.2 dB/km, for standard 1550 nm SMFs. This is due to a coupling difference between transmission fiber and the DCU.

This effect will have to be taken into account when designing the link.

5

Optical Amplifiers

5.1 Introduction

[1]Signal propagation in an optical fiber is limited because of attenuation. Attenuation, dispersion, nonlinearities, and other harmful effects cause the signal level in an optical fiber to degrade with their accumulation (transmission length). To sustain optical communication, the receiver (photo detector) must be able to detect or read signal pulses and distinguish between 1s and 0s efficiently.

The signal before reaching the detector suffers from multiple attenuations (it adds noise due to decrease in signal level and increase in noise due to accumulation); therefore, its signal-to-noise ratio (SNR) is degraded.

In a communication channel, the signal level can be boosted at intervals with *optical amplifiers*.

These monolithic blocks (subsystem modules) can optically amplify a signal (completely in the optical domain—with no electronic regeneration) and, therefore, raise the signal level. Optical amplifiers are functionally identical to electrical amplifiers or repeaters. Repeaters are 3R (reshape, reamplify, and retime) O-E-O regenerators, which completely detect, amplify, and retransmit a signal. In contrast, optical amplifiers have an advantage over repeaters in the sense that the data streams being amplified are amplified entirely in the optical domain.

Moreover, optical amplifiers are completely transparent to signals and protocols. Three basic types of amplifiers are being deployed:

- Doped fiber amplifiers (such as Erbium doped fiber amplifiers, or EDFAs)
- Raman amplifiers (scattering amplifiers)
- Fiber-semiconductor optical amplifiers (SOAs)

5.2 EDFA: Erbium doped fiber amplifier

An EDFA is a doped fiber amplifier that is functional in the C band and the dopant used is Erbium ions. With characteristics of moderately high (yet uneven) gain spectra, doped fiber amplifiers exhibit optical gain because of stimulated emission of the higher excited state. In principle, a doped fiber amplifiers such as EDFA depicts three energy levels.[1]

Upon application of an optical pump (1480 nm/980 nm continuous wave), electrons in the stable ground state-E1 absorb quantities of energy and rise to a meta-stable state of energy-E2.

The existence of such a state is governed by two material factors: the atomic transition frequency-w0 corresponding to the longest lifetime state2, and the transition wavelength on which a major chunk of pump energy is transitioned. The transition wavelength is in the strategic 1550 nm band;

Therefore, *EDFAs are popular in commercial WDM networks.*

5.3 Noise in Amplifiers

However, noise is inherent within an optical amplifier; it is a by-product of optical amplification. The noise degrades the signal quantity and affects overall signal to noise ratio (SNR). A figure of merit for optical amplifiers is the noise figure (NF). *NF*, as shown next, can be defined as the ratio of input OSNR to the output OSNR in an optical amplifier.[1]

$$NF = \frac{SNR_{input}}{SNR_{output}}$$

Noise in amplifiers is essentially due to spontaneous emission. Spontaneous emission in amplifiers is a by-product of the gain media, whereby the optical amplifier emits electrons that abruptly fall from various levels, emitting uncontrolled light of random phase and frequency distribution.

The emitted light is noise or random perturbations and is called *amplified spontaneous emission* (ASE). ASE in an optical amplifier is a serious cause of concern that severely affects system performance; ASE impairment can create ripples in the power budget. Currently, it is impossible to suppress ASE due to the continuous nature of ASE signal throughout the entire spectral width of the WDM channels. [6]

ASE constitutes perhaps the most severe impairments that limit the reach and capacity of the WDM System. Each EDFA contributes ASE, which can be expressed as

$$P_{ASE} = 2hv.\Delta v.n_{sp}(G-1)$$

Where Pase is the ASE power (noise) in an optical bandwidth Δv, h is the Planck's constant, v is the optical frequency, Nsp the spontaneous emission factor and G is the optical amplifier gain.

The following figure shows how the ASE Noise from EDFA amplifier affects the signal:

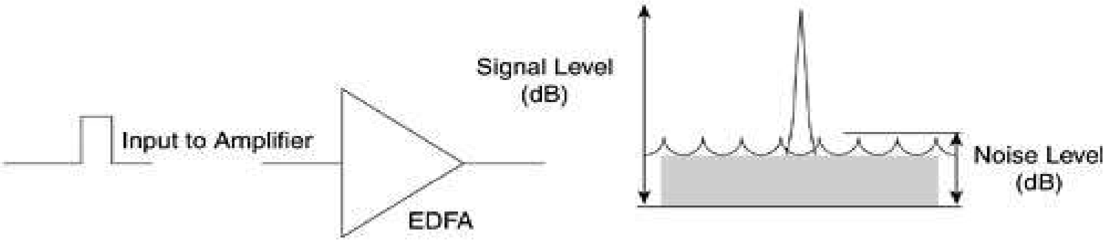


Figure 22. Single Stage Amplifier and Noise associated with a signal

On an optical amplifier-based network where the signal fades(suffers from attenuation) in every span and it is necessary to place an EDFA amplifier to boost the power of the signal, the overall effect can be depicted below:

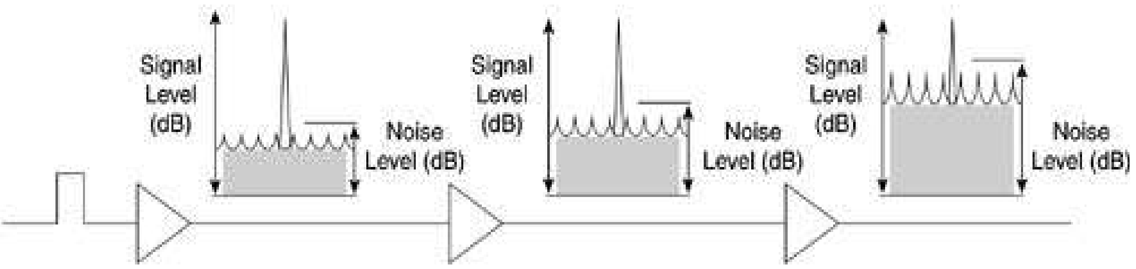


Figure 23.Noise Accumulation resulting from multistage Amplification.

These contributions of ASE noise add cumulatively along the amplifier chain, and gives rise to signal spontaneous beat noise at the receiver, which is the fundamental noise limit in an optically amplified transmission system. Thus, it will create an OSNR penalty, important for the system.

In a multistage amplification the OSNR can be expressed as:

$$OSNR_{db} = 58 + P_{in} - \Gamma(db) - NF_{db} - 10\log N$$

Where NF is the Noise Figure, Γ is the span loss and N the number of Spans.
In the calculation of system design, amplifier noise is considered the predominant source for OSNR penalty and degradation.
The following figure depicts the behaviour of the OSNR along the amplifier chain

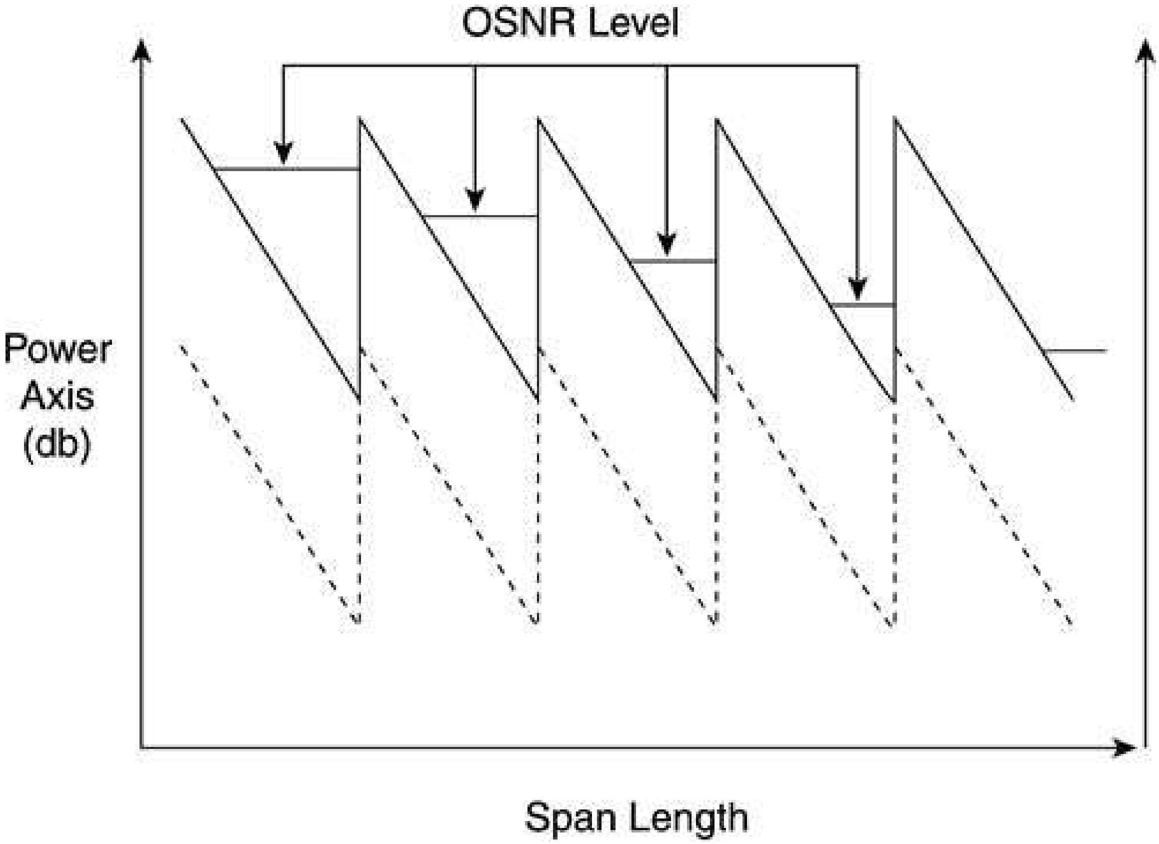


Figure 24.OSNR levels in terms of signal and noise power levels for multistage WDM transmission

6

ROADM

6.1 Technology of ROADM

A ROADM (reconfigurable optical add-drop multiplexer) is a device used for routing and multiplexing purposes in WDM systems. It allows wavelengths to be added, dropped or passed through a single mode fiber (SMF) across an optical network. ROADM is a form of OADM that adds the ability to remotely switch traffic from a WDM system at the wavelength layer.
This allows individual or multiple wavelengths carrying data channels to be added and/or dropped from a transport fibre without the need to convert the signals on all of the WDM channels to electronic signals and back again to optical signals

"Add" and "drop" is used to refer to the capability of the device to add one or more new wavelength channels to an existing multi-wavelength WDM signal, and/or to drop (remove) one or more channels, passing those signals to another network path.
All the light paths that directly pass an OADM are termed cut-through light paths, while those that are added or dropped at the OADM node are termed added/dropped lightpaths.

A traditional ROADM consists of three stages: an optical demultiplexer, an optical multiplexer, and between them a method of reconfiguring the paths between the optical demultiplexer, the optical multiplexer and a set of ports for adding and dropping signals. The optical demultiplexer separates wavelengths in an input fiber onto ports.

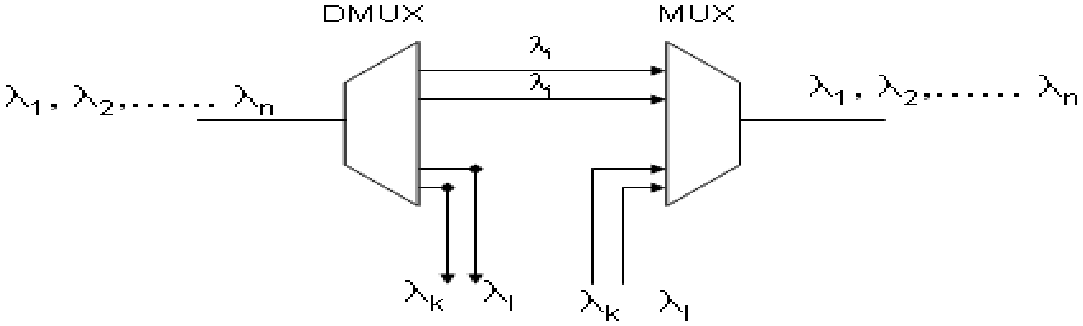


Figure 25.Scheme of a ROADM

Two major ROADM technologies are in current use:

- Wavelength blocking (WB)
- Planar light-wave circuit (PLC).

Wavelength blocking, also called first-generation ROADM technology is the older of the two.

Both technologies include optical filters to separate the wavelengths. The signal passes through a number of these nodes and the resultant filter cascade reduces the effective bandwidth making the system more susceptible to laser and filter pass band misalignment.

Depending upon the analytical transfer function, we can distinguish three types:

- Fibre Bragg Gratings (FBG)
- Arrayed Waveguide Gratings (AWG)
- Thin Film Filter (TFF)

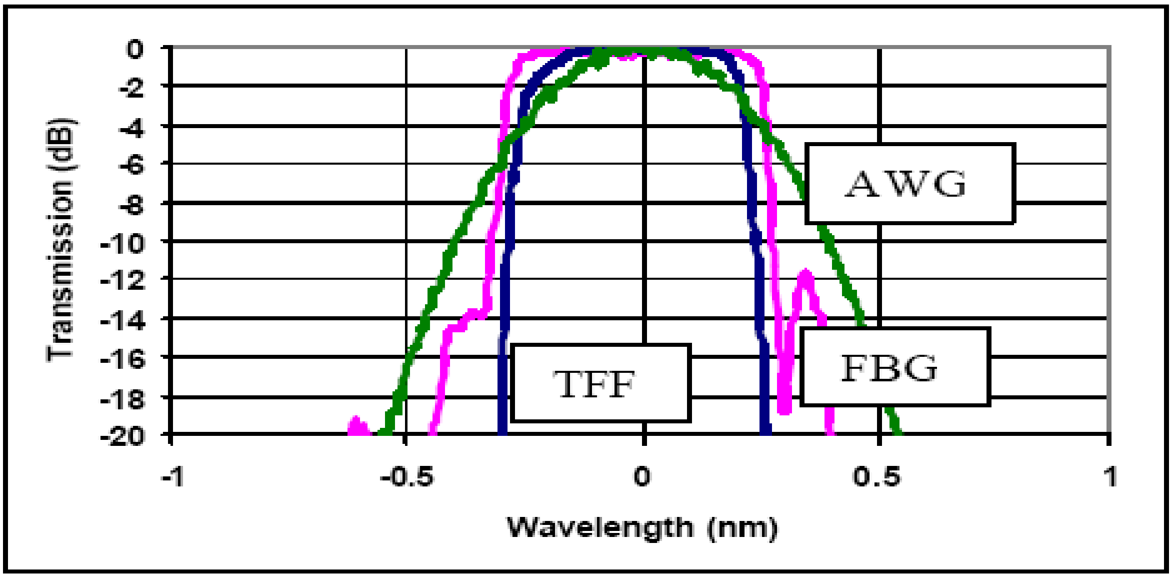


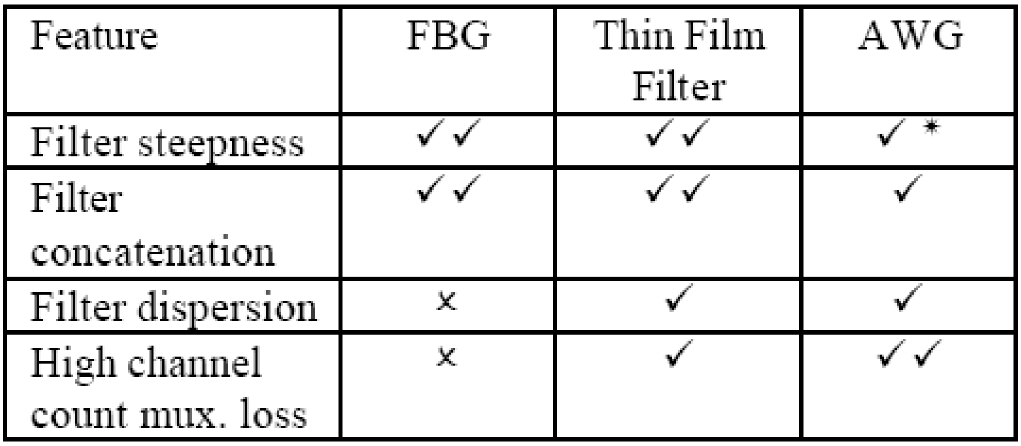
Figure 26.Comparison of measured amplitude responses of thin film(TFF), AWG and FBG filters

Some of the highlights of each technology is for example that Thin film filters and AWGs both have low dispersion. Thin film filters have a better filter amplitude response leading to lower bandwidth reduction as they are concatenated.

For low channel counts, the thin film filters perform well. For high channel counts, the lower loss of AWGs is an important consideration

Fibre Bragg Grating (FBG) filters have higher dispersion than the other filter types

These features can be summarized on the following table[9]:



Feature	FBG	Thin Film Filter	AWG
Filter steepness	✓✓	✓✓	✓ *
Filter concatenation	✓✓	✓✓	✓
Filter dispersion	x	✓	✓
High channel count mux. loss	x	✓	✓✓

Figure 27.Comparison of several filter technologies

6.2 Implementation

For Simulation purposes we have modelled a ROADM as:

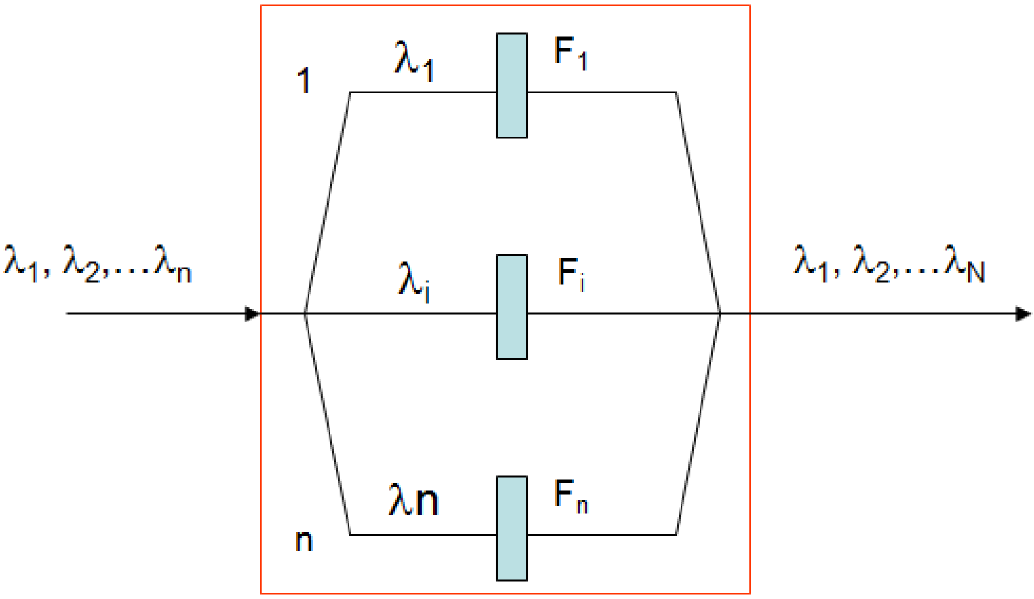
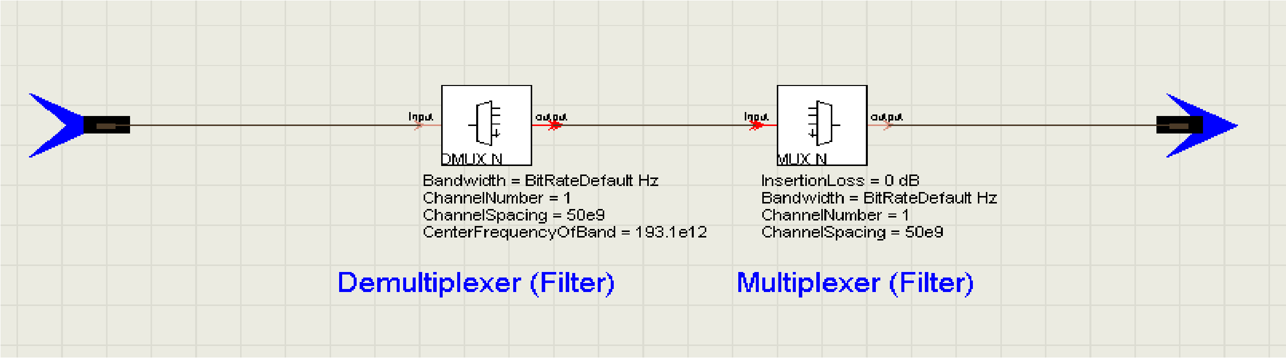


Figure 28.ROADM for simulation purposes

Here, each of the wavelengths takes a different path, then they pass through the filter and finally they get together back again into a single WDM signal. This is the worst-case scenario where no adding or dropping occurs.

As it is modelled, a ROADM is a network device that degrades the signal as it passes through it due to the filtering involved in the process.

Among the three different transfer functions, we have chosen for our simulations the TFF as it offers great performance when it is concatenated. It has been modelled as a 3rd order Butterworth filter with 0 dB of insertion losses. (Ideal behaviour) [20]



Bandwidth = BitRateDefault Hz
ChannelNumber = 1
ChannelSpacing = 50e9
CenterFrequencyOfBand = 193.1e12

InsertionLoss = 0 dB
Bandwidth = BitRateDefault Hz
ChannelNumber = 1
ChannelSpacing = 50e9

Figure 29.ROADM for VPI purposes

7

Modulation Formats

7.1 Need for modulation formats

[12] In single-mode optical fibers, the optical field has three physical attributes that can be used to carry information:
Intensity, phase (including frequency) and polarization.
Depending on which of the three quantities is used for information transport, we distinguish between intensity, phase (or frequency), and polarization data modulation formats

Few years ago in links up to 10 Gpbs, intensity modulation NRZ was used, due to its simplicity and low cost. However it exhibits an undesirable behaviour when increasing the bit rate due to its wide channel spacing.

The recent drive towards a 100G Ethernet standard and burgeoning traffic demand indicates that solutions are required for long-haul transmission with high spectral Efficiency [7].
A good modulation format suitable for high bit rates has to comply with the following requirements:

- Resilient to noise from OAs and in-band crosstalk
- Tolerant to CD and PMD
- Robust to fiber nonlinearity and inaccuracies in dispersion maps
- Amenable to repeated optical filtering due to OADMs
- Narrowband to enable high Spectral efficiency

Phase modulation formats are a good balance of these requirements and are ready to face the challenge of high bit rates and change the actual links of 10 Gpbs.

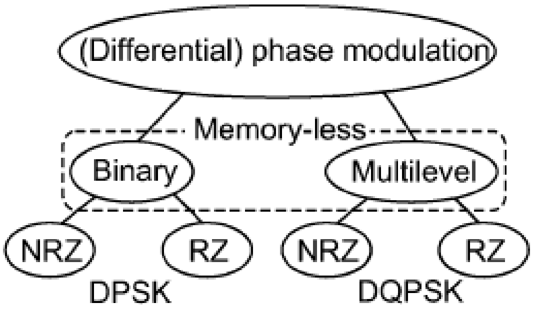


Figure 30.Phase modulation formats

It is challenging to realize such bit rates with binary formats (DPSK), as the required bandwidth of the electrical components in the transponder is difficult and costly to realize. Multi-level formats, such as differential quadrature phase shift keying (DQPSK) provide a promising alternative as they operate at a lower symbol rate for the same total bit rate. Hence, they require lower-speed, but generally more, transponder components compared to binary formats.

In our study we have focused just on these 2 modulation formats.
The main difference between DPSK and DQPSK is the symbol rate [5].

- DPSK encodes 1 bit per symbol
- DPQSK encodes 2 bits per symbol.

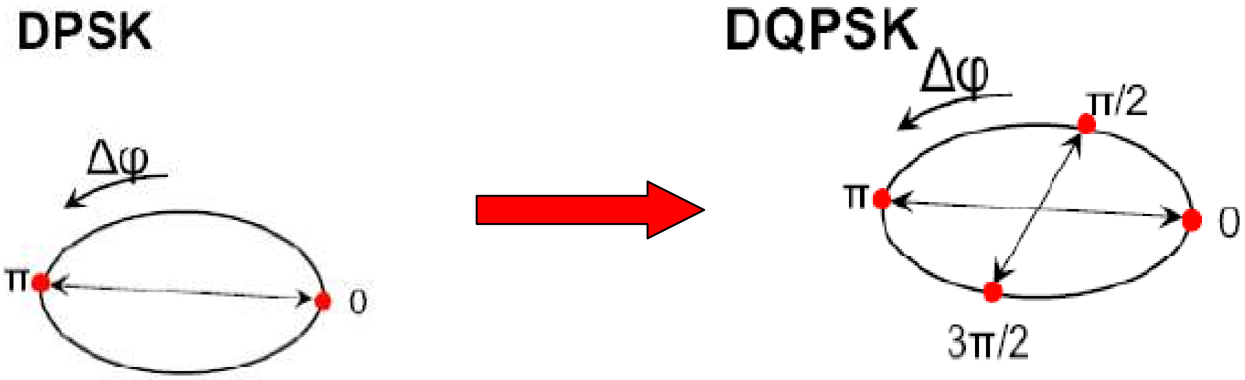


Figure 31.Constellation Diagram for DPSK and DPQSK modulation format

Apart from the symbol rate, both present different complexities, but still lower than other modulation formats, one of the main reasons for their deployment in optical links:

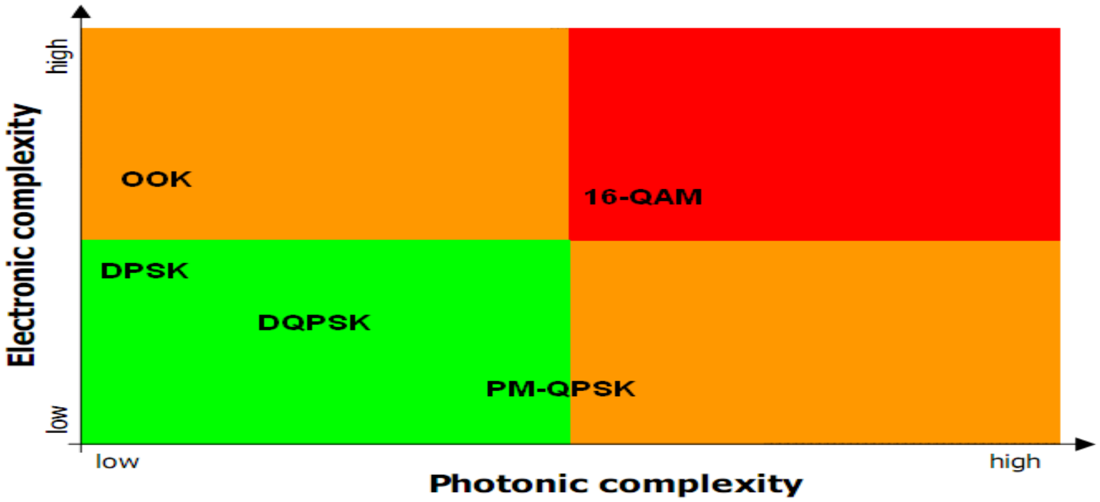


Figure 32.Photonic and electronic complexity of modulations

It is interesting to note finally, the shape of the spectrum for both modulation formats:

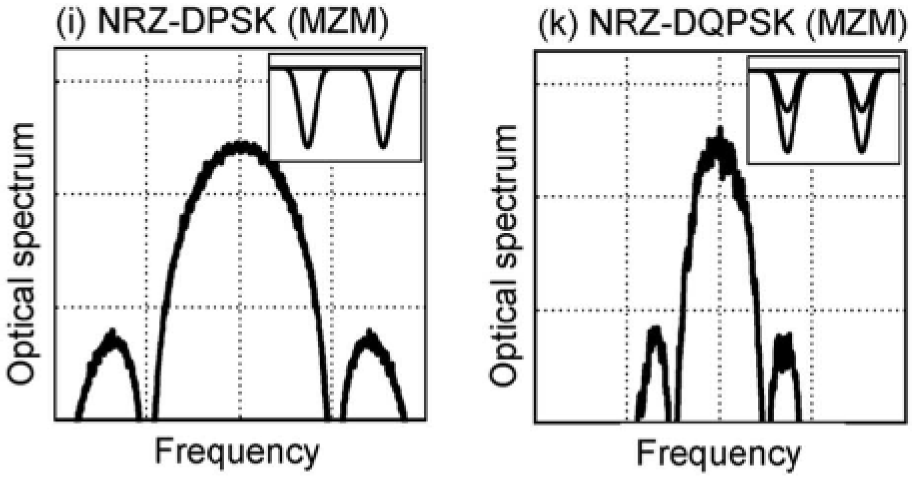


Figure 33.DQPSK vs. DPSK spectrums

As it can be seen in figure 33, both shapes are alike but DQPSK is half the size of DPSK due to the transmission of 2 bits per symbol, thus it gets reduced by a factor of 2.[15] This spectral compression is extremely beneficial for WDM systems as it will be shown in following sections, showing a better behaviour versus Chromatic dispersion for example. Likewise, higher symbol duration makes DQPSK stronger to PMD effects.

The following section presents with more detail each modulation format in terms of structure:

7.2 DPSK modulation format

[1] Differential binary PSK (DBPSK or simply DPSK) encodes information on the binary phase change between adjacent bits: a 1-bit is encoded onto a π phase change, Whereas a 0-bit is represented by the absence of a phase change. Like OOK, DPSK can be implemented in RZ and NRZ format. The main advantage from using DPSK instead Of OOK comes from a 3-dB receiver sensitivity improvement [20],

[16] An optical DPSK transmitter is shown in Fig. 34. The data signal is first differentially encoded at the transmitter, which avoids error propagation that may occur by differential decoding at the receiver. The precoding operation is visualized by the two bit patterns in Fig. 34. The phase of the optical field of a narrow-line width laser source is then flipped between 0 and π using the precoded data sequence.

