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Modulation format comparison in PMD-impaired 40 Gbps systems

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Modulation format comparison in PMD-impaired 40 Gbps systems

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Abstract

This dissertation is on the comparison of several modulation formats to infer which is better suited for PMD (Polarization Mode Dispersion) mitigation.

The comparison is numerically performed using a commercial simulation package, more specifically, Virtual Photonics Interface from VPISystems.

This comparison has been chosen to be performed against PMD since it represents one present impairment in Optical Fibre Communications, that have yet to be successfully tackled. Arising due to refractive index differences between orthogonal axes, in monomode fibres, which are caused by external stresses and manufacturing defects. Extremely hard to compensate for, since its value varies throughout time in a random way, some advances in active compensation systems might hold a promise. Still, the extreme complexity of such systems makes their use prohibitive, thus focusing researchers attention in modulation formats capable of mitigating PMD, or, at least, greatly reduce its effects. This dissertation pursues precisely this aim.

Simulation starts with the most conventional modulation formats: Non Return to Zero and Return to Zero. Although being sure ways to convey information, these have long been disregarded in terms of Optical Fibre Communications, as its simpleness is synonym of poor performance in present fibre links.

Duobinary holds a promise and its resilience to dispersion is a recurrent theme of debate. Imposing different phase to ones interleaved by zeros in a effort to perform some cancellation between ones should dispersion become large, it has, nevertheless a reduced bandwidth which indeed proves to be an advantage in longer fibre spans.

Differential Phase Shift Keying is indeed the most elaborate of the group, as phase is used to convey data, not only this but also the receiver must be specific, far from the conventional PIN diode with simple filters used for all other simulated modulations.

Carrier Suppressed Return to Zero can be considered as reinventing Return to Zero modulation, since suppressing the carrier reduces transmitted power, which is a good measure against nonlinear effects.

This dissertation, therefore, tries to give a clear view on which of these modulation formats is the better countermeasure against PMD.

Resumo

Esta dissertação é sobre a comparação de vários formatos de modulação, para determinar qual o mais adequado para compensar PMD (Dispersão devida à Polarização).

A comparação é realizada através de simulações numéricas, fazendo uso de um pacote de simulação comercial, mais especificamente o Virtual Photonics Interface da VPISystems.

Decidiu-se efectuar esta comparação em relação a PMD já que este representa uma limitação actual nas Comunicações por Fibras Ópticas, que ainda não foi eliminada com sucesso. Surgindo devido a diferenças no índice de refracção entre eixos ortogonais, em fibras monomodo, que são causados por tensões externas e defeitos de fabrico. Extremamente difícil de compensar, já que o seu valor varia ao longo do tempo de uma forma aleatória, alguns avanços em sistemas de compensação activa podem ser uma esperança. Mesmo assim, a complexidade extrema de tais sistemas torna o seu uso proibitivo, focando assim a atenção dos investigadores em formatos de modulação capazes de compensar PMD, ou, pelo menos, reduzir grandemente os seus efeitos. Esta dissertação segue precisamente este objectivo.

A simulação começa com os formatos de modulação convencionais: NRZ e RZ. Embora representem formas simples e fiáveis de transportar informação, têm sido desde há muito descartados em Comunicações por Fibra Óptica, já que a sua simplicidade é sinónimo de fraco desempenho nas ligações por fibra actuais.

O Duobinário apresenta vantagens, sendo a mais importante a sua insensibilidade à dispersão que é um tema recorrente de debate. Impondo diferentes fases aos ums com zeros entre eles para realizar algum cancelamento entre ums caso a dispersão seja grande, apresenta, no entanto uma largura de banda reduzida que de facto prova ser uma vantagem em ligações mais longas.

DPSK é de facto a mais elaborada do grupo, já que a fase é usada para transportar dados, não só por isto mas também porque o receptor tem de ser específico. O díodo PIN convencional com filtros simples usados para todas as outras modulações simuladas, já não pode ser usado.

CSRZ pode ser considerada como uma reinvenção da modulação RZ, já que ao suprimir a portadora a potência transmitida é reduzida, o que é uma boa medida contra efeitos não lineares.

Esta dissertação, tenta, então dar uma visão clara sobre qual destes formatos de modulação é uma contra medida mais eficaz contra PMD.

Acronym List

- CSRZ – Carrier Suppressed Return to Zero
- DCF – Dispersion Compensating Fibre
- DGD – Differential Group Delay
- DI – Delay Interferometer
- DL – Polarization Dependent Change in Chromatic Dispersion
- DPSK – Differential Phase Shift Keying
- FIR – Finite Impulse Response (filter)
- ISI – Intersymbol Interference
- MZI – Mach-Zehnder Interferometer
- NRZ – Non Return to Zero
- NRZ-L – NRZ-level
- PCD – Polarization Chromatic Dispersion
- PDA – Photonic Design Automation
- PM – Phase Modulator
- PMF – Polarization Maintaining Fibre
- PSP – Principal States of Polarization
- RZ – Return to Zero
- VPI – Virtual Photonics Interface

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1 Introduction

Optical Fibre communications have come a long way since their début in the 70s and enormous growth in the 80s, all the way from simple modulation formats and high attenuation, to more complex modulation formats and low attenuation monomode fibres.

What early systems lacked in link length, modern systems gained in dispersion, nonlinear effects and PMD. Since the advent of low attenuation fibres allied with optical amplification, link lengths extended into the hundreds, if not thousands, of Kilometres. At this lengths, impairments that were otherwise negligible became ever more present and started to present serious problems to the ambition of creating longer links.

One of these impairments is chromatic dispersion, owing its name to the fact that different frequencies travel through the fibre at different speed, thus creating large differences in signal arrival times at the end of the fibre. Although proving to be a serious impairment it, nevertheless has a simple, yet effective method of compensation, which involves a negative chromatic dispersion fibre. This fibre can be used at the beginning of the link or at its end. Undoing the ill effects of chromatic dispersion is then a simple exercise of calculating the appropriate length of DCF.

Having one ill effect compensated for is a simple task, one not so simple would be to compensate them all. Such simple compensations as the one for chromatic dispersion are not available for nonlinear effects and neither for PMD.

1.1 PMD as an impairment

PMD is an ill effect, affecting monomode fibres, that is apparent in long links. Arising from birefringence, a refractive index differences in orthogonal modes in the fibre. This, in turn, causes speed differences, and thus, dispersion. This effect would not be problematic if its effect was only this. Some other facts are of importance, especially the cause of this difference in refractive index, which can be accounted to external stresses and manufacturing defects. And these external stresses pose the biggest problem, as they change throughout time, imposing a random characteristic in PMD, this is especially problematic as no static system can compensate it, the only choice is an active one. Not only PMD is random, but it does not grow linearly with fibre length. One might think that randomness could be between known values that would change in a linear fashion as fibre length increased. This is not the case as PMD effect in a fibre can be seen as a divided fibre in sections, each section having random refractive index difference between orthogonal axes, then each section is randomly aligned in respect to each other, meaning that PMD can grow if two sections are aligned in a certain way, and could even decrease if these sections are aligned in another way, this is why PMD increases as fibre length increases, but not linearly. On top of this, there is also the problem of random variation due to external stresses, which can be as simple as temperature change, thus yielding PMD variation, but there are others. For all this PMD is hard to compensate for, so the simplest way would be to have some sort of modulation format that could accomplish this, better yet, one that could be decoded by a conventional receiver like the one commonly used for NRZ and RZ modulations.

1.2 Dissertation Scope

As PMD is so hard to compensate for, its effects could at least be minimized by the use of the correct modulation format. This is precisely what this dissertation intends, to infer which is the most appropriate modulation format for PMD mitigation.

Several modulation formats are put to the test: NRZ, RZ, Duobinary, DPSK and CSRZ. These simulations are performed using the commercial software VPI, from VPISystems, which is very versatile, allowing different types of fibres and combination of these to perform DCF compensation. With this software these modulation formats will be compared in several situations, to determine their behaviour, allowing results to be compared to find each modulation format's merits and flaws.

NRZ and RZ are conventional modulation formats owing their widespread use to their simplicity, this does not account obviously for their dismissal as standards in Optical Fibre Communications since longer links require some more complex approaches to work in consonance with high demands for bandwidth and low error rates.

Duobinary has been gaining a quite a reputation as much investigation work has been developed and its beneficial characteristics have been praised. Since it imposes different phases to ones interleaved by zeros it has the unexpected effect of performing some cancellation between ones in large dispersion situations. One further advantage is its reduced bandwidth which indeed proves to be an advantage in longer fibre spans.

DPSK and CSRZ are new flavours in Optical Fibre Telecommunications and subject of fierce investigation, being the first the most complex, as phase is used to convey data. Its complexity extends not only to the transmitter but also to the receiver which must be specific, unlike the one used for CSRZ and remaining modulation formats in this dissertation. CSRZ is basically a new form of RZ modulation with a suppressed carrier which reduces transmitted power, a good measure against nonlinear effects.

1.3 Dissertation Organization

Having five main chapters, each one dedicated to a particular subject, this dissertation has in each chapter an introductory consideration on the subject, and at the end some final remarks, introducing the reader into the scope of the next chapter.

Chapter two is an in depth look at PMD where its causes and effects are discussed. Its characterization is also discussed.

Chapter three references the modulation formats used throughout this dissertation, each having its own sub chapter, some longer than others whenever modulation format complexity demands it. NRZ and RZ are only briefly discussed. In this chapter are also presented the modulators and demodulators used in VPI.

Chapter four describes briefly VPI's workings and simulation techniques. A brief explanation is also made at some of the most important modules used in simulations.

Chapter five concerns all simulations, having results shown block of histograms for comparison purposes, not only this but also tables are presented whenever necessary to allow for an unambiguous interpretation of the results.

Chapter six discusses the results and conclusion that can be attained from chapter five.

Chapter seven discusses future work than can be done in this subject.

2 Polarization Mode Dispersion

2.1 Introduction

PMD (Polarization Mode Dispersion) is a type of dispersion that, although neglected for years, has lately become of great importance. As system capacities have been pushed to the limit, leading to very long fibre spans, PMD as well as other effects, mainly related to polarization, became more noticeable. Since then, these impairments related to polarization effects have been gaining a greater interest from developers seeking maximum transmission distance and capacity.

Although a simple technique like the use of negative dispersion fibres can mitigate chromatic dispersion, the simplicity of this approach is not suitable for PMD compensation. The problem is that chromatic dispersion is more or less constant throughout time and temperature, while PMD is not. To make compensation even more difficult, simple mechanical stresses can change PMD.

PMD is not an intrinsic characteristic of an ideal fibre. For example an ideal fibre will have no PMD, since PMD is the delay between two orthogonally polarized modes in single mode fibres. If both modes propagate at the same speed they arrive at the end of the fibre at the same time i.e. no delay between the two modes and there will be no PMD.

Unfortunately, the world is not ideal and neither are the fibres, so some amount of PMD may be expected in a fibre. One cause is manufacturing defects and the other is mechanical stresses. These causes lead to an effect called birefringence, which means that the fibre has different refractive indexes for each orthogonal mode. This makes modes travel at different speeds, and that means they will arrive at the end of the fibre at different instants, so there will be a delay between them and we have PMD. Not only this is an impairing effect, but the orientation of birefringent axes changes randomly throughout the length of the fibre, making it even harder to compensate for. Obviously, this effect is not to be dealt with if transmission rate is slow. Since dispersion effects are bitrate and thus bit period dependent, the faster the transmission rate we have, the worse dispersion will be. When PMD value is a good part of the bit period, normal operation of the system is compromised.

In this chapter, the underlying causes of PMD, what makes it a random phenomenon and why it is so hard to compensate for, will be discussed to a greater depth.

2.2 Birefringence

PMD is caused by birefringence in the fibre. Birefringence is a phenomenon common to crystals of calcite $(CaCO_3)$, where a light beam is split into two beams, each going through different routes

Fig. 2.1 A calcite crystal laid upon a paper with some letters showing birefringence effect [Image Released to the public domain by Adrian Pingstone in May 2003]

inside the crystal. In Fig. 2.1 we can see two different images of the letters underneath the crystal. Although this phenomenon has a detrimental effect in what we see through the crystal, the problem it causes to communication systems is much more serious.

Here we see two images, and since we are reading a text from a static piece of paper, the presence of birefringence still allows us to read the text, even with some effort. By now, we can suspect that the effect in a communication system that uses pulsed or modulated light beams is far more troublesome.

What makes birefringence problematic for communication systems is a fact that can be considered as a defiance of common sense: in a single mode fibre we have two modes. At this point, we may think that there is some sort of trick in this sentence, perhaps it is implying that at a given light frequency a single mode fibre becomes multimode or some other case? None of the two, but rephrasing may help: an ideal single mode fibre has two orthogonally polarized HE_{11} modes. Although this goes against common sense, this is true, and it can be explained by the fact that we can inject polarized light from a laser in a monomode fibre, rotate it 90º and inject light again, if the fibre is short or ideal with no interference between the two modes, both polarizations can be recovered at the other end of the fibre. So, if a fibre can carry two orthogonal modes in two different instants, then it can carry both modes at the same time. Furthermore if there was only one mode in a single mode fibre, there would be no PMD. But there can be no PMD in a perfect fibre with these two modes; again the fibres manufactured today are real and not ideal, so there will be PMD.

The two polarization modes are caused by manufacturing defects, and are therefore named intrinsic perturbations, which in turn cause birefringence to occur in the fibre. Some of the most relevant are: noncircular core which will cause geometric birefringence and nonsymmetrical stress fields in the glass around the core which will cause stress birefringence, in Fig. 2.2 both perturbations can be easily seen.

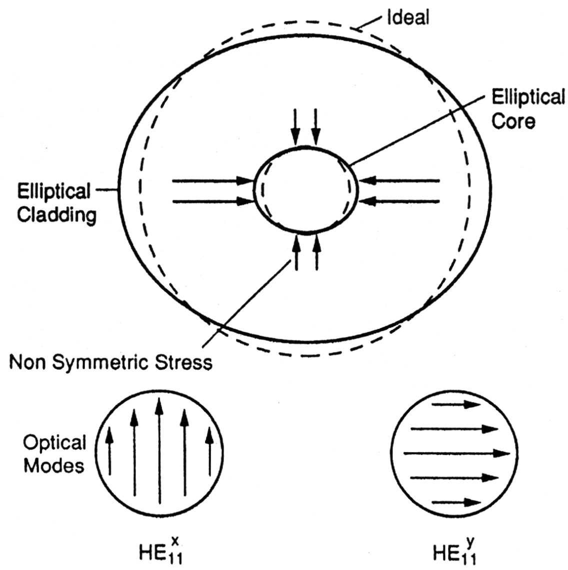


Fig. 2.2 Optical Fibre manufacturing defects and optical modes [1]

One might think that techniques have evolved past intrinsic perturbations and that we can now manufacture a very perfect circular stress free fibre. The answer is: yes we can, but merely 1% deviation of a perfect circle in the core can result in a great deal of PMD, this degree of precision would not be so hard to achieve if the fibre section was big, but it is so small, that these microscopic tolerances are hard to maintain.

Extrinsic perturbations occur when the fibre is exposed to external perturbations such as cabling, transport or installation, these perturbations are also a cause of birefringence. In these situations the fibre will be subject to compression, bending and twisting, as seen in Fig. 2.3.

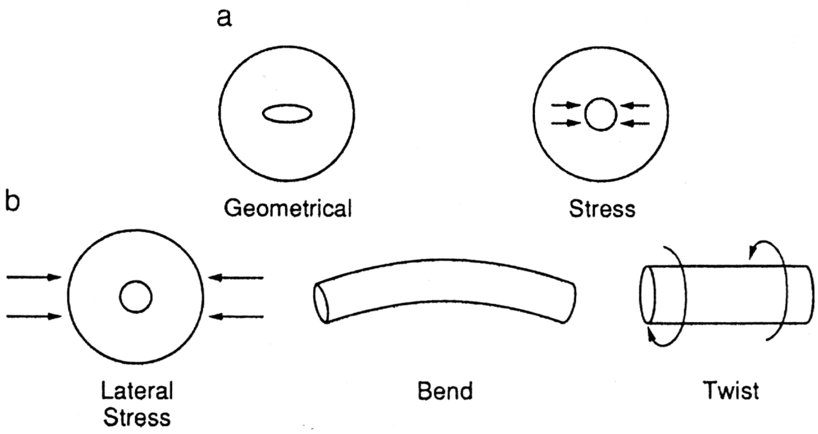


Fig. 2.3 a) Intrinsic and b) extrinsic mechanisms of fibre birefringence [1]

Birefringence in a fibre is not uniform, it varies throughout the fibre as stress and manufacturing quality varies, but in short lengths, birefringence can be considered to be uniform, as long as in the considered region the fibre has constant perturbations. The difference between propagation constants of both modes is given by the following equation [2]:

$$\Delta\beta = \frac{\omega n_s}{c} - \frac{\omega n_f}{c} = \frac{\omega \Delta n}{c} \qquad (2.1)$$

being ω the angular optical frequency, c the speed of light in vacuum and $\Delta n = n_s - n_f$ the difference of refractive index between both orthogonal modes (named slow and fast). Since there is a difference in speed from these two orthogonal modes, there can be the case that polarization changes throughout the fibre. This is clearly seen when we inject linearly polarized light into the fibre in a way that both birefringent axes receive power. As each component propagates with

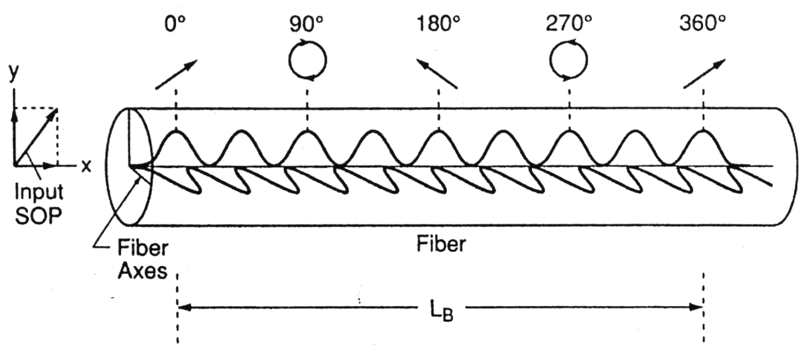


Fig. 2.4 Changes in polarization throughout a fibre caused by birefringence [1]

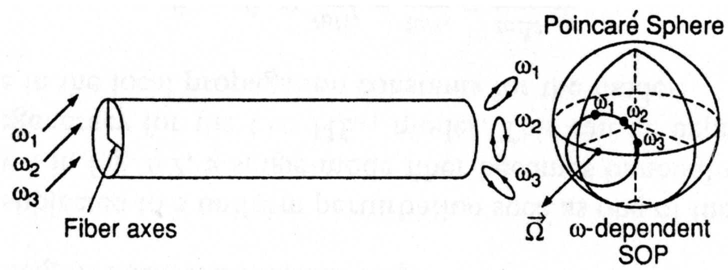


Fig. 2.5 Depiction of polarization change due to PMD in a short fibre when the light frequency is changed, the output is the circle while the input is vertical polarized light [1]

different speed, at each length of fibre we have a different polarization changing from linear at 45º to elliptical, then to circular and elliptical again back to linear polarization; this last polarization is opposite to the initial one, therefore -45º. The process is repeated until we have the initial polarization and is repeated over and over as seen in Fig. 2.4. Also this phenomenon happens when we have a short fibre and we change the light frequency. This is easy to see in a Poincaré sphere as seen in Fig. 2.5.

The Poincaré sphere is a visual representation of light polarization, which is represented by a point in a sphere where the three axes represent: vertical polarization, 45º polarization and right circular polarization. The opposite point of each of these axes represent the opposite polarization, being horizontal polarization for vertical polarization, -45º polarization for 45º polarization and left circular polarization for right circular polarization. We can represent any type of polarization by choosing any point in the sphere, thus we can have any combination of two or three of the original polarizations.

One interesting phenomenon occurs due to PMD, as the injected light in the fibre changes frequency, the output light changes frequency and also polarization. This can be best seen in a Poincaré sphere as in Fig. 2.5 and Fig. 2.6.

At this point there is one new characterization parameter that can be inferred, thus represents the length of fibre that makes light polarization change back to the original polarization. As seen before polarization changes throughout the fibre in a cycle, so this length is a measurement of the polarization cycle. This measurement is called beat length and can be expressed by [2]:

$$L_b = \frac{\lambda}{\Delta n} \tag{2.2}$$

being the distance it takes to build a difference of 2π between both modes.

Usually beat lengths are around 10m which leads to an index difference of roughly 10^{-7}, a value much smaller than that of the difference between core and cladding. This makes sense, since fibre

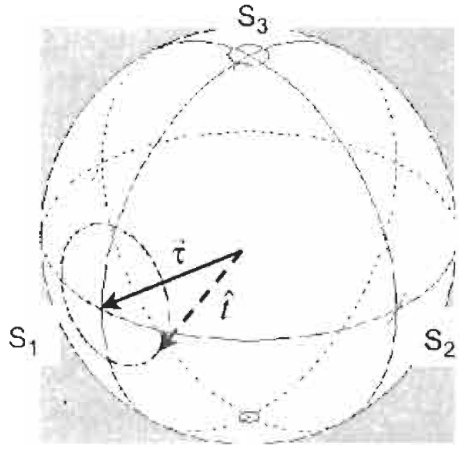


Fig. 2.6 Depiction of polarization change due to PMD in a short fibre when the light frequency is changed, the output is the circle while the input is vertical polarized light [2]

core is made from only one type of material, at least in step-index fibres. It would not be logical that refractive index differences between the same material were bigger that refractive index differences between different materials (core and cladding). As this value 10^{-7} proves, being smaller than the usual refractive index difference between core and cladding, which is usually $\sim 3\times10^{-3}$. Index differences in the core are in the range of 10^{-5} to 10^{-7}.

There are some fibres that have a bigger index difference, although not as big as the difference between core and cladding. These fibres are called Polarization Maintaining Fibres (PMF), this bigger index difference makes them have a beat length of about 3mm.