To perform optical phase modulation, one can either use a straight-line phase modulator (PM) or an MZM .

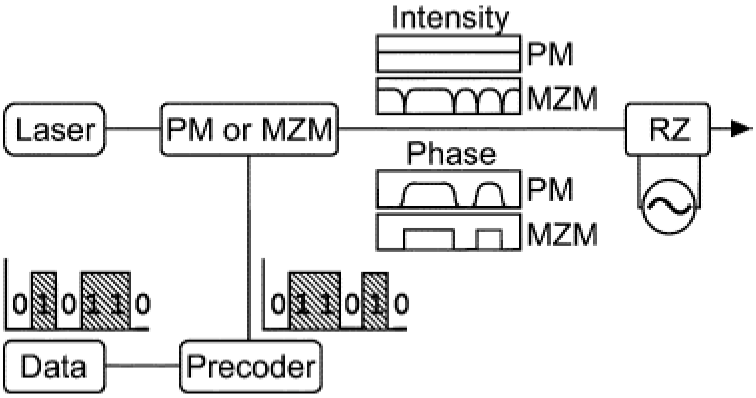


Figure 34. Setup of a RZ-DPSK transmitter

Since exact phase modulation is more important for DPSK than a constant optical intensity, practical DPSK transmitters are most conveniently implemented using an MZM as a phase modulator.

7.2.1 Implementation

For simulation purposes, there is a module already created in VPI which represents a RZ- DPSK transmitter.

7.3 DQPSK modulation format

DQPSK is the only true multilevel modulation format (more than one bit per symbol) that has received appreciable attention in optical communications so far [12]. It transmits the four phase shifts {0, + π/2, -π/2, π} at a symbol rate of half the aggregate bitrate. As in the case of DPSK, a DQPSK transmitter is most conveniently implemented by two nested MZMs operated as phase modulators as shown in figure 35.

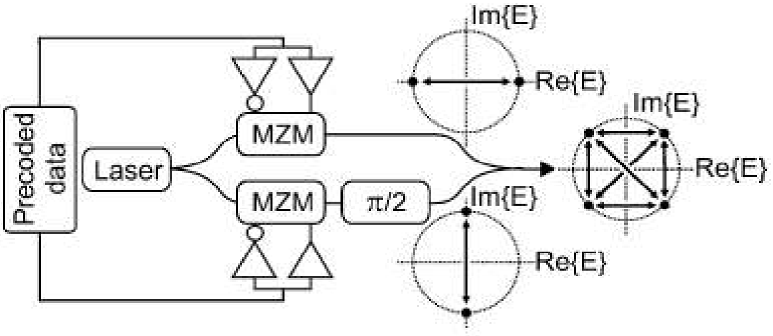


Figure 35.Setup of a DQPSK transmitter

Fig. 35 shows the corresponding transmitter setup consisting of a continuously operating laser source, a splitter to divide the light into two paths of equal intensity, two MZMs operated as phase modulators, an optical π /2-phase shifter in one of the paths, and a combiner to produce a single output signal. The symbol constellations of the upper and lower paths as well as at the modulator output are also shown, together with the symbol transitions. By using this transmitter structure, one first takes advantage of the exact π phase shifts produced by MZMs, independent of drive signal overshoot and ringing. Second, this transmitter structure requires only binary electronic drive signals, which are much easier to generate at high speeds than multilevel drive waveforms[14].

7.3.1 Implementation

For simulation purposes, there is a module already created in VPI which represents a DQPSK transmitter.

8

VPI transmission Maker

8.1 Presentation of the tool

The software tool used to perform the scenarios is “VPI transmission Maker” from the enterprise VPI systems. The tool used to run the simulations is VPItransmissionMaker™ WDM from VPI photonics. Both tools in conjunction have enabled the possibility to perform all the work shown next.

VPItransmission maker is an integrated design environment for individual designers and collaborative design teams. It is nowadays a “standard” within the industry of optical communications to perform tests and simulations. Apart from its great potential features, that has been the main reason to work with such software

Likewise, it is a very powerful simulator for optical communications based in modules. Each module can act as a device or a component and they can range from a standard optical fiber to a sophisticated laser or a customized EDFA amplifier. Everything is possible, as the user can create his own modules as wished.

Every module is a “star”, a module within a module is called a “galaxy”. And any simulation based on stars and galaxies is called a “universe”

The program assists the user with many universes already created, ready to play, which represent modern optical fiber links or any real scenario. For a beginner, that is of great help due to the complexity of its graphical interface.

One of the main bugs of the program is the execution time of the simulations. Sometimes it can last long and limit the simulation. Thus, we shall be careful to choose the adequate parameters. A high Bit Rate or little Sample Rate can create the simulation to last very long.

8.2 VPItransmissionMaker™ Applications

The core mission of VPI Photonics is to develop and support sophisticated design tools for photonic devices, components, systems and networks. The way it solves these challenges it is illustrated in Figure 36 along an example signal path. Many design issues have to be considered along this path:

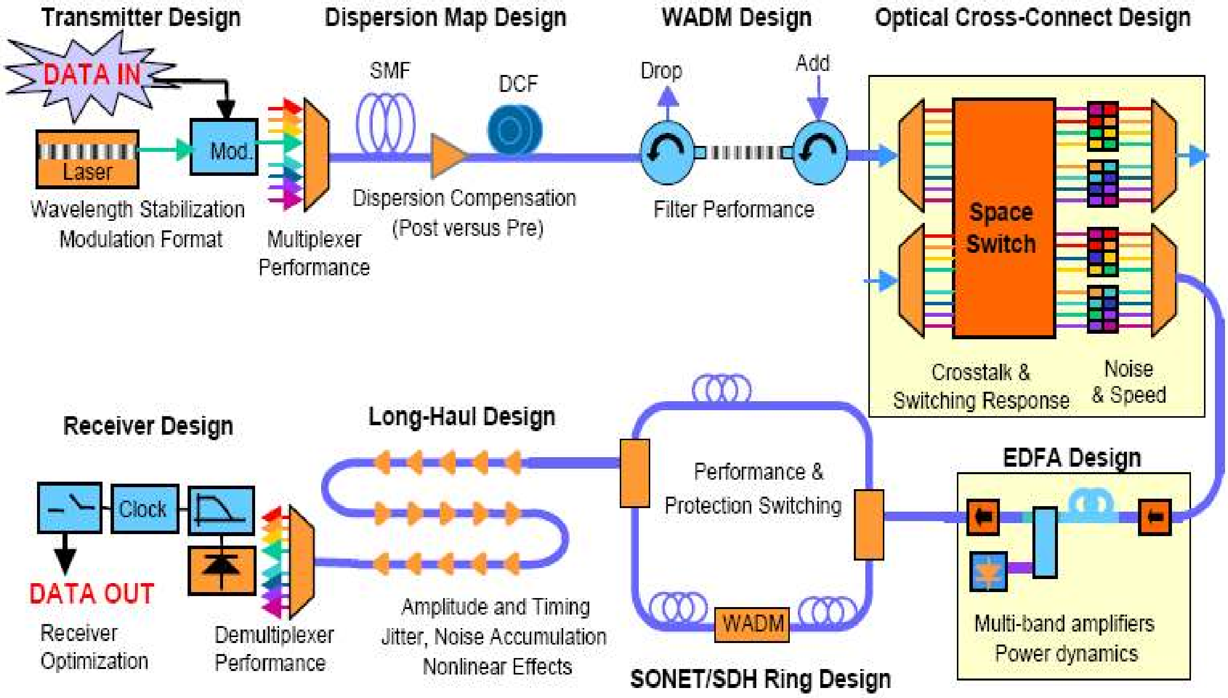
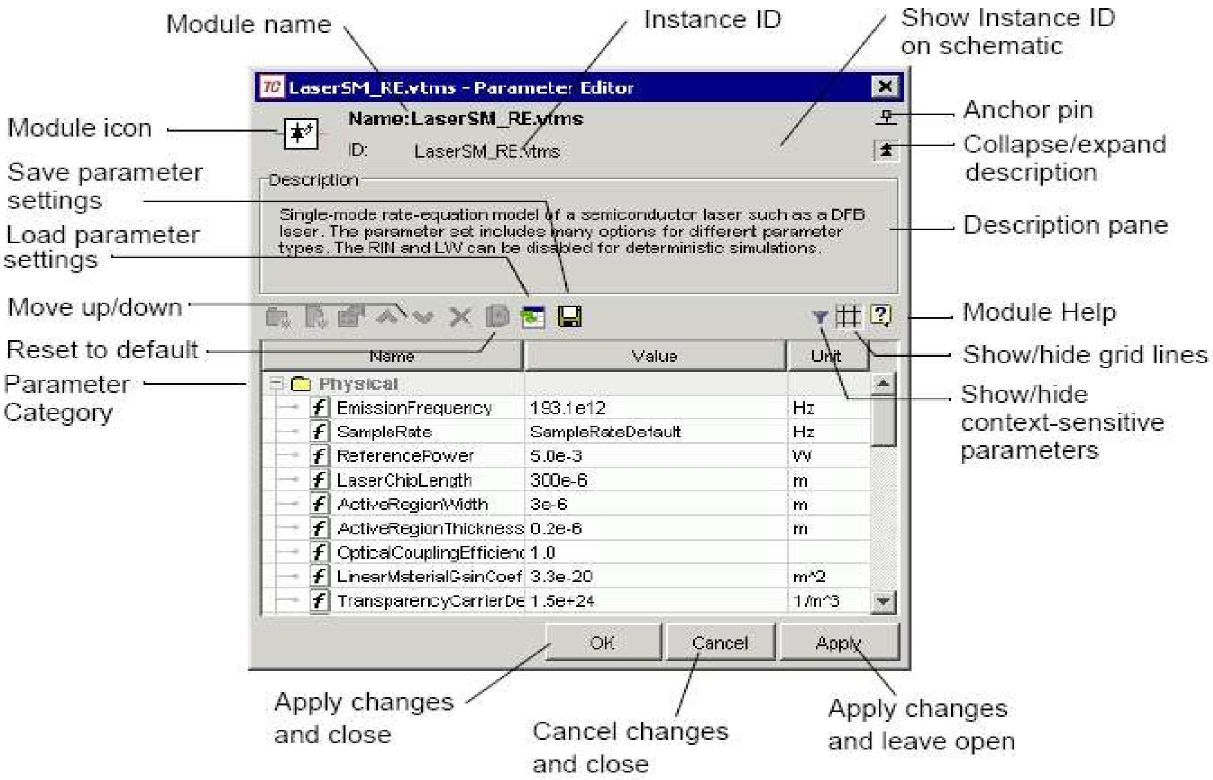


Figure 36.Applications of VPI TransmissionMaker

This figure is an universe comprised of many modules which shall be carefully designed. Figure 37, shows the graphical interface to set up the properties of any module: EDFA amplifier, Optical Fibre, Laser Transmitter…:



Name:LaserSM_RE.vtms

ID: LaserSM_RE.vtms

Description

Single-mode rate-equation model of a semiconductor laser such as a DFB laser. The parameter set includes many options for different parameter types. The RIN and LW can be disabled for deterministic simulations.

Name	Value	Unit
Physical		
EmissionFrequency	193.1e12	Hz
SampleRate	SampleRateDefault	Hz
ReferencePower	5.0e-3	W
LaserChipLength	300e-6	m
ActiveRegionWidth	3e-6	m
ActiveRegionThickness	0.2e-6	m
OpticalCouplingEfficienc	1.0	
LinearMaterialGainCoef	3.3e-20	m^2
TransparencyCarrierDe	1.5e+24	1/m^3

Figure 37.Parameter Editor for a module

Next comes a screenshot of a generic workspace where it can be visualized how is the user interface of the program:

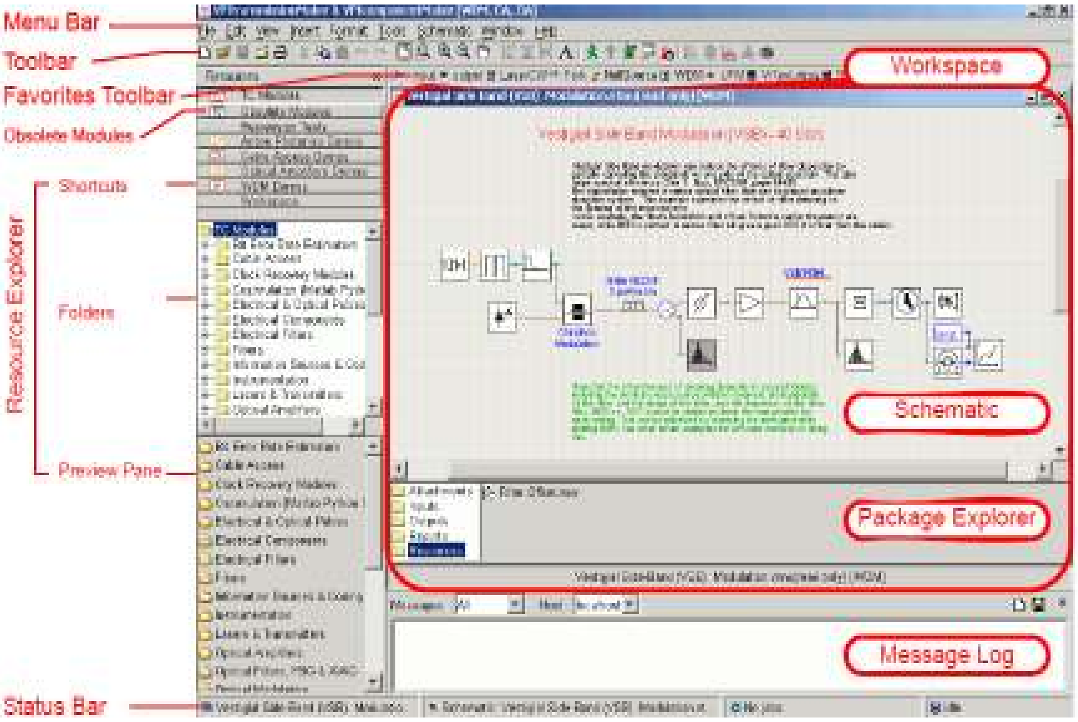


Figure 38.Open Schematic of VPI transmissionMaker

8.3 Functionalities

The aim of this project is to assess the impact of different factors such as the optical fibre, optical amplifiers, ROADMS on the OSNR vs. BER performance.
Because many tests varying some parameters have been performed, one of the main functionalities which has made all possible is the "Sweep" tool, which allows creating a sweep of any variable varying another variable which affects the first.

Likewise, the help of VPI photonics to visualize the results displaying them in graphs has been of extreme importance to illustrate "OSNR vs. BER" graphs.

In order to visualize the results, previously we have to set the features of the simulation. The main ones are:

- *Time window:* Establishes the gap of time for data acquisition. It sets the resolution of the spectral graphs as well as the accuracy for BER estimations.
- *Sample mode bandwidth:* Establishes the Sample rate of all signals
- *Sample mode centre frequency:* Sets the central frequency of the carrier for all signals
- *Sample rate default*: Sample rate of signals by default. It is used by default everywhere in the program, but it can be set accordingly
- *Bit rate default*: Allows to set the bit rate of the communication

It is of extreme importance to set up the right values for those parameters, as an unlucky setting could produce errors or processes to last very long.
Based on some tests and searching for accuracy as well as a decent execution time, we have come up with the following figures for all of our simulations:

- *Time window*: 64/bit rate default.
- *Sample mode bandwidth*: 64* bit rate default.
- *Sample mode center frequency*: 193.1e12.
- *Sample rate default*: 64*Bit rate default
- *Bit rate default*: 40e9 and 100e9 (40Gbps and 100Gbps)

8.4 Photonics Analizer

VPI photonics analyser is the tool used to visualize the simulations. It allows six different modes to represent any signal: OSA, Scope, EYE, RFSA, Poincare and Numerical. The first five are good enough to represent signals of all kinds. For optical signals is widely used OSA, Scope, Eye and Poincare

For our purposes, it has been used both OSA (Optical Spectrum Analyzer) to visualize spectrums of signals and Numerical, to obtain "OSNR vs. BER" graphs.
An example of how a "Numerical" mode displays a signal is Figure 39:

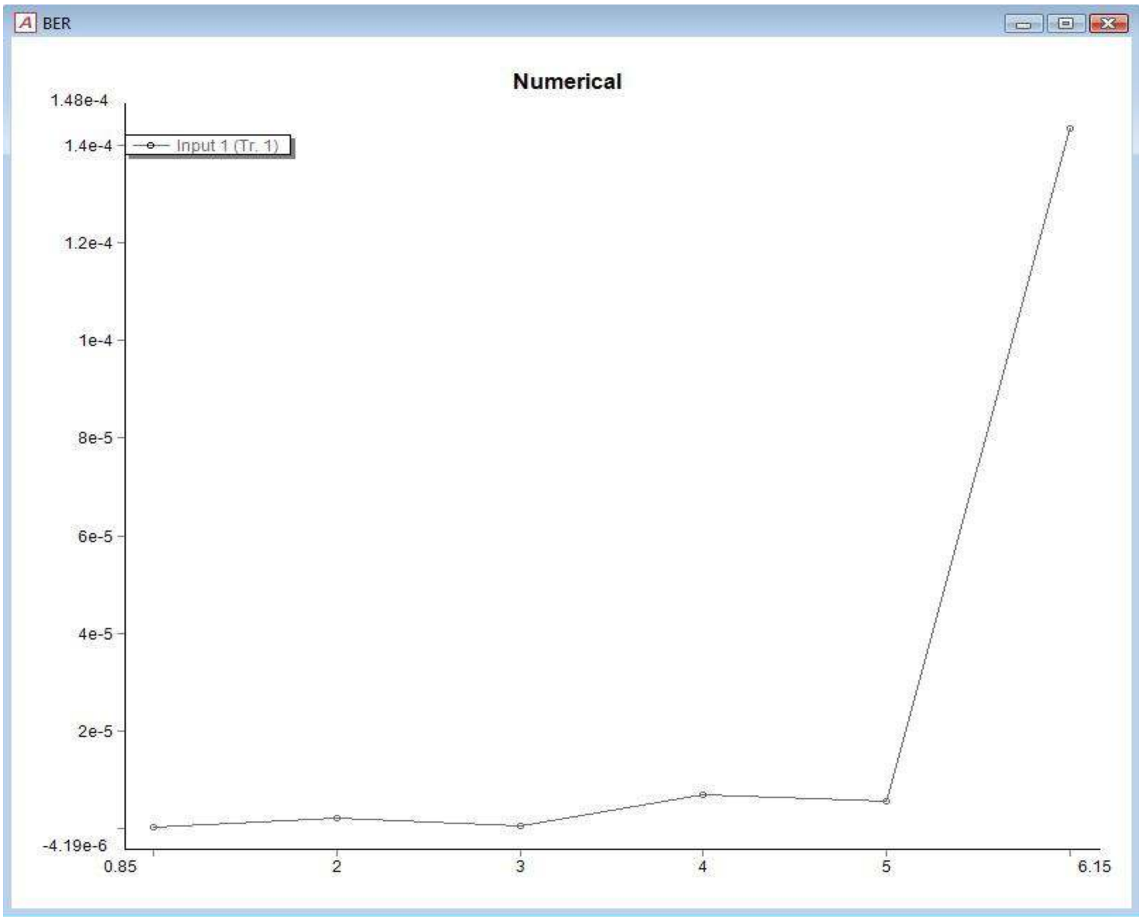


Figure 39.Example of Representation in "numerical" mode

Where in this example, BER vs. Number of Spans is represented, where the acceptable BER threshold is $4*10^{-5}$, let us say, 5 spans of optical fibre of certain length.

9

Tests and Results

At this stage, the scenarios and parameters of simulation will be shown and described. The whole purpose is to show the behaviour of links of optical fiber when the signal goes through concatenation of elements such as optical fiber, amplifiers of filters under different circumstances like bit rate or modulation formats.

9.1 Previous considerations

In a real life scenario using a DWDM technique to transport the information, a common scenario consists of N transmitters using a certain modulation format all multiplexed within the fiber and powered up with a booster. Depending upon the network topology, generally we are likely to find N spans of fiber +amplifier+ roadm, a fiber which makes up for the total chromatic dispersion (DCF) and then the receiver, just as depicted below

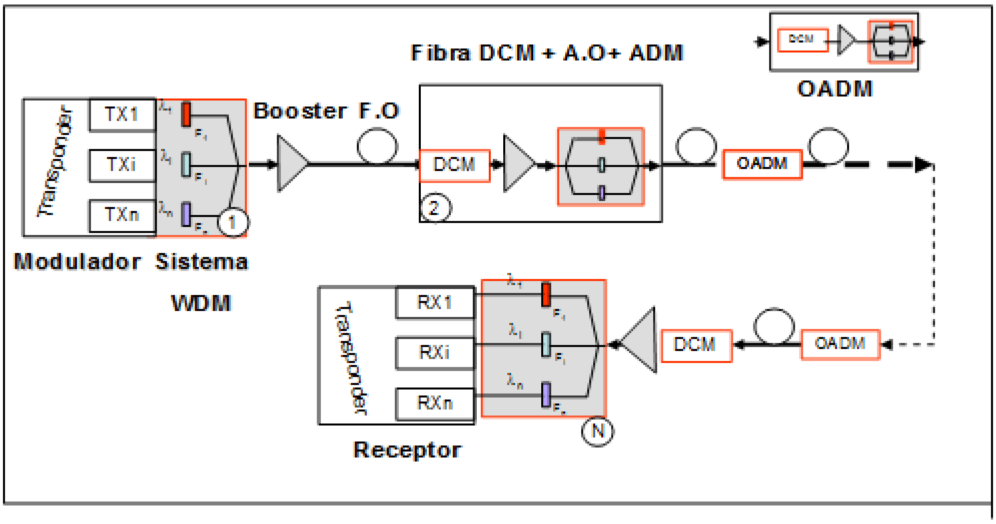


Figure 40.Real life DWDM scenario

The ultimate goal pursued with this thesis is to assess the performance of the whole system. As it has been described in the introduction, the parameter used to evaluate this behaviour is the OSNR (optical signal to noise ratio) due to its direct relationship to BER. *The first condition* used to evaluate the performance of the link, is generally BER at the receiver. Simulations are done trying to approach and obtain at the receiver a Minimum BER of 10^{-4}. Any simulation throwing a BER< 10^{-4} at some point will show that the link is not consistent and reliable from that point onwards.

It has been assumed the use of FEC techniques used for correcting errors and bringing them down to from 10^{-4} to 10^{-12}

These techniques are the standard G.709 (Reed-Solomon(255,239)), which introduce a 7% of overhead on the transmission. Due to this parameter when speaking from now on of bit rates of 40 Gbps and 100Gbps, we will be actually treating with velocities of **42.8 Gbps** and **107 Gbps.**

The second condition used to evaluate the performance of the link, in terms of individual elements is the OSNR penalty is defined as the OSNR increment required to achieve a desired BER, with respect to the back-to-back condition. This will give us the impact of a single element on the link.

9.2 Tests

The way tests have been thought and planned is to show the importance of each parameter of the link (described above) on the overall performance.
The following tasks have been carried out:

- Study of the **effect of the modulation format**: This section intends to study the needs of OSNR vs. BER on a back-to-back scenario over 3 different modulation formats: ASK, DPSK and DQPSK. It illustrates which format is better for a back-to-back case over a link of 40 Gbps.

- Study of the **effect of the optical fibre:** This study is widely covered on the second section of results. It analyses the impact of Dispersion (Chromatic Dispersion and Polarization Mode Dispersion) on the system. It is measured through OSNR penalty for DQPSK and DPSK modulation formats for different bit rates of 40 Gbps and 100 Gbps

- Study of the **effect of the optical amplifier**: This section aims to cover the main source of OSNR Penalty: Noise Figure. It discards a possible source of penalty: the gain of the amplifier. Ends with a useful equation to measure the impact of ASE noise (Noise Figure)

- Study of the **effect of optical filters**: On this fourth section, ROADMS are analysed over two modulation formats: DQPSK and DPSK. It shows the penalty induced when they are concatenated for each modulation format.

- Study of the **optimal configuration**: For a good network planning and management, this section explains which of the six different topologies (Fiber + Filter+ Amplifier) is better when is concatenated in terms of OSNR penalty

- Study of **BER and OSNR on a real scenario:** How the parameters act on a whole scenario. Graphs of maximum distance allowed for a given BER and OSNR will be obtained.

9.3 Scenarios

The 2 key scenarios of this thesis are explained here due to their importance on the overall results and their complexity. The other two scenarios will be explained later as they are pretty much self explanatory.

On the first scenario, In order to measure the OSNR penalty caused by single elements such as the optical fiber or the filters, the following theme has been modelled following the IsoBER test:

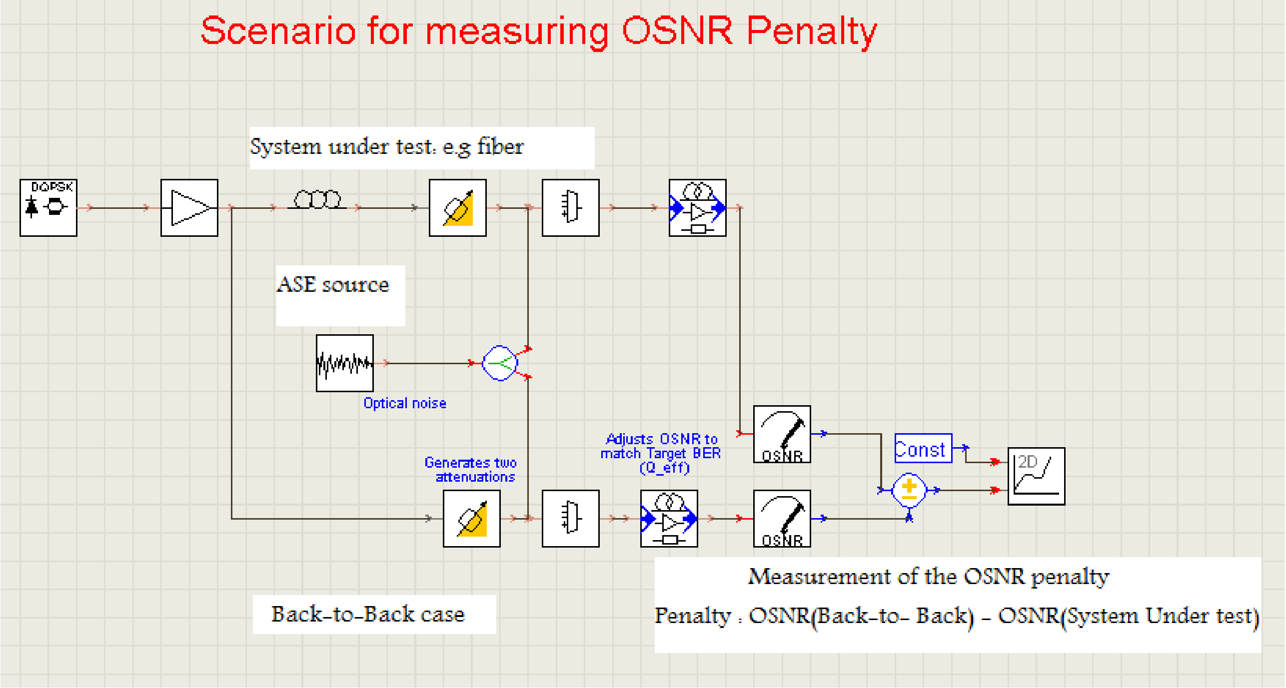


Figure 41.Scenario for measuring OSNR penalty

Let us remind again that the concept of OSNR penalty is commonly used to describe the impact of propagation impairments. It is defined as the difference in optical SNR that is required to reach a certain target BER (Q effective) for the case of propagation over the system-under-test and the back-to-back case.

Linear interpolation is used to find the correct OSNR values. The OSNR is varied by adjusting the signal power and keeping the noise power constant. The noise is added from a broadband ASE source. For this approach to work accurately enough, it is critical to set the two attenuation values of the variable optical attenuator in front of the receiver such that the target BER lays in between the two calculated BER values.

For simulation purposes, the attenuator goes from 11dB (lowest attenuation) to 1 dB in 2 runs with a delta increment of 5 db on each run. By diminishing signal power and keeping the noise constant the right value of OSNR will be obtained for each path for a BER= 10^{-4}. At the receiver, the ASE is filtered by an optical filter to obtain ASE noise just in the region of interest (region where the optical spectrum of the signal is) so it can be added to the signal.

After measuring the OSNR of each way, a subtracter will be placed finally to perform the subtraction of the OSNR of the system under test and the back-to-back case and then it will display the OSNR penalty.