Another essential characteristic is the Differential Group Delay (DGD), this is a measure of the difference between slow and fast modes and is defined by [2]:

$$\frac{\Delta\tau}{L}=\frac{d}{d\omega}\left(\frac{\Delta n\,\omega}{c}\right)=\frac{\Delta n}{c}+\frac{\omega}{c}\frac{d\Delta n}{d\omega} \qquad (2.3)$$

this formula shows an intrinsic PMD Δτ/L, usually expressed in picoseconds/Km; this concept is only used when birefringence is uniform in a short fibre, never for long fibres. Keeping this in mind

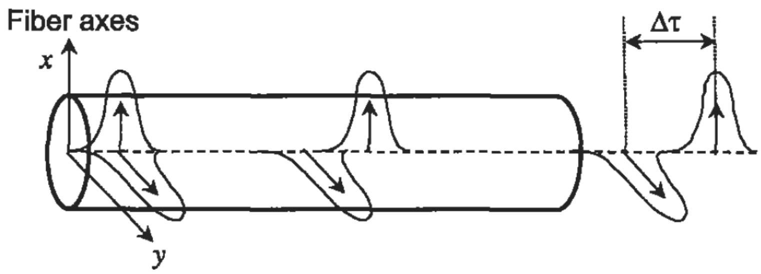


Fig. 2.7 PMD effect in a short fibre, a single pulse is split in two and one is delayed in comparison with the other, this difference Δτ is DGD [2]

PMD could be seen as a delay of one pulse in respect to the other like in Fig. 2.7. The difference in the output of the two signals is DGD and is expressed by Δτ.

But how much DGD do we have in a single optical cycle or beat length L_b ? The answer is [2]:

$$\Delta \tau_b = L_b \frac{\Delta n}{c} = \frac{\lambda}{c} = \frac{1}{v} \tag{2.4}$$

which can be 5.2fs at 1550nm for example.

2.3 Polarization Mode Coupling

One might think, from what was seen before, that the most effective countermeasure to PMD is to transmit and receive using one propagation mode and discard the other. It might seem that in this way we can avoid dispersion due to PMD since we will be selecting one signal from one mode and not both signals from the two orthogonal modes, therefore producing DGD. If we can detect the axes alignment, this is possible to do, but only in short fibres. After a reasonable length of fibre, the effect of PMD is greater, since a longer fibre will make the DGD greater as the signal from one mode travels faster than the other for a longer time, because the fibre is longer. So the longer the fibre, the bigger the PMD, but not linearly bigger. In long fibres the axes vary in a random way throughout the fibre, this causes polarization-mode coupling. A long span of fibre can be seen as a large sequence of short fibre segments, each of these spans will have its own orientation. These segments have different orientation that vary in a random manner, this variation will cause polarization-mode coupling.

So, Polarization-mode coupling is a phenomenon that occurs when slow and fast polarization modes from one fibre segment are fed into slow and fast polarization modes of the next segment, and this is done in such a way that the signal that was in the fast mode of the first segment is not completely fed to the fast mode of the next segment, so at each segment both signal are mixed a certain amount depending on the angle the second segment has when compared to the first segment. A good example of this can be seen in Fig. 2.8. Not only this angle difference occurs but also each segment has different propagation speeds between slow and fast axes.

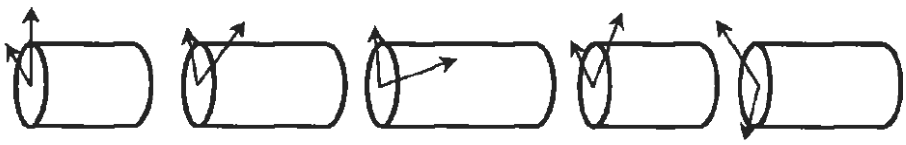


Fig. 2.8 Randomly oriented fibre section and with different propagation speeds that make up the model of a long fibre [2]

Polarization-mode coupling occurs from stresses and manufacturing defects, just like PMD. Mode coupling may or may not have a detrimental effect in overall PMD, depending on the orientation of the axes and their magnitude.

It is straightforward to understand how polarization-mode coupling prevents PMD from increasing linearly throughout the fibre to unconpensatable levels. Let's imagine that we have two fibre sections with same propagation speed difference, one is rotated 90º so that the fast axis of the first is aligned with the slow axis of the second and vice versa. The first section causes PMD since there is a propagation speed difference between both modes. When light propagates to the second section the mode that propagated faster will now propagate slower and to the other happens the opposite. At the receiver end, both signals will arrive at the same time, since they faced the same delay. The second section eliminated PMD. There is an extremely low probability that this exact occurrence may happen, especially in a long fibre. This example shows that PMD can be reduced, or not grow so fast, due to polarization-mode coupling.

This effect makes DGD grow in a distinct manner from fibre length growth. If a fibre span is long enough, DGD grows on average with the square root of distance. Yet another way to characterize a fibre is by it's correlation length L_c, also called coupling length. This parameter is used to characterize random polarization modes alignment of a fibre with mostly uniform birefringence and subject to random external perturbations. So, for a fixed input polarization, such as light from a laser, the probability of each output polarization is the same, whatever that polarization is. Throughout the fibre, polarization is characterized by $\langle p_x \rangle - \langle p_y \rangle$, the average of all powers in x and y polarizations. If we have a laser at the input then we have $\langle p_x \rangle = 1$ and $\langle p_y \rangle = 0$, the difference starts from the value 1 at the start of the fibre, at the end of a long fibre we have the value 0. Having seen this, L_c is the point where this difference is $\langle p_x \rangle - \langle p_y \rangle = 1/e^2$. Typical correlation lengths are less than one meter for spooled fibre and roughly 1Km for cabled fibre, but almost any force and manufacturing defects or processes can affect these values.

So far we have seen these two types of PMD growth with distance: the one for short fibres and the one for long fibres, but what defines the boundary between these two is in fact L_c . We can consider a fibre short, in relation to PMD, when the fibre satisfies $L \ll L_c$ and DGD increases linearly with distance. But for $L \gg L_c$ the fibre is considered long and DGD grows with the square root of distance. Notice that as ">>" was used before, there is a boundary region where a fibre is not short nor long, in relation to PMD obviously. In this region we can call the fibre length intermediate.

Considering typical correlation length values stated earlier, it is easy to verify that most communication systems use long fibres, so PMD is usually measured in $ps/(Km)^{1/2}$. Typical values for present fibres are $0.1\, ps/(Km)^{1/2}$ and for obsolete fibres $0.8\, ps/(Km)^{1/2}$.

Since PMD varies randomly, it makes sense that it is treated statistically. The expression that links mean square DGD of a fibre to L_b and L_c that is valid for short, intermediate and long fibres can be seen in Eq. 2.5 [2].

$$\langle \Delta\tau^2 \rangle = 2\left(\Delta\tau_b \frac{L_c}{L_b}\right)^2 (L/L_c + e^{-L/L_c} - 1) \tag{2.5}$$

If we have $L \ll L_c$ the equation is simplified to [2]:

$$\sqrt{\langle \Delta\tau^2 \rangle} = \Delta\tau_{rms} = \Delta\tau_b L/Lb \tag{2.6}$$

and for $L \gg L_c$, we will now have [2]:

$$\Delta\tau_{rms}=(\Delta\tau_b/Lb)\sqrt{2LL_c} \quad (2.7)$$

Both represent well DGD relationship with fibre length, being one linear and the other growing with the square root of distance.

2.4 The Principal States Model

This chapter starts with a surprising fact: in a short or long fibre for a given wavelength we can always find two orthogonal polarization modes at the input that will make the output signal undistorted in respect to PMD. Given the randomness of polarization modes orientation, this is in fact surprising, so we can choose to inject the signal aligned with each one of the two axes available and thus the pulse will travel faster or slower depending on the selected axis, this is immediately apparent in Fig. 2.9.

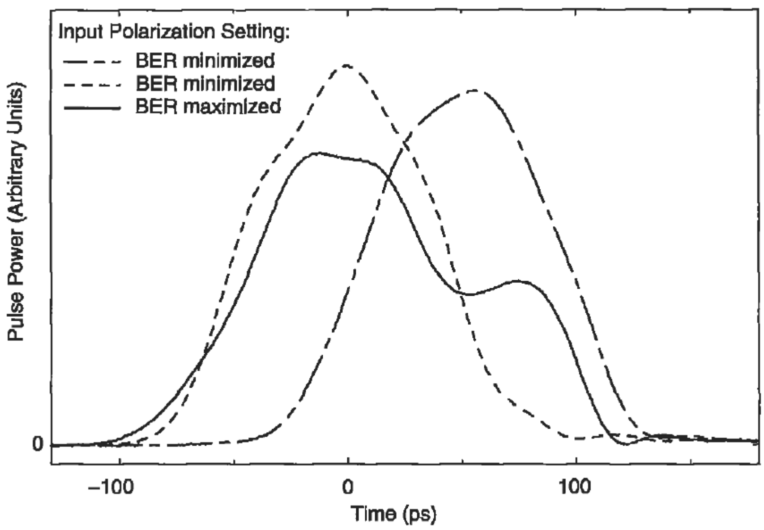


Fig. 2.9 Output pulses for three different polarizations at 10Gb 50% duty cycle RZ signal in a 48Km fibre with 60ps DGD, dashed and dot-dashed pulses show polarizations alignments that eliminate distortion and thus BER, the solid line was selected to maximise distortion and BER [2]

As can be seen, there is a difference in the arrival of both pulses that minimizes BER, this is due to the fact that one is travelling using the equivalent of the fast axis and the other uses the equivalent of the slow axis, this difference in arrival time of both pulses is the DGD. The third pulse is more distorted than the others since it was not launched with the polarizations that minimizes pulse distortion, since there are only two polarizations that allow BER to be minimized and pulses undistorted due to PMD, all the others induce some distortion. To achieve this result, pulse bandwidth must be small and pulse length must be greater than DGD, because PMD is an interference phenomenon, and its effect is due to the adding of pulses that have been previously split in both axis of previous sections. In the case of a large bandwidth input pulse we will have several output pulses and not only one for each mode, as seen here.

The model used to characterize PMD is the Principal States Model, originally developed by Poole and Wagner. This model has time and frequency characterization of PMD. For frequency domain, the definition states that for a given length of fibre and for a given frequency there are two polarization states, named Principal States of Polarization (PSP) that make the output polarization independent of frequency in the first order, or in a small frequency range. If there is no polarization dependent loss, these PSP are orthogonal, which means that for each pair of input PSP, there is also a pair of output PSP that are orthogonal. As with any output polarization that is related to the input polarization by means of the fibre transmission matrix, PSP shares this property.

2.5 PMD Vector

Under the Principal States Model, PMD is characterized by the PMD vector [2]:

$$\vec{\tau}=\Delta\tau\,\hat{p} \tag{2.8}$$

this vector is in Stokes space where $\Delta\tau$ corresponds to DGD. The vector $\hat{p}$ points in the direction of the slow PSP and the vector $-\hat{p}$ points in the direction of the orthogonal fast PSP. In Stokes space, both vector have π difference. The relationship between input and output PMD vectors is $\vec{\tau}=R\vec{\tau}_s$ where $\vec{\tau}_s$ is the input vector; now the derivative of $\hat{t}=R\hat{s}$ leads to the law of infinitesimal rotation [2]:

$$\hat{t_\omega}=\frac{d\hat{t}}{d\omega}=\vec{\tau}\times\hat{t} \tag{2.9}$$

where $\vec{\tau}\times=R_\omega R^T$ and R^T is the transpose of R. This in turn describes how the output polarization $\hat{t}$ makes a circle around $\vec{\tau}$ as the frequency varies as seen in Fig. 2.6. The direction of $\hat{t}$ relative to $\vec{\tau}$ determines the angle of rotation and the magnitude, $\Delta\tau$ determines the rate at which one revolves around the other. In a worst case scenario, being the best case scenario the one where we inject light which has a polarization that is one of the PSP, we are injecting light with equal power in both PSP, then $\vec{\tau}\times\hat{t}$ will have its largest value and the largest change in output polarization will happen whenever there is a frequency change $\Delta\omega$. The rotation will have magnitude $\phi=\Delta\tau\Delta\omega$ being ϕ the rotation angle on the Poincaré sphere. If $\hat{t}$ is aligned with $\pm\vec{\tau}$, then there will occur no rotation in the Poincaré sphere and there will also be no alterations due to changes in frequency, this means that light is being injected with polarization equal to one of the PSP. Polarization maintaining fibres (PMF) have constant PMD vectors that do not change with frequency, as seen in Fig. 2.6 we will have a circle traced in the Poincaré sphere as frequency changes, but in real fibres both the length and direction of the PMD vector changes with frequency as in Fig. 2.10.

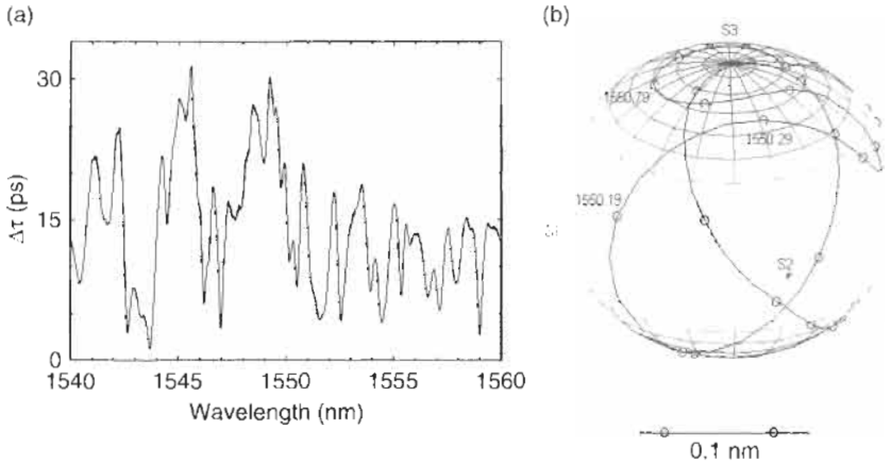


Fig. 2.10 Measurement of the PMD vector using a 14.7ps mean DGD fibre, in (a) we can see the vector magnitude as frequency changes, in (b) we can see the direction of the slow PSP as frequency changes, markers indicate 0.1nm wavelength intervals [2]

The rotation law still applies here but only locally, the change in direction of $\hat{t}(\omega)$ are arcs for small changes in frequency. For such small frequency changes the behaviour of real fibres is similar to that exhibited by PMF fibres, the vector describes circles in the Poincaré sphere. As DGD varies throughout frequency, we can expand it into two different concepts. Instantaneous DGD is, as the name states, the DGD for a given instant, frequency related in this case. Mean DGD is the average of all the instantaneous DGDs.

Higher order PMD explains the fact that a complete circle is not present in the Poincaré sphere in Fig. 2.10, but the output polarization makes arcs with different radii throughout the Poincaré sphere. Because we are changing frequency, we need a continuous wave, but when we are dealing with DGD measurement, as seen earlier in this chapter, we use pulses which in turn lead to an alternative physical interpretation when we are making a relationship between the DGD parameter $\Delta\tau$ and the rotation speed seen before. This time domain view uses Jones vectors to characterize polarization and a transmission matrix that relates the input to the output vectors that are $|s>$ and $|t>$; in this way $|s>=T|t>$, the PSP vectors are $|p>$ and $|p->$, corresponding to stokes vectors $\hat{p}$ and $-\hat{p}$ previously seen. Usually, polarization can be determined by an orthogonal basis, in this case the PSP can be a basis for the characterization of the polarization, so any vector can be a sum of two components, or the two polarizations that are the PSP; using this notation, the output electric field from a fibre would be [2]:

$$\vec{E}_{out}(t)=a|p>E_{in}(t-\tau_0-\Delta\tau/2)+b|p->E_{in}(t-\tau_0+\Delta\tau/2) \qquad (2.10)$$

where $E_{in}(t)$ is the input electric field, a and b are coefficients to determine the field amplitude launched in the fibre aligned with both PSP, τ_0 is the transmission delay not dependent on polarization delay, finally $\Delta\tau$ is the DGD, as seen before. This equations shows us that PMD occurs when light with a polarization that can be divided into both PSP is injected in the fibre, since $\Delta\tau$ is preceded by different signs in each part of the equation, the effects will be the opposite to the light belonging to each PSP, so, in the end there will be a difference in arrival time of both modes, that difference is $\Delta\tau$ and we have PMD. Conversely if light is injected with a polarization aligned with one PSP there will be no DGD, and therefore no PMD since one part of the equation is equal to zero and $\Delta\tau$ will only add or subtract to total delay, this was not the case before.

2.6 Second Order PMD

We have already seen that the PMD vector changes as frequency changes, usually for large signal bandwidths a Taylor series expansion of $\vec{\tau}(\omega)$ is used, using the variation $\Delta(\omega)$ around the carrier frequency ω_0 [2]:

$$\vec{\tau}(\omega_0+\Delta\omega)=\vec{\tau}(\omega_0)+\vec{\tau}_\omega(\omega_0)\Delta\omega+... \qquad (2.11)$$

and second order PMD is described using the following derivative [2]:

$$\vec{\tau}_{\omega} = \frac{d\vec{\tau}}{d\omega} = \Delta\tau_{\omega}\hat{p} + \Delta\tau\,\hat{p}_{\omega} \tag{2.12}$$

where the subscript ω indicates differentiation. Since $\hat{p}_{\omega}$ is not an unit vector and is perpendicular to $\hat{p}$, which means that $\hat{p}\cdot\hat{p}_{\omega}=0$, the first term on the right hand side is $\vec{\tau}_{\omega}\|$, or the component

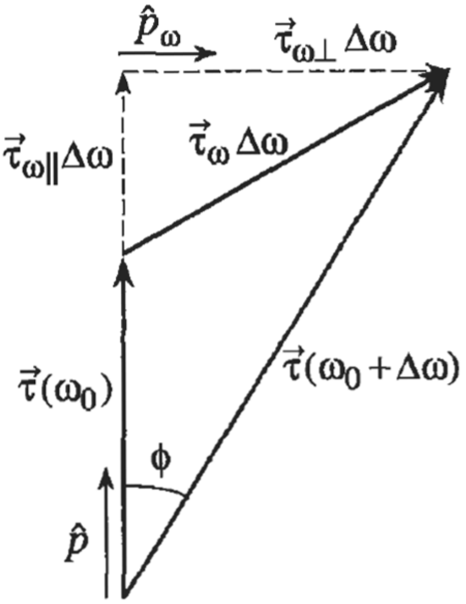


Fig. 2.11 PMD vector $\vec{\tau}(\omega)$ and second order PMD components [2]

of $\vec{\tau}_{\omega}$ that is parallel to $\vec{\tau}$, and conversely the second term is $\vec{\tau}_{\omega}\perp$, or the component of $\vec{\tau}_{\omega}$ that is perpendicular to $\vec{\tau}$. In Fig. 2.11 we see a diagram depicting these vectors.

As seen before, $\Delta\tau_{\omega}$ is the change of DGD due to the change in frequency, which causes chromatic dispersion that is polarization dependent (PCD). Chromatic dispersion causes pulse compression and broadening, and in this case the compression and broadening are polarization dependent, so, as we change the light frequency, we are making a polarization dependent change in the chromatic dispersion; this is Polarization Dependent Change in Chromatic Dispersion (DL) and is described by an effective dispersion [2]:

$$(DL)_{eff} = DL \pm \tau_{\lambda} \tag{2.13}$$

and PCD is defined as [2]:

$$\tau_{\lambda} = -(\pi c/\lambda^2)\Delta\tau_{\omega} = \frac{1}{2}\frac{d\Delta\tau}{d\lambda} \tag{2.14}$$

PCD is then proportional to the wavelength derivative of the DGD spectrum. Note that the $\pm$ signs in Eq. 2.13 correspond to the alignment with both PSP, and the magnitudes $\vec{\tau_\omega}\|$ and $\Delta\tau_\omega$ are equal, finally $\Delta\tau_\omega \equiv \tau_\omega$ sign is negative whenever $\vec{\tau_\omega}\|$ points in the opposite direction of $\hat{p}$. Next we see the PCD from the fibre in Fig. 2.12.

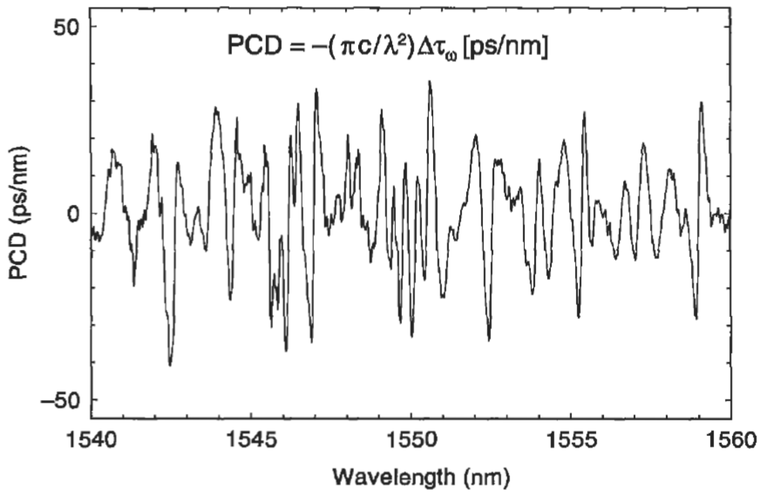


Fig. 2.12 Result of the numeric differentiation of DGD values in Fig. 2.10, the result is Polarization Chromatic Dispersion (PCD) [2]

From this we can see that PCD makes the effective dispersion change rapidly with PMD, this means that slight variations in laser light frequency will cause a much faster dispersion change than the one we would have if we only experienced first order PMD. The second term $\Delta\tau\,\hat{p}\omega$ describes the rotation of PSP with changes in frequency, since PMD changes due to frequency changes, it is only normal that there will also be a change of the PSP. This phenomenon is named PSP depolarization and its effects are overshoots and added signal of satellite pulses.