The previous schema is known as the IsoBER test and it can be summarized as a sequence of processes [17]:

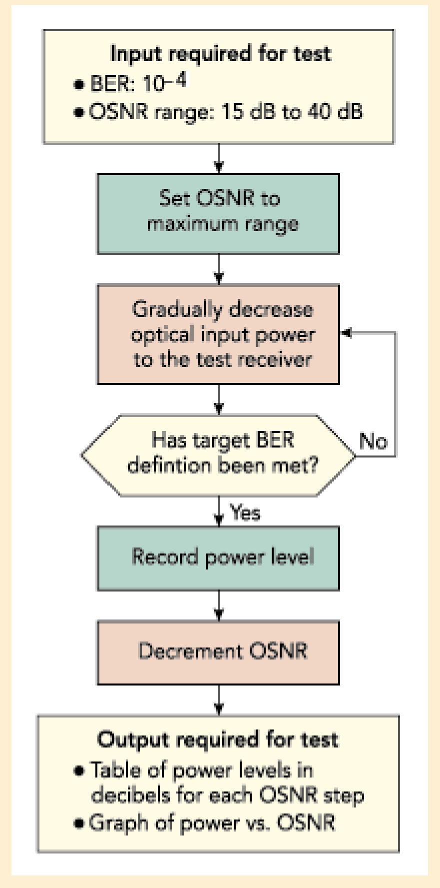


Figure 42.Procedure for IsoBER test

2. .In order to measure OSNR vs BER and obtaining maximum distance reached over a real-life link, the following scenario has been modelled:

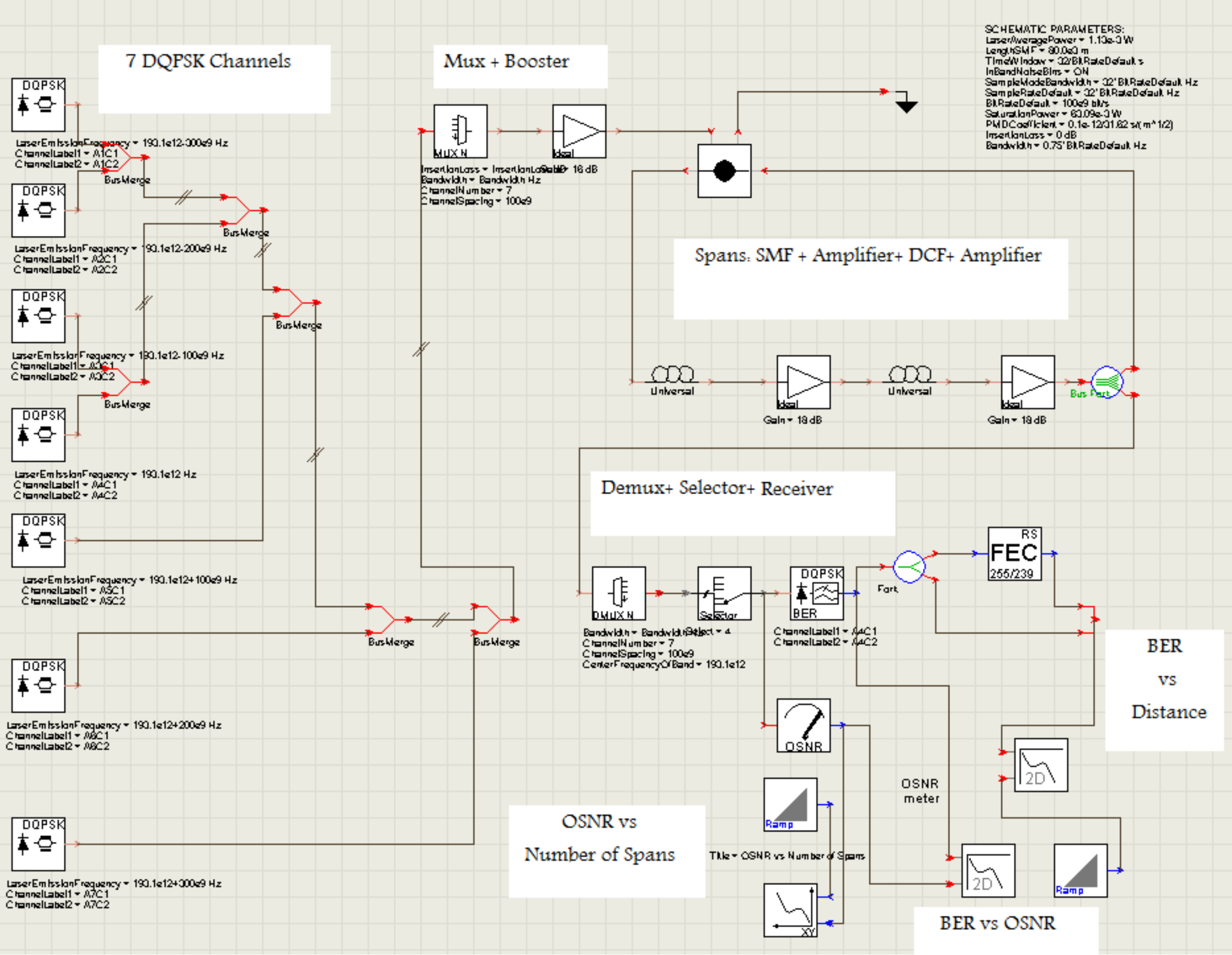


Figure 43.Multichannel scenario for obtaining maximum distance

The scenario consists of 7 DQPSK transmitters (ideally would be 8) but due to asymmetry problems with even numbers when representing spectrums, we will take 7. (there is an extra section for 15 signals)

The 7 signals get multiplexed within the fiber and boosted thanks to an amplifier. Then they enter in the loop section, consisting of a span of fiber, and amplifier to compensate for the losses, a fiber which compensates for the dispersion; and an amplifier to compensate for these last losses. This would be the scenario for a **point-to-point link**, for a **point-to-multipoint** transmission, we will place a ROADM next to the amplifier.

On the reception, they get demultiplexed and the central channel (worst case scenario) gets analysed. With that basis, graphs are obtained. These graphs include:

- OSNR vs. Number of spans
- BER vs. Distance

9.3.1 Simulation Parameters

Bit Rate is 100 Gbps with 7 Channels. Due to possible saturation problems of the amplifiers, the maximum power per channel allowed is defined as:

$P_{channel} = 4 - 10 \log_{10}(N) + 5$ with N= Number of channels
So power after the booster is 17 dBm.

From the upper expression we come up with the following table of power/channel

Number of Channels	**Power per channel**
8	1.13 mW
16	0.529 mW
32	0.3 mW

Figure 44. Table of number of channels vs. power per channel

These powers are the output power of the laser (not the transmitter). VPI considers a DQPSK transmitter as 2 lasers injected to the modulator. In this process of injection 5 dB are lost, that is why 5 extra dB are added into the formula.

In the filtering process, as previously commented, the optimum bandwidth has been equal to the binary rate for 100 Gbps, thus. For 100 Gbps, the bandwidth= Bit Rate.

For this purposes the separation among channels follows this expression:
Number of channels (100Ghz)= 193.1 Thz (central channel) ± k*100Ghz , k=1…32.

The spans consist of:

- Optical Fibre (SMF):
    - Length= 80 km
    - α= 0.3 dB/km
    - D_{CD}= 20 ps/nm*km
    - D_{PMD}= 0.1ps/(km)^(1/2);
- EDFA amplifier:
    - NF= 3 dB
    - G= 24 dB
- Optical Fibre (DMF):
    - Length= 16 km
    - α= 0.5 dB/km
    - D_{CD}= -100 ps/nm*km
    - D_{PMD}= 0.1ps/(km)^(1/2);
- EDFA amplifier:
    - NF= 3 dB
    - G= 8dB
- ROADM (only for point-to-point to multipoint links)
    - Bandwidth= 100 Gbps

At the receiver, the signal gets demultiplexed and the central channel (193.1 Thz) gets analysed with a OSNR measurement resolution of 12.5 Gb (ITU-standard)

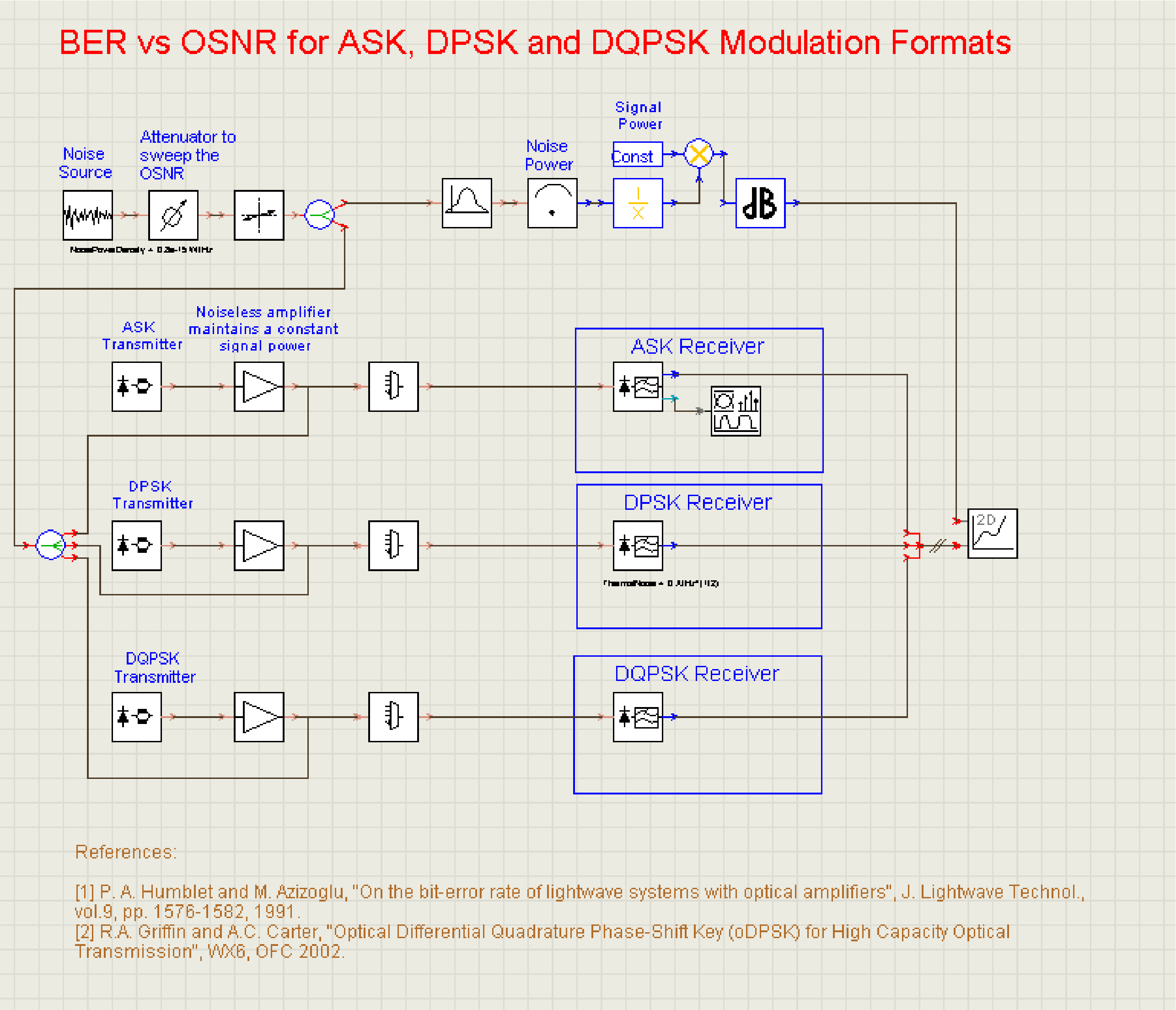
9.4 Results

9.4.1. Study of the effect of the modulation format

The aim of this scenario is to show the importance of how depending on given a modulation format the performance will vary.

More specifically the performance of ASK, DPSK and DQPSK will be investigated.

The parameter to show this effect will be BER vs. OSNR in the back-to-back case, with no devices in between. A schema of how things were proposed is shown next:



References:

[1] P. A. Humblet and M. Azizoglu, "On the bit-error rate of lightwave systems with optical amplifiers", J. Lightwave Technol., vol.9, pp. 1576-1582, 1991.
[2] R.A. Griffin and A.C. Carter, "Optical Differential Quadrature Phase-Shift Key (oDPSK) for High Capacity Optical Transmission", WX6, OFC 2002.

Figure 45.Scenario for the Study of the effect of the modulation format

The following figure shows the advantage of using both DPSK and DQPSK over ASK format. The intention was to show, how both formats are suitable for long-haul transmission as well as to establish a distinction between both of them.

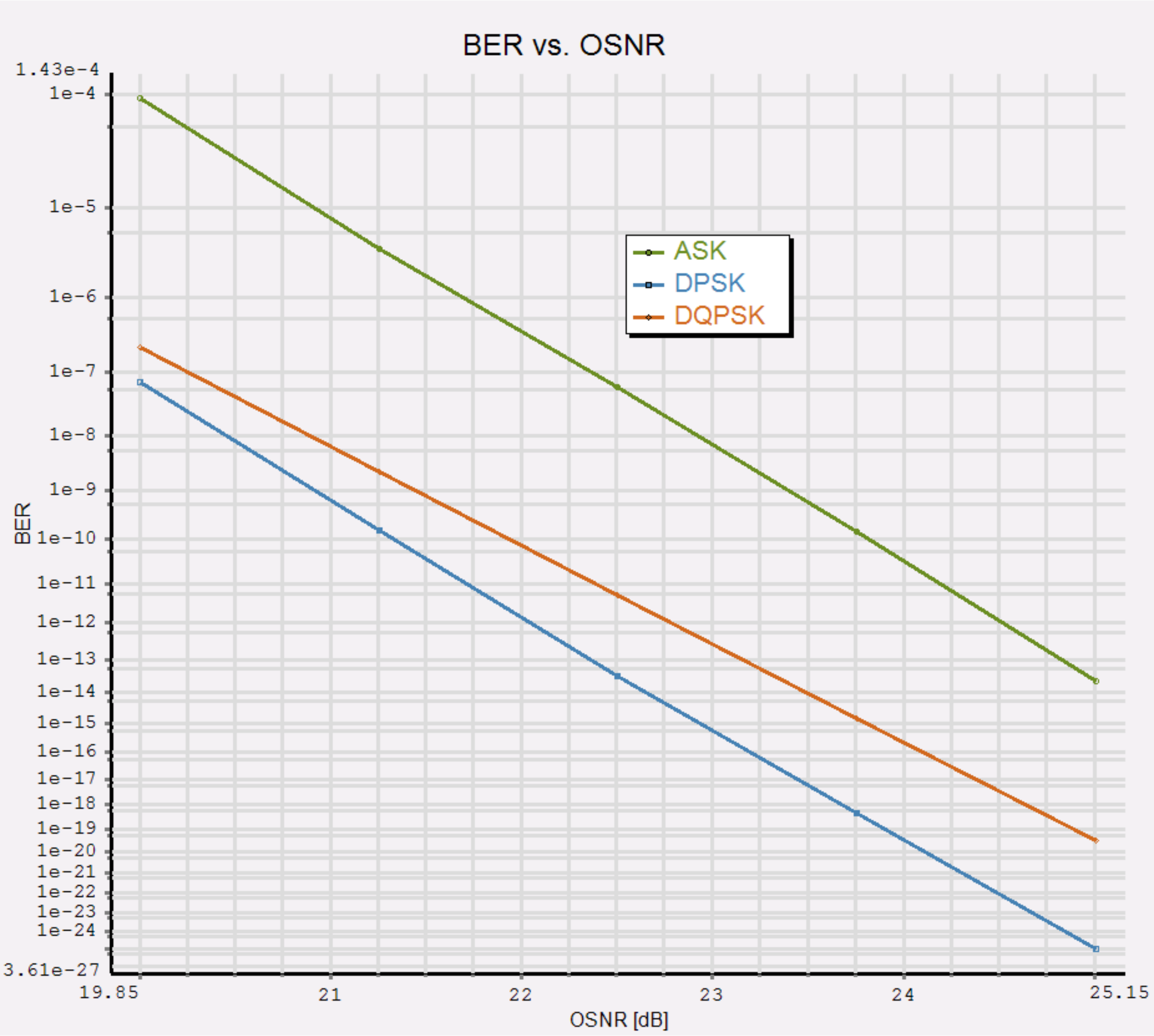


Figure 46.BER vs. OSNR for ASK, DPSK and DQPSK modulation formats

DPSK shows a slightly higher performance in the back to back case due to its simplicity. However as it will be remarked, the huge impact of filtering concatenation and the fiber on DPSK, makes DQPSK the ideal candidate for long-haul transmission.

9.4.2. Study of the effect of the optical fibre

The Optical Fiber is the cornerstone of the optical link as it carries the information from one place to another. That is why we will discuss secondly the impact of such element on the OSNR of the system.

Not only the amplifiers create ASE Noise, but also passive devices such as the fiber can create and modify the existing OSNR level.

To measure the impact of the fiber, we have modelled a scenario where we will be performing measurements "playing" with the following parameters:

- Modulation Formats: DQPSK and DPSK
- Bit Rate: 40 Gbps and 100 Gpbs
- Chromatic Dispersion and Polarization Mode Dispersion

Shown next is the scenario used to perform the simulations:

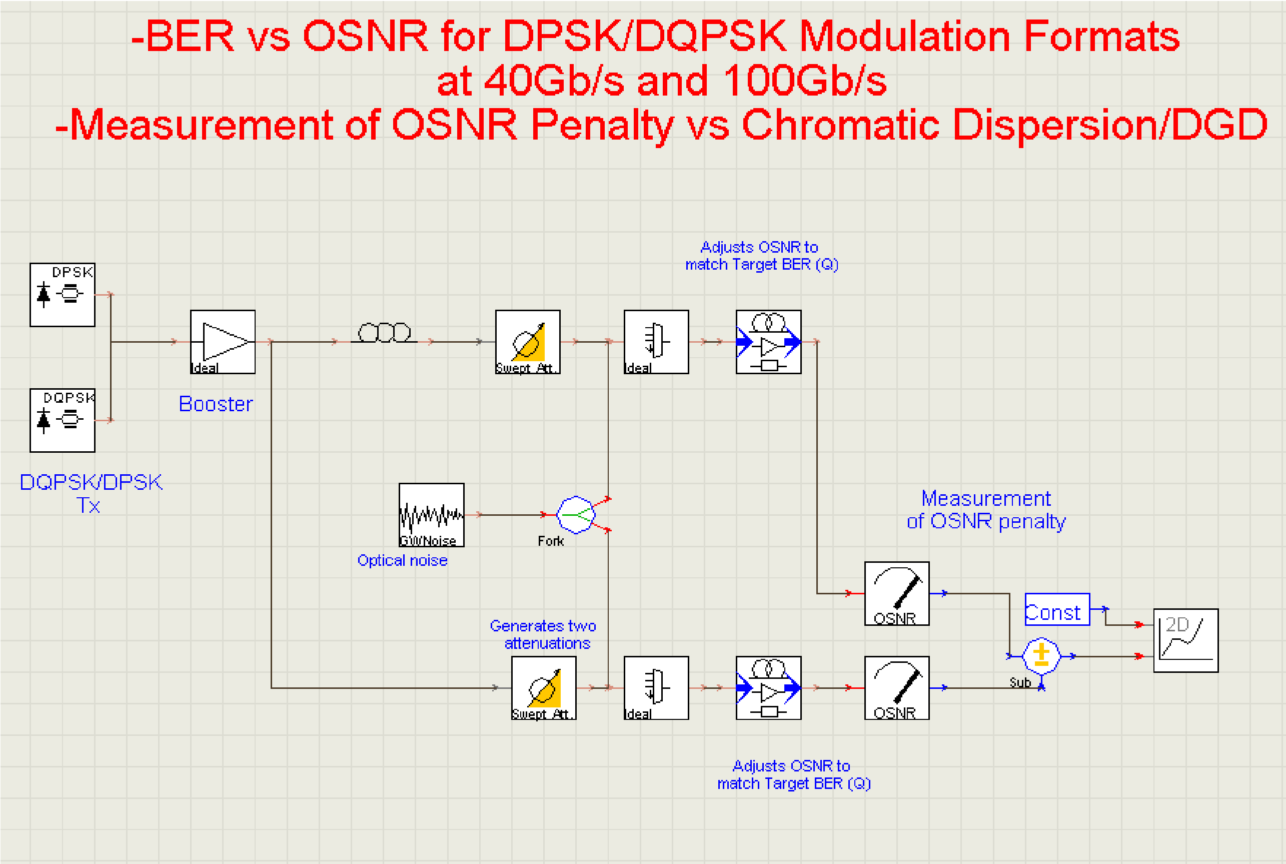


Figure 47.Scenario for the Study of the effect of the fiber

In the next two sub-sections we will be showing the influence of Chromatic Dispersion and Polarization Mode Dispersion. They both combined create an ONSR penalty which shall be taken into account.

9.4.2.1 Chromatic Dispersion:

This first section addresses the impact of Chromatic Dispersion on both DQPSK and DPSK formats.

9.4.2.1.1 DQPSK format at 40 Gb/s

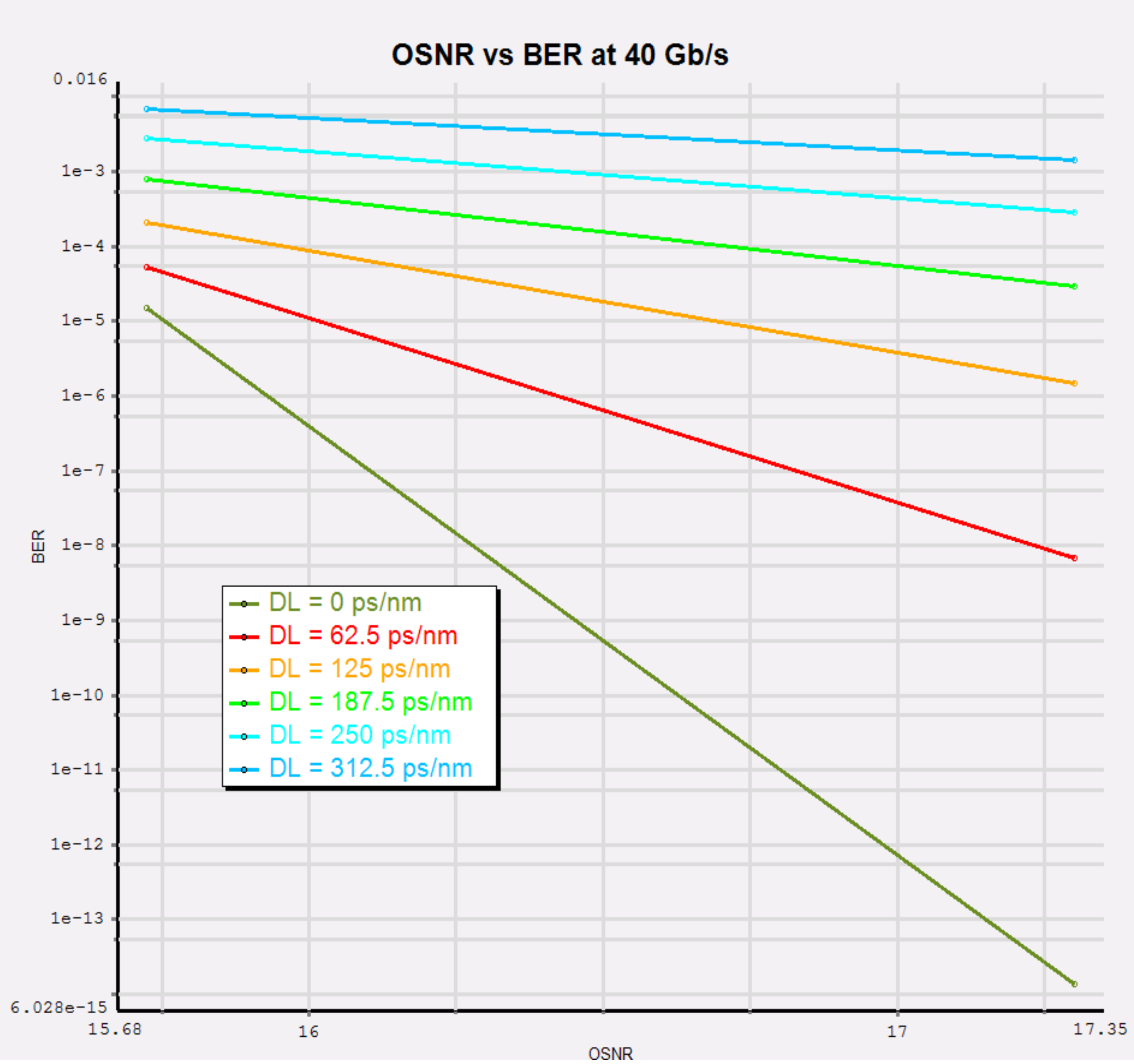


Figure 48.OSNR vs BER for DQPSK format at 40 Gb/s with CD

The following figure shows the OSNR penalty induced by Chromatic Dispersion measured in ps/nm. As we can see it shows a linear decay along the distance. Thus it is not very problematic.

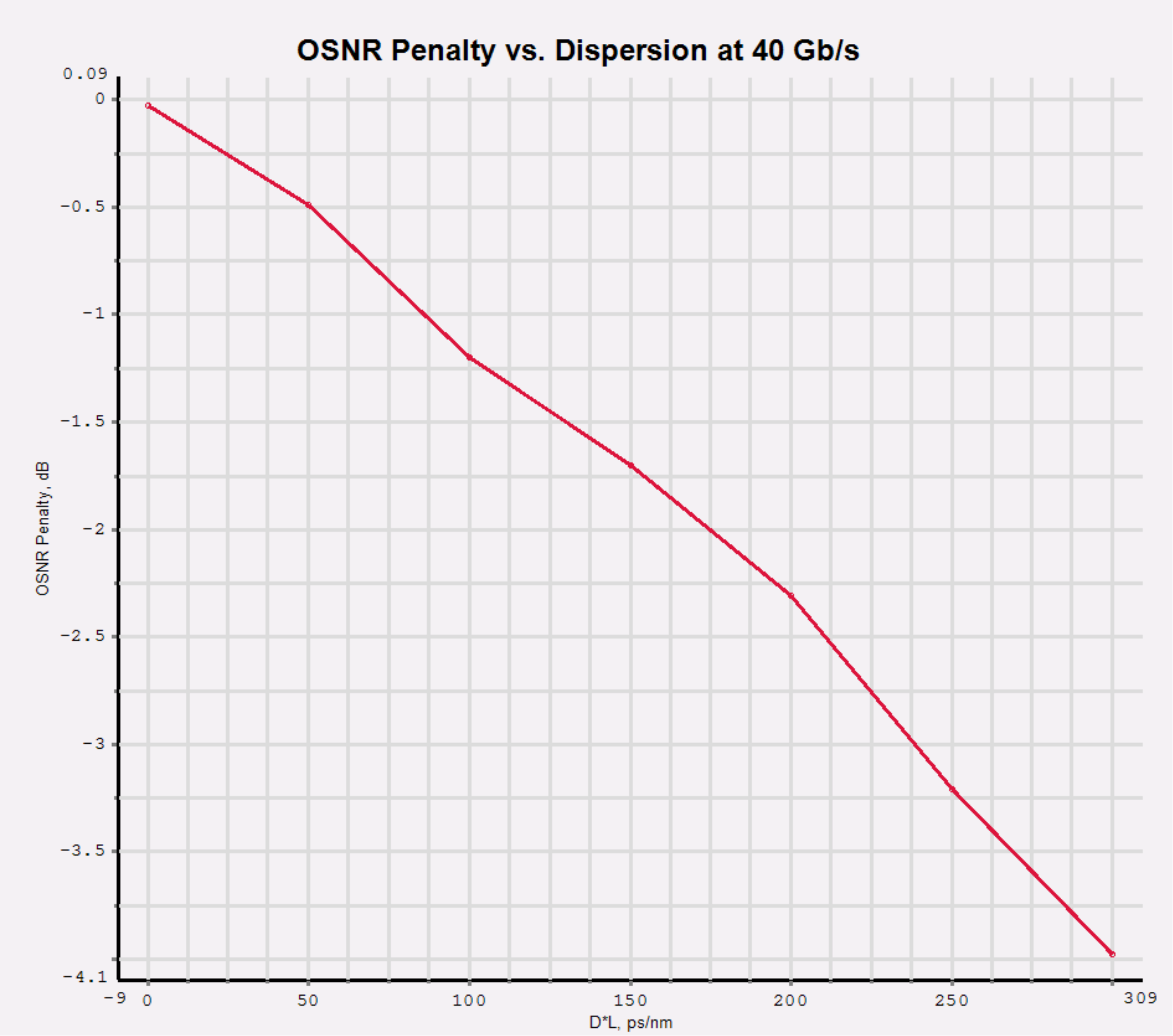


Figure 49.OSNR Penalty vs. Chromatic Dispersion for DQPSK format at 40 Gb/s

9.4.2.1.2 DQPSK format at 100 Gb/s

When increasing the Bit Rate, the probability of ISI (inter symbol interference) is greater, thus, the Bit Error Rate tends to become bigger, and barely any chromatic dispersion is acceptable for an adequate performance as shown next:

Figure 50.OSNR vs. BER for DQPSK format at 100 Gb/s with CD

The following figure shows the OSNR penalty induced by Chromatic Dispersion measured in ps/nm. At a high bit Rate like 100 Gb/s there is a cleared threshold shown in the next graph which shall not be surpassed otherwise the system cannot be designed. This threshold starts at about 100 ps/nm:

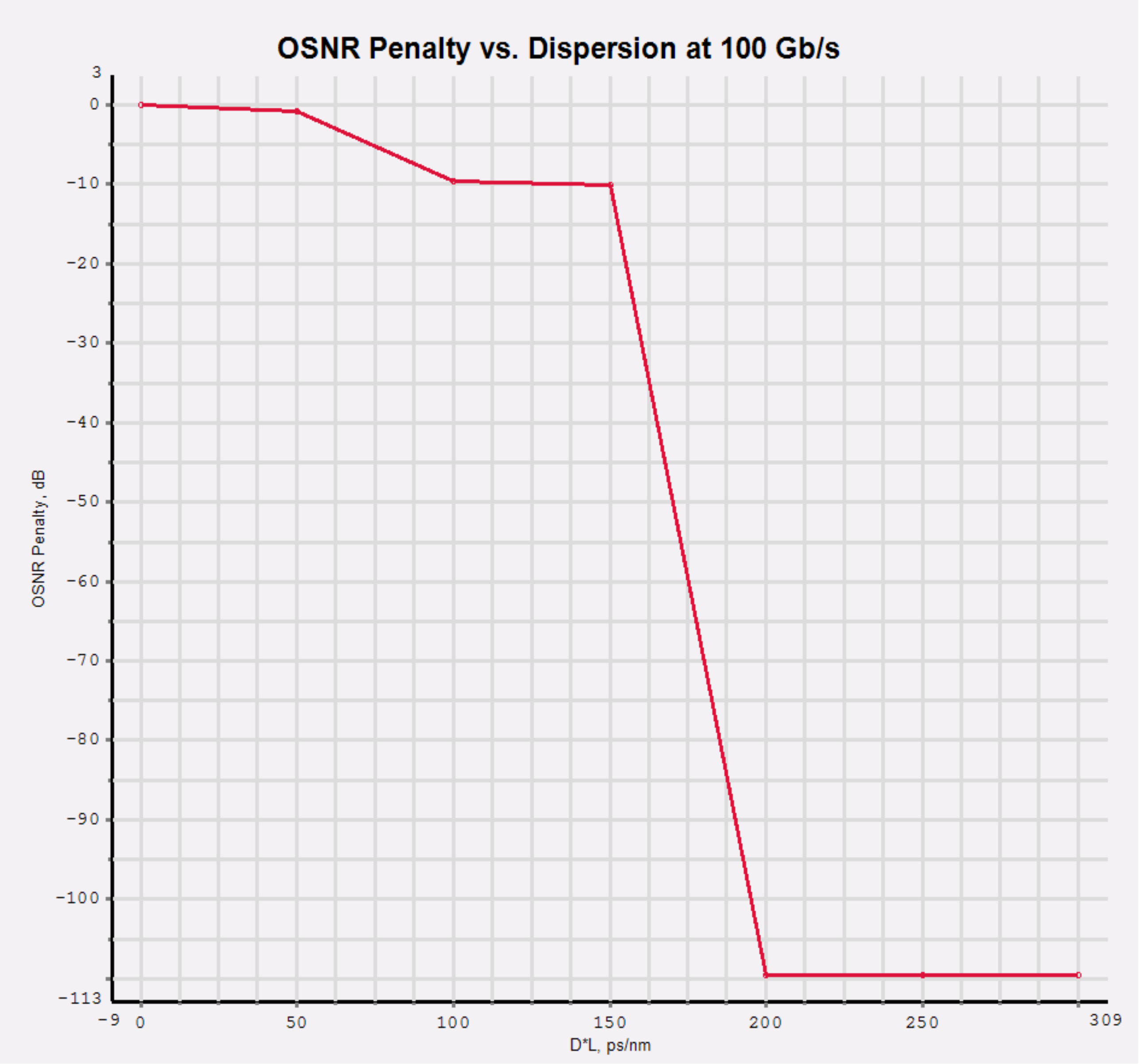


Figure 51.OSNR Penatly vs. Chromatic Dispersion for DQPSK format at 100 Gb/s

9.4.2.1.3 DPSK format at 40 Gb/s

As it has been highlighted, the wider spectrum of DPSK in contrast to DQPSK spectrum makes it very prone to suffer from Chromatic Dispersion. As it can be seen, very little chromatic dispersion already affects the system making it error sensitive.

Figure 52.OSNR vs. BER for DPSK format at 40 Gb/s with CD

The following figure shows the OSNR penalty induced by Chromatic Dispersion measured in ps/nm. It shows a linear decay, thus it is not very problematic, but again, it is important to highlight how very little dispersion already creates a big power penalty.

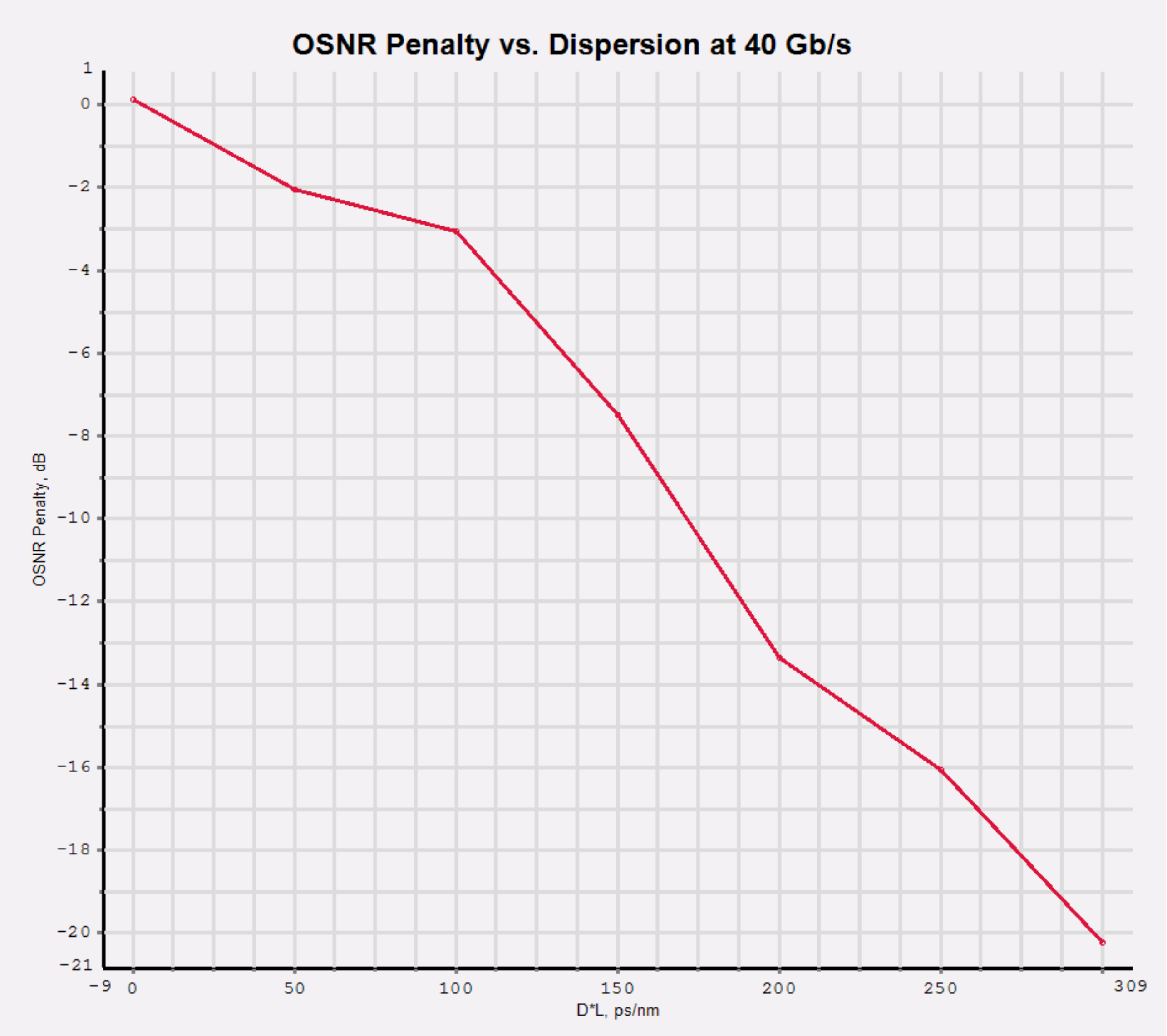


Figure 53.OSNR Penalty vs Chromatic Dispersion for DPSK format at 40 Gb/s

9.4.2.1.4 DPSK format at 100 Gb/s

When increasing the bit rate, it becomes more crucial the dispersion on the overall performance of the system. As it can be seen, as soon as there is some dispersion, the system already does not work. It is due to the use of DPSK format at a high bit rate.

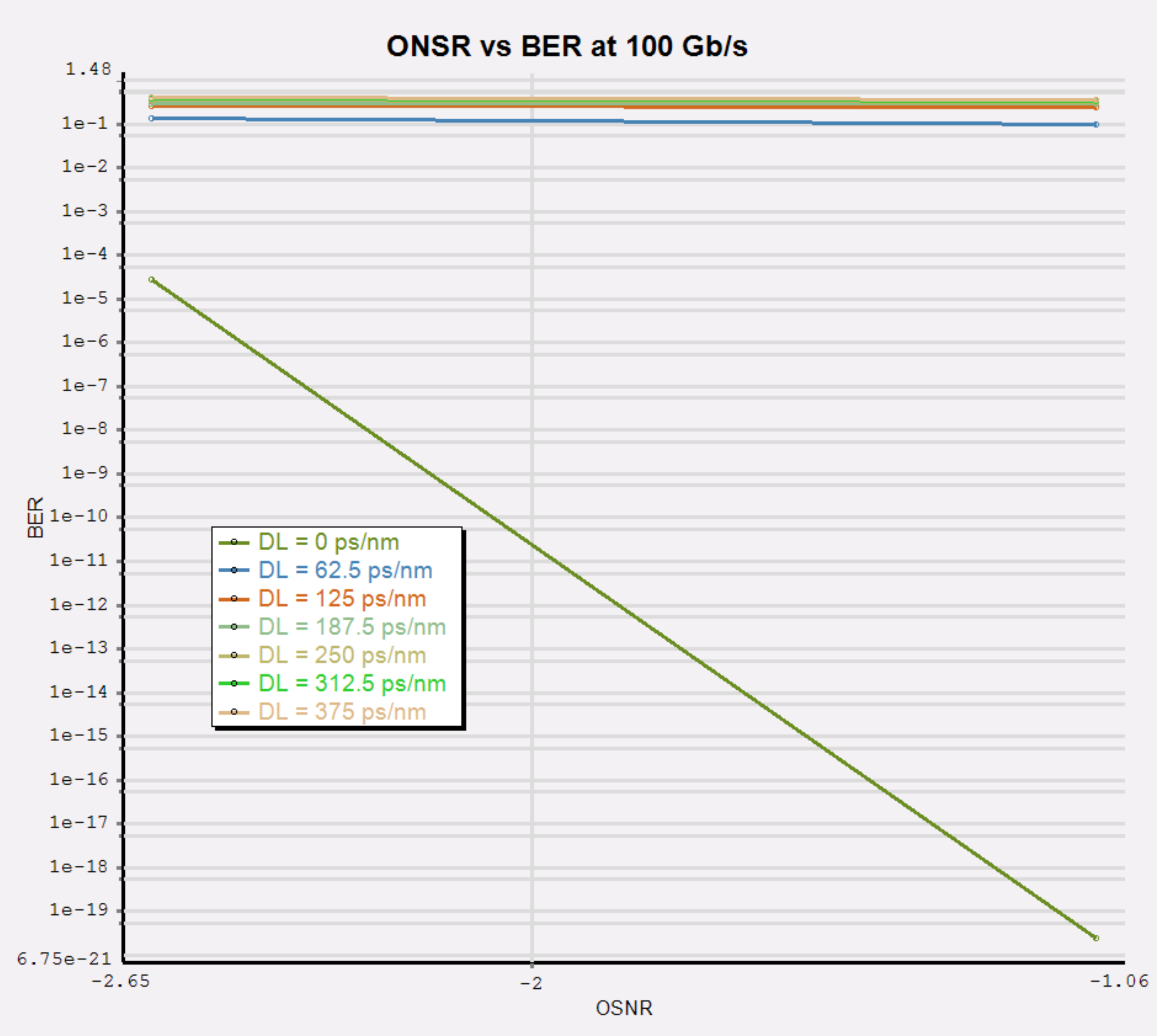


Figure 54.OSNR vs. BER for DPSK format at 100 Gb/s with CD

The following figure shows the OSNR penalty induced by Chromatic Dispersion at a high rate. It is shown that almost no dispersion is acceptable for the system to work out.

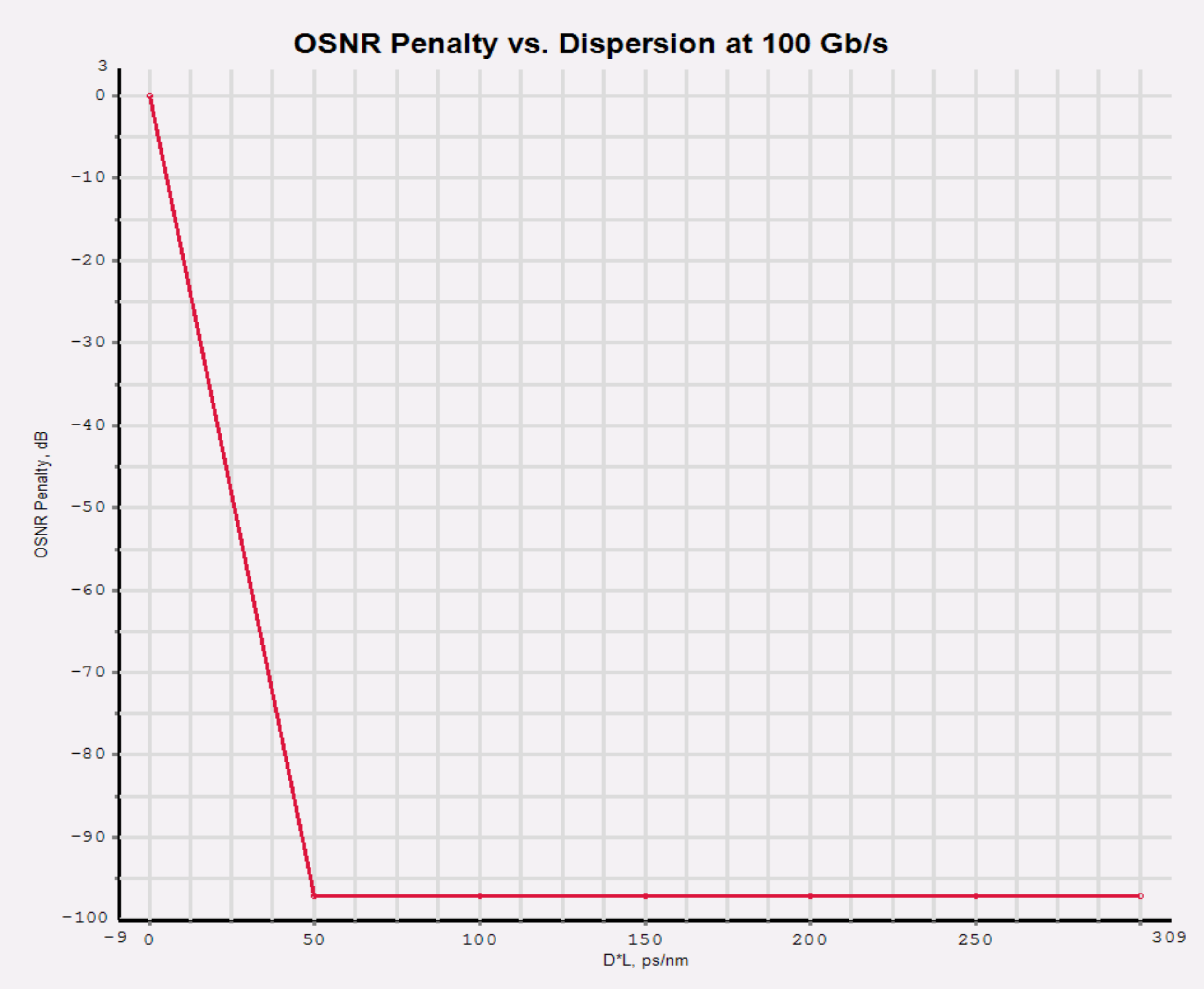


Figure 55.OSNR Penalty vs. Chromatic Dispersion for DPSK format at 100 Gb/s

9.4.2.2 Polarization Mode Dispersion:

This first section addresses the impact of Polarization Mode Dispersion on both DQPSK and DPSK formats.

9.4.2.2.1 DQPSK format at 40 Gb/s

For different PMD coefficients of the fiber, the figure has been graphed:

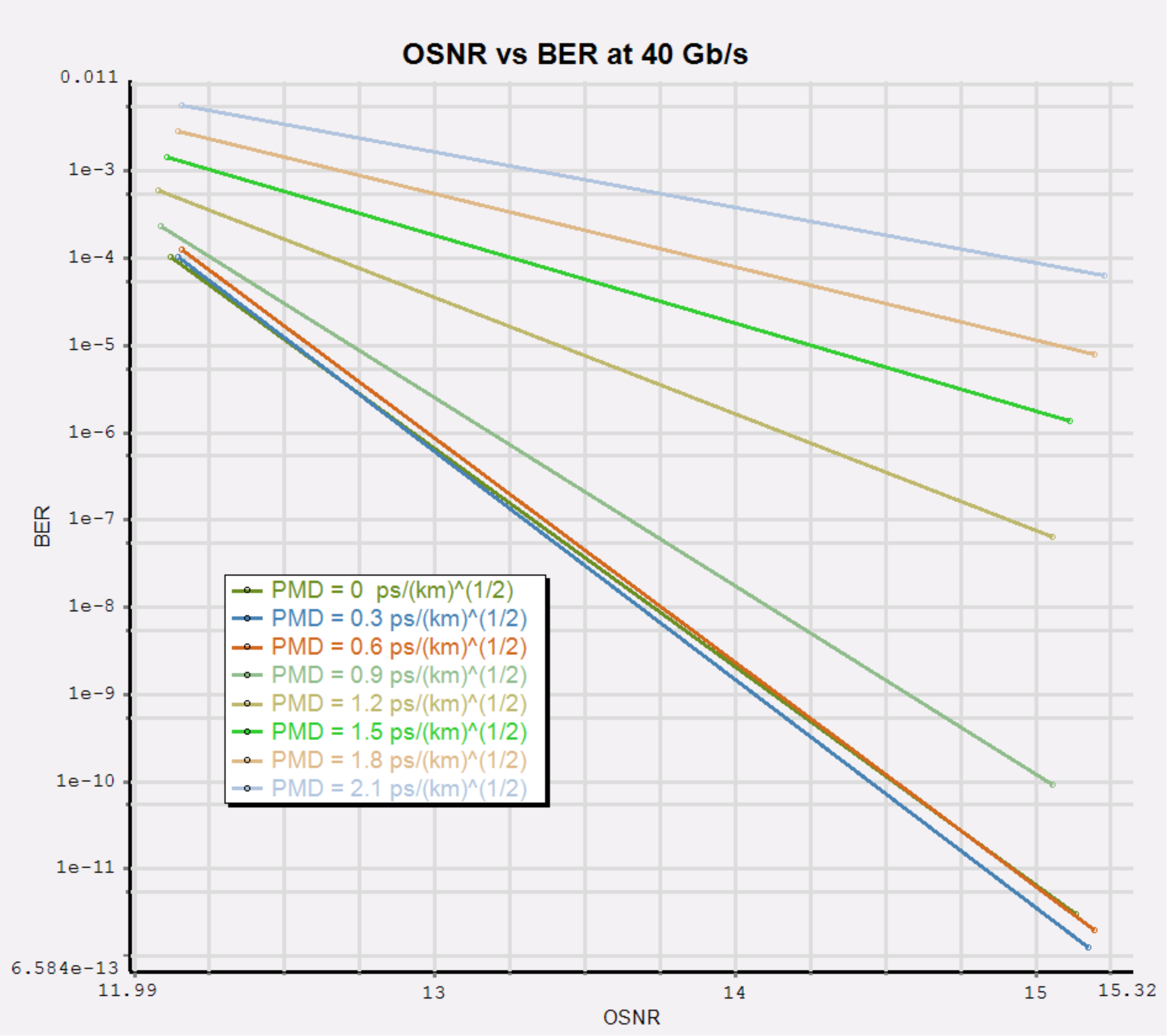


Figure 56.OSNR vs. BER for DQPSK format at 40 Gb/s with PMD

The following figure shows the OSNR penalty induced by DGD (differential group delay) measured in ps. There is just 2 dB of Penalty for 30 ps, thus DQPSK shows a robust performance versus DGD

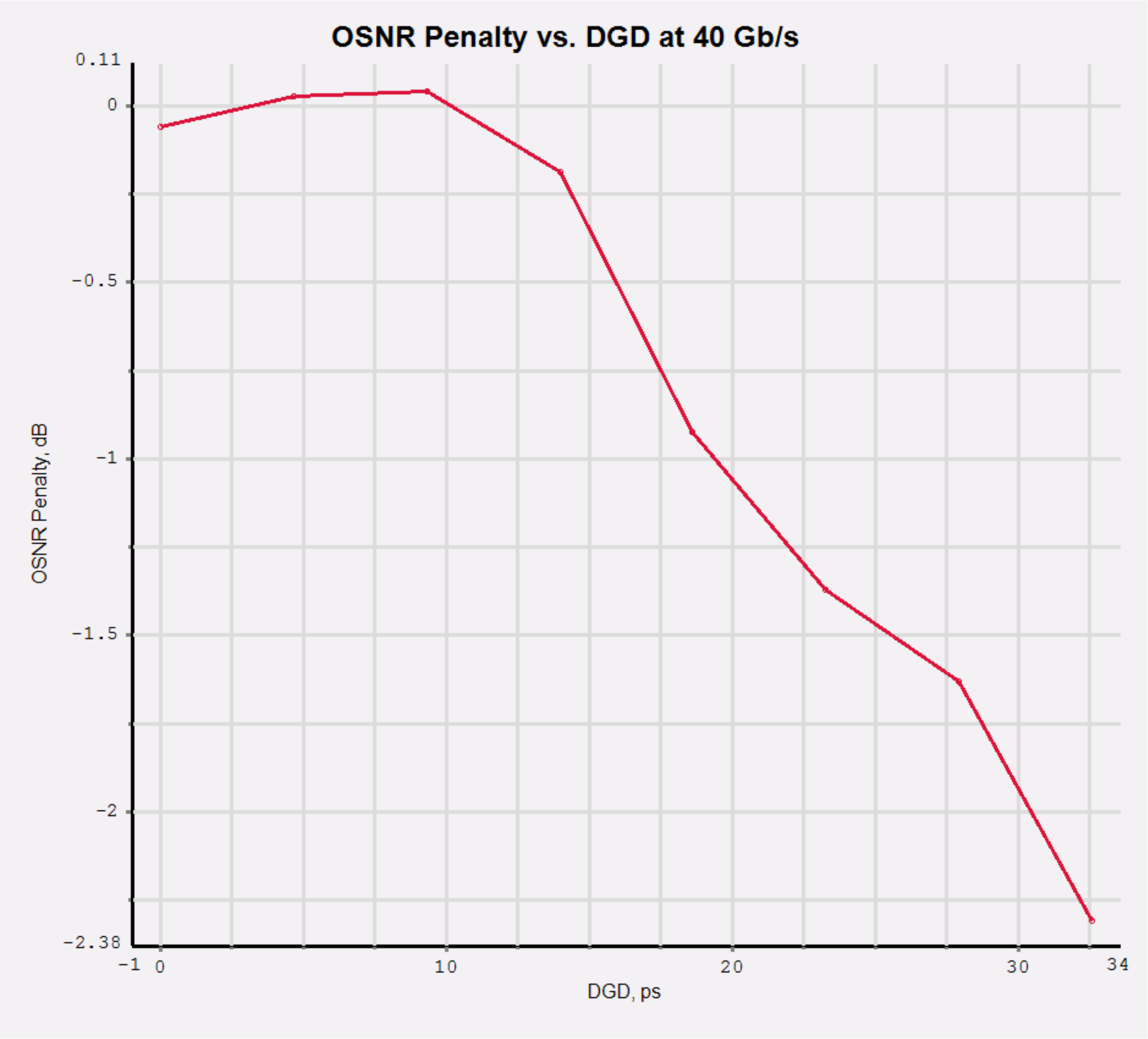


Figure 57.OSNR Penalty vs. DGD for DQPSK format at 40 Gb/s

9.4.2.2.2 DQPSK format at 100 Gb/s

When increasing the bit rate, the performance will subsequently be degraded very quickly. In comparison to 40 Gb/s, here, not a high PMD is allowed:

Figure 58.OSNR vs. BER for DQPSK format at 100 Gb/s with PMD

At 40 Gb/s for 30 ps we had an acceptable penalty. Here for 30 ps the system will not work automatically. Its performance is severely degraded as it can be seen

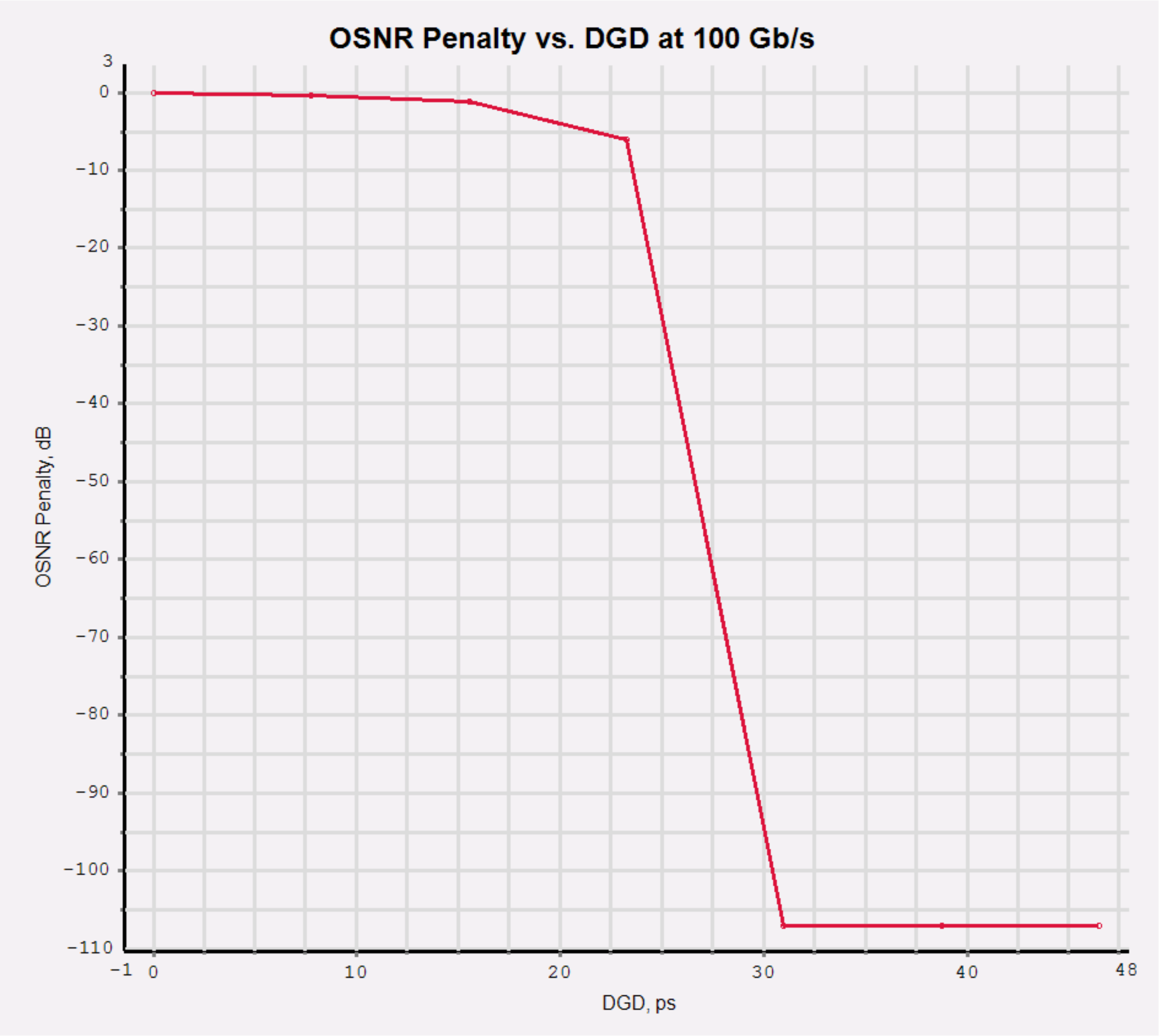


Figure 59.OSNR Penalty vs. DGD for DQPSK format at 100 Gb/s

9.4.2.2.3 DPSK format at 40 Gb/s

At 40 Gb/s we can see that the effect of PMD is undesirable from 1.0 ps/km^(1/2). Below that is acceptable, as modern fibers never reach that high coefficient. So it is not very problematic but still a bit worse than DQPSK for the same bit rate

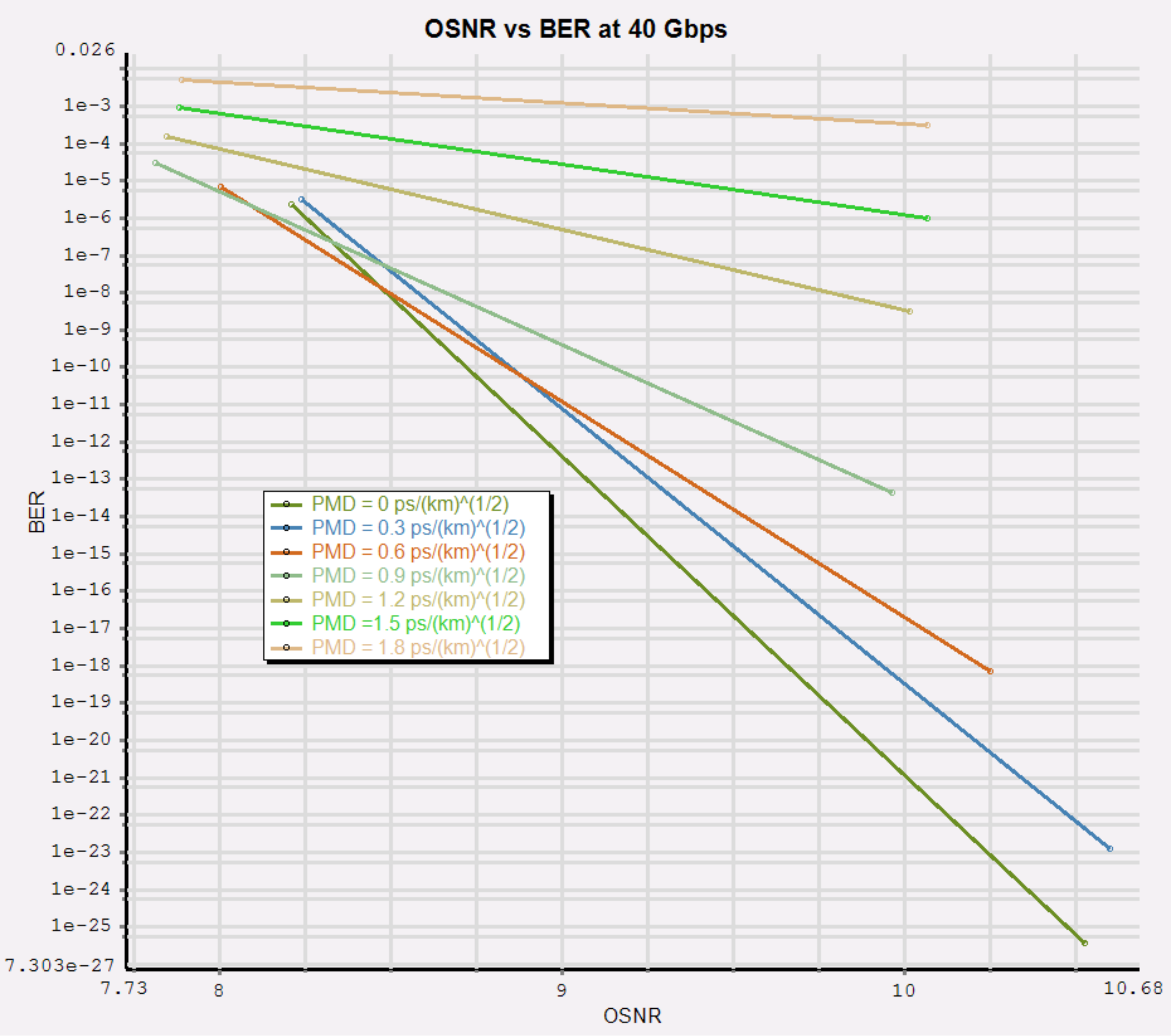


Figure 60.OSNR vs. BER for DPSK format at 40 Gb/s with PMD

Here is shown the penalty induced by DGD at 40 Gbps for DPSK modulation format. Due to its narrow spectrum, the graph exhibits a strong decay in terms of penalty from 11 ps onwards. It shall be noticed that very little ps. Have a great penalty effect on the system.