2.7 Final Remarks

This chapter has covered ground in what concerns the main impairment covered in this dissertation. The simplest countermeasure against PMD is a modulation format, these will be covered in the next chapter, its merits and downfalls can be perceived by comparing special techniques used to convey information.

3 Optical Modulation Formats

3.1 Introduction

For as long as there is some form of telecommunication, be it the most advanced or a more primitive form, there have always been some sort of modulation formats. Ever since the sound modulation using a drum performed by cave dwellers, or the famous modulation of a column of smoke, up to the most advanced bandwidth saving modulations used in cutting edge dense wavelength division multiplexing systems.

Being the primitive, not referred as modulations, to the modern modulations, named of its own right, all are needed to perform communication, since a continuous signal or a signal that transmits only one bit is incapable of information transmission, since its state is predictable at all times.

As stated there have been evolutions, throughout time, and concerning fibre optics, this is more so, we are far from the simplicity of NRZ and RZ, since the capacity of optical fibres have been drawn to its limit, new modulation formats have come forth since, enabling new transmission distances to be conquered.

In this chapter all modulation formats used in the simulations will be covered. The most complex ones, Duobinary and DPSK, will have an approach with greater depth, since they are more complex to modulate and demodulate.

3.2 NRZ

Non Return to Zero is the simplest possible modulation format. Having been used throughout time, as its simplicity seldom limited its capacity. Nowadays this is not true any more, NRZ simplicity did not stand the high data rates demanded by telecommunication systems. In fibre optics NRZ has suffered a set of evolutions until its performance became unacceptable as for example the change from direct modulation of the laser to indirect modulation, where laser generates a continuous wave and an MZI is used to modulate light.

NRZ in its simplest form NRZ-Level (NRZ-L) is modulated in the following way: a one is represented by light occupying the whole bit period, when there is no light throughout the bit period we have a zero; an alternative approach is where the correspondence of one to light is inverted, and now zero corresponds to light. Both alternatives work in the same way and share the same problems. Lets admit for the sake of coherence that a one implies transmitted light and a zero means no light transmission.

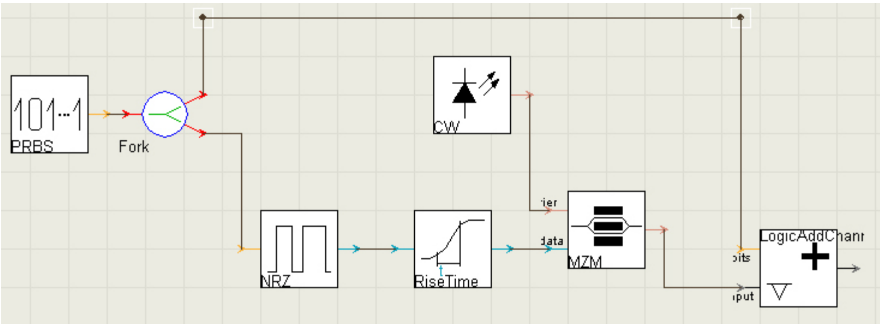


Fig. 3.1 NRZ modulator

The main problems of NRZ modulation are: no error monitoring or correcting capabilities and no clock information. One consequence of these problems is the baseline wander effect, that occurs whenever there is a long sequence of ones. The low frequency AC-coupling filter at the receiver

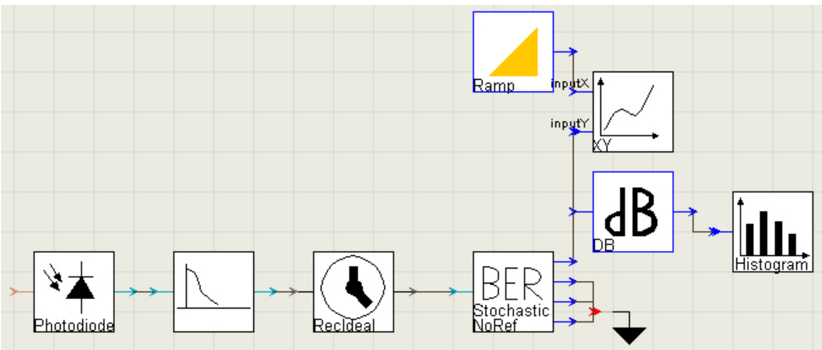


Fig. 3.2 NRZ receiver, and BER estimator, this receiver is used for all modulations except DPSK

causes the signal to lower its amplitude, the first zero will experience a pulse tail, then the filter will cause this tail to be reduced and normal operation to be restored. The problem arises whenever the next one has a low amplitude, since, due to the baseline wander, signal amplitude is lower than normal, as seen in Fig. 3.3.

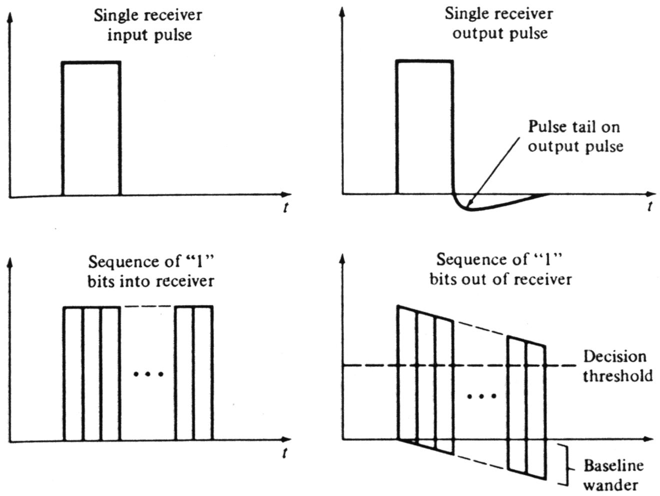


Fig. 3.3 Baseline wander in NRZ transmission [3]

A long sequence of ones or zeros can also lead to the other mentioned problem, the lack of clock information. Since the sequence of ones is a continuous signal, there are no transitions and therefore no clock information, which means that the receiver must have a very precise clock or an external clock source, which leads to extra cost. To prevent the appearance of a long sequence of ones, the

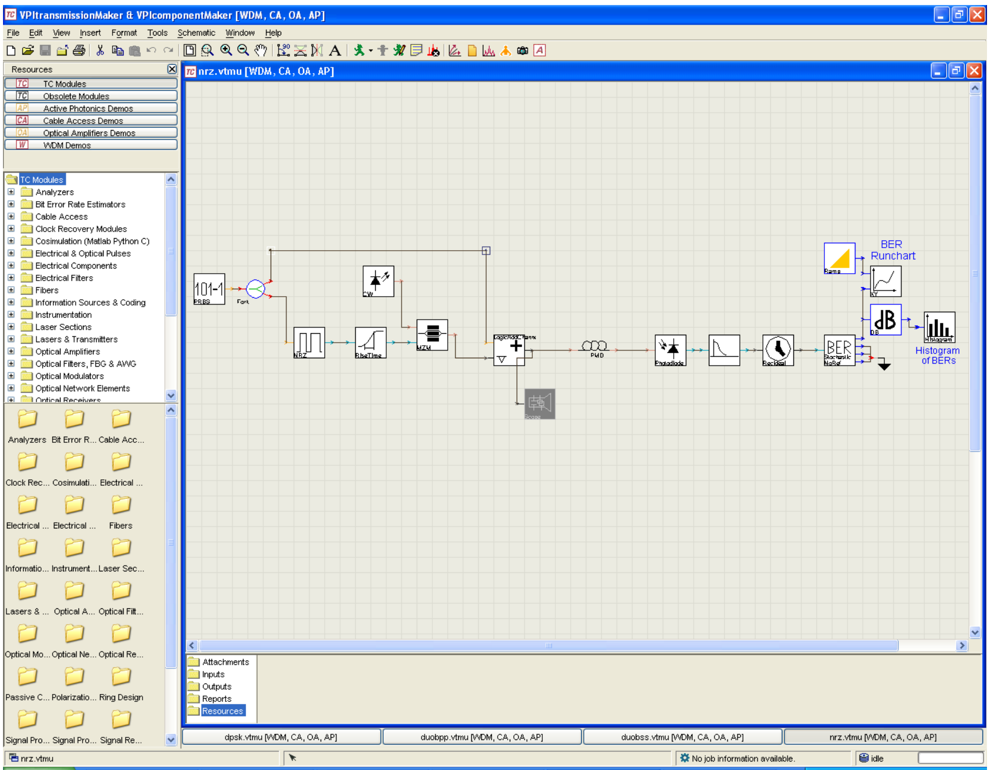


Fig. 3.4: NRZ modulation simulation set-up

signal can be scrambled, this is accomplished by a modulo-2 addition of the original bit sequence with a known bit sequence, which will case the signal to have a pseudo random component, thus reducing the probability of long sequences of ones. But alas this also adds unwanted complexity to the transmitter as well as the receiver.

Even with some drawbacks NRZ is still important as a base for experiment or comparison, as used in this dissertation.

3.3 RZ

The last problem discussed in the NRZ chapter, leads us to another solution, other than the ones previously discussed. The problem was the lack of clock information, as there was a possibility of a

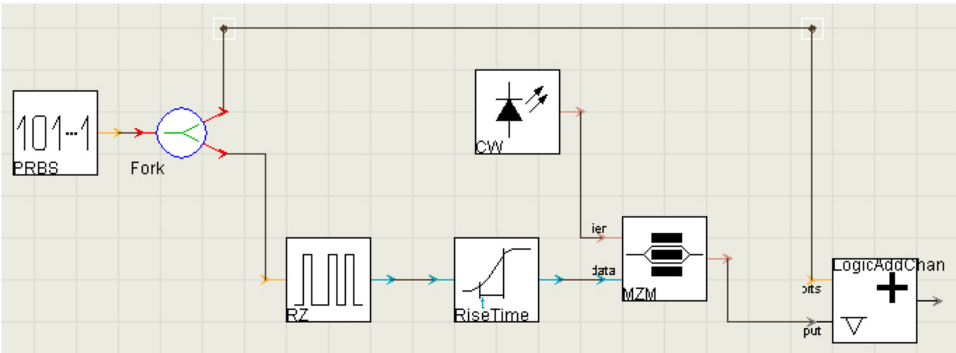


Fig. 3.5 RZ modulator

long sequence of ones, preventing the receiver to obtain good clock synchronization. To solve this in a simple manner, a new modulation format was created, Return to Zero (RZ). Unlike NRZ, RZ is still used extensively today in cutting edge technologies like ethernet, although not in its original form, but as Manchester coding, a special case of RZ.

In RZ modulation, there is a transition for every one, which means that, no matter how long a sequence of ones is, clock information is always present, unless there is a long sequence of zeros. This problem arises because a zero is coded in the same way as in NRZ, no light transmission. To solve yet this problem, Manchester coding was proposed. In this code, every bit has a transition, which means that it is unaffected by long sequences of ones and zeros. There is one problem with RZ modulations, the bit transitions lead to an increase in signal bandwidth, which, depending on the transmission system can present problems, like added chromatic dispersion which is bandwidth dependent.

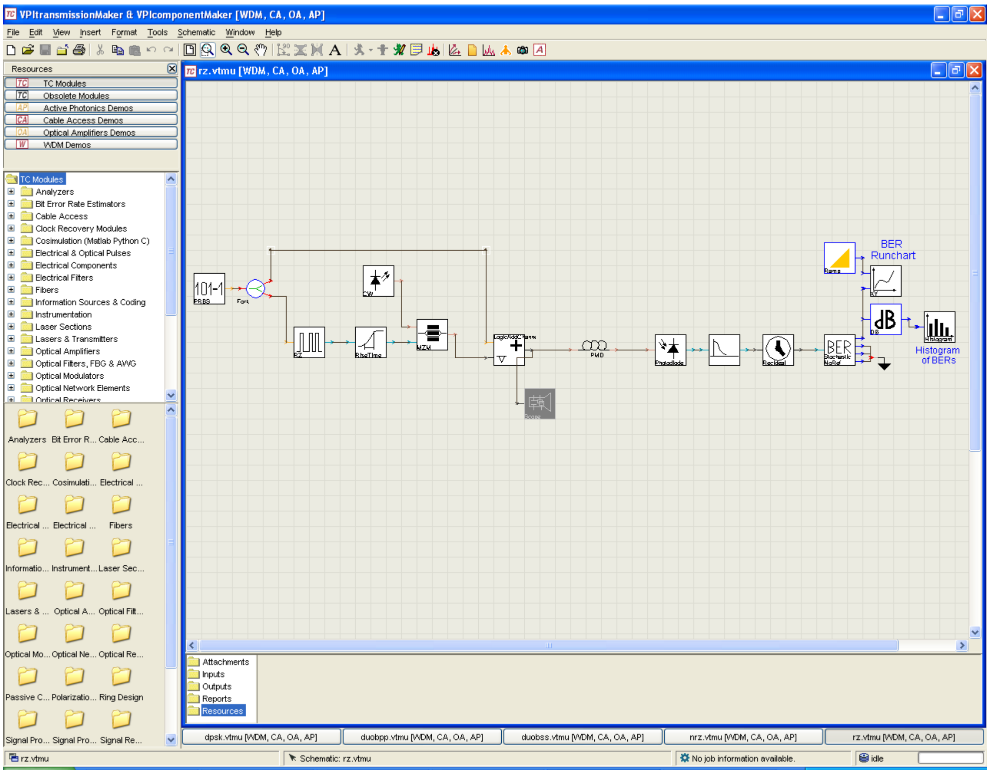


Fig. 3.6: RZ modulation simulation set-up

3.4 Duobinary

3.4.1 Introduction

NRZ modulation has been extensively used for decades, not only because it is easier to implement but also because it makes sense. If we want to transmit one bit of information that is binary, we have only to turn a laser on or off. Unfortunately even NRZ modulation uses far too much bandwidth for the amount of data being transmitted nowadays. This obviously causes unwanted dispersion, although this can be compensated for by using a fibre with negative dispersion. In the case where we have uncompensated single mode fibres NRZ turns out to be a poor choice. Designers are forced to choose another modulation format, one that ideally should be simple to implement and that would be more resilient to dispersion, in this case the modulation format of choice is Duobinary.

3.4.2 Working Principles

In a short theoretical approach, Duobinary is a modulation scheme that transmits R bits/s using less than R/2 Hz of bandwidth. Shannon theory tells us that the maximum transmission rate for an error free transmission is [4]:

$$C = W \log_2\left(1 + \frac{S}{W N_0}\right) bits\ per\ second\ (b/s) \qquad (3.1)$$

where W is the channel bandwidth, S is the average signal power and N_0 is the Gaussian noise power in a one cycle band. Concurring with this, the Nyquist-Shannon theorem states that: when sampling a signal (e.g. converting from an analogue signal to digital) the sampling frequency must be greater than twice the bandwidth of the input signal in order to be able to reconstruct the original from the sampled version. So because Duobinary modulation has a sampling frequency that is less than twice the bandwidth, one should not be able to reconstruct the signal from the sampled or transmitted version due to intersymbol interference (ISI). Actually this is not true since ISI is induced in a controlled manner, and it can easily be subtracted, enabling us to recover the original signal.

The transmitted signal is then [5]:

$$x(t) = \sum_{k=-\infty}^{\infty} d_k q(t - kT),\ d_k = 0,1 \qquad (3.2)$$

where $\{d_k\}$ are data bits, $q(t)$ is the transmitted pulse, $T = 1/R$ is the bit period, and the pulse $q(t)$ is usually chosen so that there is no ISI at the sampling instances, which are $t = kT$, $k = 0,1 \pm 1, \ldots$, so for NRZ we have [5]:

$$q(kT) = \begin{cases} 1 & k = 0 \\ 0 & k \neq 0 \end{cases} \qquad (3.3)$$

which transmits R bits/sec using R Hz so there is no ISI since the Nyquist bandwidth is R/2 Hz. Now for Duobinary modulation we have [5]:

$$q(kT)=\begin{cases}1 & k=0,1\\ 0 & otherwise\end{cases} \tag{3.4}$$

so we can now see that at the sampling instance kT, d_k does not reach the receiver but instead what we get at the receiver is $(d_k - 1 + d_k)$, which means that we have a smaller bandwidth since the transmitted pulse is narrower in the frequency domain. Due to the narrow spectrum, the signal is less prone to dispersion.

3.4.3 Generating

One way to generate a Duobinary signal is to digitally filter the binary data stream with a two tap finite impulse response filter (FIR) and then use a low-pass filter on the output signal to obtain the analogue waveform that is a Duobinary signal. But this can also be accomplished using a suitable low pass filter. Since a two tap FIR is anyway a simple low pass filter, for our purpose it should have around $2.5 \times BitRate$. When we have a binary input on the FIR (being the binary levels -1 and 1) we also have [5]:

$$\begin{gathered} 0.5\times(-1+(-1))\rightarrow -1 \\ 0.5\times(-1+1)\rightarrow 0 \\ 0.5\times(1+1)\rightarrow 1 \end{gathered} \tag{3.5}$$

so a Duobinary signal is a three level signal. Another property of this signal is that it is correlated and all possible sequences of the three values cannot occur: a 1 can never precede a -1 without a 0 in between and vice versa, a 1 can never precede a 1 with a 0 in between:

$$possible\begin{cases}-1 \;\; 0 \;\; 1\\ 1 \;\; 0 \;\; -1\end{cases}$$

$$not\ possible\begin{cases}1 \;\; 0 \;\; 1\\ -1 \;\; 0 \;\; -1\\ 1 \;\; -1\\ -1 \;\; 1\end{cases} \tag{3.6}$$

this type of coding also helps to fight dispersion.

3.4.4 Encoding

The ISI that we have present in the transmitted signal due to $(d_{k-1}+d_k)$ can be removed at the receiver, since this ISI is the sum of a bit with a previous one, we can always subtract the last bit that was decoded by the receiver from the information now received. It is important to point out the differences between decoded information and received information:

- Received information is what the receiver gets from the optical link, at this point we are assuming that what is transmitted is received and the are no penalties, being this $(d_{k-1}+d_k)$.
- Decoded information is the output of the receiver or decoder, depending on the situation.

Therefore the receiver must subtract the received signal by the last decoded information, or using formulae: let the transmitted signal be $(d_{k-1}+d_k)$ at each sampling instance kT, so the receiver indeed receives $x_k=(d_{k-1}+d_k)$, where $x_k=x(kT)$ and $x(t)$ satisfies Eq. (3.4), so if the previous decoded bit is $\hat{d}_k-1$ this can be subtracted from the received signal and we get [5]:

$$\hat{d}_k=x_k-\hat{d}_{k-1} \tag{3.7}$$

but what happens if the previous decoded bit is wrong? We will then have a catastrophic failure that is caused by error propagation that goes *ad eternum*, but this can be avoided simply by doing a pre-coding in the transmitter instead of decoding in the receiver and since it is very likely to have errors, this system would not be able to function properly. The precoder encodes the data bits d_k differentially in the following manner [5]:

$$c_k=c_{k-1}+d_k \quad (note\ that + represents\ modulo\ 2\ subtraction) \tag{3.8}$$

So the transmitted signal will now be [5]:

$$x(t)=\sum_{k=-\infty}^{\infty} c_k q(t-kT) \tag{3.9}$$

so now $q(t)$ satisfies Eq. (3.4).

3.4.5 Physical Applications

Since the pre coder uses modulo 2 subtraction, and this is the same as making XOR of two signals, to physically implement a pre coder, one should use a XOR gate as in Fig. 3.7. The problem with this arrangement is the feedback and delay path, since this makes the circuit construction critical, especially at high data rates of 10Gbit/s or more, as 40Gbit/s used in simulations. A circuit that does not have such high demands in construction is one that does not involve the feedback and delay path, it just uses an AND gate and a counter that divides by two, or even easier, a T Flip-flop. First we feed the data and a clock signal to the AND gate, then the resulting signal is fed to the Flip-flop. This arrangement makes the Flip-flop change state whenever data is in high state, which is the same as adding 1 modulo 2. When the data is in low state the Flip-flop does not change state, and this is equivalent to adding 0 modulo 2 as in Table 3.1.

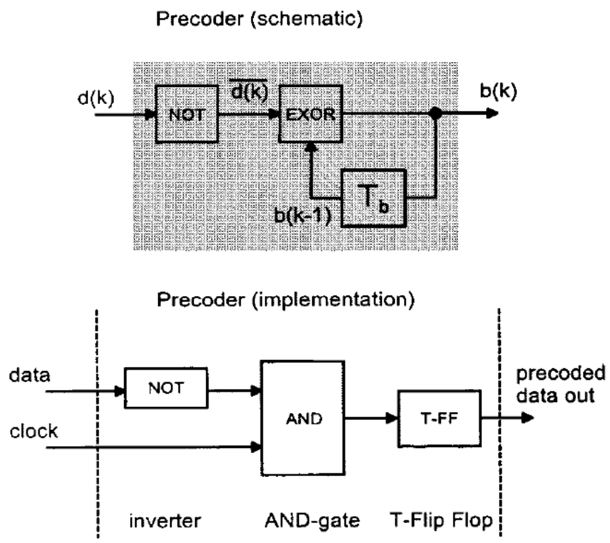
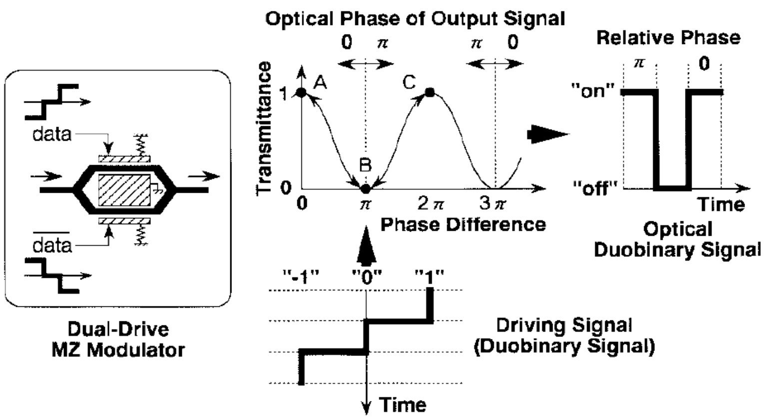


Fig. 3.7 Two possible Duobinary precoders with one using a XOR with feedback and the other using an AND gate and a Toggle Flip-Flop [6]

XOR truth table			*Modulo 2 subtraction*	
0	0	0	0+0	0
0	1	1	0+1	1
1	0	1	1+0	1
1	1	0	1+1	0

Table 3.1 XOR and Modulo 2

We now have to optically modulate the signal that will have the same three levels as the electric signal does. To do this we need a Mach-Zehnder Interferometer (MZI) biased at it's null point and fed with the original signal and an inverted version of the same signal to induce push-pull operation:



(a) (b)

Fig. 3.8 a) Configuration of dual-drive MZ type optical intensity modulator for optical Duobinary modulation and (b) operation of the MZI modulator [7]

and the output electric field is described by the equation [7]:

$$E(t)=E_0\cos\frac{\Delta\phi(t)}{2}\cdot\exp\left(\frac{-j\cdot\phi_0}{2}\right) \tag{3.10}$$

where E_0 is the input electric field, $\Delta\phi(t)$ is the phase difference between the two arms of the MZI which we want to be π, and ϕ_0 is a constant when we are using the MZI in push-pull operation.

For a zero signal, no light is transmitted (Fig. 3.8 point B), and for +1 and -1 signal light will indeed be transmitted (Fig. 3.8 points A and C), but what makes these two signals different is that they have different electrical fields. One has E+ and the other has E- or a phase difference of π. Notice that although in Fig. 3.8 points A and C have a 2π phase difference they share the same phase since 0 degrees is the same as 2π degrees. This means that even tough +1 and -1 have the same transmitted optical power, they have different phases. Since photodiodes can only detect optical power and not phase, a typical receiver will detect a logical one for both optical signals +1 and -1, or E+ and E-. This is a great advantage since we have a three level optical system that is converted to a two level electrical system by the receiver's photodiode, meaning that Duobinary modulation can be used wherever there are conventional PIN photodiode receivers.

3.4.6 Benefits

This arrangement greatly reduces the effects of dispersion in the fibre, because the power spectrum is narrower than NRZ as seen in Fig. 3.9, also as there is no carrier frequency (notice the Dirac impulse in Fig. 3.9 b) that does not exist in Fig. 3.9 a)) in Duobinary, this means that fibre input power limitation due to Stimulated Brillouin Scattering is relaxed [7]. But, the most interesting phenomenon is that, as a pulse travels down the fibre, it spreads itself in the time domain. In NRZ transmission we have each zero being an optical zero and each one mapped as E+ (or we can do it in the inverse way but we would then need an inverter at the receiver), this can never happen in Duobinary since the sequence {1 0 1} can never occur because it would lead to {E+ 0 E+}, which does not take advantage of Duobinary benefits, what occurs instead is a {1 0 -1} which in turn leads to the optical signal {E+ 0 E-} as in Fig. 3.10.

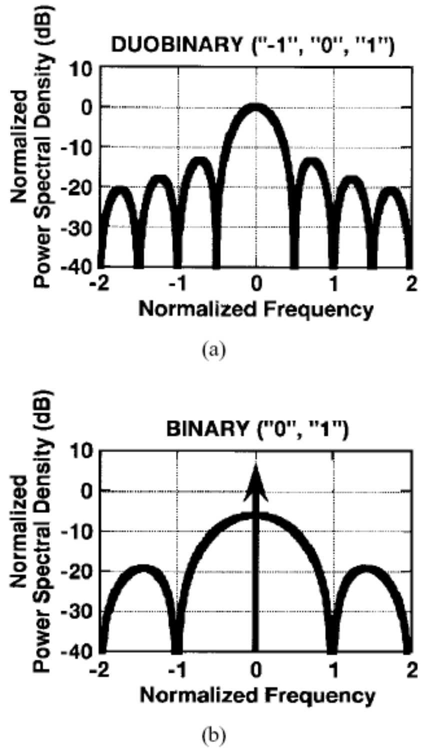


Fig. 3.9 Power spectra: a) Duobinary signal, b) binary signal [7]

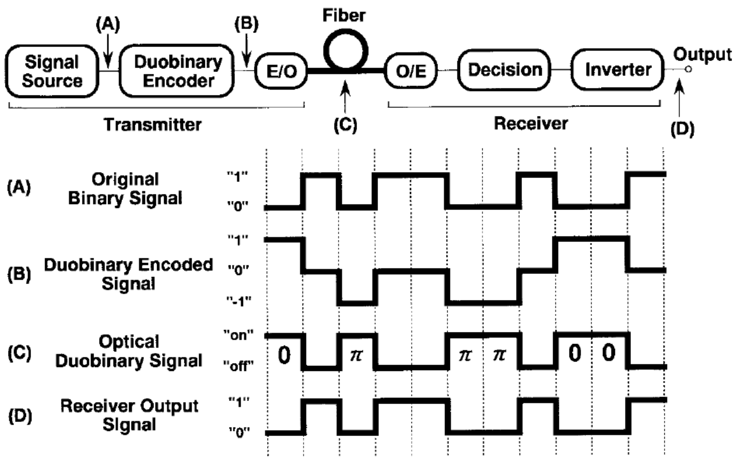


Fig. 3.10 Schematic diagram of the proposed optical Duobinary transmission system, and an example of original binary signal, corresponding Duobinary encoded signal, optical Duobinary signal, and receiver output signal [7]

The great advantage here is that, when dispersion affects a train pulse such as {E+ 0 E+}, the E+ pulses are spread to the point where there is no zero. Using Duobinary and the same pulse spreading one might think that the same thing happens, i.e. the zero disappears since the ones have spread enough to cover the zero. In fact it doesn't occur, as the pulses spread and cover the zero, they also cancel themselves out because they have opposite phases. This is the benefit of Duobinary modulation if pulses representing one spread to the space occupied by a zero, they will cancel themselves or at least some degree of cancellation will happen since dispersion affects the phase of both pulses. One problem that could happen is that there is a boundary condition where the pulses have spread enough to make the zero disappear but not enough to cancel themselves out in such a way that makes the zero reappear. This is why there is a penalty for working with Duobinary modulation, that penalty sits between small lengths of fibre, where almost no dispersion has occurred and between lengths of fibre where dispersion has occurred in such a way that the boundary condition does not exist any more, this can vary with data rates and fibre characteristics, making Duobinary modulation better suited for long haul transmission than for short length transmission.

3.4.7 Simulation Models

There are two simulation models present in VPI, these differ in the way they transform the electric Duobinary signal in the optical Duobinary signal. The first one is the push-pull model that is

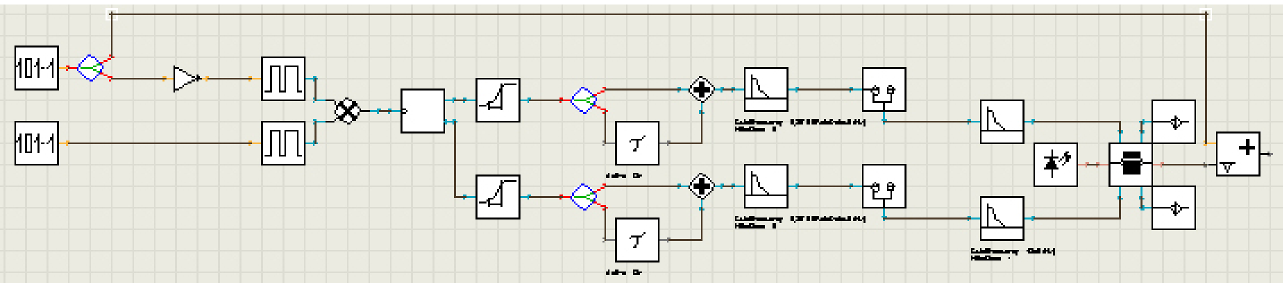


Fig. 3.11 Push-pull Duobinary modulator using differential MZI

described above, the working principle is based in the fact that feeding two signals that are inverted to the MZI will result in a push-pull operation. If the MZI is correctly biased we can have transmission with opposite phases. The schematic of this modulator is shown in Fig. 3.11.

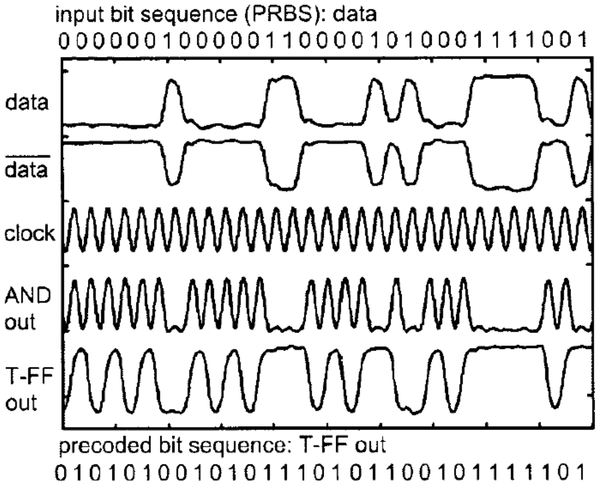


Fig. 3.12 Bit sequences that illustrate the various stages of the Duobinary precoder [6]

This modulator works in a straightforward manner, the top Pseudo Random Binary Sequence Generator generates a pseudo random sequence while the other used used merely to generate a mark and space sequence having double of the bitrate of the first, this sequence is to be a clock signal, which can be best seen in Fig. 3.12. A NOT is used to invert the original signal. Then an AND is

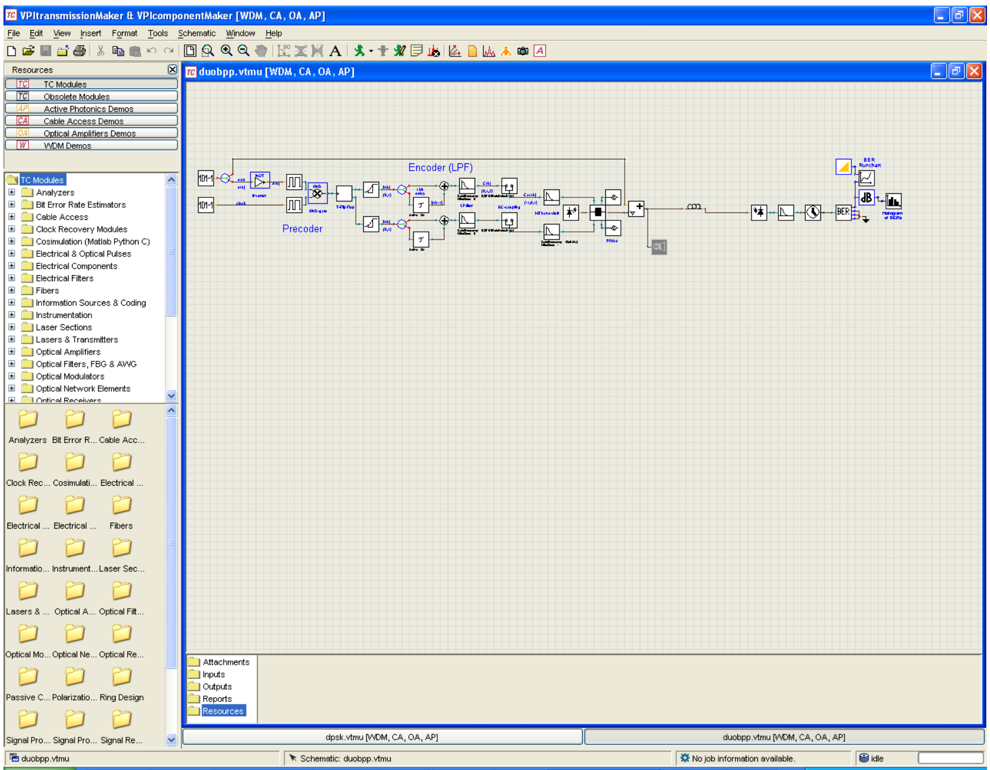


Fig. 3.13: Push-pull duobinary modulation simulation set-up

used to combine both, this has the effect of having clock signal where before was a zero in the original signal. Later the Toggle Flip-Flop will halve the signal bitrate. At the end we have a signal where original zeros are represented by as oscillating signal with the original bitrate and original ones will have complementary representations whenever they appear after an original zero.

So as we make this interleaved transformation of the zeros of the inverted original signal we are assuring that we follow the rules to generate Duobinary correctly. Although the signal that comes out of the Flip-Flop is not yet a Duobinary signal; it will become one after the one bit delay and ADD thus making it a three level electrical signal, which will be fed to both arms of the MZ where it will indeed become a Duobinary signal. The Bessel filters are there to reduce the bandwidth even further to increase the maximum possible transmission distance even more. The simulation model in Fig. 3.14 is a simplified version of the one presented above and it differs in several ways, one is that it only uses one arm of a MZI.

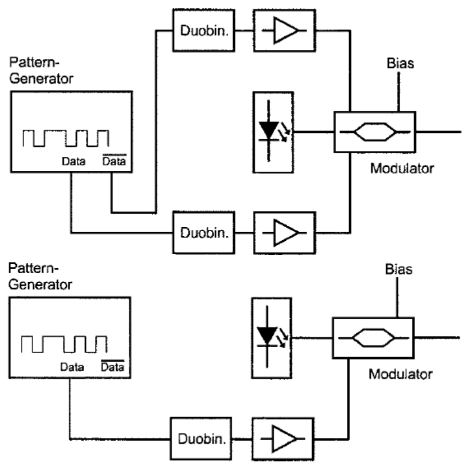


Fig. 3.14 Single-sided Duobinary modulator with push-pull MZ (top) and simplified version (bottom) [6]

It is just as simple as this, the difference is more than using only one arm of the MZ instead of two: the signal that is fed to the MZ must have special characteristics; this is apparent in the schematic of the Duobinary generator used in VPI, as seen in Fig. 3.15.

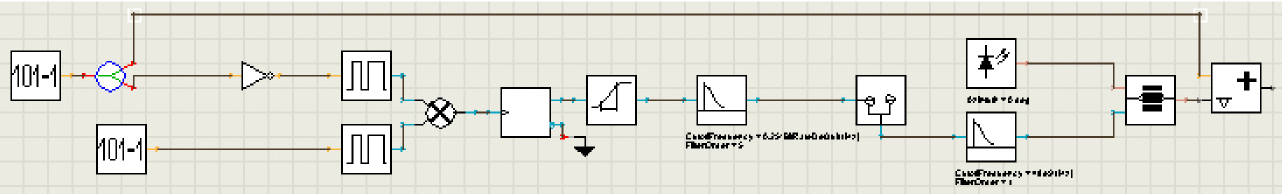


Fig. 3.15 Single-sided Duobinary modulator using single drive MZI

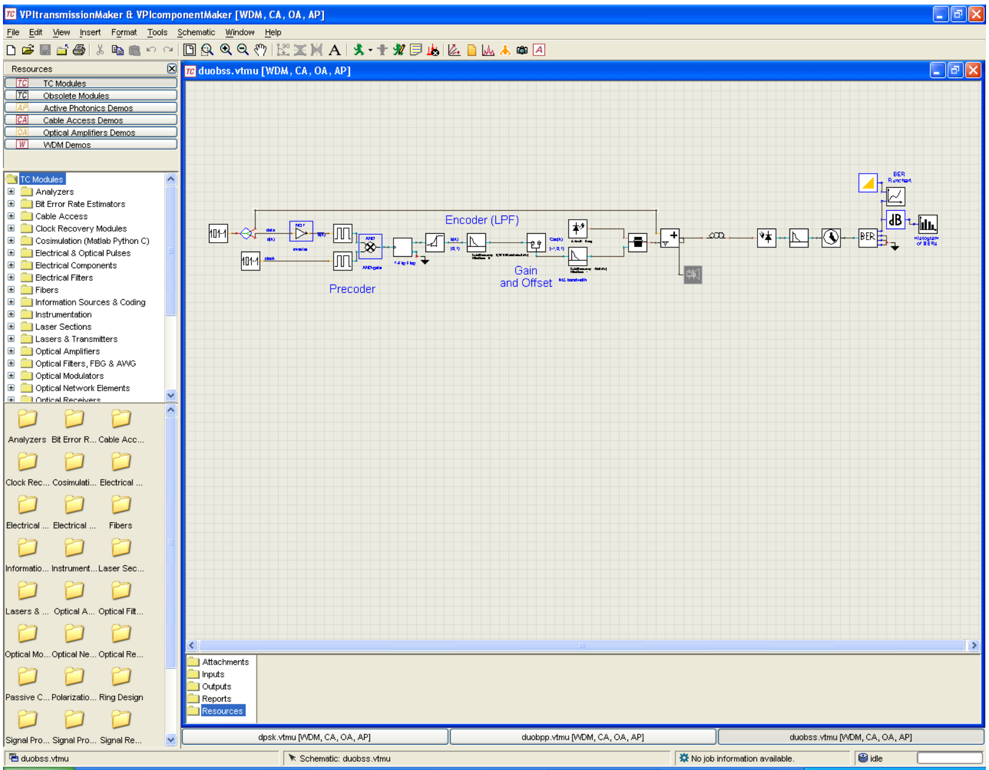


Fig. 3.16: Single-sided duobinary modulation simulation set-up

In this case there is no delay and add so the signal is never an electrical Duobinary signal, instead the signal that is present in Fig. 3.12 with the label "T-FF out" is what will be fed to the MZ minus filtering, and also the DC component of the signal will be such that the MZ will be overdriven, thus creating the Duobinary optical signal.

3.5 DPSK

3.5.1 Introduction

Differential Phase Shift Keying or DPSK is the new flavour in cutting edge optical fibre communication systems. As fibre spans get longer, ever more complex modulation formats are needed, many times trading easiness of equipment implementation and manufacturing for increased dispersion immunity. As Duobinary modulation, DPSK encodes information in the lightwave. Duobinary encodes information not related to the signal, each zero that is preceded by a one has a π/2 phase change relative to the previous zero, the signal can be decoded without this information, since the receiver detects light intensity and not phase. Whereas DPSK is a continuous wave that is modulated in phase. The DPSK receiver is then more complex than the simple Duobinary receiver, which in fact is the same as used for NRZ and RZ modulations.

3.5.2 Working Principles

As stated before, DPSK modulation binary data is encoded as two different phases: 0 and π. Also stated was that DPSK was a continuous wave. This is partial truth since DPSK has two variants, and the difference is related to this fact. One variant is the one stated before, a continuous light wave, and as optical power never returns to zero, this variant is named NRZ-DPSK. For the other one, optical power returns briefly to zero between bits, and this will obviously be named RZ-DPSK.

As for benefits, the main benefit of DPSK is that it needs less power at the receiver to achieve the same BER when compared with standard OOK modulations, like NRZ for example. This difference is about 3dB, and this actually can be perceived just by looking at constellations for both modulation formats, as shown in Fig. 3.17.

Having this, the difference in symbol distance between these two modulation formats is around $\sqrt{(2)}$, this means that only half of the average optical power is needed to achieve the same bit error rate, thus the approximate 3dB difference. Note that this advantage is only possible to achieve if a balanced receiver is used.

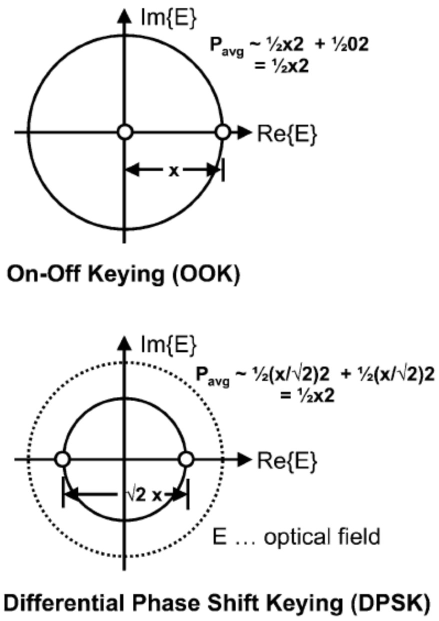


Fig. 3.17 Signal constellations of OOK and DPSK [8]

There are some other benefits, one is due to the fact that optical power plays no role in decoding the original signal, which means that this modulation is unaffected by power fluctuations. Some nonlinear effects do not affect DPSK or do so to a much less extent. Since optical power is constant, there will be resilience to nonlinear effects that are bit pattern dependent. As less optical power is needed, there will be less power dependent nonlinear effects.

3.5.3 Modulating

As far as DPSK modulating is concerned, there are two ways of performing it. These are not completely different from each another, in fact their only difference is one component.

DPSK modulation can only be accomplished by means of external modulation, and here we have the difference, there are two external modulators to use: a phase modulator (PM) or a Mach-Zehnder modulator. These can even be followed by an extra MZI named a pulse carver in order to produce RZ-DPSK thus preventing optical power to appear between different bits.

The PM will only change the phase of the optical field modulating it, this will create a constant envelope optical signal. The greatest drawback of using a PM is that it can produce chirp in bit transitions, because modulation change does not occur instantaneously. To counter this

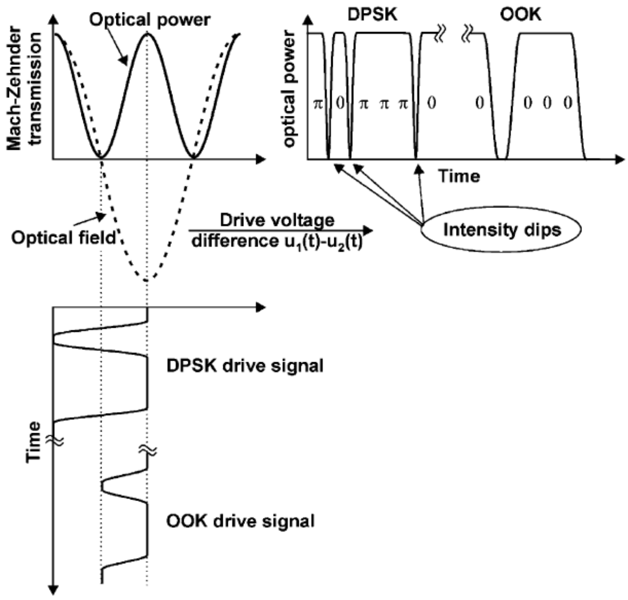


Fig. 3.18 Principle of phase modulation using a Mach–Zehnder modulator [8]

phenomenon a second MZI can be used as the previously described pulse carver to prevent transmission of the chirp.