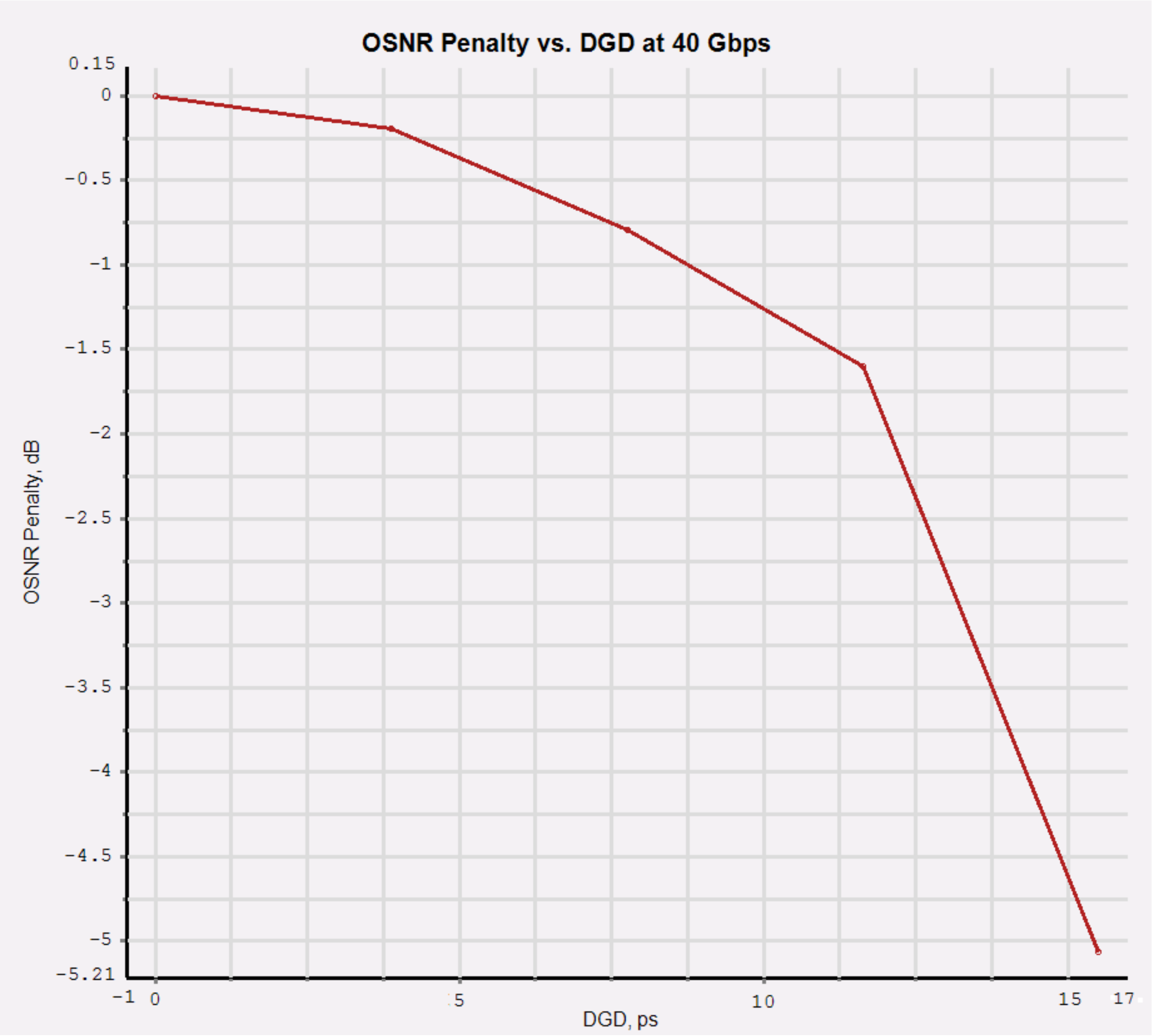


Figure 61.OSNR Penalty vs. DGD for DPSK format at 40 Gb/s

9.4.2.2.3 DPSK format at 100 Gb/s

When increasing the bit rate, it makes sense to expect a worse behaviour. Here at 100 Gb/s almost at any PMD coefficient, DPSK suffers a lot as it is not ready to work with high bit rates (one of the main limitations of this modulation format) as it can be seen in the following graph:

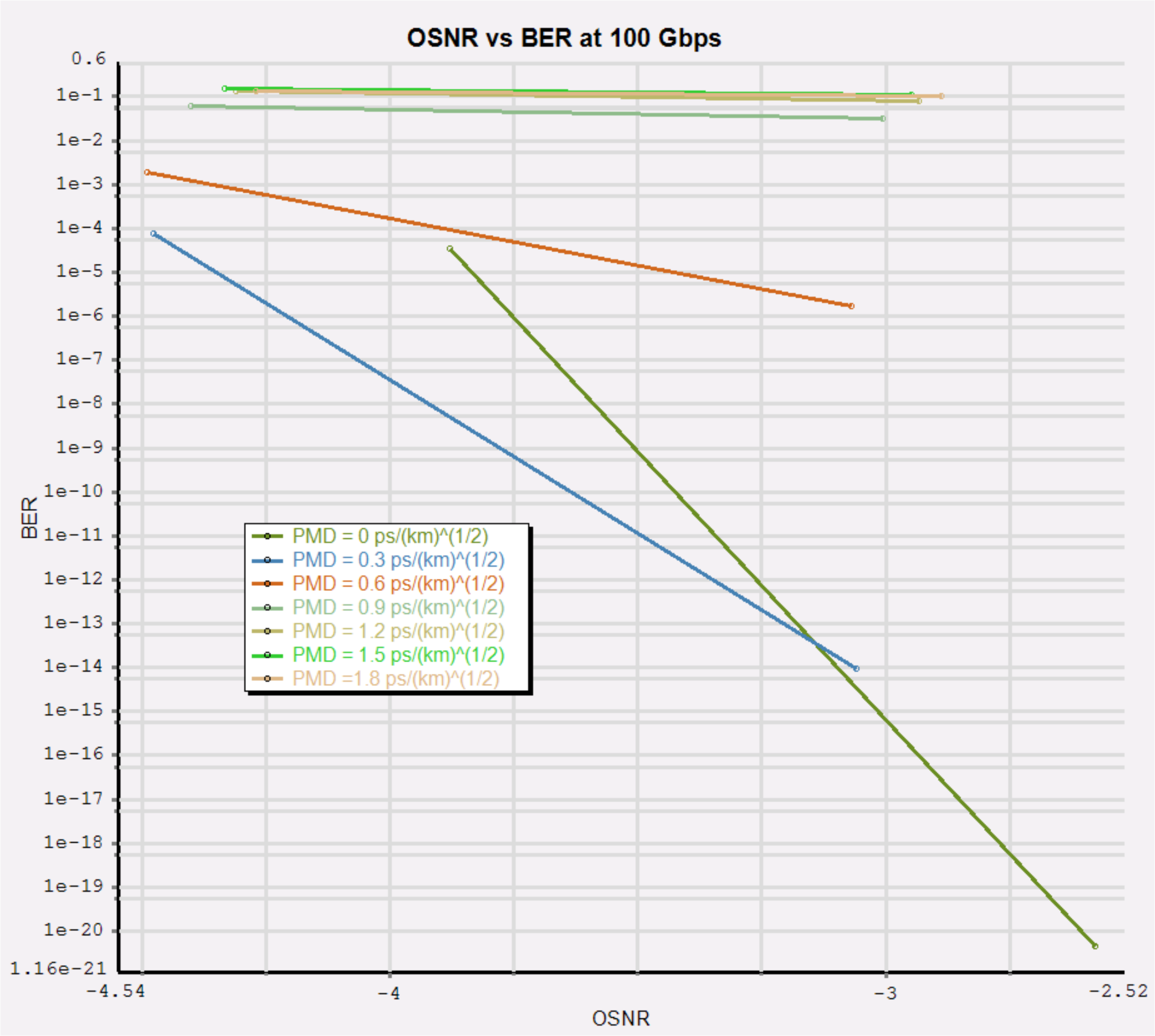


Figure 62.OSNR vs. BER for DPSK format at 100 Gb/s with PMD

Keeping a close relation to what it was stated before; here we can observe the penalty induced by DGD at 100 Gbps. We can see how the level falls dramatically from 10 ps onwards causing an infinite penalty on the system, and thus, making it unrealizable.

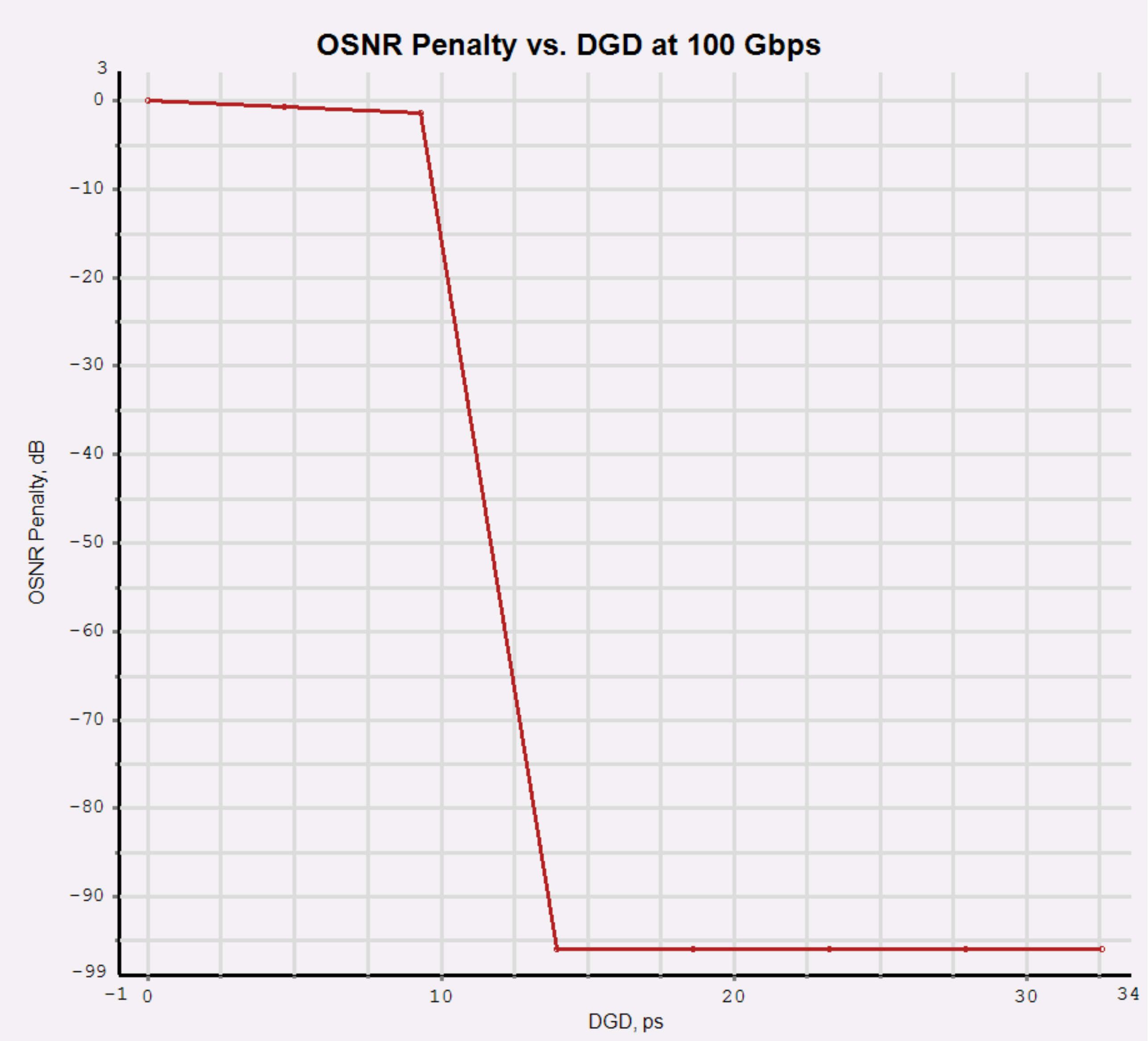


Figure 63.OSNR Penalty vs. DGD for DPSK format at 100 Gb/s

9.4.3. Study of the effect of the Optical Amplifier

This section aims to discuss the impact of Optical Amplifiers on the performance of the system. It is widely known that Optical Amplifiers are the major source of ASE noise on a system and subsequently the greatest source of power penalty.

In the following scenario, it has been carried out an studio of this impact, varying the source of this penalty which is the Noise Figure (NF) of the amplifier

In order to isolate this impact, an attenuator has been used rather than a fiber which would introduce some Dispersion. Basically the amplifier makes up for the span loss and then the measurement is conducted.

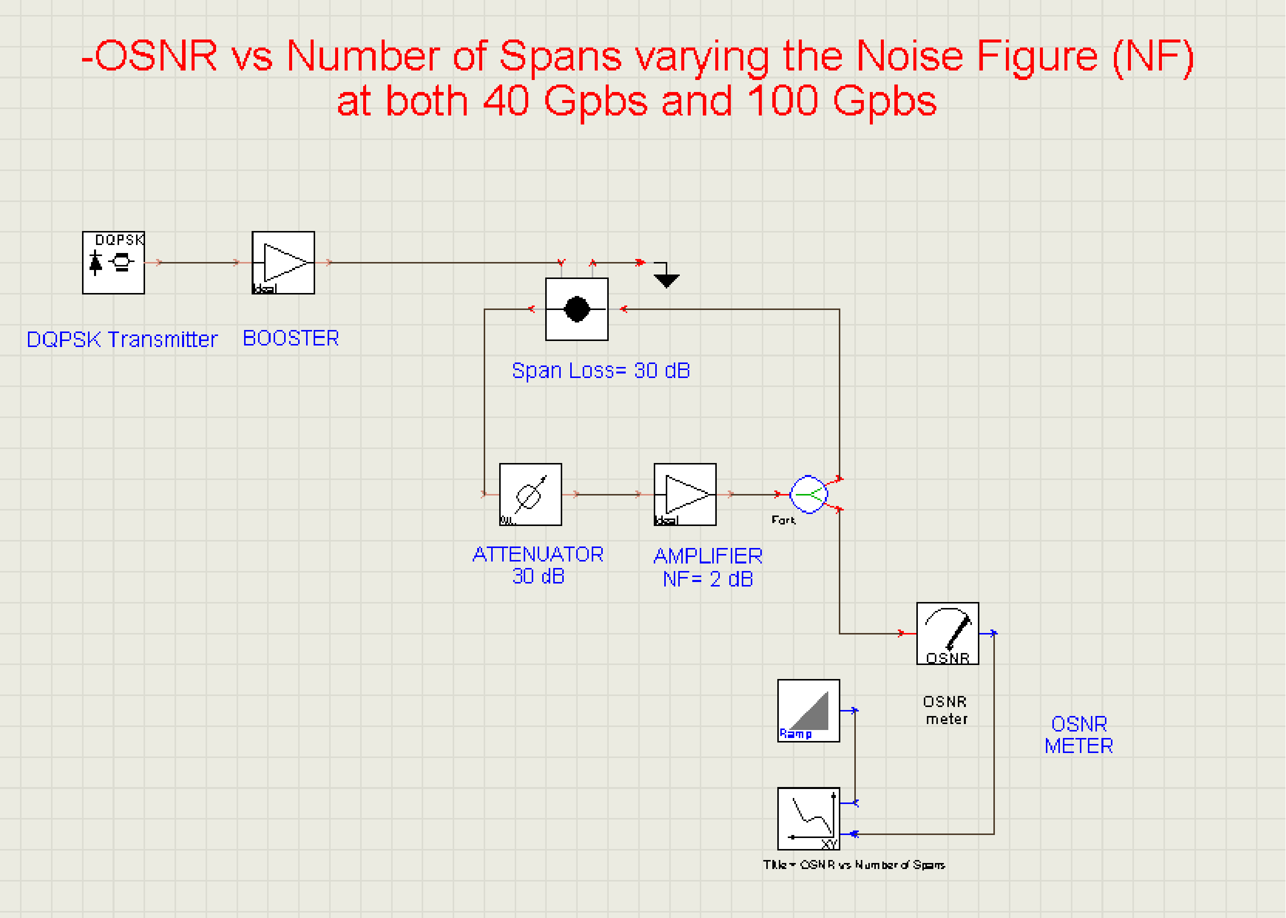


Figure 64. Scenario for measuring the effect of amplification

For the first test, the upper scenario has been modelled with the following parameters:

Modulation Format: DQPSK
Number of Spans: 12
Span Loss: 5 dB
Gain=5 dB
Noise Figure: 2 dB
Pinput= 1mw

This test has been conducted to assess the impact of the Amplifier gain on OSNR. It is a common misconception to believe that Gain affects OSNR.

As it can be seen, there is no impact at all as long as the span loss is compensated with the gain, in the cases where the gain is higher than the loss, OSNR increases in 1% which is insignificant. Thus, *Amplifier gain does not affect OSNR in a big manner.*

This result is rational, as OSNR is a ratio, and the gain affect both ASE noise and Signal power in the same way:

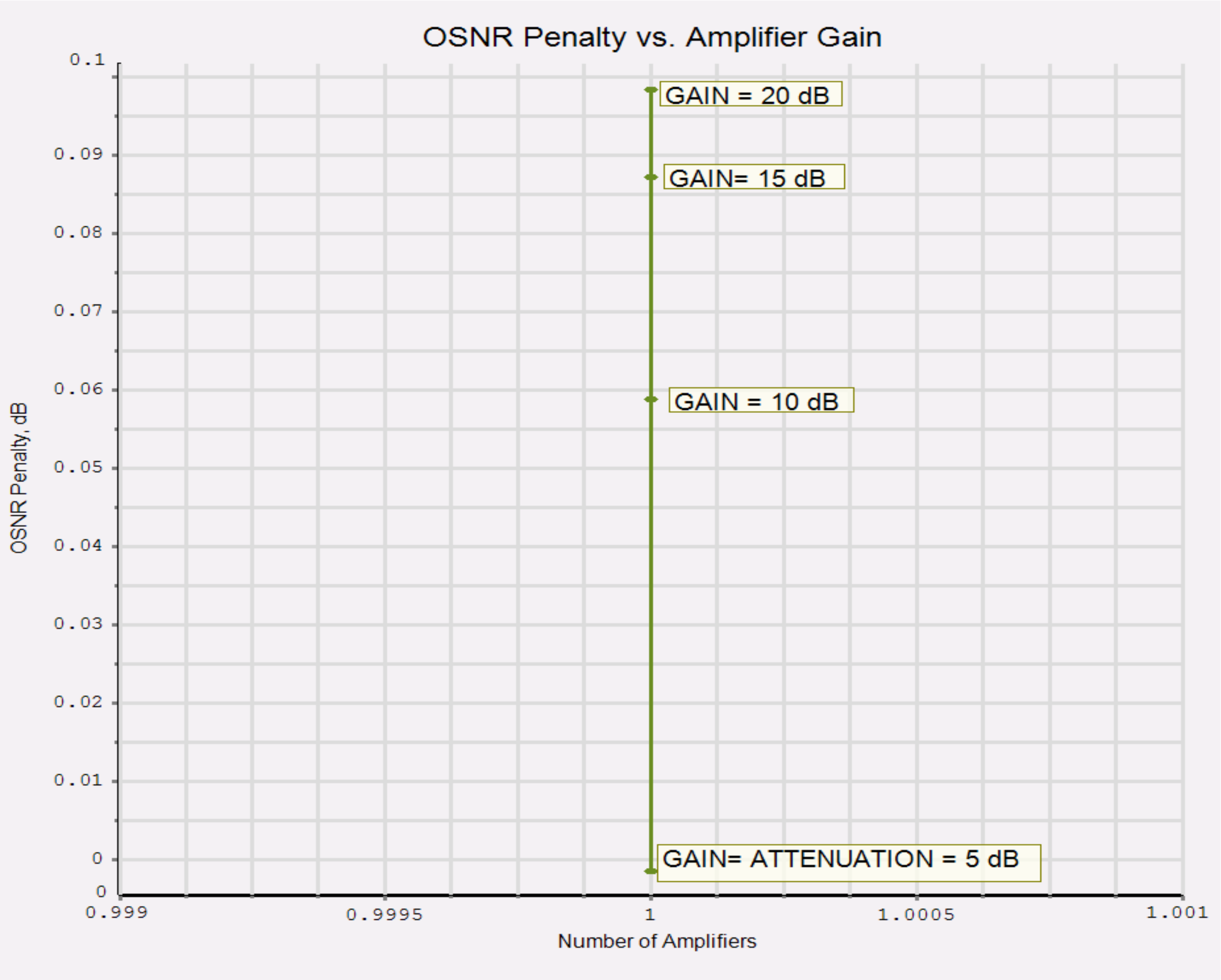


Figure 65. OSNR penalty vs. Amplifier gain

For the second test, the scenario has been modelled with the following parameters:

Modulation Format: DQPSK
Number of Spans: 12
Span Loss: 30 dB
Gain=30 dB
Noise Figure: 2 dB
Pinput= 1mw

The aim of this second test is to assess the importance of the Noise Figure of the amplifier on the overall performance. Once amplifier gain has been discarded as a possible source of penalty, we will focus on the noise figure which indeed will affect OSNR. And this makes sense, as the more noise is present the lower OSNR becomes.

Mathematically speaking the way OSNR is measured in a multi-stage amplification system is given by the following expression:

$$\textbf{OSNR (dB)} = \mathbf{58 + P_{IN}} - \textbf{Span Loss (dB)} - \textbf{NF (dB)} - \mathbf{10 \log_{10}} \textbf{(Number of Spans)}$$

For the above parameters, the expected theoretical result would be:

OSNR(dB) = $58 + 0$ dBm $-30 -2 -10\log_{10}(12) \sim$ **15. 5 dB**

As it can be seen, OSNR is degraded with the number of spans and Noise Figure mainly.

To illustrate this concept, the following graph displays OSNR vs. Number of Spans when varying Noise Figure from 0 dB to 10 dB with a step width of 2 dB.
For the upper case, the simulation throws a **17 dB** value for a NF=2 dB which results in an error of approximately 10%.

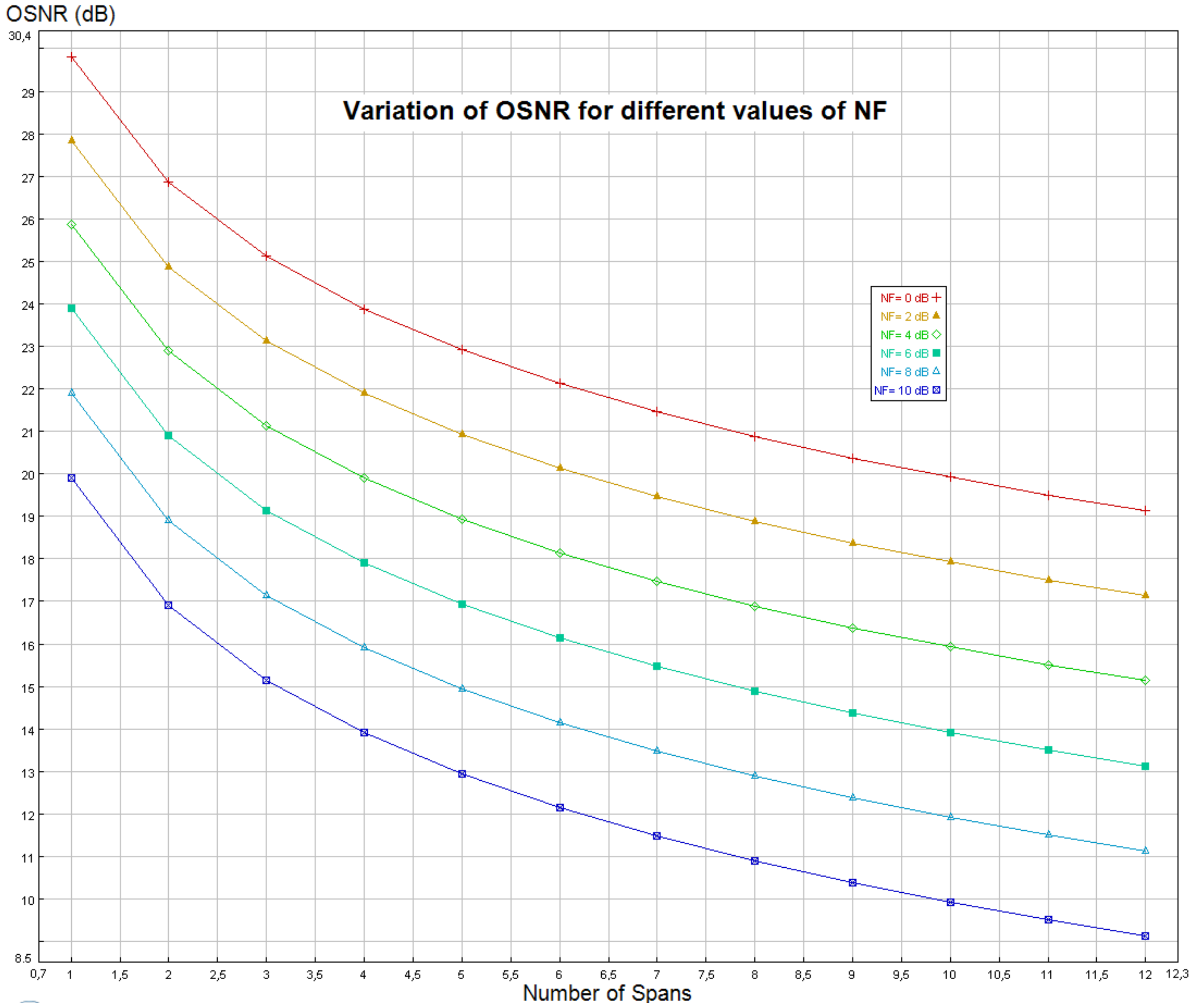


Figure 66. Variation of OSNR as a function of NF

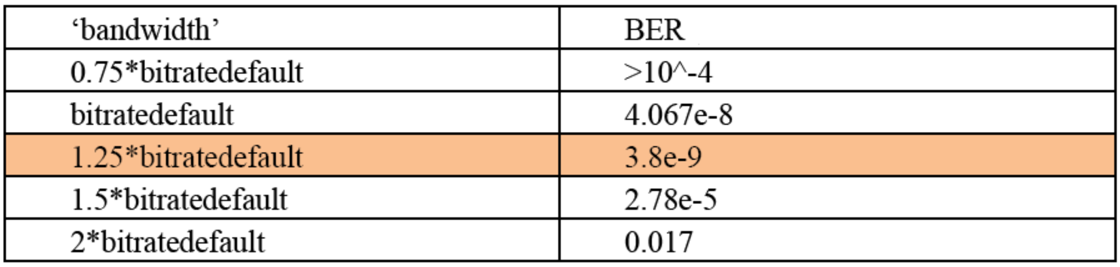
As it can be seen, there is an exponential decay along the length of the link. The Noise Figure lowers the latest value in 2 dB for each curve. Results are quite accordingly to theoretical values.

9.4.4. Study of the effect of filtering concatenation

The purpose of this section is to assess the importance of a key parameter on a point to multipoint link: The OADM. The OADM allows wavelengths to be added or dropped throughout the way, thus allowing a multipoint connection. However on doing so, there is a penalty involved which will be analysed.