When using MZI for phase modulations, it must be biased at its null, and then driven at twice the switching voltage used in NRZ modulation. Single ended as well as differential MZI can be used, being that the differential MZI driven in a push-pull configuration can reduce chirp. This was used in simulations as seen in Fig. 3.22.

The main advantage of using a MZI is that phase changes occur at the minimum in the power transition curve, so a near perfect 180º shift is obtained. There will still be some residual amplitude modulation in bit transitions. This is not a problem as only phase is important for demodulation, and this can be removed using the same method as before, using a pulse carver. In Fig. 3.19 all these different situations can be better seen.

There are still some other drawbacks worth mentioning, waveform imperfections will be mapped by the PM in the optical phase. For PM there is some dependency in terms of driver output power and driver and modulator bandwidth, if one is incapable of setting these high enough there will be a penalty, these characteristics are especially hard to keep high in high bitrate systems. In Fig. 3.20 this can be seen, this figure presents the results of numerical simulation [8] of Optical Signal to Noise Ratio penalty for a 33% RZ-DPSK signal having BER = 10^{-10} as a function of PM or MZI

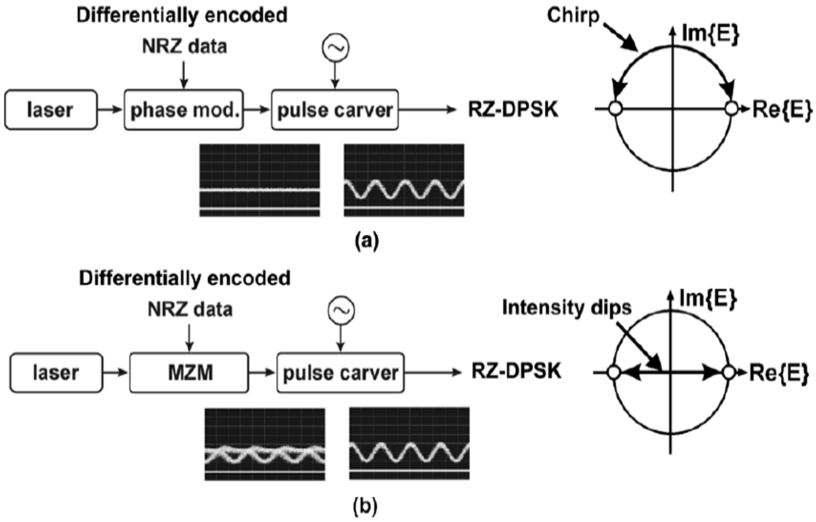


Fig. 3.19 Phase modulator and Mach-Zehnder DPSK modulators along with their transitions present in signal constellations [8]

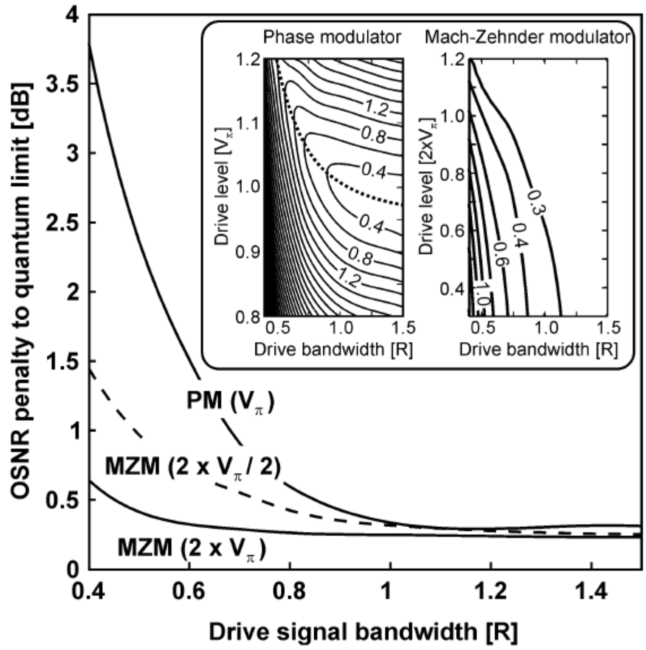


Fig. 3.20 Numerical calculations for the OSNR penalty at BER = 10^{-10} *for 33% RZ-DPSK due to limited drive bandwidth for PM or MZI phase modulation. Inset: Contour plots of the OSNR penalty (in dB) as a function of the drive level and the drive bandwidth [8]*

drive signal bandwidth (normalized to the data rate, R). The drive signal is assumed to have first order low pass characteristics. As seen, for PM the driver bandwidth dependence is large, especially at low bandwidth values, notice the growth of BER when compared to MZI, this happens since insufficient driver bandwidth causes pattern dependent, reduced phase shifts. Contrary to this, the same situation when using a MZI will affect the intensity of the residual amplitude modulation in bit transitions, but will not affect phase. In fact we can go as far as use half of the drive voltage $2\times V_{\pi}/2$ instead of $2\times V_{\pi}$ for the MZI and the penalty will not be considerable. In the inset of Fig. 3.20 one can see contour plots of OSNR penalty as a function of drive level and drive bandwidth for both modulator types, PM and MZI. The inset concurs with the main graph, PM has specific needs in order to minimize modulated signal degradation, nevertheless increasing the drive level can reduce some of the problems of the lack of bandwidth, but only marginally. Notice that dotted line represents in PM contour plot represents optimum drive level for each bandwidth, as seen on the left of the inset. On the right of the inset MZI proves to be almost insensible to variations in drive bandwidth and drive level.

As said before, to prevent problems in bit transitions, especially when using a PM, is to use a pulse carver, therefore turning the previous NRZ-DPSK in a RZ-DPSK. This approach, however is not devoid of problems, in fact, the MZI used as a pulse carver, can itself produce chirp. To prevent adding chirp to the signal, by the mean chosen to remove it, the MZI used for pulse carving must have infinite DC extinction and be driven in push-pull operation. As seen, in Fig. 3.21 these requirements must be scrupulously kept.

There are several ways to accomplish pulse carving, in Fig. 3.21 we have some based on applying a sinusoidal wave to the pulse carving MZI. This sinusoidal wave can have different duty cycles, each one of these will change the resulting signal in different ways. Using 67% duty cycle will lead to Carrier Suppressed Return to Zero (CSRZ) modulation if a standard OOK modulator is used. Here it will simply invert the logic but does not alter the spectrum like a CSRZ signal had its spectrum altered. Since we are using 50% duty cycle we are carving the signal with the same rate as the original signal, the residual optical phase variations will be the same for each bit, by contrast, when carving at half the rate of the original signal, as in 33% and 67%, optical phase variations will be different for adjacent bits. As a matter of fact, for 50% duty cycle, optical phase variations have the same frequency as the original signal, while the same cannot be said for 33% and 67% duty cycles, where optical phase variations have half of the original signal frequency, this is obviously due to the

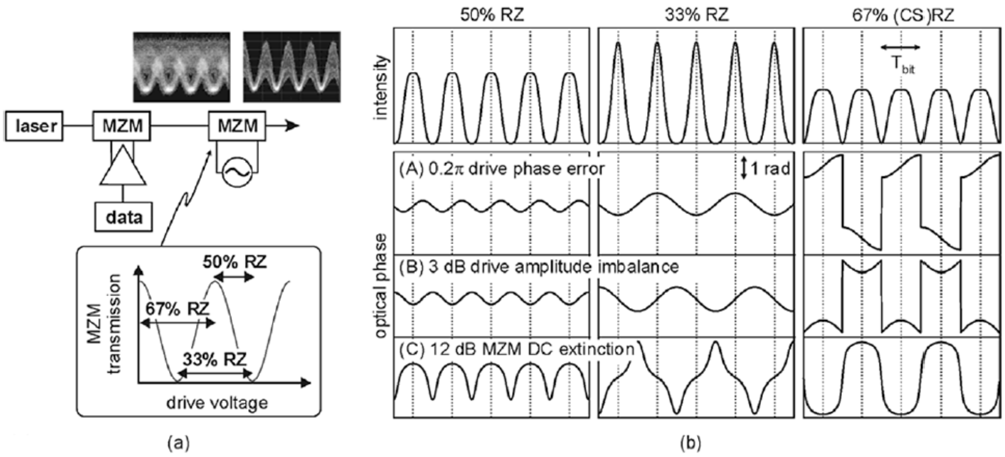


Fig. 3.21 a) MZI based RZ-DPSK transmitter, b) optical intensity and phase waveforms generated by an imperfect pulse carver [8]

fact that the signal is being carved at half of the original signal rate, therefore half of the original frequency. The problem here is that, for 33% and 67% we have a large phase error between adjacent bits, and since demodulation is made using phase difference of adjacent bits, this will be a problematic occurrence. Not so for 50% duty cycle where optical phase variation is much smaller.

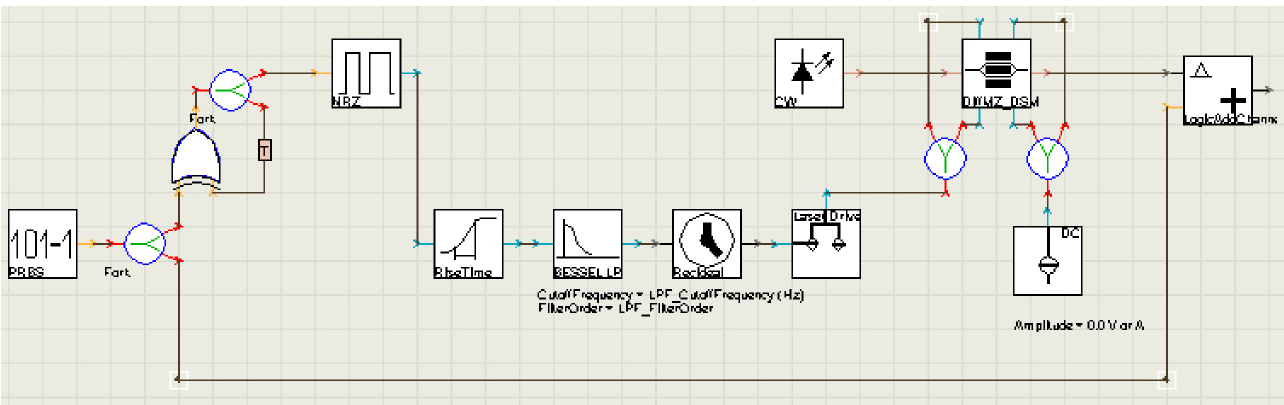


Fig. 3.22 DPSK modulator

At 33%, for drive amplitude imbalance we have linear phase transitions in the centre of the bit pulse, while for drive signal phase error there will be a phase offset in the centre of the bit pulse, i.e. each bit will have a different phase error. On the one hand, a linear phase transition in the centre of the bit pulse does not affect phase detection, since this phase transition passes through zero radians, so the phase error will be zero radians for every bit, and the centre of the bit pulse has the most contribution for the demodulated signal. On the other hand, phase offset has a detrimental effect on phase detection, since each bit has a different alternating opposite phase difference. This means that for 33% duty cycle, there is higher tolerance for drive amplitude imbalance than for drive phase errors. The opposite will be the case for the 67% duty cycle.

Another problem clearly seen in Fig. 3.21 is the chirp due to finite DC extinction ratios, but this can be partially compensated for by introducing an imbalance in drive signal amplitudes.

3.5.4 Receiving

Having a DPSK transmitter of such complexity is pointless without a receiver capable of decoding this modulation format. This will by no means be a typical receiver, since phase needs to be decoded, and photodiodes are not capable of detecting optical phase, only optical intensity. This calls for a different approach.

As stated before, the preceding bit serves as a reference to the bit being decoded (hence the name Differential Phase Shift Keying (DPSK)), therefore a method of comparing bits is needed, one method would be to delay the bit being decoded in order to make it a reference bit to the following bit. This delay will be accomplished by the use of a Mach-Zehnder Interferometer which will be used to perform the delay, therefore named Delay Interferometer (DI). The chosen delay will be equal to the bit period. Being named Interferometer, the DI will cause interference between two adjacent bits, and in this interference, the phase difference will be perceived. The interference will be constructive or destructive. This method is necessary for direct detection only, if coherent detection is used a reference laser will cause constructive and destructive interferences. The DI will have two ports, one for destructive and other for constructive interferences, the first is adjusted for destructive interference whenever there is no phase modulation, the latter will have constructive interference due to energy conservation. This means that these two ports will show the same information but inverted in respect to each other, obviously this only happens when DPSK modulation is present at the input of the receiver. There is one extra interesting occurrence: from the constructive port of the DI we will get Duobinary modulation, from the destructive port we will have alternate-mark inversion modulation.

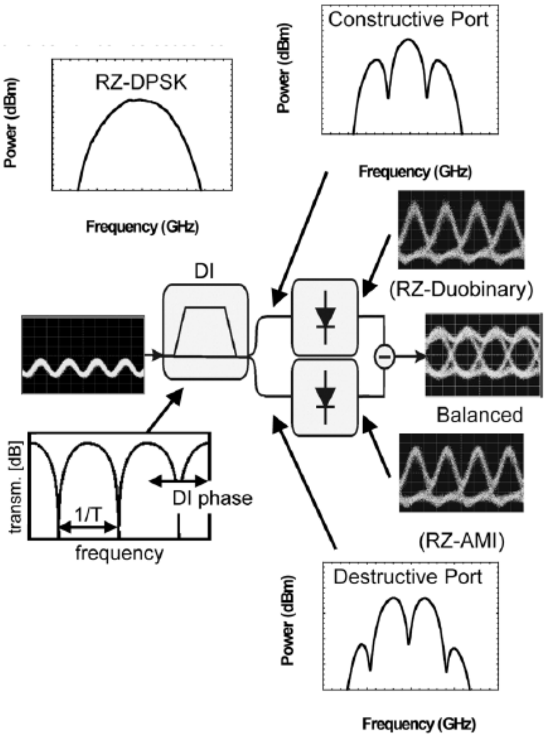


Fig. 3.23 Typical DPSK receiver, eye diagrams were obtained using a 32-GHz measurement diode) for a 42.7Gb/s RZ-PSK signal with 33% duty cycle at various points within the receiver [8]

Having all the information needed in each arm, one can use detection of one arm using only one photodiode, this will be single ended detection, but obviously one can use two photodiodes to perform balanced detection.

But which to choose from? Single ended or balanced detection? Fortunately there are simulations [8] that help in this decision. First let us look at the following equation [8]:

$$\beta = \frac{S_A - S_B}{S_A + S_B} \tag{3.11}$$

being β the amplitude imbalance, S_A and S_B are the overall opto-electric conversion factors, and each letter representing one arm of the DI: A represents destructive, while B represents constructive output. Balanced detection will be achieved whenever β=0, meaning that $S_A = S_B$. By contrast, constructive detection has β=-1 and destructive detection will have β=1. So, some differences exist between both alternatives. In Fig. 3.24, we can see just how good balanced detection is, here we see numerical simulations [8] that show balanced detection to be 2.7dB better than single ended detection, being that constructive or destructive have no benefits from one another. Also seen is a dashed line that represents the limit OSNR for OOK, which is independent of β and about the same for single ended detection of DPSK. It is perfectly clear that balanced detection is well under this limit, thus providing better operation. The aforementioned 3dB advantage of DPSK is only possible when balanced detection is used, as seen in Fig. 3.24, in fact this proves not to be 3dB but 2.7dB.

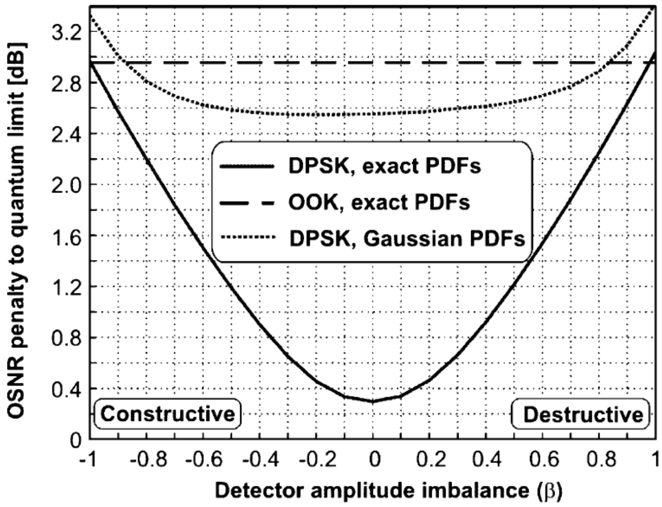


Fig. 3.24 Numerical calculations for the required OSNR at BER= 10^{-10} *for 33% RZ-DPSK (solid line) as a function of receiver amplitude imbalance, also shown (dashed) is the required OSNR for OOK, which is (by definition) independent of [8]*

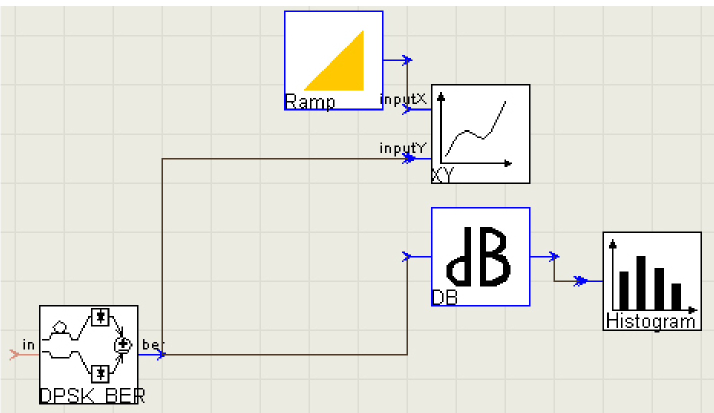


Fig. 3.25 DPSK receiver and BER estimator

DI can be constructed using fibres or planar based circuits, in both cases these have to be fine tuned, since manufacturing alone does not provide DI with the needed accuracy out from the box, an extra heating element is used in one of the arms to provide sufficient accuracy in DI tuning, therefore yielding good interference quality.

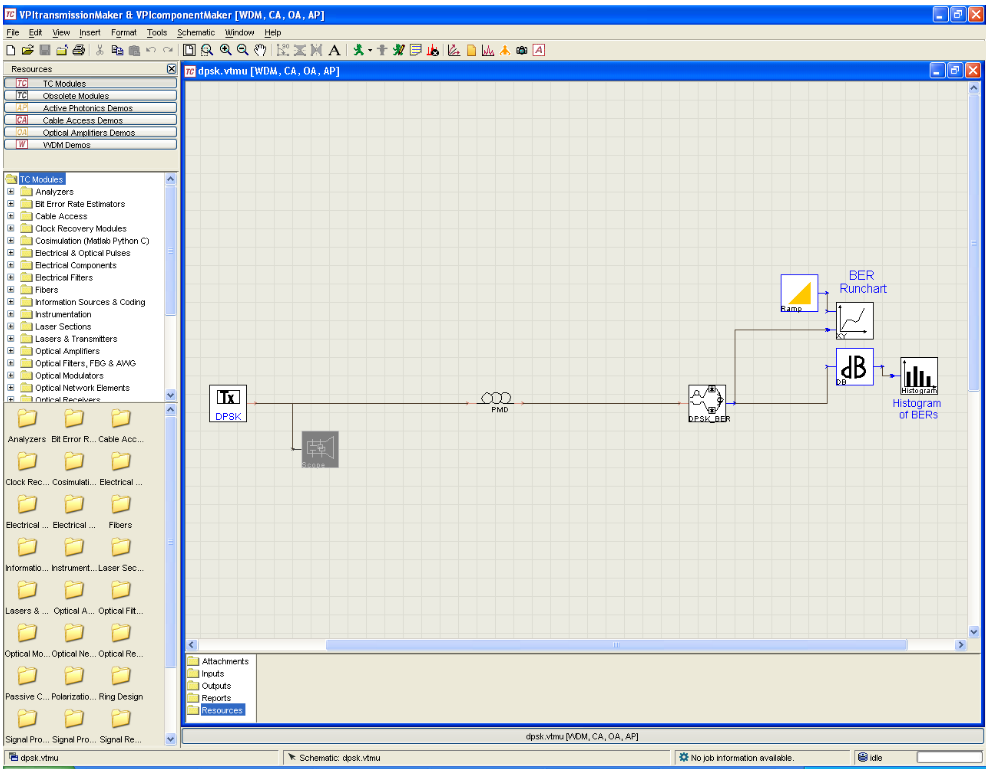


Fig. 3.26: DPSK modulation simulation set-up

3.6 CSRZ

3.6.1 Introduction

Last but not least, Carrier Suppressed Return to Zero (CSRZ) is a special case of Return to Zero (RZ) modulation, where, as the name states, the optical carrier will be suppressed, much like its electrical counterpart Double Sideband modulation. This modulation, as DPSK, is a new flavour in optical fibre communications, having received much attention lately. Being briefly mentioned in the

DPSK chapter, one might suspect that to modulate CSRZ a second MZI is necessary, and this is true, as we will see.

3.6.2 Generating

Using the same setup as DPSK, and with 67% duty cycle for the pulse carver, CSRZ can be obtained. The CSRZ modulator is closely resembles the DPSK one, but instead of having the same frequency as the bitrate it will have half of the bitrate, in this case 20GHz as seen in Fig. 3.27.

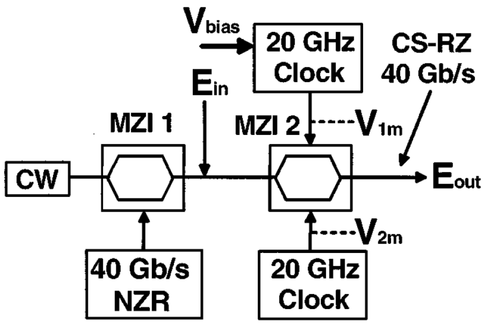


Fig. 3.27 CSRZ modulator [9]

The first MZI will generate a NRZ signal, while the second can transform it not only into CSRZ but some other signals as well. This versatility can be described mathematically as [9]:

$$E_{OUT} = j\,E_{IN} \sin\left[\frac{(\phi_1 - \phi_2)}{2}\right] \exp\left[j\frac{(\phi_1 + \phi_2)}{2}\right] \tag{3.12}$$

where E_{IN} and E_{OUT} describe the optical input and output of the second MZI. ϕ_1 and ϕ_2 will be the phases of the modulator arms, having ϕ_1 a direct bias current V_{bias}, as seen here [9]:

$$\phi_1 = \frac{\pi}{2}\frac{V_{1m}}{V_\pi}\sin(\omega t + \Psi) + V_{bias} \tag{3.13}$$

$$\phi_2 = \frac{\pi}{2}\frac{V_{2m}}{V_\pi}\sin(\omega t) \tag{3.14}$$

V_{1m} and V_{2m} will represent the amplitude of the signals fed to the arms of the second MZI while Ψ represents the phase difference between the two signals. For CSRZ these equations will be simplified since the second MZI will be biased at its null point, making $V_{bias} = 0$, $V_{1m} = V_{2m} = V_\pi$ and $\Psi = \pi$. This will simplify the equations [9]:

$$\phi_1 = \frac{\pi}{2}\sin(\omega_0 t + \pi) \tag{3.15}$$

$$\phi_2 = \frac{\pi}{2}\sin(\omega_0 t) \tag{3.16}$$

and substituting we will have [9]:

$$E_{OUT} = -j\,E_{IN}\exp(-j\beta L)\sin\left[\frac{\pi}{2}\sin(\omega_0 t)\right] \tag{3.17}$$

E_{OUT} will be the modulated CSRZ signal. This signal will have some advantages over a normal RZ signal: not having a carrier means that for the same usable signal power, there will be less total power in the fibre since no information is conveyed by the carrier; there is also the advantage of reduced bandwidth. As seen in Fig. 3.28 CSRZ lacks the carrier, only the sidebands are present.

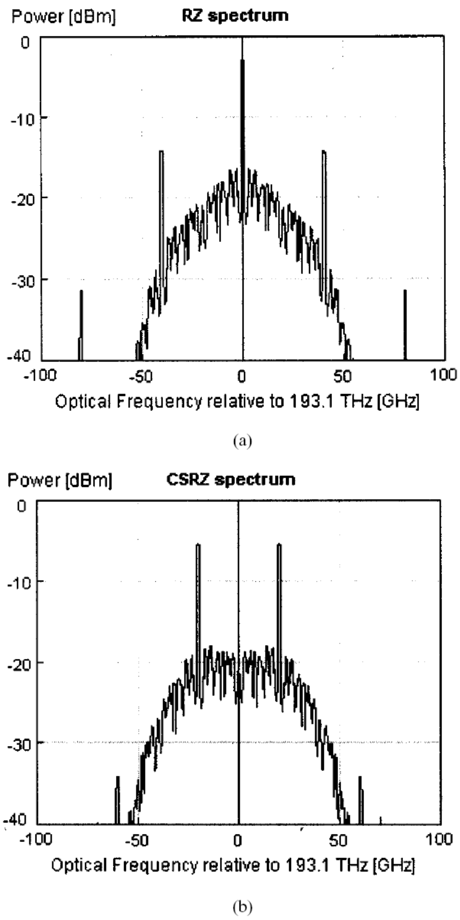


Fig. 3.28 a) NRZ spectrum, b) CSRZ spectrum [9]

Sideband spacing for RZ is twice than that for CSRZ, which is an advantage, since the signal is less prone to be affected by chromatic dispersion.

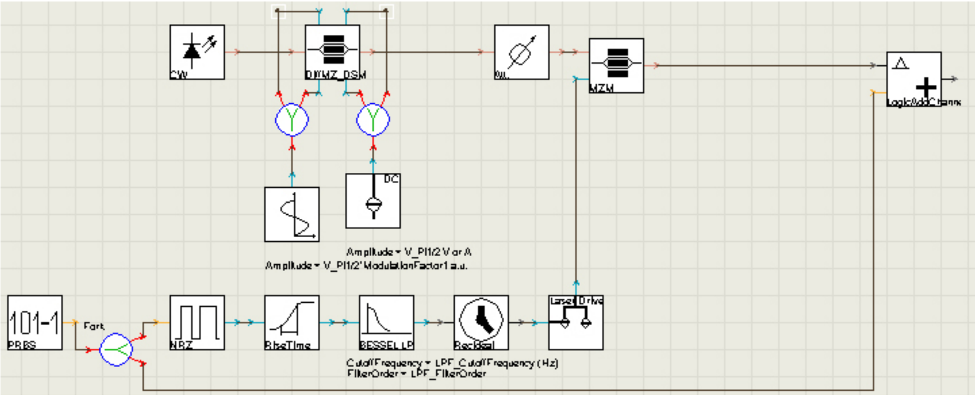


Fig. 3.29 CSRZ modulator

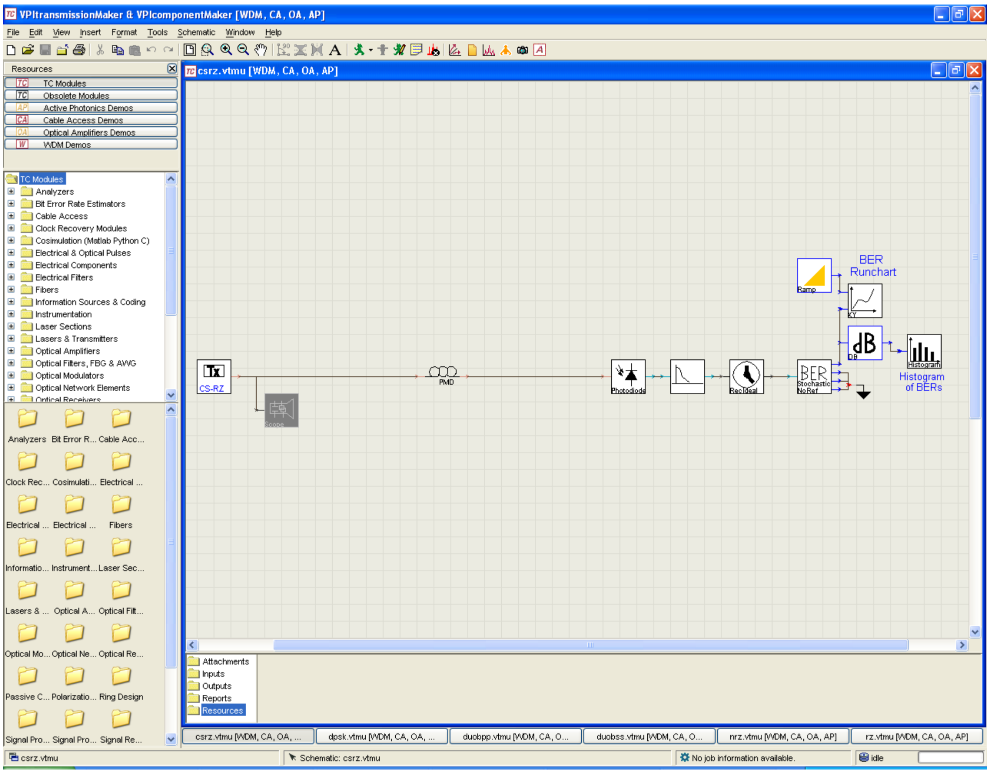


Fig. 3.30: CSRZ modulation simulation set-up

3.7 Final Remarks

As seen in this chapter, there are several modulation formats with their merits and downfalls, which will all be compared using VPI. For this, simulation models have to be developed and tested. Thus, before going into details of these models, it is worthwhile to briefly explain VPI workings, as well as describe some of its basic building blocks.

4 Virtual Photonics Interface

4.1 Introduction

Virtual Photonics Interface (VPI), presents itself as a fourth generation Photonic Design Automation (PDA), capable of very complex simulations.

VPI is a product of VPISystems, who first used the term PDA to describe design methodologies, software tools and services used to design complex optic networks. As technology evolves, new products appear in the photonic design field, therefore providing more choices for the designer. These choices can be between: Erbium Doped Fibre Amplification (EDFA), Raman Amplification, NRZ, RZ, CSRZ, Duobinary, fibre type, among many others. All these choices mean that designing a fibre optic system is not as straightforward as when only one choice was available. Since the costs involved in a system like this prevent trial and error approaches, virtual simulation is the way to go, as all possibilities can be exhaustively tried before making any decision. This is why VPI had a wide acceptance by system designers.

As straightforward as it might be to use these tools, this does not mean that this task is a simple one, large bandwidths have to be coped with, for example when simulating Wavelength Division Multiplexing (WDM) systems; due to such complexity, simulation times can be more than what is acceptable, so some effects can be neglected to reduce simulation time.

PDA tools are divided in generations, according to important evolutions. The first generation PDA tools were aimed at single component simulation, like lasers and fibres, where different software from different makers simulates only one component. In this case, the designer must learn how to work with different user interfaces of each software and simulate each component separately, many times unable to simulate interactions between them. The second generation evolved to allow several components to be connected, therefore allowing the simulation of a complete system; the disadvantage was the limitation to a single signal format, which was best suited to a particular scale or problem. The third generation solves this problem by allowing the best signal format to be chosen not only for the system, but for areas or even components, therefore maximizing simulation accuracy while reducing simulation time.

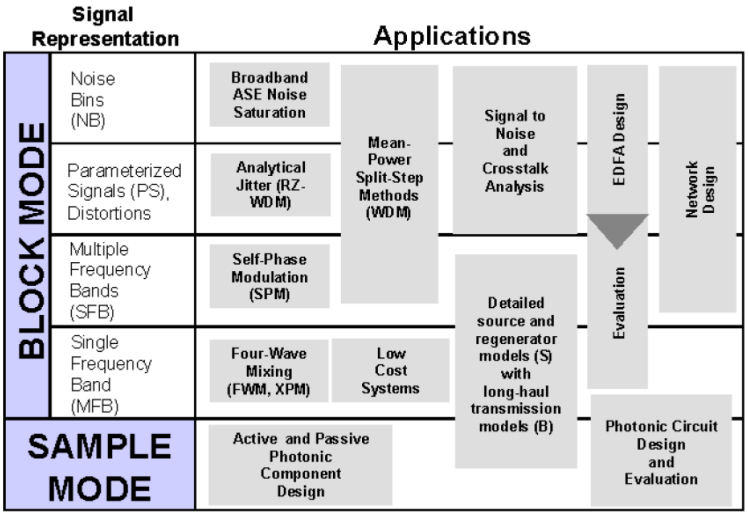


Fig. 4.1 VPI applications and modelling techniques for five signal representations [10]

The last instalment of PDA is the fourth, and it brings forth innovations in the simulation repetition and collaborative work areas as well as abstraction levels, where one can enclose a whole system inside a module, since different development teams might work at different abstraction levels.

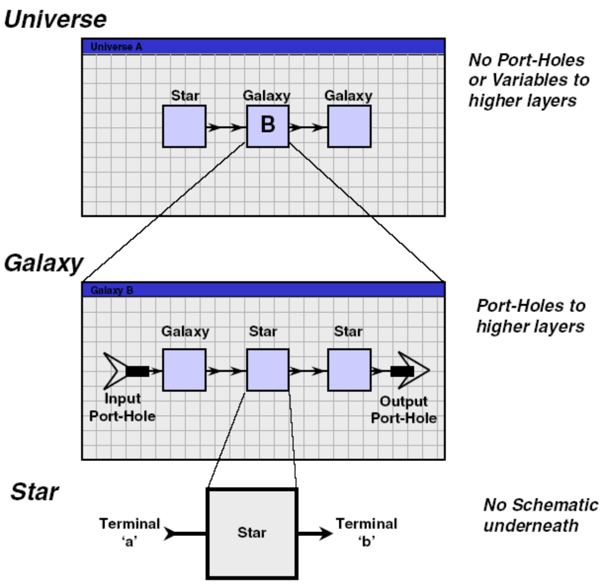


Fig. 4.2 VPI abstraction levels [10]

4.2 Interactive Simulations

Interactive simulations play an important role in determining optimum component characteristics, to compare system behaviour due to changes in some factor or factors. There are four interactive simulation types to chose from, the typical design workflow can be seen in Fig. 4.3.

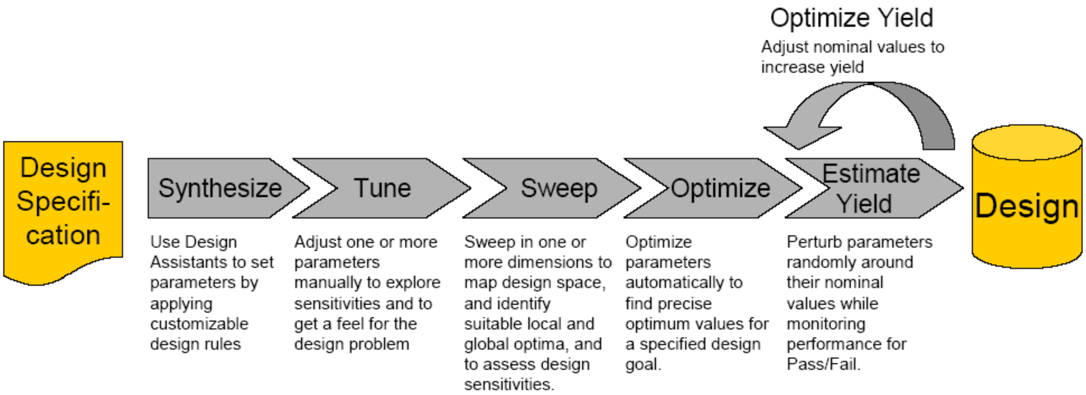


Fig. 4.3 VPI design process [10]

Although not being an interactive simulation, Initial Topology Synthesis is an integral part of the design process. On its simplest form this can be just putting some models on a schematic, on its more complex form, the synthesis engine may be programmed to set parameters using design rules.

Interactive Tuning uses sliders to alter component characteristics which can be monitored in real time, thus allowing the designer to have a better understanding of which parameters affect performance and what range of values they allow for reasonable operation.

Interactive Sweep, as the name implies, sweeps one or more parameters, in other words, several simulations are run, where chosen parameters are changed in defined ranges and with any sweep step. In Fig. 4.4 we can see such a sweep, note that the sweep step misses the optimum performance point, which can be a problem. Usually a sweep is used to have some insight on how the system is affected due to parameter changes, after running the sweep in Fig. 4.4, one can determine the values near to optimum performance, the next interactive simulation can then be used to determine this exact point.

Optimization identifies values quickly, it can maximise, minimise or try to reach a target value of just about any output. It is wise to use optimization together with interactive sweep, since optimization can reach a local maximum and not a global one, depending on the starting point. In the case of Fig. 4.5, the global maximum is found with as less iterations as possible, as the algorithm is continuously getting closer to the maximum.

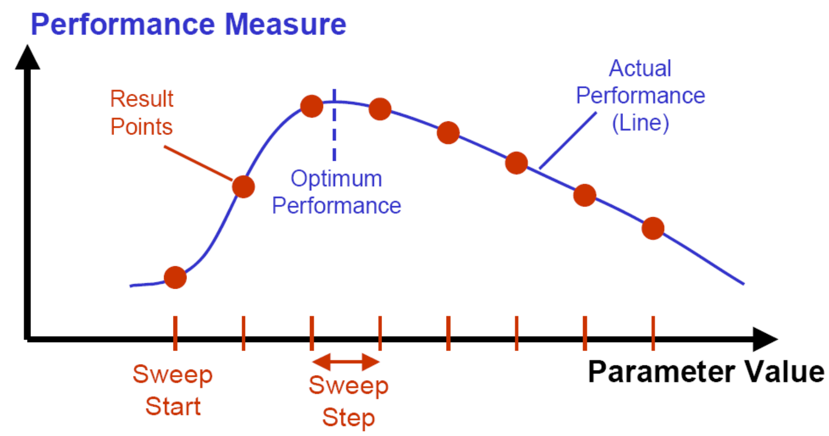


Fig. 4.4 Typical sweep results compared to the system's performance line [10]

Yield is used especially when simulating a system that will be used commercially. Commercial systems, due to the manufacturing volume of components, will exhibit small variations. These variations need to be taken into account at the design stage, as a system that barely works at the

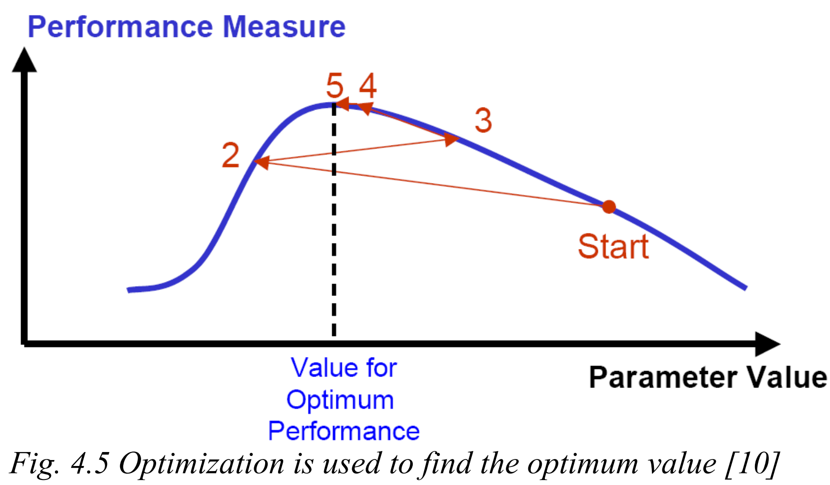


Fig. 4.5 Optimization is used to find the optimum value [10]

simulation stage, might not work after is has been installed. For each components, the parameters likely to vary due to manufacturing are chosen, then these variables are randomly affected in each simulation and the system performance is compared against a threshold, the Yield will then be calculated from the number of times the system performance is over the threshold in respect to the number of simulations. The percentage of yield is accumulated over many simulation runs, as more simulations are performed, the more accurate will be the results. Yield can be seen in Fig. 4.6.

Yield Optimization is used to optimize yield. As seen in Fig. 4.6 the probability curve is not centred

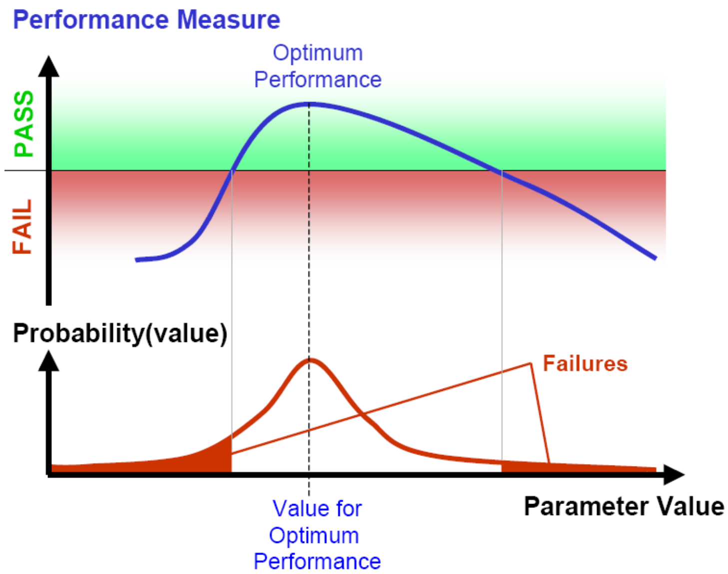


Fig. 4.6 Yield threshold and resulting probabilities [10]

in respect to the points where fails are present. In Fig. 4.6 is easy to see that if the probability peak could be shifted to the right, the yield would be optimized. This is what yield optimization

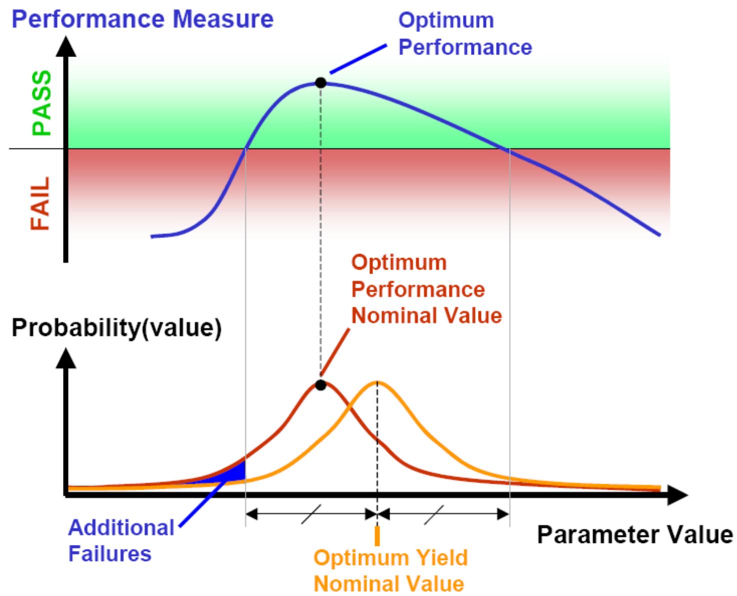


Fig. 4.7 Yield for optimum performance vs optimized yield [10]

accomplishes, through simulation, the parameters that are ideal will be changed to non ideal ones in order to optimize the probability curve, thus optimizing yield. Optimizing yield will lessen system problems, as it accommodates greater component characteristic changes without compromising the normal functioning of the system.

4.3 Modules

4.3.1 FiberNLS_PMD

4.3.1.1 Description

This module was the fibre of choice whenever simulations involving mainly PMD were made. The full name is Fiber NLS Random Birefringence PMD. This module solves a system of two coupled non-linear Schrödinger equations that describe the propagation of two orthogonal polarization components of optical signals in fibres with random birefringence, and allows a statistical model of PMD.

Fig. 4.8 PMD Fiber symbol [10]

Because two polarizations are modelled, it is more time consuming than the single polarization module.