When going through an optical filter the spectrum gets narrowed. The more optical filters the greater is the narrowing. This effect will be proportional to the bandwidth of the filters. An optimal design will be considered.
Some tests have been conducted to assess the optimum filtering bandwidth under the following characteristics [5]:

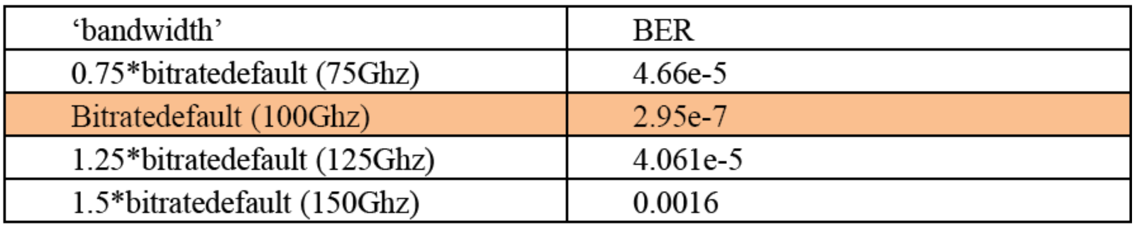
Number of Channels: 5
Bit Rate: ***40 Gbps***
Laser Average Power: 0 dBm
Channel Spacing: 50 Ghz
Length of Fiber:: 1 Span (80 km)



‘bandwidth’	BER
0.75*bitratedefault	>10^-4
bitratedefault	4.067e-8
1.25*bitratedefault	3.8e-9
1.5*bitratedefault	2.78e-5
2*bitratedefault	0.017

Figure 67. Optimum filtering bandwidth at 40 Gbps

Number of Channels : 5
Bit Rate: ***100 Gbps***
Laser Average Power: 0 dBm
Channel Spacing: 100 Ghz
Length of Fiber : 1 Span (80 km)



‘bandwidth’	BER
0.75*bitratedefault (75Ghz)	4.66e-5
Bitratedefault (100Ghz)	2.95e-7
1.25*bitratedefault (125Ghz)	4.061e-5
1.5*bitratedefault (150Ghz)	0.0016

Figure 68. Optimum filtering bandwidth at 100 Gbps

From these results we can conclude that the optimal filtering bandwidth is equal to channel spacing = 50 Ghz for 40 Gpbs and 100 Ghz for 100 Gpbs

For our work purposes, we have considered an OADM as 2 filters concatenated. Therefore, when we refer to 5 OADM, we will be considering 10 optical filters in conjunction.

To study the filtering effects the following experiment has been conducted [13]:

Modulation Format: DQPSK
Number of Channels: 1
Bit Rate: ***40 Gbps***
Laser Average Power: 0 dBm
Length of Fiber: 1 Span (80 km)
12 OADM in cascade: Each OADM consists of 2 AWG with 3^{rd} *order filter with Gaussian distribution*

The following plot shows the narrowing effect:

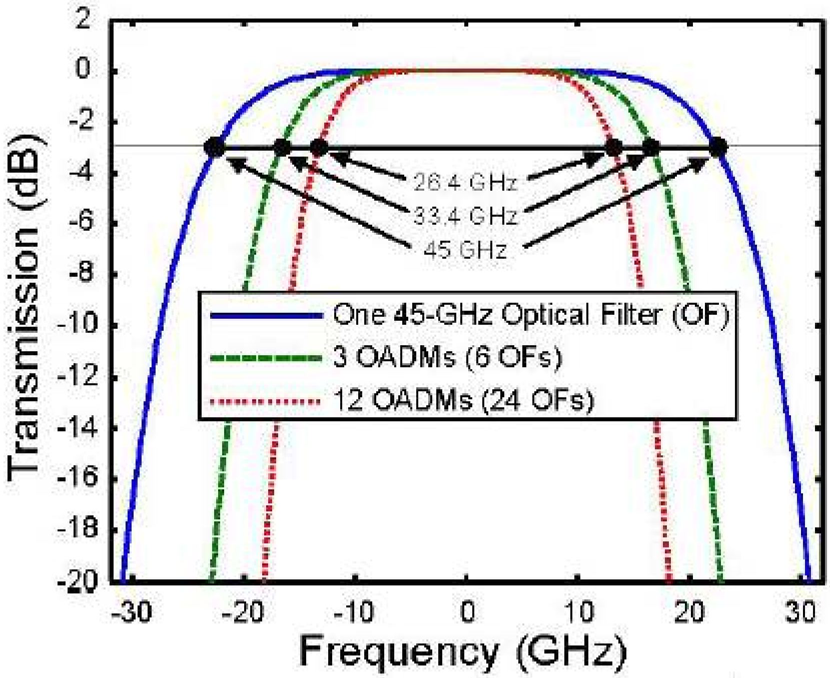


Figure 69. Filter narrowing effect

As it can be seen, the remaining bandwidth after 12 filters is closer to 59%
(26.4 Ghz/ 45 Ghz)
It shall be noticed that the choice of filter shape will greatly affect the amount of bandpass narrowing that occurs when filters are cascaded

So far, we have been working on our experiments with 2 modulation formats:
DQPSK and DPSK.

Highlights and drawbacks have been studied for each modulation format for each factor affecting OSNR.

Next, we will show the influence on OSNR for both modulation formats when cascading a certain number of OADMs.

Modulation Format: DQPSK
Number of Channels: 1
Bit Rate: ***40 Gbps***
Laser Average Power: 0 dBm
Length of Fiber: 1 Span (80 km)
20 OADM in cascade: Each OADM consists of 2 AWG with 3rd order filter with Gaussian distribution

The following graph outputs the penalty induced by cascading OADMs along the way:

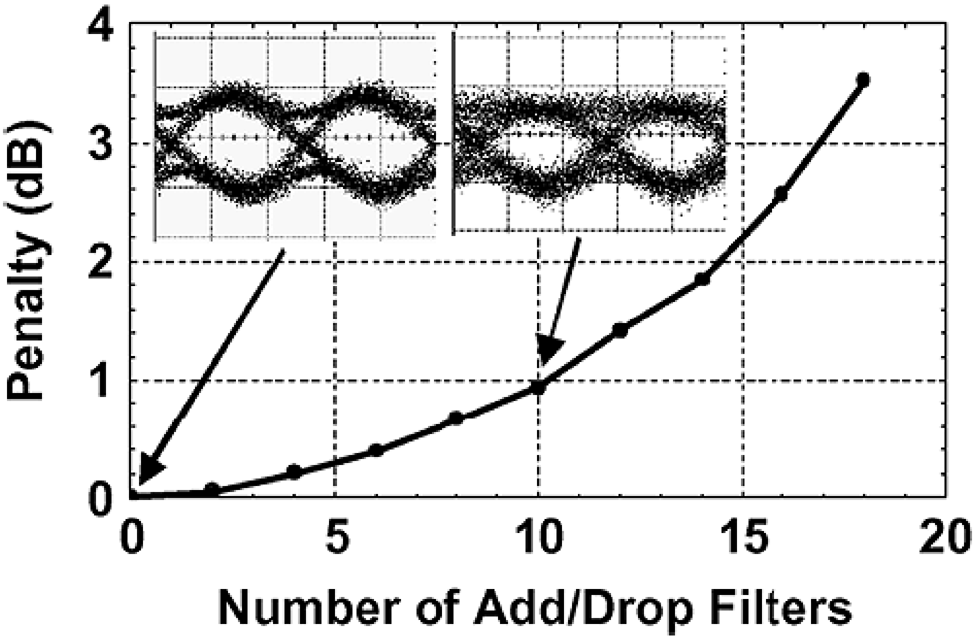


Figure 70. OSNR penalty as a function of OADM

The last simulation of this section intends to show the existing difference between DPSK and DQPSK when going through a concatenation of optical filters (OADMs)[13].
The OSNR required to achieve a BER= 1e-3 (FEC limit) is plotted as a function of the number of OADM where each OADM consists of 2 optical filters:

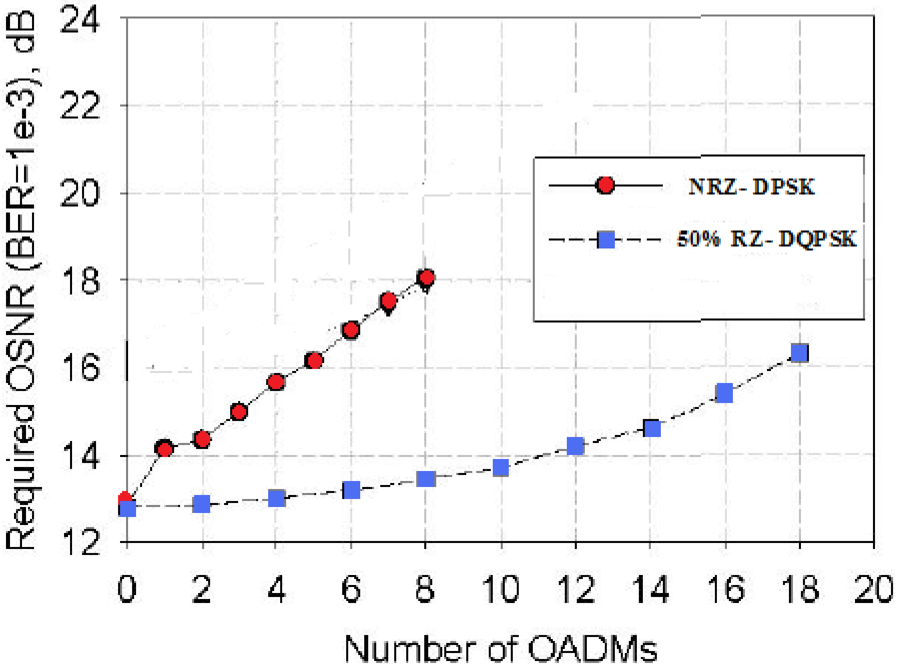


Figure 71. OSNR vs. OADM for DPSK and DQPSK

As it can be appreciated DQPSK exhibits a greater performance when passing through optical filtering, this is caused due to the shape of its spectrum being half of DPSK. DPSK is wider, thus it suffers more from the filtering effect.

9.4.5 Study of the optimal configuration

On our process for a good network planning and management, it is necessary to know how individual sections affect the overall performance. This issue has been the aim of sections 1 through 4.

In the present section number 5, we aim to discuss what the optimum configuration is given a single node of our optical network, In other words, which concatenation of elements is the best in terms of OSNR vs. BER.

To address this issue, we have conducted an experiment where we measure the back to back OSNR (no devices in between) and the OSNR of the way where all devices are present. Both OSNR have been measured at a BER= 10^{-4}. And power penalty has been calculated:

Modulation Format: DQPSK
Number of Channels: 1
Bit Rate: ***100 Gbps***
Laser Average Power: 0 dBm
Length of Fiber: 1 Span (80 km)
1 OADM: consists of 2 TFF with 3rd order filter with Gaussian distribution
1 Optical Amplifier: Noise Figure of 3 dB

Having three elements: 1- Fiber 2- Optical Amplifier and 3- Filter

We have measured the OSNR penalty for the four possible configurations:

Configuration 1)

Fiber + Filter + Amplifier as depicted below:

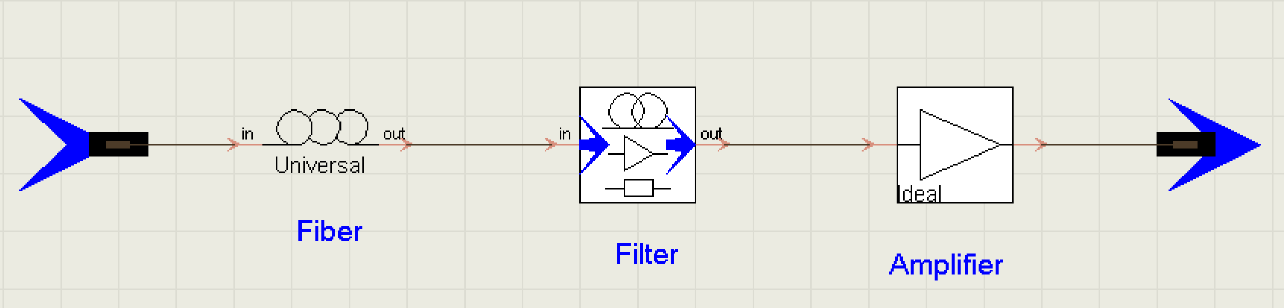
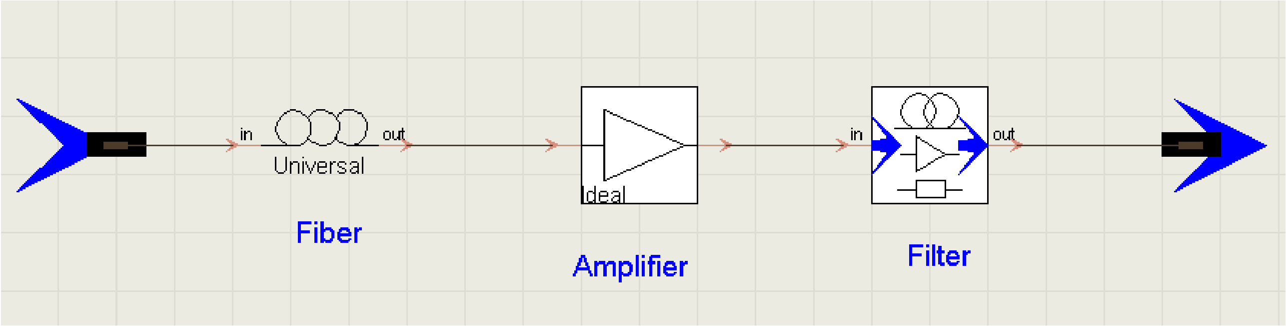


Figure 72. 4 possible optimal configurations

PENALTY= -11,96 dB

Configuration 2)

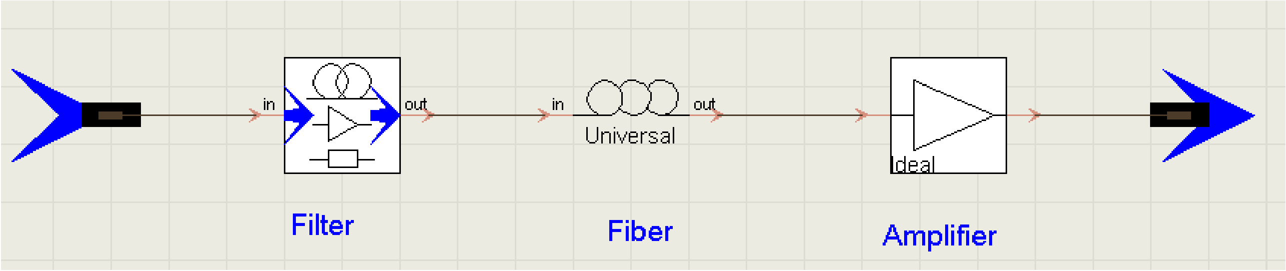
Fiber + Amplifier+ Filter as depicted below:



PENALTY= -10,81 dB (optimal)

Configuration 3)

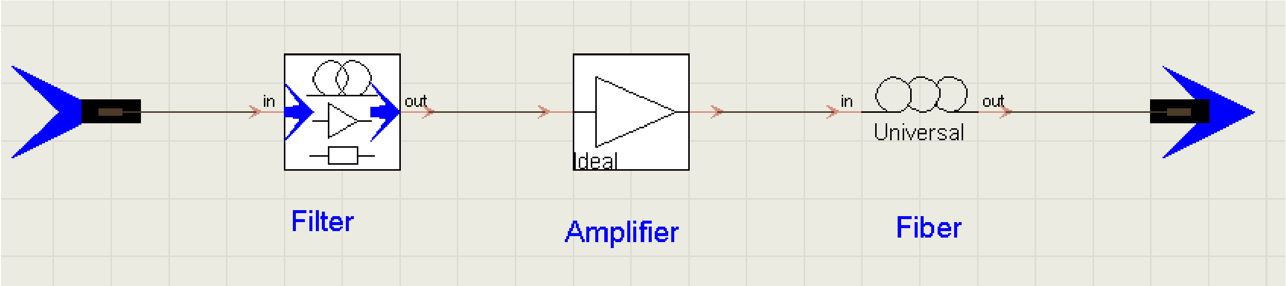
Filter + Fiber + Amplifier as depicted below:



PENALTY= -15,08 dB

Configuration 4)

Filter +Amplifier + Fiber as depicted below:



PENALTY= -15,08 dB

9.4.6 Study of a real life scenario

As it was explained in section 9.3 when defining the scenario the scenario consists of 7 and 15 DQPSK transmitters (ideally would be 8 and 16) but due to asymmetry problems with even numbers when representing spectrums, we will take 7 and 15.
The 7 /15 signals get multiplexed within the fiber and boosted thanks to an amplifier. Then they enter in the loop section, consisting of a span of fiber, and amplifier to compensate for the losses, a fiber which compensates for the dispersion; and an amplifier to compensate for these last losses. This would be the scenario for a **point-to-point link**, for a **point-to-multipoint** transmission, we will place a ROADM next to the amplifier

The first of the graphs intends to show the relationship between maximum distance accomplished and the resulting BER for 7 channels (no ROADM) at 40 Gbps:

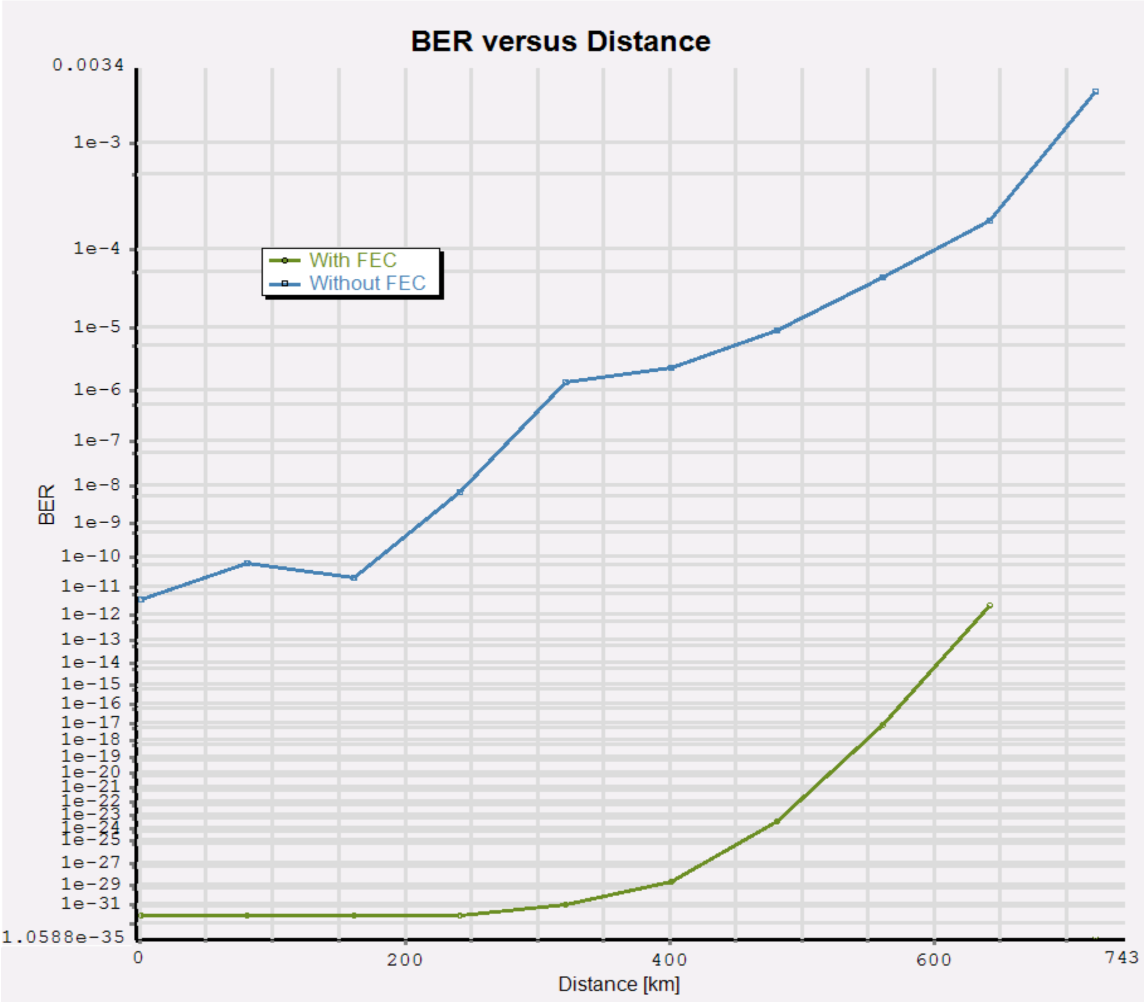


Figure 73. BER vs. Distance for a real scenario

As it can be noticed from the graph, it has been depicted BER vs. Distance assuming no FEC correction and FEC correction. The threshold value is 10^{-12} for FEC correction, and that is the condition of maximum reach allowed. So for this multichannel system of 7 channels with no ROADM, 630 km are allowed before collapsing and make it error-sensitive.

Another important parameter that was studied with this scenario is how OSNR degrades with distance (number of spans). The following graph helps us to understand more the concept:

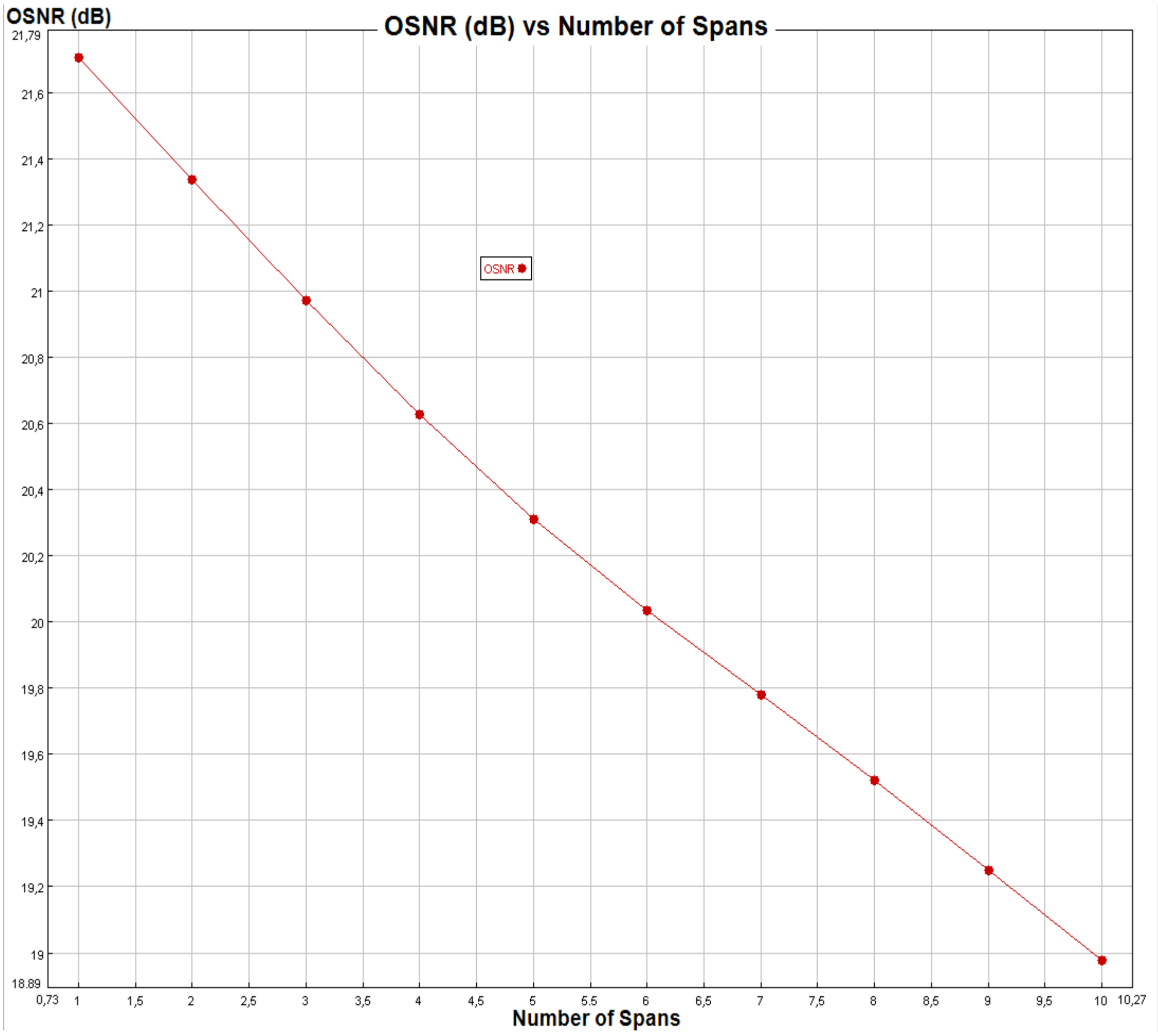


Figure 74.OSNR vs. Number of Spans for a real scenario

The system started with 21.79 dB and it degraded until reaching around 19.6 dB in almost 630 km, distance which was established as maximum reach equal to a BER of 10^{-12}. If more distance wants to be accomplished BER drops dramatically producing system failures.

For the rest of the simulations, including the multi-point links with the presence of OADM, instead of showing all graphs we will summarize the results displaying them in the following table:

Number Of Channels	Bit Rate (Gbps)	Reach without OADM	Δ OSNR (dB)	Reach with OADM	Δ OSNR (dB)
7	40	8 spans (640 km)	21.79-19.5= 2.29 dB	7 spans (560 km)	21.79-18.9= 2.89 dB
	100	6 spans (480 km)	10.46-7.85= 2.6 dB	5 spans (400 km)	10.46-7.02= 3.44 dB
15	40	7 spans (560 km)	16.55-14.8= 1.75 dB	6 spans (480 km)	16.55-14.1 = 2.45 dB
	100	5 spans (400 km)	4.76-4.46= 0.3 dB	4 spans (320 km)	4.76-4.2= 0.46 dB

Figure 75. Summarized results for all experiments

All explanations about these results can be found in the next section of conclusions where we explain why we are obtaining these results and a way to improve them.

10

Conclusiones y líneas abiertas de investigación

10.1 Conclusiones Genéricas

A la vista de la teoría expuesta y los resultados obtenidos a lo largo de éste trabajo se procede en esta parte del estudio a extrapolar conclusiones.

Aquí se abarcará, desde la teoría expuesta, con definiciones de BER y OSNR y por qué es interesante su uso, hasta cómo y de qué manera influye el OSNR en el sistema. Así se puede afirmar de manera genérica lo siguiente:

- La tasa de error (BER) caracteriza a un enlace cualitativamente, como es muy difícil de computar, se toma la alternativa de calcular un parámetro auxiliar directamente relacionado con el BER que es la OSNR (optical signal to noise ratio), un ratio que expresa la relación entre señal y ruido óptico de un enlace, y que es mucho más fácil de calcular. La OSNR se mide en decibelios (dB) y sirve para caracterizar cuantitativa y cualitativamente cualquier enlace de transmisión óptico

- Varios parámetros afectan de gran manera a la OSNR, y por tanto al enlace bajo estudio, como son: formato de modulación, tasa binaria, fibra óptica, filtros ópticos y amplificadores.

- Para estudiar el impacto de éstos elementos se introduce el concepto de OSNR penalty que es la diferencia requerida para alcanzar un BER de 10^{-4} (valor umbral si se suponen técnicas de corrección de errores, FEC, en el receptor) entre la señal con camino directo (back to back) y la señal que atraviesa el enlace per sé, ambos caminos con las mismas condiciones de filtrado.

- Existe una concatenación óptima de elementos en términos de OSNR para cualquier enlace de fibra óptica

- La OSNR para un sistema multicanal difiere en gran manera, dependiendo de si el enlace es punto a punto o multipunto (presencia de OADM).

Así, los siguientes apartados tratan de explicar todos los factores anteriormente expuestos de una manera más detallada.

10.2 Impacto del formato de modulación en la ONSR (back-to-back)

El objetivo de esta sección es describir cómo afectan diferentes formatos de modulación en la OSNR (back-to-back), es decir simplemente, se ha medido la OSNR sin ningún otro parámetro que pueda afectar, como puede ser la fibra.

En nuestro estudio, nos hemos centrado en dos formatos de modulación como son DPSK y DQPSK, aptos para enlaces long-haul. Ambos formatos deben tener una OSNR baja y una tolerancia fuerte a efectos no lineales, a la par que ofrezcan una alta eficiencia espectral. Es interesante obtener una eficiencia ≥ 1.0 bit/s/Hz.

En nuestro análisis hemos hecho una gráfica de OSNR vs. BER para 3 formatos distintos: DPSK, DPQSK y ASK

- Las modulaciones PSK (DQPSK y DPSK) se presentan como una alternativa viable frente a otras como ASK para enlaces long-haul, debido a su baja OSNR.

- Idealmente, DPQSK tiene los mismos requerimientos de OSNR que la modulación DPSK ya que ambos usan 2 dimensiones ortogonales de señalización (I y Q). Sin embargo para DQPSK la demodulación con un MZDI (Mach-Zehnder delay interferometer) es subóptima y resulta en una penalización comparado con DPSK.

- Por tanto, En un escenario back-to-back, DPSK se comporta mejor que DQPSK debido a su simplicidad en el demodulador.

- Para una tasa de error (BER) cercana al límite FEC, la diferencia en OSNR de es de 0.5 dB y se incrementa a 1dB para un BER de 10^{-9}

- Ésta diferencia se podría anular y hacer que ambos formatos tengan los mismos requerimientos de OSNR si se emplea detección coherente en el demodulador DPQSK. El problema está en la complejidad de la misma ya que requiere recuperar la fase de la portadora en el receptor y, por ello, circuitos para estimar la fase que suelen ser generalmente complejos y caros [23].

- Por tanto, habrá que elegir uno u otro formato de modulación sabiendo dicho compromiso eficiencia-coste según **la configuración** de cada enlace como se verá más adelante en la sección de conclusiones de fibra óptica y filtros ópticos.

10.3 Impacto de la fibra óptica en la OSNR

El objetivo de esta sección es el de analizar cómo afecta la fibra óptica a un enlace óptico, y más detalladamente, se caracteriza cuantitativamente su impacto global (OSNR penalty) a un enlace cualquiera de fibra óptica.

Por ello se han realizado diversas pruebas sobre los parámetros de la fibra, que de alguna manera afectan a la calidad del sistema:

- *Dispersión cromática (ps/nm)*
- *Dispersión por modo de polarización (differential Group delay (DGD) en ps)*

Las siguientes 2 subsecciones analizan de manera global el impacto de cada una de los dos tipos de dispersiones existentes.

10.3.1 Dispersión cromática

Las simulaciones llevadas a cabo cuentan con los siguientes parámetros:

- Formato de modulación: DPSK y DQPSK
- Tasa binaria: 40 Gb/s y 100 Gb/s

Se han obtenido los siguientes resultados globales:

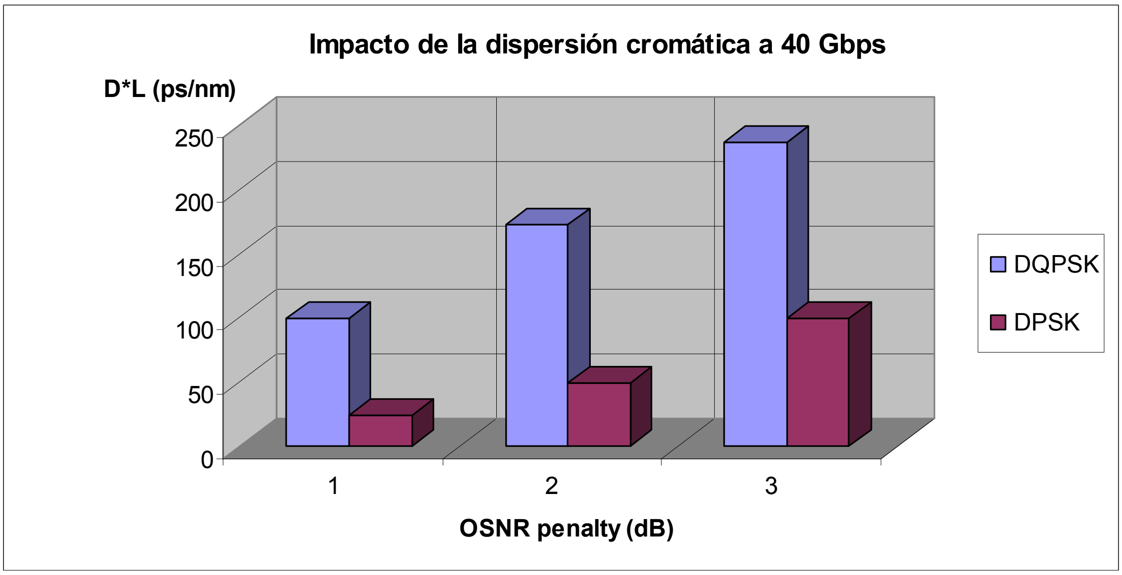


Figure 76. Impacto de la dispersión cromática a 40 Gbps

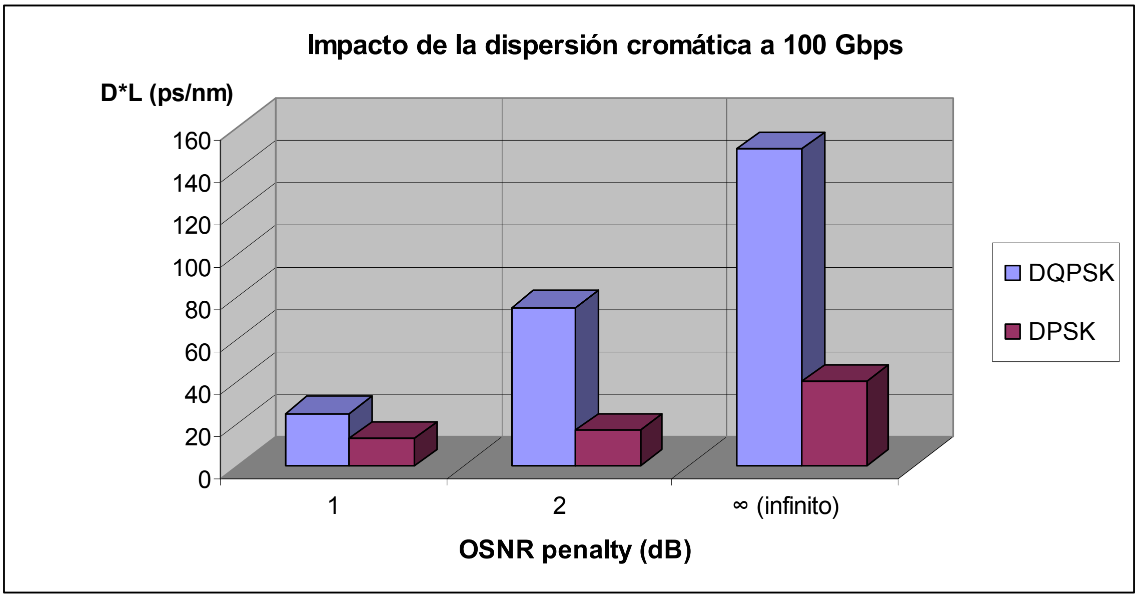


Figure 77. Impacto de la dispersión cromática a 100 Gbps

Con lo estudiado anteriormente y estos resultados, podemos extraer las siguientes conclusiones:

- La dispersión cromática acumulada aumenta con la distancia. Ésta produce Interferencia entre símbolos (ISI) y por tanto da lugar a una penalización

- La penalización aumenta con la tasa binaria, que es el principal factor limitante. A bajas tasas binarias (<10Gbps) la penalización es inapreciable mientras que a 100 Gbps es un factor muy peligroso.

- Así, tanto para 40 Gbps como para 100 Gbps se observan diferencias muy grandes entre los 2 formatos de modulación usados. A 40 Gbps, DQPSK puede agauntar *161 ps/nm* a una penalización de 2 dB mientras que DPSK solo aguanta *60 ps/nm*

- A 100 Gbps se acentúa esta diferencia ya que DPSK exhibe un peor comportamiento a tasas mayores. De tal forma que DQPSK podría aguantar hasta *150 ps/nm* con cierta penalización, mientras que a DPSK a partir de *45 ps/nm* hace que la comunicación sea inexistente, con un penalty infinito.

- La dispersión cromática se puede compensar hasta hacerla inexistente, pero ello viene a costa de una mayor dispersión por modo de polarización y mayor atenuación, lo que implica la necesidad de situar un amplificador óptico extra.

- Por tanto, se ha visto que DQPSK se comporta mucho mejor frente a DPSK debido a su gran tolerancia frente a la dispersión cromática. Ello se debe a una menor duración de tiempo de símbolo para la misma tasa binaria.

La siguiente subsección, va a analizar de forma análoga los efectos de la dispersión por modo de polarización.

10.3.2 Dispersión por modo de polarización

Las simulaciones llevadas a cabo cuentan con los siguientes parámetros:

- Formato de modulación: DPSK y DQPSK
- Tasa binaria: 40 Gb/s y 100 Gb/s

Se han obtenido los siguientes resultados globales:

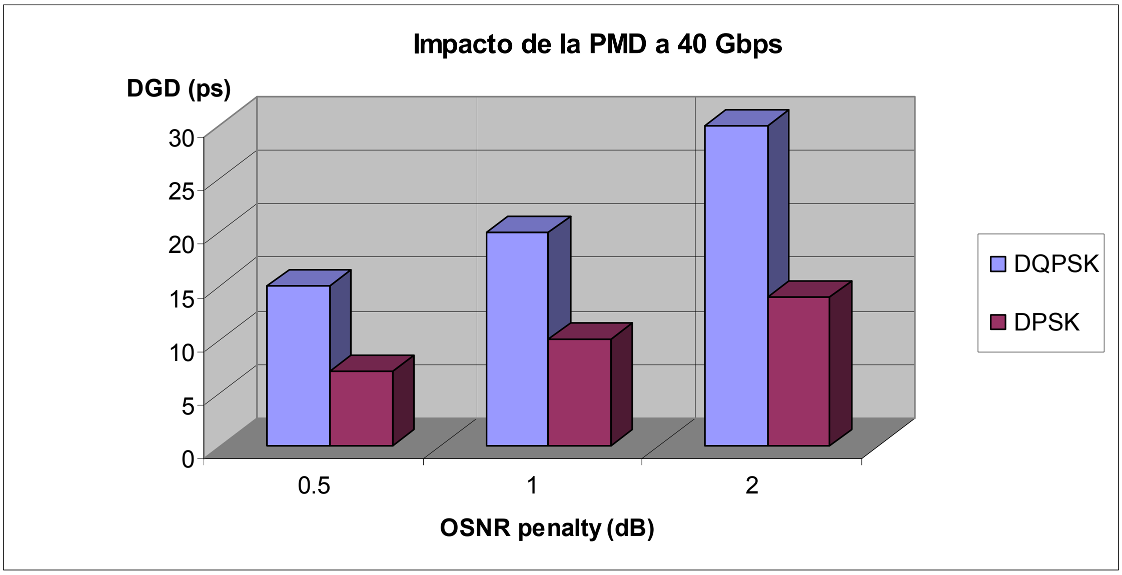


Figure 78. Impacto de la PMD a 40 Gbps

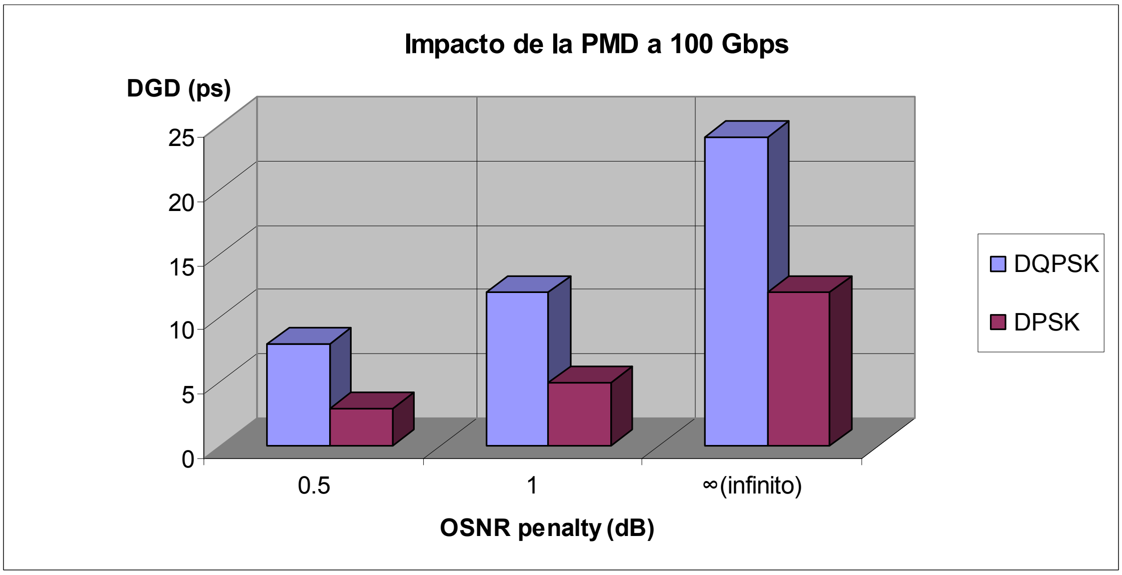


Figure 79. Impacto de la PMD a 100 Gbps

Con lo estudiado anteriormente y estos resultados, podemos extraer las siguientes conclusiones:

- La dispersión por modo de polarización aumenta con la distancia y se mide a través del DGD. Depende del coeficiente de PMD de la fibra según la expresión:

  $$DGD\ (ps) = (Coeficiente\ PMD) * (Longitud)^{1/2}$$

- Al igual que con la dispersión cromática, la penalización por DGD aumenta con la tasa binaria y a tasas binarias muy elevadas es un factor muy peligroso.

- Así, tanto para 40 Gbps como para 100 Gbps se observan diferencias muy grandes entre los 2 formatos de modulación usados. A 40 Gbps, se observa que para DQPSK se obtiene una penalización de 1 dB a *20 ps*, mientras que DPSK sólo aguanta *10 ps*.

- Más notorios son los resultados a 100 Gbps que muestran la debilidad de DPSK frente a DQPSK, ya que DPSK aguantaría hasta *13 ps* sin "romper" la comunicación mientras que DQPSK aguantaría hasta *26 ps*.

- Se observa que la tolerancia de DQPSK al DGD es el *doble* que DPSK. Esto se debe a que el periodo de símbolo es el doble para DQPSK (su espectro es el doble que el de DPSK) y por tanto tolera mucho mejor el DGD.

De manera global, el impacto de la fibra óptica viene dado de la mano de estos 2 tipos de dispersiones. Como se ha visto, DQPSK se modela como el candidato idóneo para enlaces long-haul debido a su gran robustez frente a la dispersión.

A pesar de ser un poco más complejo que DPSK, habrá que apostar por dicho formato por exhibir un gran comportamiento a tasas binarias elevadas, como se exige hoy en día el mundo de las Telecomunicaciones.

10.4 Impacto del amplificador óptico en la OSNR

- Como se ha visto, la presencia en un enlace del amplificador óptico es necesaria ya que compensan en cada tramo las perdidas sufridas por la señal en su propagación

- Sin embargo al hacer esto, añade ruido ASE, que es el *factor más perjudicial* para la OSNR del sistema. Así, el amplificador óptico será el responsable de la mayoría de la penalización de un enlace, al contribuir como el que más a la creación de ruido ASE.[11]

- La ganancia del amplificador no afecta a la OSNR. Al ser la OSNR un ratio, la ganancia amplifica por igual al ruido y a la señal de potencia.

- Conforme aumenta la longitud del enlace, aumenta el número de amplificadores que contribuyen al ruido ASE y por tanto al final disminuye la OSNR. Así, podemos concluir que en un sistema con amplificación, la OSNR se comporta según la expresión[1]:

  $$OSNR_{db} = 58 + P_{in} - \Gamma(db) - NF_{db} - 10\log N$$

  Donde NF es el "Noise Figure" o Factor de Ruido, Γ son las pérdidas en dB de cada tramo de fibra ; N, el número de tramos amplificados y Pin la potencia del canal en el amplificador

- De la anterior expresión se deduce que la OSNR se degrada logarítimicamente según el número de vanos de repetición; directamente proporcional al factor de ruido y a la atenuación y longitud de la fibra en cada tramo.

- Suponiendo que la distancia entre amplificadores es fija, por cada 1 dB que mejora la OSNR, el alcance del sistema aumenta en un 25% y si lo hace en 3 dB el alcance total es el doble

- Para optimizar la OSNR, sería interesante, usar fibras comerciales con baja atenuación que trabajen en la zona de 1550 nm.

- Limitar el uso de amplificadores si se puede, usar amplificadores LNA (con factor bajo de ruido) o incluso amplificadores Ramán que se comportan muy bien al tener muy bajo factor de ruido. Habrá que evitar saturar el amplificador inyectando la potencia adecuada de entrada (Pin).

10.5 Impacto del filtro óptico en la OSNR

El objetivo de esta sección es el de analizar cómo afectan los filtros (OADMs) a un enlace óptico, y más detalladamente, se caracteriza cuantitativamente su impacto global (OSNR penalty) a un enlace cualquiera de fibra óptica. Por ello se han hecho pruebas de concatenación de OADM para 2 formatos de modulación: DPSK y DQPSK. A la vista de estas pruebas podemos concluir para los OADM que:

- El ancho de banda óptimo de filtrado es de *50 Ghz* para *40 Gbps* y de *100 Ghz* para *100 Gbps.*
- La elección de la función de transferencia del filtro afecta a la OSNR [8].

- Concatenar filtros en cascada reduce el ancho de banda de gran manera. 12 OADM en cascada (24 filtros ópticos) reducen el ancho de banda al 59%.

- Dicha concatenación produce pérdidas que son medibles. Así para DQPSK, se pueden concatenar 10 OADM con 1 dB de penalización o 18 OADM con 3 dB de penalización.

- De nuevo existen grandes diferencias entre DPSK y DQPSK. Para un BER de 10^{-3} (límite FEC) se han realizado diversas pruebas y en ellas la degradación de la señal en DPSK es *lineal* con el número de filtros mientras que en *DQPSK* se comporta de manera *logarítmica.* Es decir se comporta mucho mejor.

- Para alcanzar 10^{-3} (límite FEC) y con 8 OADM en cascada, se necesita una OSNR de *13 dB* en DQPSK frente a los *18 dB* de DPSK

- DQPSK es mucho más robusto que DPSK, esto se debe a su espectro que es más ancho (el doble que DPSK), así, resiste mejor el filtrado y por tanto es más fuerte frente a la concatenación de OADM.

10.6 Configuración optima de elementos

El objetivo de esta sección es el de analizar cómo afectan la concatenación de elementos a un enlace óptico, y más detalladamente, se caracteriza cuantitativamente su impacto global (OSNR penalty) a un enlace cualquiera de fibra óptica. Para ello se midió el penalty de las 4 configuraciones posibles:

- Fibra óptica + amplificador + OADM
- Fibra óptica + OADM + amplificador
- OADM + amplificador + fibra óptica
- OADM + fibra óptica + amplificador.

Con el objetivo de analizar cuál es la configuración óptima, es decir qué configuración de las arriba mencionadas se comporta mejor (en términos de penalización) cuando se concatena y se mide el OSNR. Los resultados fueron los siguientes:

- La configuración **óptima** es fibra óptica+ amplificador + filtro. Es la que más baja OSNR penalty ha dado de las 4.

- La segunda configuración mejor ha sido fibra óptica + filtro + amplificador, resultando en una diferencia de 2 dB con respecto a la primera. Esto se debe a las pérdidas de inserción (1-2 dB) que introduce el OADM, ya que para los estudios no se ha considerado ideal. El filtro antes que el amplificador hace que los factores de ruido se sumen e introduzcan mayor penalty

- En las 2 restantes configuraciones en las que el filtro es el primer elemento de la serie, resulta en las mayores penalizaciones, ya que el filtro introduce pérdidas de inserción, atenúa la señal en la banda de paso y posteriormente se amplifica algo que ya ha sido atenuado previamente. Es la configuración que no se debe utilizar nunca.

- Si los elementos fueran ideales, cualquiera de las configuraciones sería óptima, pero éste no es un escenario realista. Para multicanal, sería mejor el filtro antes del amplificador, pero no es práctico como se ha comentado.

- En un sistema monocanal la presencia del filtro óptico (OADM) es ventajosa ya que elimina los lóbulos secundarios de la señal, optimizando el rendimiento y pasando el lóbulo principal responsable del 90% de la potencia de señal.

10.7 Escenario Real punto a punto y multipunto

El objetivo de esta última sección del proyecto es el de analizar un enlace real y cómo se comporta bajo diferentes parámetros de simulación. Más detalladamente, las pruebas que se han hecho son para un enlace punto a punto y multipunto (presencia de OADM) .

Para todas las pruebas, el formato de modulación usado ha sido DQPSK por haber demostrado ser el más robusto en presencia de filtros ópticos y dispersión.

Se han llevado a cabo las siguientes pruebas:

Medida de OSNR, máxima distancia (=BER (10^{-12})) y penalización de cada enlace para:

- **7 y 15 canales**
- **Sin OADM (escenario punto a punto) y con OADM (escenario multipunto)**
- **A tasas binarias de 40 y 100 Gbps.**

Así, se pueden obtener las siguientes conclusiones:

- En un enlace real como ya se ha visto, la fibra, el amplificador, los filtros ópticos y la tasa binaria son fuentes de penalización de OSNR, y por tanto se ha de cuidar mucho su correcta elección y disminuir en la medida de lo posible el impacto global de cada uno de ellos según lo visto en secciones anteriores donde se ha cuantificado el impacto de cada elemento.

- El mejor caso de los estudiados en cuanto a alcance es para 7 canales a 40 Gbps sin OADM alcanzándose 8 vanos, mientras que el peor caso es para 15 canales a 100 Gbps con OADM, con solo 4 vanos de distancia

- Los enlaces punto a punto se comportan mejor que los multipunto (presencia de OADM). La penalización que introducen los OADM es de genéricamente un vano de longitud, es decir aproximadamente entre el 15% y 20% de la distancia total en general.

- Entre un enlace punto a punto y multipunto con las mismas características hay una diferencia de 0.3-0.8 dB. Esta diferencia viene marcada por la presencia del OADM como ya se ha comentado. En las curvas de OSNR vs. Distancia, se puede apreciar cómo 0.3 dB de OSNR penalty ya supone un vano menos de distancia.

- El número de canales también afecta. El doblar el número de canales (pasar de 7 a 15) supone en todos los casos un vano de penalización de distancia total. Por tanto a menos canales en un sistema multicanal, mejores prestaciones.

- La tasa binaria es otro factor muy importante de penalización, para todos los estudios punto a punto y multipunto, el cambio de 40 Gbps a 100 Gbps supone una penalización del 25% del alcance total para todos los casos.

- Para 100 Gbps el incremento de OSNR es muy pequeño, esto significa, que 0.1 dB ya hacen una gran diferencia en penalización. Por tanto, a altas velocidades habrá que tener muy en cuenta la configuración del enlace para penalizar lo menos posible (dispersión, presencia de filtros, amplificadores…etc).

Así, con este proyecto se ha podido cuantificar el impacto de los elementos de un enlace por fibra óptica a la hora de planificar y diseñar una red de larga distancia. Según la topología de la red a diseñar, habrá que hacer una sabia elección de los elementos de la misma de cara a tener grandes prestaciones a bajo coste.

Con este proyecto se ha podido dar una idea clara de la importancia de una buena elección de los elementos de cara a cumplir con requisitos establecidos por el cliente para una correcta planificación de la red.

La tasa binaria, el formato de modulación, la fibra óptica y su indeseada dispersión, los amplificadores y los filtros, todo ello estudiado y correctamente aplicado marcarán la diferencia, en términos de prestaciones (alcance máximo y baja OSNR) en cualquier enlace por fibra óptica que se proponga y seremos capaces de poder resolverlo de manera óptima y con el menor coste posible.

10.8 Líneas abiertas de investigación

Siguiendo el trabajo realizado, en un futuro sería muy interesante hacer un estudio sobre otros factores. Desde aquí se proponen:

- Mejora en en el modelado de los filtros ópticos (OADM). Incluir distintos modelos con distintas funciones de transferencia de filtrado con el objetivo de analizar qué filtro es óptimo en términos de OSNR y BER.

- Diferentes formatos de modulación. Profundizar en el estudio de más formatos de modulación con el objeto de cuantificarlos todos ellos. Especial atención al formato POL-MUX y cómo afecta a la OSNR

- Implementación en VPI de algún método para compensar la PMD. Una vez compensada la dispersión cromática, la PMD es el siguiente factor a compensar.

- Analizar cómo afectan los amplificadores Ramán a la OSNR. En un principio, por su menor factor de ruido (NF), parece que se comportan mejor, pero un estudio frente a los EDFA aclararía dicho concepto.

10

Conclusions and open issues

10.1 General Conclusions

Once theory has been reviewed and results have been obtained, we proceed now in this section to draw up the final conclusions.

We will cover now, the theory, with definitions of BER and OSNR and why is necessary to implement them, until how does OSNR affect system performance. Thus, the following statements can be declared:

- Bit Error Rate (BER) fully characterizes and optical link in terms of quality. As it is very hard to compute it, a different alternative is taken to ease the procedure with an auxiliary parameter related to BER which is OSNR (optical signal to noise ratio) which express the relation between signal and optical noise on a link and it is easier to be obtained. OSNR is measured in dB and fully characterizes too any optical link.

- Few parameters have been detected to affect OSNR and thus the transmission link under study. These include: Modulation format, binary rate, optical fibre, OADM and amplifiers

- In order to study how much they impact on the overall performance, a new concept is introduced: “OSNR penalty” and it is the difference in OSNR required to obtain a BER of 10^{-4} (FEC techniques assumed) between the back-to-back path and the path of the signal through the link. Both with same filtering conditions

- There is an optimum concatenation of elements in terms of OSNR for any optical link.

- ONSR for multichannel purposes differs depending upon the configuration of the link: Point to point link or multipoint link (presence of OADM)

Thus, the following sections intend to cover thoroughly these factors mentioned above.

10.2 Impact of the modulation format on OSNR (back-to-back case)

The aim of this section is to analyse how different modulation formats have an impact on the system's OSNR, in the back-to-back case, or rather, OSNR has been measured with no other element influencing on the result, as it could be the fibre.

For the purpose of the study, we have just focused our scope on 2 modulation formats such as DPSK and DQPSK, both suitable for long-haul links. Both formats should require a low OSNR and a strong tolerance towards non-linear effects offering optimum spectral efficiency. Note that it is interesting to obtain an efficiency ≥ 1.0 bit/s/Hz

In the results section a graph of BER vs. ONSR was obtained for DPSK, DQPSK and ASK:

- PSK modulations (DPSK and DQPSK) are a feasible solution in comparison to ASK for long-haul links, due to their low OSNR.

- Ideally, DQPSK has the same OSNR requirements as DPSK because both use 2 orthogonal signalling dimensions (I and Q). However for DQPSK, demodulation with a MZDI (Mach-Zehnder delay interferometer) is suboptimal and results in a penalty as opposed to DPSK.

- Therefore, in a back-to-back scenario, DPSK exhibits a greater behaviour than DQPSK due to its simplicity on the demodulation process.

- For a Bit error rate (BER) close to the FEC limit, the difference in OSNR is of 0.5 dB and it raises to 1 dB for a BER of 10^{-9}

- This difference could be compensated so both formats have the same OSNR requirements if coherent detection is used on the DQPSK demodulator. The issue is to bring back the carrier's phase on the receiver and thus, complex circuits to estimate the phase which usually are very expensive.

- One or another modulation format will be chosen knowing the trade-off efficiency vs. cost depending upon **the configuration** of each link as it will be shown in the upcoming sections of optical fibre and OADM.

10.3 Impact of the optical fibre on OSNR

The aim of this section is to analyse how the optical fibre has an impact on the system's OSNR, and moreover its global impact is fully characterized in terms of OSNR penalty for any optical link.

To carry out with the experiment, diverse tests have been run over the fibre parameters that somehow affect the system's performance:

- *Chromatic Dispersion (ps/nm)*
- *Polarization mode dispersion (differential group delay (DGD) ps))*

The next 2 subsections analyse the importance of each factor.

10.3.1 Chromatic Dispersion

The different experiments conducted take into account the following parameters:

- Modulation format: DPQSK and DPSK
- Binary rate: 40 Gb/s and 100 Gb/S

With the following results:

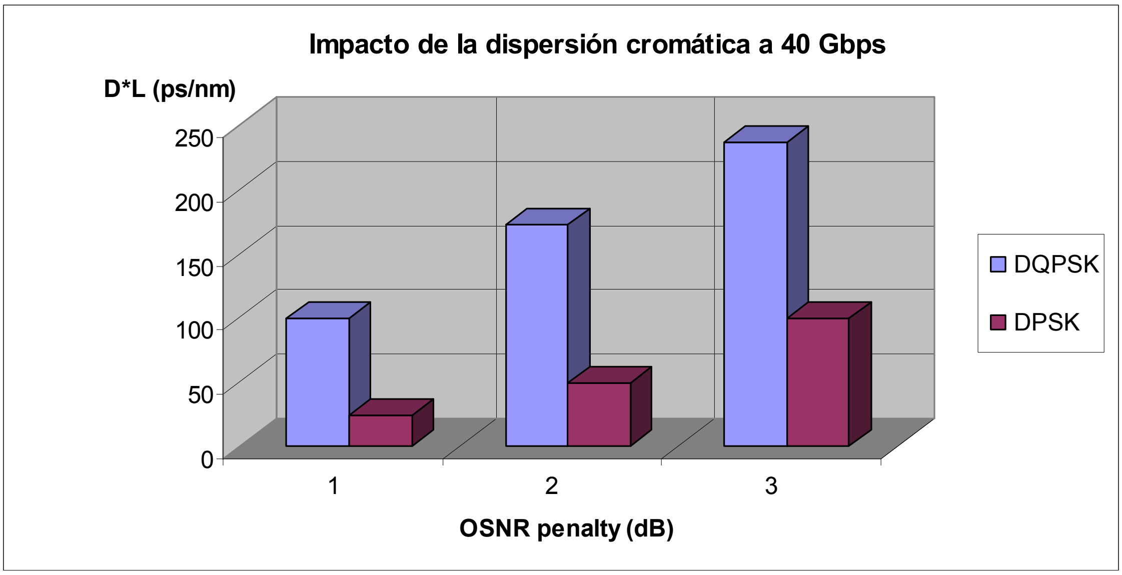


Figure 80. Impact of Chromatic dispersion at 40 Gbps

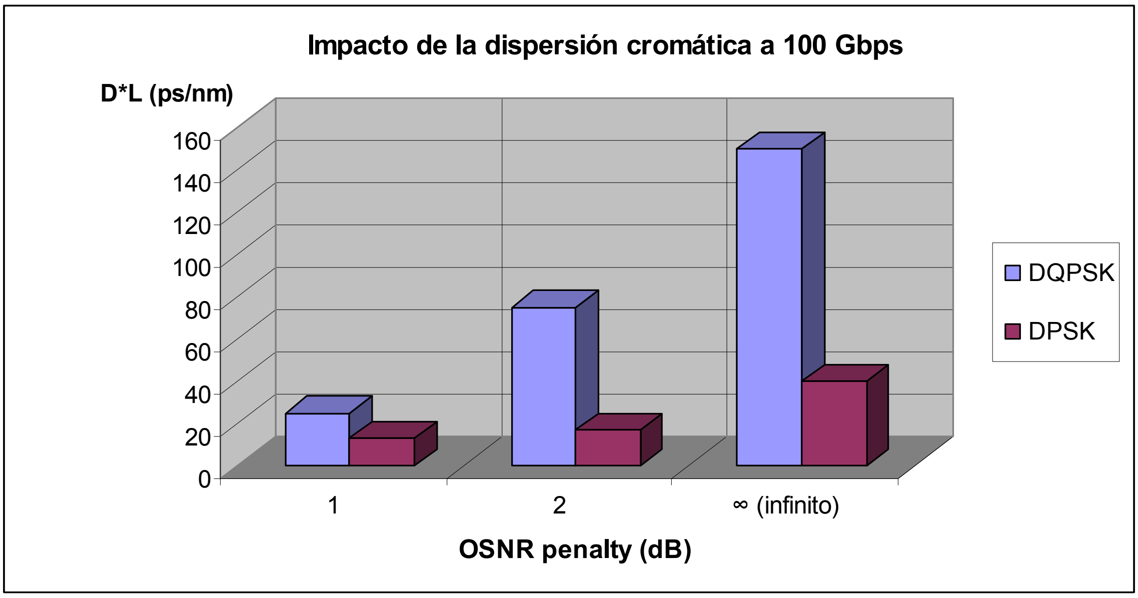


Figure 81. Impact of chromatic dispersion at 100 Gbps

From these results and with the previous background we can conclude that:

- Chromatic dispersion increases with distance. This phenomenon produces ISI (Intersymbol interference) which gives rise to penalties.