To calculate polarization effects in fibres, the used method is coarse-step. As seen in the PMD chapter, to simulate birefringence variations in a fibre several small sections are used with constant birefringence, after each section the polarization is changed to mix both fast and slow axes from the preceding section with the following section, as can be seen in Fig. 4.9.

The length of each section is randomly selected from a Gaussian distribution.

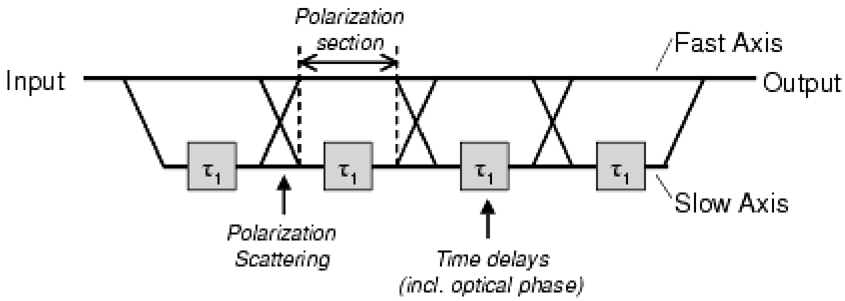


Fig. 4.9 Fibre sections used in by the coarse-step method to simulate PMD in an optical fibre [10]

4.3.1.2 Importance Sampling

This module uses Importance Sampling algorithm to simulate PMD, there are some advantages in using this method in detriment of Monte-Carlo. There is more accuracy when large DGD values are present and rare probabilities in the tails of the probability density function are estimated requiring less iterations. To perform the simulation each section is defined by a frequency-dependent Jones matrix, its eigenvectors coincide with the rotation axis in the Stokes space. By multiplying the input field by the matrix we rotate the polarization vector in the Poincaré sphere around the rotation axis. If the Jones matrix eigenvectors are known, the matrix can be diagonalized. The scattering matrix is then constructed from the diagonalization matrices of subsequent scattering sections.

As for the axes alignment of scattering sections, these can be chosen randomly, or aligned close to the alignment of the previous scattering section. As seen before, if there is no random axes alignment, DGD will grow with length.

4.3.2 Universal Fibre

This fibre will be used for all realistic simulations, it simulates a wideband non-linear signal transmission for bidirectional signals, stimulated and spontaneous Raman and Brillouin scattering, multiple Rayleigh scattering, Kerr nonlinearity, dispersion, PMD effects, local insertion loss and reflectance at each joint between spans. Although made with pumping for

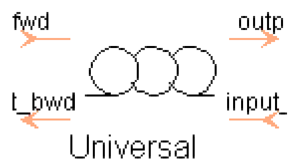


Fig. 4.10 Universal Fiber symbol [10]

optical amplification in mind, this is the model of choice since it incorporates almost all phenomena. This can be seen in the following table from VPI help file:

Dispersion Properties	Optical Non-linearities	Polarization Properties
chromatic dispersion	self phase modulation cross phase modulation four-wave mixing (modulation instability) (soliton formation) stimulated and spontaneous Raman scattering stimulated and spontaneous Brillouin scattering	polarization mode dispersion polarization dependent gain/loss

Table 4.1 Universal fibre simulate phenomena [10]

4.3.2.1 Brief description of optical phenomena present in the fibre

A small description of each phenomenon present in the fibre is in order, as to show at what depth this fibre simulates them.

Attenuation happens whenever the power of the signal in the fibre reduces throughout the length of the fibre, this happens due to absorption by the fibre glass, impurities and Rayleigh scattering.

Dispersion present in monomode fibres is due to chromatic dispersion or group velocity dispersion for the fundamental mode. In these sort of dispersions, different spectral components, or in other words different wavelengths, propagate at different velocities. Even using a laser with narrow linewidth, the spectral components still differ in wavelength enough for chromatic dispersion to be felt, and since they travel at different speeds, this means that they will not arrive at the receiver at the same time, thus causing pulse spreading. The main difference between both dispersions is the magnitude of wavelength difference between spectral components needed to cause enough dispersion to be noticed.

Raman Scattering is actually the common name for two phenomena: Stimulated Raman scattering and Spontaneous Raman scattering. Stimulated Raman scattering is an inelastic process by which light is scattered, causing molecules to vibrate. This, in turn, causes low energy photons to be created from high energy photons, due to absorbed energy. This attenuates short wavelengths and amplifies long wavelengths. The effect is commonly used to provide optical amplification, in which, a pump laser having a short wavelength emission of light is used to provide energy to longer wavelength signals in the fibre which will be amplified.

Rayleigh Scattering happens when light encounters microscopic variations and and small differences in the refractive index in the fibre. Light is then scattered in all directions, but some is sent back to the emitter, as seen in Fig. 4.11. This scattered light can, due to the same phenomenon, be re-scattered back to the receiver again. This process is usually called Double Rayleigh scattering and can induce noise in communications.

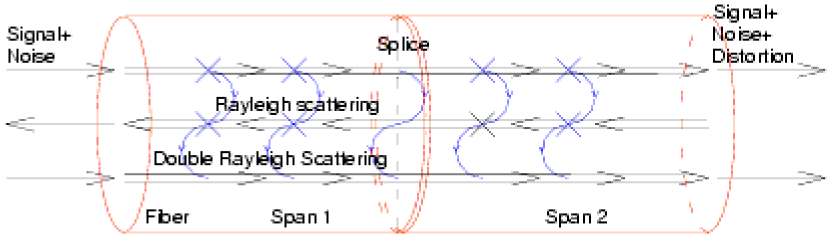


Fig. 4.11 Schematic representation of Double Rayleigh Scattering in optical fibres [10]

Brillouin Scattering and **Raman Scattering**, are the designations of two phenomena also known as stimulated and spontaneous. The stimulated version of Brillouin Scattering at high optical intensities, the light waves create a sound wave in the fibre, this sound wave forms a travelling index grating, since it slightly compresses and expands the fibre. This grating will behave like a Bragg grating, reflecting light. For narrow bandwidth signals Stimulated Brillouin scattering is stronger since a strong coherent grating is produced. Whereas for Stimulated Raman Scattering occurs due to vibrational excitation of molecules, transferring energy and creating lower energy photons from higher energy photons. Although being an impairment, it can be seen as an advantage since it can allow amplification using the standard fibre as medium, where high energy photons are injected to amplify the signal of low energy photons.

Self-Phase Modulation and **Cross-Phase Modulation** arise from the fact that in a non-linear fibre, the variation of the intensity of the signal, modulates its own phase. Both phenomena increase the bandwidth of the original signal, which in turn, broadens the signal due to chromatic dispersion. These phenomena are polarization dependent.

Four-Wave Mixing is caused by the same self-modulating phenomenon, but, in this case, multiple signals cause variations in the refractive index, which modulates the original carriers and produces side bands at new frequencies. This can occur between channels, between tones within a channel and between noise and channels. This phenomenon is one known problem with low dispersion fibres, since signals have a phase match throughout long distances in the fibre. This phenomenon is polarization dependent.

Polarization Mode Dispersion is due to fibre's non circular section and also due to local stresses. These faults change birefringence axes alignment throughout the fibre's length, thus light is split in two polarizations that travel at different velocities due to differences in the refractive index encountered by each polarization. The fact that there are two different refractive indexes for each mode is due to birefringence. The trouble with Polarization Mode Dispersion compensation is that birefringence varies randomly with time, so there will be random coupling between the modes. This forces the analysis of this phenomenon to be statistical.

Point Reflections and Losses occur whenever the fibre is connected to another fibre or equipment, this in turn causes reflective and nonreflective events. Reflections can be caused in the fibre-air-fibre interface, when poorly-mated connectors are used. Losses can be expected when numerical

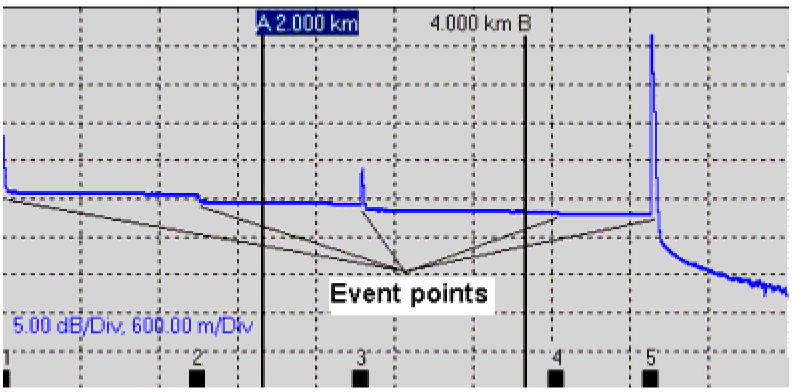


Fig. 4.12 Optical Time Domain Reflectometer trace of a fibre link composed of four fibre spans [10]

apertures or core diameters mismatched, nonconcentric fibre cores and misalignment of connectors. These cause some of the light not to be inject into the fibre. Also bends can induce loss. These losses are represented as discontinuities, known as event points, by an Optical Time Domain Reflectometer as seen in Fig. 4.12.

4.3.3 Pseudo Random Binary Sequence Generator

This module is the one used to generate the sequence of ones and zeros that will be the information being coded and transmitted in all simulations. Different pseudo random data sequences can be generated and with any duty cycle. Despite the model's name, it can also generate an alternate sequence of ones and zeros, which will be useful for Duobinary modulation. Not only this, but also pre- and post-sequence zeros, alternate ones and zeros, predefined sequences, all ones, all zeros. This module is capable of producing a sequence of N bits with m zeros preceding and n zeros succeeding the bit sequence as seen in Fig. 4.14.

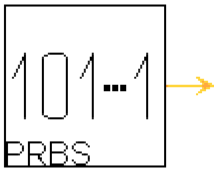


Fig. 4.13 Pseudo Random Binary Sequence Generator Symbol [10]

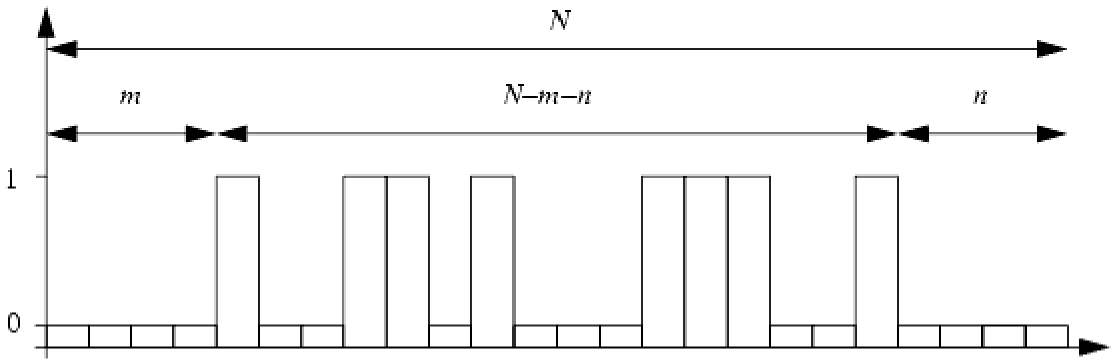


Fig. 4.14 A sequence of N bits contains m preceding and n succeeding zero bits [10]

4.3.4 Continuous Wave Laser

This laser module is one among many to choose from, its use is standard in VPI, being present inside many complex modules, except when laser oriented simulations are in order. It models a Distributed Feedback Laser that generates a virtual optical signal with the chosen power, frequency, linewidth, and polarization. All simulations will use this laser for light emission purposes. Since all modulation is performed by one or more MZI the used laser can be a continuous one. This is due to the high bitrates used.

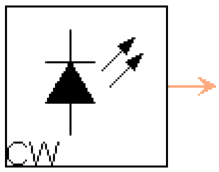


Fig. 4.15 Continuous Wave Laser Symbol [10]

4.3.5 Deterministic BER Estimator

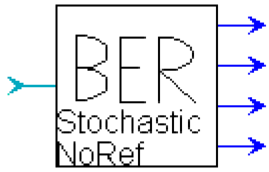


Fig. 4.16 Deterministic BER Estimator Symbol [10]

This module is used to deterministically estimate Bit Error Rate (BER) in simulations, wherever a direct detection system is present; a different module will be used to estimate BER for angular modulations. Not only BER is present at the outputs, but also: Q-factor, effective Q-factor and absolute decision threshold. This module can use two different approaches: Gaussian or χ^2. To be defined in the module are the characteristics of the receiver, PIN or APD, since these are taken into account in this module instead of being simulated in the receiver module. The original bit sequence in the logical channel is used to determine marks and spaces in the signal.

Stochastic and deterministic approaches are used for BER estimation. The variance in optical beat noise and mean values for marks and spaces are calculated from the statistics of the input signal. By comparison, electrical noise due to post detection equipment is calculated deterministically, as stated before, these are specified by the user. In making the estimation of BER, this module can also account for intersymbol interference.

Although there are reasons to opt for Gaussian or χ^2, these were not taken into account since the model used for BER measurements of DPSK modulation only has χ^2 as the estimation method, therefore to make the comparison as even as possible, χ^2 was chosen for all BER estimators.

The Gaussian estimation method should be used when the signal has significant noise contributions from other sources, namely shot noise and post-detection electrical noise, as it is more accurate. Whereas the χ^2 method is for situations when the dominant noise sources are of a spontaneous nature from pre-detection. This optical noise is statistically of a non-Gaussian nature. After detection the electrical current statistics will follow one of a family of χ^2 probability densities. This probability density function is affected by the low-pass filter that usually follows detection. As in an ideal integrate and dump receiver, the statistics of the electrical signal retains the χ^2 form, therefore whenever we have an approximation of this ideal receiver by means of a low pass filter followed by a sampling circuit, a χ^2 model for the received optical beat noise statistics will be more suitable than the Gaussian approximation.

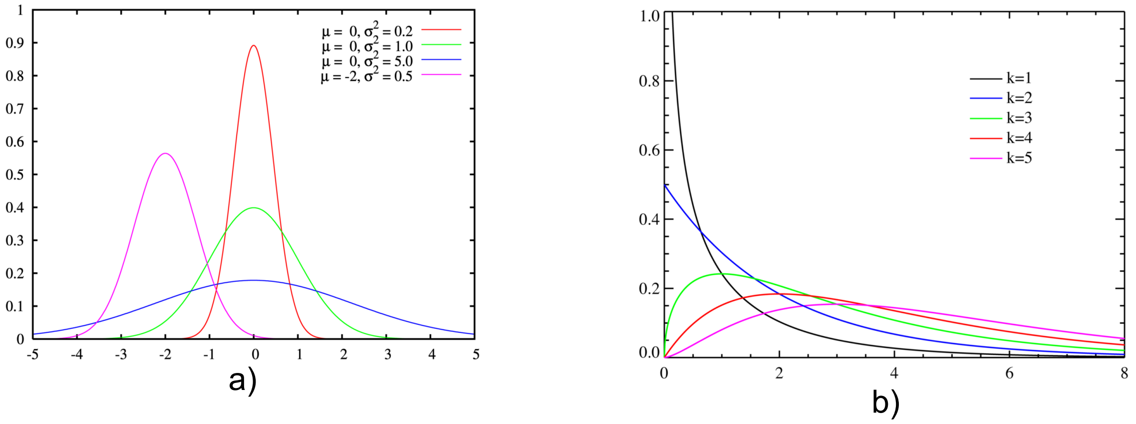


Fig. 4.17 Probability density functions of the two mentioned distributions: a) Gaussian and b) χ^2 [images have been released in the public domain]

4.3.6 DPSK BER Estimator

Fig. 4.18 DPSK BER Estimator Symbol [10]

This module is a Bit Error Rate estimator like the previous model, but is used for balanced receivers. The same noises are accounted for, plus source phase noise. As in the previous model, intersymbol interference is also taken into account. Unlike the previous stochastic model, this one is semi-deterministic but also uses χ^2 method to estimate BER.

4.3.7 Photodiode

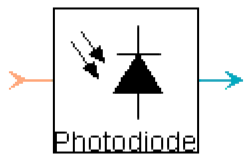


Fig. 4.19 Photodiode Symbol [10]

This module models a PIN or APD photodiodes. All simulations feature PIN photodiodes. There are several characteristics to change, predefined responsivity, avalanche multiplication, dark current and noise. Also voltage and temperature dependence can be simulated. All these characteristics will be set as ideal in simulations, since they are to be set with their desired values at BER estimators. Electric frequency response must be modelled by an external filter. Throughout this dissertation this module simulated only PIN photodiodes.

4.3.8 Clock Recovery Ideal

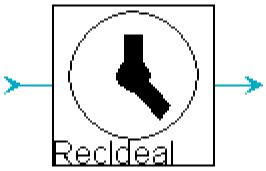


Fig. 4.20 Dideal Clock Recovery Symbol [10]

This module is used before the BER estimator, and its function is to determine the delay between the incoming signal and the original sinal which is read from a logical channel. Using information in the logic channel like pulse shape, coding and modulation, the time delay is calculated by the cross correlation of the incoming signal and the regenerated signal. Whenever the incoming signal is too distorted, this module will issue a warning to the console to inform us that the cross correlation between signals is too low. After calculating the delay between signals, the incoming signal is then shifted in order to synchronize it with the original signal. This model, therefore, performs a clock recovery.

4.3.9 Logic Add Channel

With this module we are able to add a logical channel to the original signal, this is done by a label, that has to be passed to all modules that need access to the original signal in order to function properly.

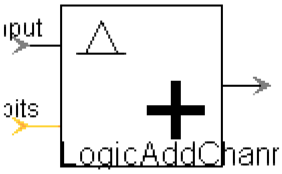


Fig. 4.21 Logic Add Channel Symbol [10]

4.3.10 Differential Mach Zehnder Modulator

This is a generic datasheet model of a Mach Zehnder Modulator, of a typical split electrode with access to DC biasing. This kind of modulator is extensively used to modulate light, since it can achieve faster bit rates than a direct modulated laser. The access to both arms enables the device to be configured so that the arm phase changes with drive be equal or opposite.

This module allows the construction of the push-pull Duobinary modulator.

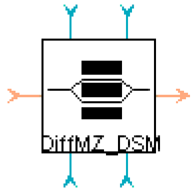


Fig. 4.22 Differential MZI Symbol [10]

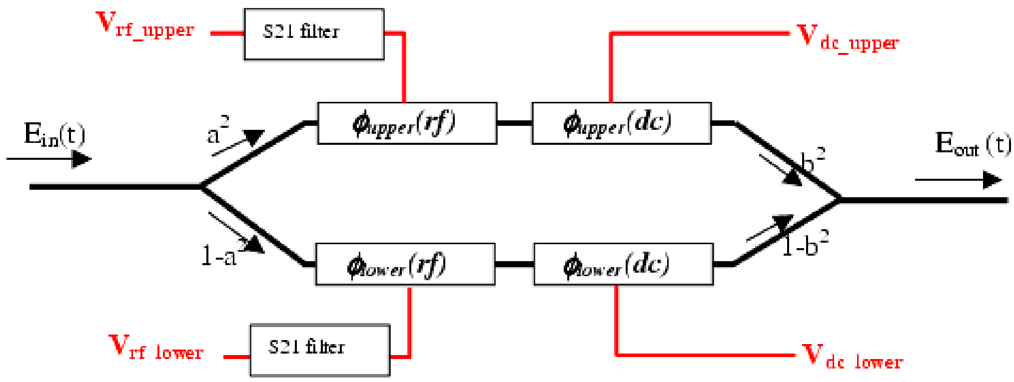


Fig. 4.23 Differential MZI schematic [10]

4.3.11 Mach Zehnder Modulator

With this module we are able to simulate a Mach-Zehnder modulator capable of simulating frequency chirp. Unlike other MZ modulators, this has a single RF drive port. The design of this modulators, namely the configuration of the electrodes with respect to the Lithium-Niobate crystal, influences their behaviour. This module has been constructed to simplify the

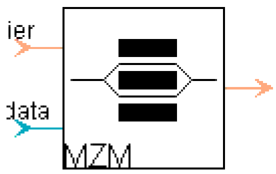


Fig. 4.24 Single Drive MZI Symbol [10]

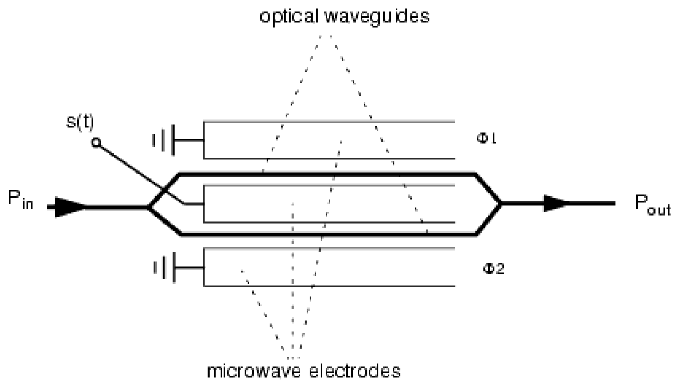


Fig. 4.25 Single Drive MZI Schematic [10]

choice of its characteristics, for example the drive voltage is less than required for full extinction. However it is not possible to control the voltage of V_π, or extinction degradation, due to imbalances in optical splitters and couplers. Although these characteristics cannot be controlled, this module simplifies its integration as it can be driven directly by the output of CoderNRZ or CoderRZ.

4.4 Final Remarks

Thus have been covered some of the most important modules used to construct the modulators, demodulators and fibres, with these in place inside VPI, numerical simulations can start so the results can be compared. The next chapter deals with the actual numerical simulations, starting with a simple test to check the numerical simulations against real results, later evolving to the simulations that allow the comparison of modulation formats.

5 PMD Impact On Modulation Format's Performance

5.1 Introduction

Throughout this dissertation, we have seen how PMD works, analysed several modulation formats and studied VPI simulation techniques and used components. All this chapters led to this one, where the actual simulation will be performed.

In this chapter, an initial simulation will be performed to infer on the correctness of simulation settings. Other simulations will be performed to determine how different modulation formats behave when fibre characteristics vary, like attenuation, chromatic dispersion and nonlinear effects.