- OSNR penalty increases with the binary rate, one of the main limiting factors. At low binary rates (<10Gbps), penalty is negligible whereas at 100 Gbps is an issue.

- For both 40 and 100 Gbps severe differences have been noticed between DPSK and DPQKS. At 40 Gbps, DQPSK can hold up to *161 ps/nm* with a penalty of 2 dB, whereas DPSK can only hold *60 ps/nm*

- At 100 Gbps, the difference is bigger as DPSK exhibits a weaker behaviour when the bit rate is increased. In such a way that DQPSK can hold up to 150 ps/nm penalizing a bit whereas DPQK has an infinite penalty (lack of communication) from 45 ps/nm onwards.

- Chromatic dispersion can be compensated until making it negligible, but it comes at the expense of having more DGD and more attenuation which implies placing an extra optical amplifier (more OSNR)

- Thus, it has been shown that DQPSK is way better than DPSK due to its big tolerance towards chromatic dispersion. This is due to a lower symbol rate for the same bit rate

The next subsection will cover alike the effect of polarization mode dispersion:

10.3.2 Polarization mode dispersion

The different experiments conducted take into account the following parameters:

- Modulation format: DPQSK and DPSK
- Binary rate: 40 Gb/s and 100 Gb/S

With the following results:

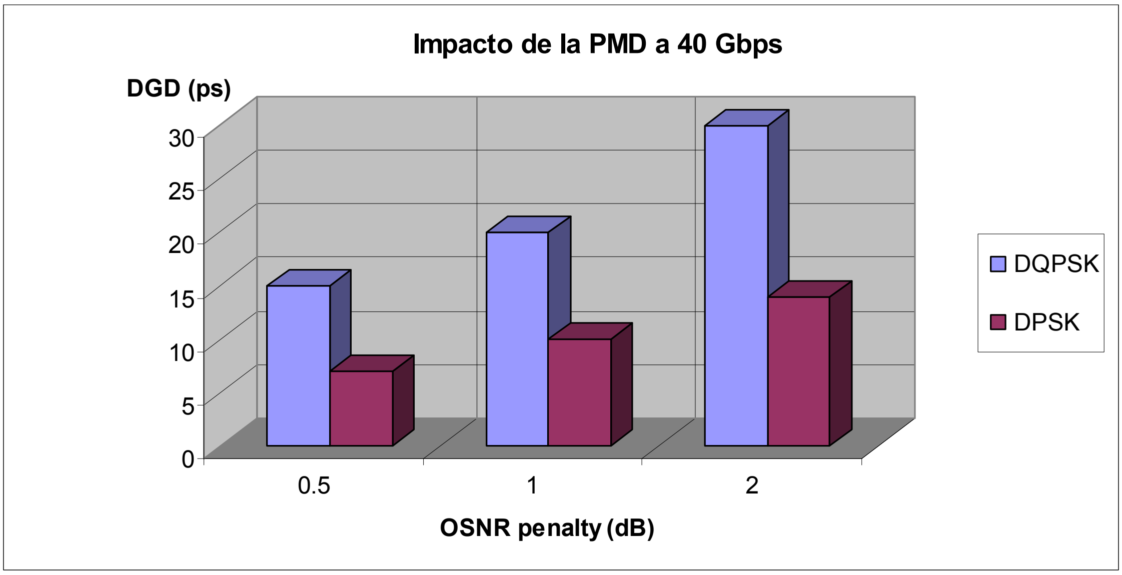


Figure 82. Impact of PMD at 40 Gbps

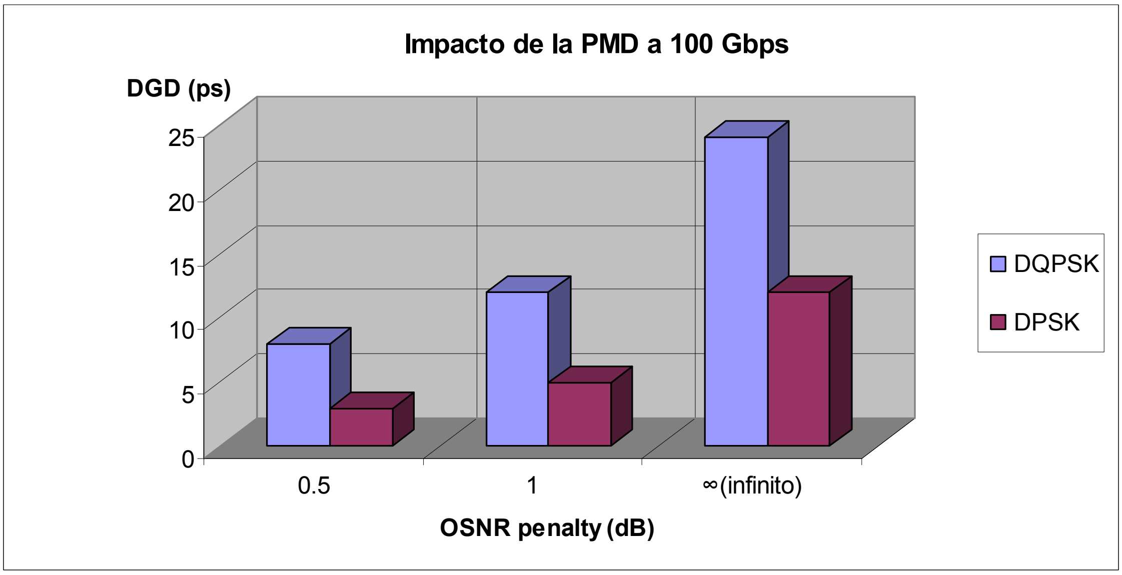


Figure 83. Impact of PMD at 100 Gbps

With the previous background and taking into account these results we can conclude that:

- Polarization mode dispersion increases with distance and it is measured via DGD. It depends on the PMD coefficient of the fibre according to the expression:

$$DGD\ (ps) = (PMD\ Coefficient) * (Length)^{1/2}$$

- Like Chromatic dispersion, DGD penalty rises with binary rate, and at high bit rates is a strong issue
- For both 40 and 100 Gbps severe differences have been noticed between DPSK and DPQKS. At 40 Gbps, DQPSK can hold up to *20 ps* with a penalty of 1 dB, whereas DPSK can only hold *10 ps/nm*
- Even more notorious are the results at 100 Gbps which show the weakness of DPSK as opposed to DQPSK, because DPSK could hold up to *13 ps* without "breaking" the link while DQPSK could hold up to *26 ps*
- It can be observed that DQPSK tolerance towards DGD is double than DPSK. This is due to the symbol rate of DQPSK being double. (its spectrum is twice as wider as DPSK) and it tolerates better DGD

In a nutshell, the impact of the fibre on OSNR is given by these 2 types of dispersion. DPQSK models itself as the perfect candidate for long-haul links due to its great tolerance towards dispersion.

In spite of being more complex than DPSK, we should bet for this format as it behaves well at very high binary rates as modern telecom systems demand nowadays.

10.4 Impact of the optical amplifier on OSNR

- As seen before, the presence of optical amplifiers on an optical link is mandatory as they make up for the losses of the signal on each spam.

- However on doing so, they add ASE noise, which is *the most harmful factor* affecting OSNR. Likewise optical amplifier is the responsible for most of the penalty induced on a link, as it creates a lot of ASE noise [11]

- Amplifier’s gain does not affect OSNR. As OSNR is a ratio it affects equally to both noise and signal power.

- As the transmission distance increases, the number of required amplifiers increases, contributing to creating more ASE noise and thus OSNR lowers at its final stages. On a multi-stage system counting with amplifiers OSNR behaves as [1]:

$$OSNR_{db} = 58 + P_{in} - \Gamma(db) - NF_{db} - 10\log N$$

  Where NF is the noise figure, Γ is the span loss in dB, N the number of amplified spasm and Pin the channel power in the amplifier.

- From the previous expression it can be noticed that OSNR degrades logarithmically with the number of spans. It is directly proportional to the noise figure and the attenuation and length of fibre on each span.

- Taking a fixed distance between amplifiers, for each 1 dB of OSNR improvement, the maximum reach increases in 25% and for 3 dB , maximum reach is twice as the original value.

- To optimize OSNR, it would be interesting to use commercial fibres with low attenuation on the region of 1550 nm

- Limiting the use of amplifiers if possible helps or even using Raman amplifiers (still to be tested) that behave well as they have a low NF. Feeding the right power into the amplifier is necessary in order to avoid intermodulation problems.

10.5 Impact of the optical filter on OSNR

The aim of this section is to analyse how the optical filter has an impact on the system’s OSNR, and moreover its global impact is fully quantify it in terms of OSNR penalty for any optical link. We have concatenated a number of OADM for 2 modulation formats: DQPSK and DPSK. We can conclude that:

- Optimum bandwidth for filtering purposes is *50 Ghz* for *40 Gbps* and *100 Ghz* for *100 Gbps*.

- The shape of the transference function affects OSNR[8].

- Filter concatenation reduces the overall bandwidth. 12 OADM in cascade (24 optical filters) make the remaining bandwidth fall to 59%.

- Filter concatenation produces loss that can be measured. For DQPSK, 10 OADM result in a 1 dB penalty and 18 OADM in a 3 dB penalty.

- There are again big differences between DPSK and DQPSK. For a BER of 10^{-3} (FEC limit) several tests have been run and signal degradation in DPSK is lineal with the number of filters whereas DPSK follows a logarithmic rhythm. In other words, DQPSK behaves much better.

- In order to reach the FEC limit and with 8 OADM for DQPSK it is necessary 13 dB versus the 18 dB of DPSK.

- DQPSK is way more robust than DPSK, this is due to its spectrum being wider, so it confronts better the filtering and thus stronger to filter concatenation.

10.6 Optimum placement of elements

The aim of this section is to analyse how element concatenation differs from configuration to configuration and how it behaves on an optical link. For those purposes, the penalty was measured over the 4 possible configurations:

- Optical Fibre + amplifier + OADM
- Optical Fibre + OADM + amplifier
- OADM + amplifier + optical fibre
- OADM + optical fibre + amplifier

With the goal of seeking the best configuration in terms of OSNR:

- The optimal configuration results to be optical fibre + amplifier + OADM. It gave the lowest OSNR among the 4 candidates.

- The second best configuration is optical fibre + OADM + filter resulting in a difference of 2 dB with respect to the 1st one. This is due to the insertion losses (1-2 dB) of the filter. Filtering before amplifying makes both noise factors to add up resulting in a greater penalty

- The other 2 configurations where the filter was placed first are the worst ones. The filter first attenuates the signal and then amplifies something which is previously attenuated 1 dB. This configuration shall never be used.

- Having ideal elements, all configurations would be equal, but this is not a realistic approach. For multichannel purposes filtering before amplifying would be beneficial but it is not realistic.

- On a monochannel system having OADM is beneficial as it gets rid of the secondary lobes of the signal, optimizing performance as the main lobe is responsible for the 90 % of signal power.

10.7 Real point-to-point and multipoint scenarios

The aim of this last section of the thesis is to analyse a real link and how it behaves under different simulation parameters. More deeply, the tests have been conducted for a point to point link and a multipoint link (with OADM). DQPSK modulation format has been chosen for its great robustness towards filter concatenation and dispersion.
We have run the following tests:
Measure of OSNR, maximum reach allowed and penalty of each link for:

- 7 and 15 channels
- No OADM (P2P scenario) and OADM (multipoint scenario)
- Bit rates of 40 and 100 Gbps

We can draw up the following conclusions:

- In a real link, the fiber, amplifiers, optical filters and the bit rates are sources of OSNR penalty and therefore care an attention needs to be payed when designing the network in order to minimize the impact of each element as described in previous sections where the impact was quantified.

- The best case scenario in terms of maximum reach is for 7 channels at 40 Gbps without OADM reaching 8 spans of fibre, whereas the worst case scenario is for 15 channels at 100 Gbps with the presence of OADM reaching only 4 spans of fibre

- P2P links behave stronger than multipoint links (with OADM) as the OSNR penalty induced by OADM is generally of 1 span of fibre (80 km), which is between 15% and 20% of the overall distance in most of the cases.

- The difference between both links under the same characteristics is of 0.3-0-8 dB. This is due to having OADM. In the curves of OSNR vs Distance, it can be appreciated how 0.3 dB already means 1 span of fibre.

- Number of channels affect significantly. Going from 7 to 15 channels, results in one less span of fibre. Therefore on a multichannel system, the least number of channels results in better performance.

- Binary rate is another important factor to consider. For all the scenarios, the shift from 40 to 100 Gbps results in a penalty of 25% of the total maximum reach.

- At 100 Gbps the increment of OSNR is very little, which means that 0.1 dB already make a great difference in terms of penalty. Therefore, at high bit rates, we will need to pay special attention to the topology and configuration of the link to minimize the penalties.

In a nutshell, with this thesis it has been possible to quantify the impact of individual elements of an optical fiber link whenever it is necessary to plan and design a long-haul network. Depending upon the network topology, a wiser solution will need to be taken so there is a great performance at low cost.

With this thesis we have shown how important a correct choice of elements is, so the client can be satisfied when demanding a certain type of network..

Binary rate, modulation format, optical fiber and its undesired dispersion, amplifiers and filters, all that correctly studied and planned will truly make a difference in terms of performance (maximum reach at low OSNR) in any optical fiber link to be constructed. We will be then able to solve for it in an accurate and optimal manner at the lowest cost possible.

10.8 Open Issues

Following up with the performed work, on a near future it would be quite interesting to conduct a study about other factors. From here, we propose the following:

- Improvement on filter modelling (OADM). Possibility of including different models with different transfer functions so a conclusion can be derived about which filter is best in terms of OSNR and BER

- Different modulation formats. Digging up on the study of more existing modulation formats so they can all be quantified. Special attention to POL-MUX and how it affects OSNR

- Implementing in VPI a method to make up for the existing PMD of the fibre. Once chromatic dispersion has been compensated, PMD is the next factor to focus on.

- Analysing how Raman amplifiers affect OSNR. Beforehand, they have a lower NF, so it seems they would behave better, but a clear study about both Raman and EDFA amplifiers would make the concept much clear.

APPENDIX

A. REFERENCES

[1] A. Gumaste, T. Anthony
"**DWDM Network designs and engineering solutions".**
Cisco-Systems, 2002

[2] A.Aguilar.
Notes on subject "Comunicaciones Ópticas",
2006-2007

[3] Circadiant Tech Brief
"BER vs. OSNR",
Paper issued on February 2003

[4] D.McGhan, C. Laperle,
"5120 km RZ-DPSK transmission over G652 fiber at 10 Gb/s
with no optical dispersion compensation"
Nortel, 3500 Carling Avenue, Nepean, Ontario, K2H 8E9, Canada

[5] E.Iglesias
"Requisitos de los sistemas de comunicaciones ópticas de muy alta velocidad",
EPS-UAM . January 2009

[6] S.Pazi, C.Chatwin, R.Young, and P. Birch
"Analysis of a WDM System for Tanzania"
PROCEEDINGS OF WORLD ACADEMY OF SCIENCE, ENGINEERING AND TECHNOLOGY VOLUME 33 SEPTEMBER 2008
ISSN 2070-3740

[7] P.Winzer, R. Essiambre.
"Advanced optical modulation formats".
Proceedings of the IEEE. Vol 94, Nº 5, mayo de 2006.

[8] G. Dhosi and J. Turner
Filter Concatenation Effects in Optical Networks
Proceedings of the IEEE

[9] E.Almström, S. Larsson, H.Carlden,
"Cascadability of Optical Add/drop Multiplexers",
ECOC'98, 589-590.

[10] J. P. Gordon and H. Kogelnik
"PMD fundamentals: Polarization mode dispersion in optical fibers"
PNAS April 25, 2000 vol. 97 no. 9 4541-4550

[11], J. Capmany
"**Redes Ópticas**"
Servicio Publicaciones Editorial Universidad Politécnica de Valencia 2006

[12] G.Raybon
“Performance of advanced modulation formats in optically-routed networks”
Bell Laboratories, Lucent Technologies 2005

[13] A. H.Gnauck, P.J.Winzer
“Linear and Nonlinear Performance of 42.7 Gb/s single-polarization RZ-DQPSK format”
IEEE photonics technology letters, VOL. 18. NO.7 April 1, 2006

[14] D. Van den Borne. S. L.Jansen. E. Gottwald. E.D. Schdmidt
“DQPSK modulation for robust optical transmission”
Eindhoven university of technology. Nokia Siemens Networks, Munich Germany

[15] G. Kramer, A.Ashikhmin
“Spectral efficiency of coded phase-shift keying for fiber-optic communication”
Lightwave technology, vol.21, no. 10. pp 2438. Oct. 2003

[16] J.H. Sinsky. A. Adamiecky. A. Gnauck
“RZ-DPSK transmission using a 42.7 Gb/s integrated balanced optical front end with record sensitivity”
Lightwave technology, vol.22, no. 1. pp 182. Jan. 2004

[17] M. Rowe
“Bits battle noise”
Test & Measurement World, 3/1/2005

[18] R.Bach
“Standardization of the Q-factor Method”
Available in www.acterna.com, November 2003

[19] **“Introduction to chromatic dispersion”**
Available in www.lunatechnologies.com

[20] **“What is a ROADM?”**
Available in www.searchtelecom.com

[21] R.Saunders et al.
“Can 100Gb/s wavelengths be deployed using 10Gb/s engineering rules”.
Cisco systems Inc.

[22] **“Chromatic dispersion: Fundamentals”**
Porta Optica

[23] “**Codification Systems”**
Avalaible in www-ee.stanford.edu

B. GLOSSARY

AMS-IX	Amsterdam Internet Exchange
AWG	Array Waveguide Gratings
BER	Bit Error Rate
CD	Chromatic Dispersion
DCF	Dispersion compensation fiber
DCU	Dispersion Compensation Units
DGD	Differential Group Delay
DPSK	Differential phase shifting keying
DQPSK	Differential quadrature phase shifiting keying
DWDM	Dense wavelength division multiplexing
FBG	Fiber Bragg Gratings
FEC	Forward Error Correction
HSPA	High Speed Packet Access
ISI	InterSymbol Interference
LTE	Long Term Evolution
MSAN	Multi Service Access Node
NF	Noise Figure
NRZ	Non-Return-To-Zero
OADM	Optical Add Drop Multiplexer
OSNR	Optical Signal to noise ratio
PMD	Polarization Mode dispersion
PON	Optical Passive Networks
ROADM	Reconfigurable Optical Add Drop Multiplexer
SDH	Synchronous digital Hierarchy

SMF	Single Mode Fiber
TFF	Thin film Filter
VDSL	Very high speed digital line subscriber
WDM	Wavelength division multiplexing
WIMAX	Worldwide interoperability for microwave access

C. PRESUPUESTO

1) Ejecución Material

- Ordenador Personal.. 2.000 €
- Renovación de la licencia de VPI transmisión maker ....1.000 €
- Material de oficina ....50 €
- Total ejecución material.. 3.050 €

2) Gastos Generales

- 16 % de ejecución material .... 489 €

3) Beneficio industrial

- 6 % de Ejecución material .... 183 €

4) Honorarios del proyecto

- 600 horas, 15 € / hora.. 9000€

5) Material fungible

- Gastos de impresión... 90 €
- Encuadernación.. 40 €

6) Subtotal del presupuesto

- Subtotal presupuesto .... 12852 €

7) I.V.A. aplicable

- 16% del subtotal presupuesto.. 2056.3 €

8) Total Presupuesto

- Total presupuesto .... 14908,3 €

Madrid, Noviembre de 2009

El Ingeniero Jefe del Proyecto,

Fdo.: Fabio Moliner García
Ingeniero Superior de Telecomunicación

D. PLIEGO DE CONDICIONES

Este documento contiene las condiciones legales que guiarán la realización, en este proyecto, llamado **Análisis del OSNR de configuraciones de enlaces de fibra óptica**. En lo que sigue, se supondrá que el proyecto ha sido encargado por una empresa cliente a una empresa consultora con la finalidad de realizar dicho sistema. Dicha empresa ha debido desarrollar una línea de investigación con objeto de elaborar el proyecto. Esta línea de investigación, junto con el posterior desarrollo de los programas está amparada por las condiciones particulares del siguiente pliego.

Supuesto que la utilización industrial de los métodos recogidos en el presente proyecto ha sido decidida por parte de la empresa cliente o de otras, la obra a realizar se regulará por las siguientes:

Condiciones generales

1. La modalidad de contratación será el concurso. La adjudicación se hará, por tanto, a la proposición más favorable sin atender exclusivamente al valor económico, dependiendo de las mayores garantías ofrecidas. La empresa que somete el proyecto a concurso se reserva el derecho a declararlo desierto.

2. El montaje y mecanización completa de los equipos que intervengan será realizado totalmente por la empresa licitadora.

3. En la oferta, se hará constar el precio total por el que se compromete a realizar la obra y el tanto por ciento de baja que supone este precio en relación con un importe límite si este se hubiera fijado.

4. La obra se realizará bajo la dirección técnica de un Ingeniero Superior de Telecomunicación, auxiliado por el número de Ingenieros Técnicos y Programadores que se estime preciso para el desarrollo de la misma.

5. Aparte del Ingeniero Director, el contratista tendrá derecho a contratar al resto del personal, pudiendo ceder esta prerrogativa a favor del Ingeniero Director, quien no estará obligado a aceptarla.

6. El contratista tiene derecho a sacar copias a su costa de los planos, pliego de condiciones y presupuestos. El Ingeniero autor del proyecto autorizará con su firma las copias solicitadas por el contratista después de confrontarlas.

7. Se abonará al contratista la obra que realmente ejecute con sujeción al proyecto que sirvió de base para la contratación, a las modificaciones autorizadas por la superioridad o a las órdenes que con arreglo a sus facultades le hayan comunicado por escrito al Ingeniero Director de obras siempre que dicha obra se haya ajustado a los preceptos de los pliegos de condiciones, con arreglo a los cuales, se harán las modificaciones y la valoración de las diversas unidades sin que el importe total pueda exceder de los presupuestos aprobados. Por consiguiente, el número de unidades que se consignan en el proyecto o en el presupuesto, no podrá servirle de fundamento para entablar reclamaciones de ninguna clase, salvo en los casos de rescisión.

8. Tanto en las certificaciones de obras como en la liquidación final, se abonarán los trabajos realizados por el contratista a los precios de ejecución material que figuran en el presupuesto para cada unidad de la obra.

9. Si excepcionalmente se hubiera ejecutado algún trabajo que no se ajustase a las condiciones de la contrata pero que sin embargo es admisible a juicio del Ingeniero Director de obras, se dará conocimiento a la Dirección, proponiendo a la vez la rebaja de precios que el Ingeniero estime justa y si la Dirección resolviera aceptar la obra, quedará el contratista obligado a conformarse con la rebaja acordada.

10. Cuando se juzgue necesario emplear materiales o ejecutar obras que no figuren en el presupuesto de la contrata, se evaluará su importe a los precios asignados a otras obras o materiales análogos si los hubiere y cuando no, se discutirán entre el Ingeniero Director y el contratista, sometiéndolos a la aprobación de la Dirección. Los nuevos precios convenidos por uno u otro procedimiento, se sujetarán siempre al establecido en el punto anterior.

11. Cuando el contratista, con autorización del Ingeniero Director de obras, emplee materiales de calidad más elevada o de mayores dimensiones de lo estipulado en el proyecto, o sustituya una clase de fabricación por otra que tenga asignado mayor precio o ejecute con mayores dimensiones cualquier otra parte de las obras, o en general, introduzca en ellas cualquier modificación que sea beneficiosa a juicio del Ingeniero Director de obras, no tendrá derecho sin embargo, sino a lo que le correspondería si hubiera realizado la obra con estricta sujeción a lo proyectado y contratado.

12. Las cantidades calculadas para obras accesorias, aunque figuren por partida alzada en el presupuesto final (general), no serán abonadas sino a los precios de la contrata, según las condiciones de la misma y los proyectos particulares que para ellas se formen, o en su defecto, por lo que resulte de su medición final.

13. El contratista queda obligado a abonar al Ingeniero autor del proyecto y director de obras así como a los Ingenieros Técnicos, el importe de sus respectivos honorarios facultativos por formación del proyecto, dirección técnica y administración en su caso, con arreglo a las tarifas y honorarios vigentes.

14. Concluida la ejecución de la obra, será reconocida por el Ingeniero Director que a tal efecto designe la empresa.

15. La garantía definitiva será del 4% del presupuesto y la provisional del 2%.

16. La forma de pago será por certificaciones mensuales de la obra ejecutada, de acuerdo con los precios del presupuesto, deducida la baja si la hubiera.

17. La fecha de comienzo de las obras será a partir de los 15 días naturales del replanteo oficial de las mismas y la definitiva, al año de haber ejecutado la provisional, procediéndose si no existe reclamación alguna, a la reclamación de la fianza.

18. Si el contratista al efectuar el replanteo, observase algún error en el proyecto, deberá comunicarlo en el plazo de quince días al Ingeniero Director de obras, pues transcurrido ese plazo será responsable de la exactitud del proyecto.

19. El contratista está obligado a designar una persona responsable que se entenderá con el Ingeniero Director de obras, o con el delegado que éste designe, para todo relacionado con ella. Al ser el Ingeniero Director de obras el que interpreta el proyecto, el contratista deberá consultarle cualquier duda que surja en su realización.

20. Durante la realización de la obra, se girarán visitas de inspección por personal facultativo de la empresa cliente, para hacer las comprobaciones que se crean oportunas. Es obligación del contratista, la conservación de la obra ya ejecutada hasta la recepción de la

misma, por lo que el deterioro parcial o total de ella, aunque sea por agentes atmosféricos u otras causas, deberá ser reparado o reconstruido por su cuenta.

21. El contratista, deberá realizar la obra en el plazo mencionado a partir de la fecha del contrato, incurriendo en multa, por retraso de la ejecución siempre que éste no sea debido a causas de fuerza mayor. A la terminación de la obra, se hará una recepción provisional previo reconocimiento y examen por la dirección técnica, el depositario de efectos, el interventor y el jefe de servicio o un representante, estampando su conformidad el contratista.

22. Hecha la recepción provisional, se certificará al contratista el resto de la obra, reservándose la administración el importe de los gastos de conservación de la misma hasta su recepción definitiva y la fianza durante el tiempo señalado como plazo de garantía. La recepción definitiva se hará en las mismas condiciones que la provisional, extendiéndose el acta correspondiente. El Director Técnico propondrá a la Junta Económica la devolución de la fianza al contratista de acuerdo con las condiciones económicas legales establecidas.

23. Las tarifas para la determinación de honorarios, reguladas por orden de la Presidencia del Gobierno el 19 de Octubre de 1961, se aplicarán sobre el denominado en la actualidad “Presupuesto de Ejecución de Contrata” y anteriormente llamado ”Presupuesto de Ejecución Material” que hoy designa otro concepto.

Condiciones particulares

La empresa consultora, que ha desarrollado el presente proyecto, lo entregará a la empresa cliente bajo las condiciones generales ya formuladas, debiendo añadirse las siguientes condiciones particulares:

1. La propiedad intelectual de los procesos descritos y analizados en el presente trabajo, pertenece por entero a la empresa consultora representada por el Ingeniero Director del Proyecto.

2. La empresa consultora se reserva el derecho a la utilización total o parcial de los resultados de la investigación realizada para desarrollar el siguiente proyecto, bien para su publicación o bien para su uso en trabajos o proyectos posteriores, para la misma empresa cliente o para otra.

3. Cualquier tipo de reproducción aparte de las reseñadas en las condiciones generales, bien sea para uso particular de la empresa cliente, o para cualquier otra aplicación, contará con autorización expresa y por escrito del Ingeniero Director del Proyecto, que actuará en representación de la empresa consultora.

4. En la autorización se ha de hacer constar la aplicación a que se destinan sus reproducciones así como su cantidad.

5. En todas las reproducciones se indicará su procedencia, explicitando el nombre del proyecto, nombre del Ingeniero Director y de la empresa consultora.

6. Si el proyecto pasa la etapa de desarrollo, cualquier modificación que se realice sobre él, deberá ser notificada al Ingeniero Director del Proyecto y a criterio de éste, la empresa consultora decidirá aceptar o no la modificación propuesta.

7. Si la modificación se acepta, la empresa consultora se hará responsable al mismo nivel que el proyecto inicial del que resulta el añadirla.

8. Si la modificación no es aceptada, por el contrario, la empresa consultora declinará toda responsabilidad que se derive de la aplicación o influencia de la misma.

9. Si la empresa cliente decide desarrollar industrialmente uno o varios productos en los que resulte parcial o totalmente aplicable el estudio de este proyecto, deberá comunicarlo a la empresa consultora.

10. La empresa consultora no se responsabiliza de los efectos laterales que se puedan producir en el momento en que se utilice la herramienta objeto del presente proyecto para la realización de otras aplicaciones.

11. La empresa consultora tendrá prioridad respecto a otras en la elaboración de los proyectos auxiliares que fuese necesario desarrollar para dicha aplicación industrial, siempre que no haga explícita renuncia a este hecho. En este caso, deberá autorizar expresamente los proyectos presentados por otros.

12. El Ingeniero Director del presente proyecto, será el responsable de la dirección de la aplicación industrial siempre que la empresa consultora lo estime oportuno. En caso contrario, la persona designada deberá contar con la autorización del mismo, quien delegará en él las responsabilidades que ostente.