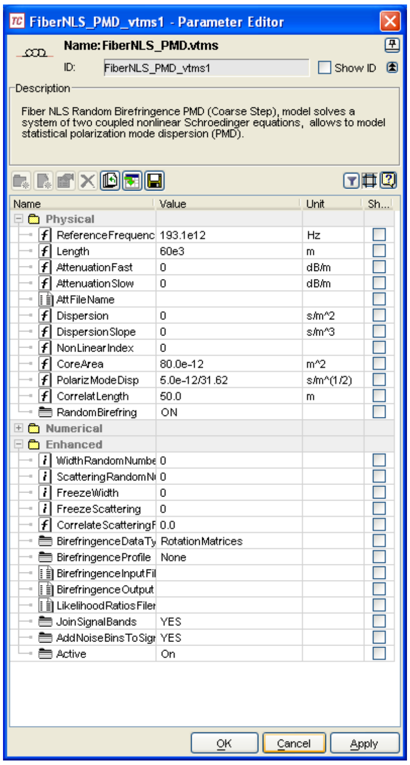


Fig. 5.1: PMD fibre characteristics when simulating only PMD

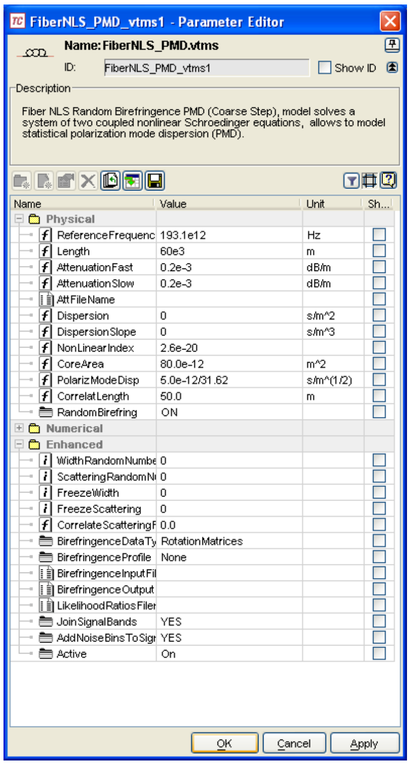


Fig. 5.2: PMD fibre characteristics when simulating PMD, attenuation and nonlinear effects

Simulations are performed using all discussed modulation formats and for three different fibre configurations: high PMD fibre, Universal fibre and Universal fibre plus Dispersion Compensating fibre. Each simulation will be performed for different fibre lengths as to determine where each modulation format becomes unsuitable for acceptable use. Modulator schematics used are consistent with the ones shown for each modulation format, along with the addition of a fibre, suitable receiver and some data gathering modules.

In what PMD fibre simulation is concerned, four different characteristics variations are used: only PMD; PMD, attenuation and nonlinear effects; PMD, attenuation and chromatic dispersion; and finally all impairments active.

For the Universal fibre only two cases are considered: no attenuation and full impairments active.

For the final simulation using a dispersion compensating fibre only full impairments are used.

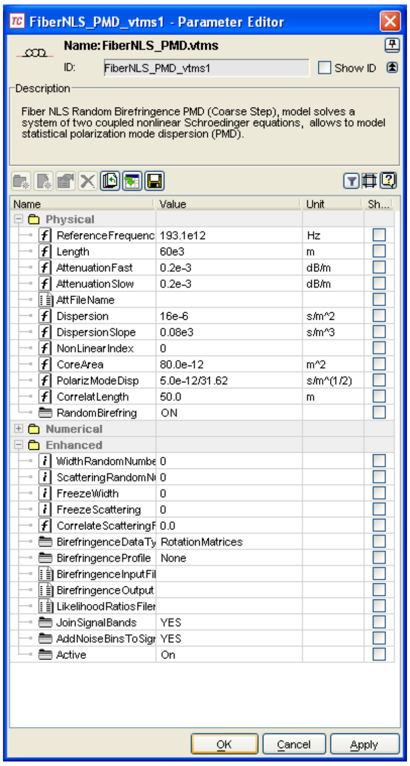


Fig. 5.3: PMD fibre characteristics when simulating PMD, attenuation and chromatic dispersion

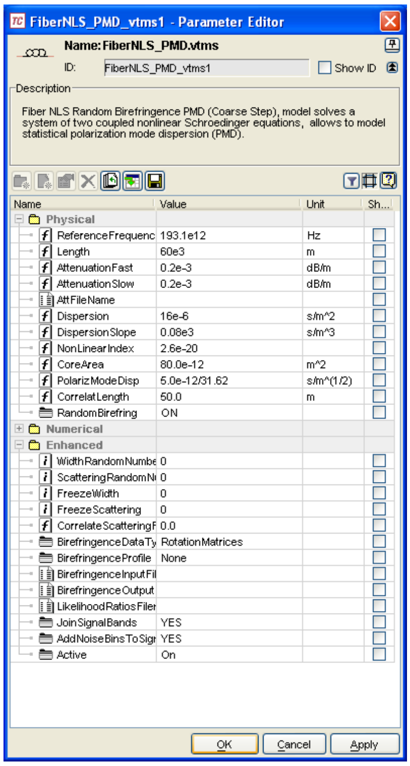


Fig. 5.4: PMD fibre characteristics when simulating full impairments

The selection of which impairment is active or not is achieved by variation of the fibre characteristics either making a characteristic have a zero value or restoring it to the previous original value. The values in question can be seen for PMD fibre from Fig. 5.1 to Fig. 5.4. For Universal fibre these can be seen inFig. 5.5 and Fig. 5.6.

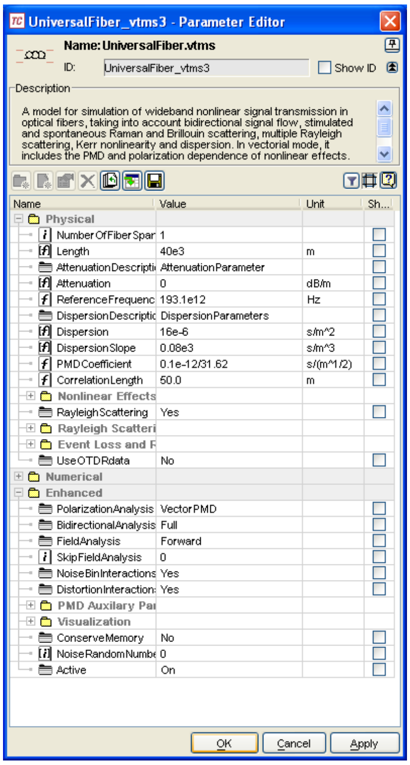


Fig. 5.5: Universal fibre characteristics when simulating without attenuation

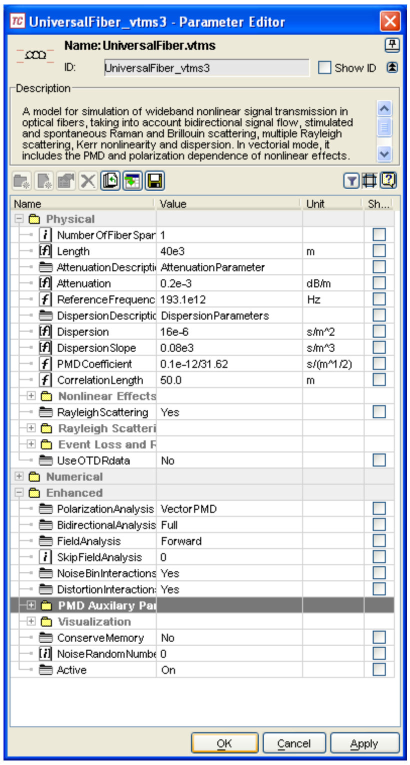


Fig. 5.6: Universal fibre characteristics when simulating using full impairments

The results will be presented as a group of histograms, four for each modulation format, since each modulation format is simulated in four different fibre lengths. Histograms were chosen since this is the best way to deal with PMD's statistical varying results, in this way one can clearly see if most of the simulations are below the threshold of system malfunction. In each histogram the comparison threshold is marked with a dashed line, to facilitate comparison; this threshold was chosen to be 10^{-12} of BER since this value is commonly regarded as the goal an optical transmission system should achieve. As the histograms are in dB, the value 10^{-12} translates to -120dB.

Even with the dashed line, there may still be some confusion as where most of the results lie, for that purpose, a table will accompany each group of histograms conveying the information of how many points lay below the threshold.

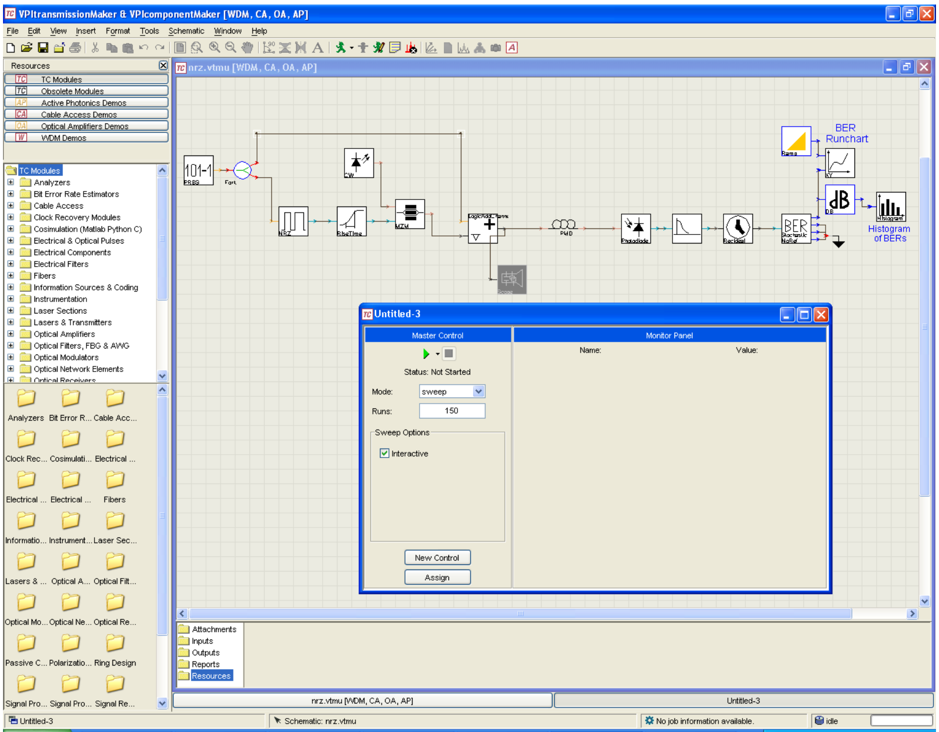


Fig. 5.7: Typical simulation with interactive simulation window showing number of iterations

All simulation are made at 40Gbit/s, each simulation outputs a histogram, for this histogram are 150 iterations having a time window of $1024/40^9$, meaning that 1024 bits are simulated per iteration with a sample rate of $2^4 \times 40^9$, thus having 16 samples for each bit. Simulation times ranged from meagre 20 minutes to 4 hours. To simulate 150 iterations and make sure that all are shown in the same histogram automatically All were performed in a PC with a AMD Sempron 2600+ Processor having 512Mbyte of Ram memory.

5.2 First simulation

A first simulation is needed, since we have no knowledge of how realistic the simulation results are. Ideally one should compare VPI results with results published in the literature. The chosen published experiment will be the one present in [6], where the single-sided Duobinary modulator is used. The same modulator will be used in VPI, the fibre will be FiberNLS_PMD, which was specially conceived to do PMD testing; this fibre will have all default parameters, in particular PMD of $1581.3 \times 10^{-15} (s/\sqrt{(m)})$. In order to perform the four simulations, first we need to make the fibre inactive so we can simulate back to back, or 0Km of fibre. Then, separate simulations will be made for 100, 200 and 252 Km, as these are the transmission lengths in [6].

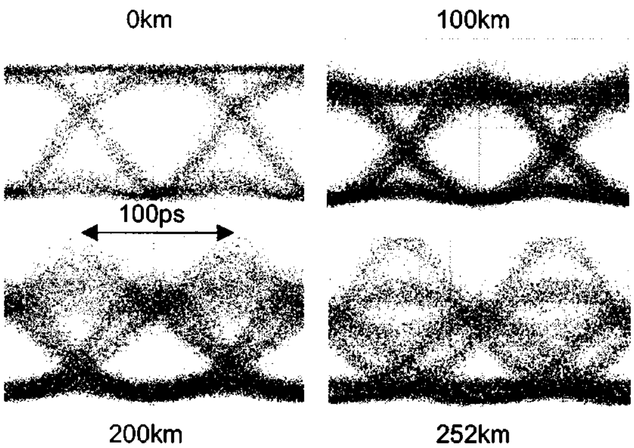


Fig. 5.8 Eye diagrams at 0, 100, 200, and 252 km of Duobinary transmission with uncompensated SSMF [6]

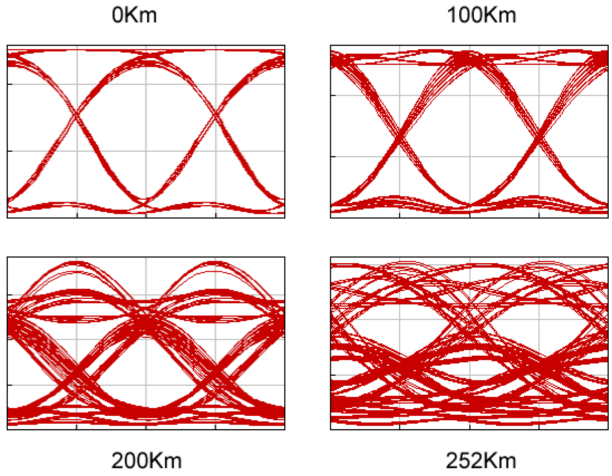


Fig. 5.9 VPI simulation results at 0, 100, 200, and 252 km of Duobinary transmission with uncompensated PMD fibre

The results obtained are quite similar except for 252Km where the eye diagram is less defined. It is possible that the lack of an optical amplifier and a receiver with pre-amplifier in the VPI simulation are to blame, since they were used in the experiment: "Our test setup comprises an inline optical amplifier (placed after 125 km of SSMF) and a standard preamplified optical receiver."[6].

This simulation has proved that simulation settings allow for confident simulation and reliable results, next the comparison will start.

5.3 PMD FIBRE SIMULATION HAVING ONLY PMD

After having confirmation that the simulation model is accurate when compared to real experiments, the next step would be to try to see how well different modulations formats stand against PMD. For this first simulation the best suited fibre for PMD simulation is chosen, FiberNLS_PMD, here only PMD's effects will be accounted for, all other impairments are inactive, like attenuation, nonlinear effects and chromatic dispersion. This means that this simulation will lead to the conclusion of which modulation format is best suited for PMD mitigation, which, although enlightening may not be applicable in realistic situations, since all fibres present impairments neglected by this simulation, to a greater or lesser extent.

The results are presented in Fig. 5.10, surprisingly enough, NRZ, RZ and CSRZ modulations seem to present better results, not only for 20Km but for almost all fibre lengths. It was said before that histograms, while useful for a global view, do not provide accurate enough results, so a table must be added.

In Table 5.1 we can see which modulation format is the one that yields the best results.

	20Km	40Km	60Km	80Km
NRZ	141	97	51	25
RZ	141	98	49	27
DUOB SS	125	74	36	27
DUOB PP	121	60	25	20
DPSK	99	37	21	7
CSRZ	139	90	44	22

Table 5.1 Number of iterations having BER under the threshold of -120dB for FiberNLS_PMD at different lengths, with only PMD as an impairment

Examining the table, the conclusion is straightforward, for small fibre lengths NRZ, RZ and CSRZ are far superior, whereas both Duobinary modulations and DPSK are the worst. Still DPSK is really the worst of the lot, showing at times half the performance of other modulations results. This inevitably means that PMD takes a high toll on DPSK's phase modulated signal. Also Duobinary's poor performance might be explained by the fact that it is not best suited for short distances, since its signal has some artefacts when compared to a NRZ signal; this is due to the fact that, although Duobinary is modulated like a NRZ signal, the adding of extra characteristics causes these artefacts to appear which will make detection at low distances complicated, distance will later be responsible to remove this artefacts, due to PMD in this case.

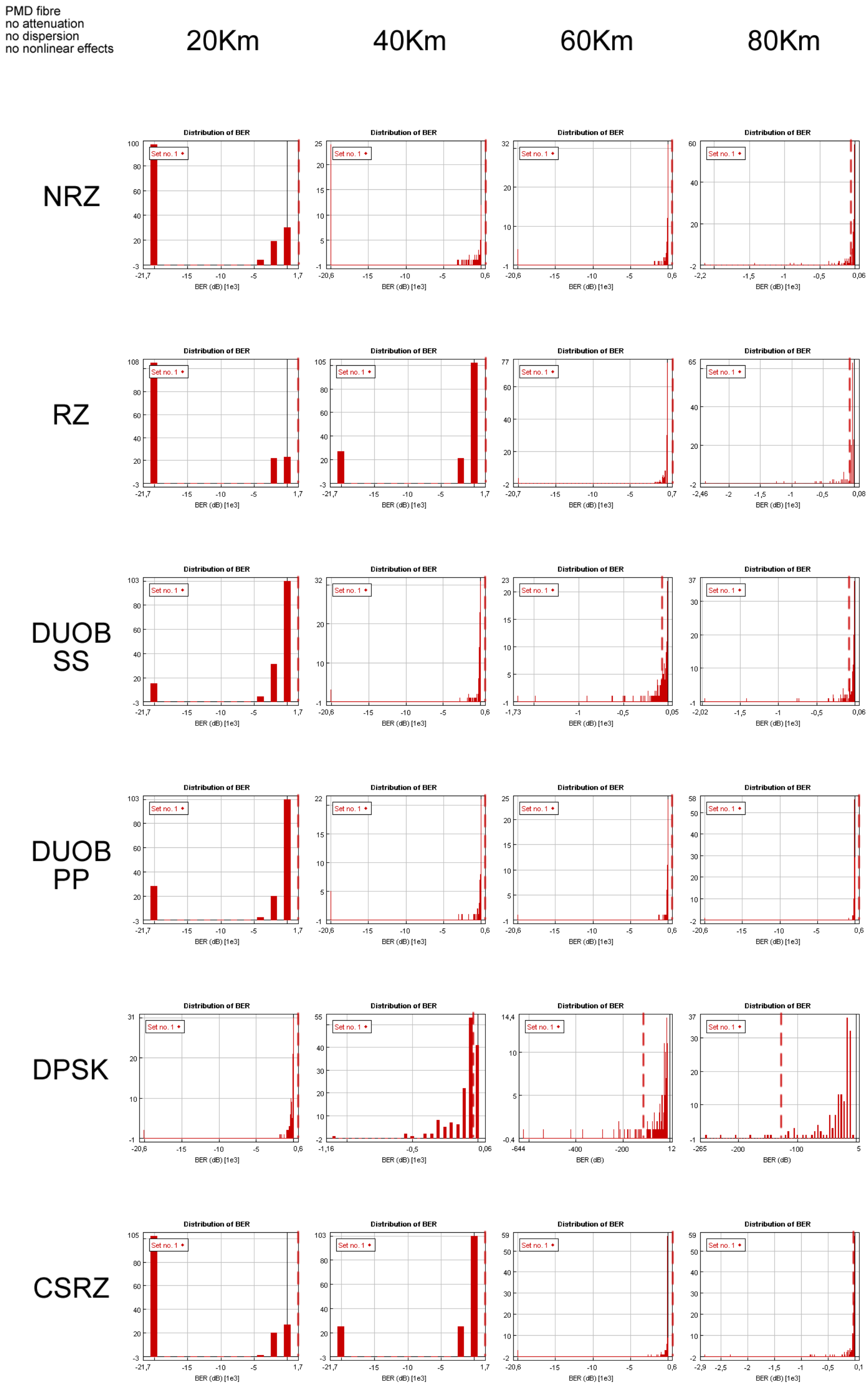


Fig. 5.10 Simulation results for FiberNLS_PMD at different lengths, with only PMD as an impairment

At 80Km, differences between modulations become less noticeable, as dispersion is so high that not many iterations present BER under the threshold. One stands out though: DPSK takes its toll on high PMD links, its results are by far the worst having less than half of the iterations under the threshold when compared to other modulation formats, this is inevitably due to the degradation of phase information in the random sections of the fibre. Will NRZ, RZ and CSRZ dominance continue as other impairments are added to the fibre?

5.4 PMD fibre simulation having PMD, attenuation and nonlinear effects

Bringing new impairments might alter the results, comparison wise. As dispersion, more specifically chromatic dispersion, is left out, these results can later be compared with the simulation having all impairments present, to infer on the effect that chromatic dispersion has when added to PMD. As the same fibre, FiberNLS_PMD, is used throughout this first series of simulations, proper comparisons can be performed. From Fig. 5.11 one can clearly see that the adding of attenuation has hampered RZ's performance, whereas other modulations seem to have the same performance difference as before. Nevertheless, the analysis of the following table may lead to new conclusions.

	20Km	40Km	60Km	80Km
NRZ	138	89	16	0
RZ	135	74	0	0
DUOB SS	121	64	11	0
DUOB PP	120	52	8	0
DPSK	98	34	14	0
CSRZ	137	74	5	0

Table 5.2 Number of iterations having BER under the threshold of -120dB for FiberNLS_PMD at different lengths, with PMD, attenuation and nonlinear effects as impairments

Looking at the table, one can see the first simulation zeros, meaning that no iteration had a BER below the threshold. As stated, RZ now performs worse than NRZ, even though for 20Km the results are almost the same, but as distance grows, differences between these two modulation formats widen. CSRZ also has a good start with values, at 20Km, close to NRZ, and RZ, but as the latter, fails to provide transmission quality at longer lengths. All modulation formats perform equally bad for 80Km, these worse results compared to the ones in the previous chapter are expected, since an impairment was added.

A new conclusion can be drawn here, NRZ performs better than RZ when attenuation and nonlinear effects are to be accounted for, although both perform the same for PMD.

Duobinary has not shown better results from last simulation.

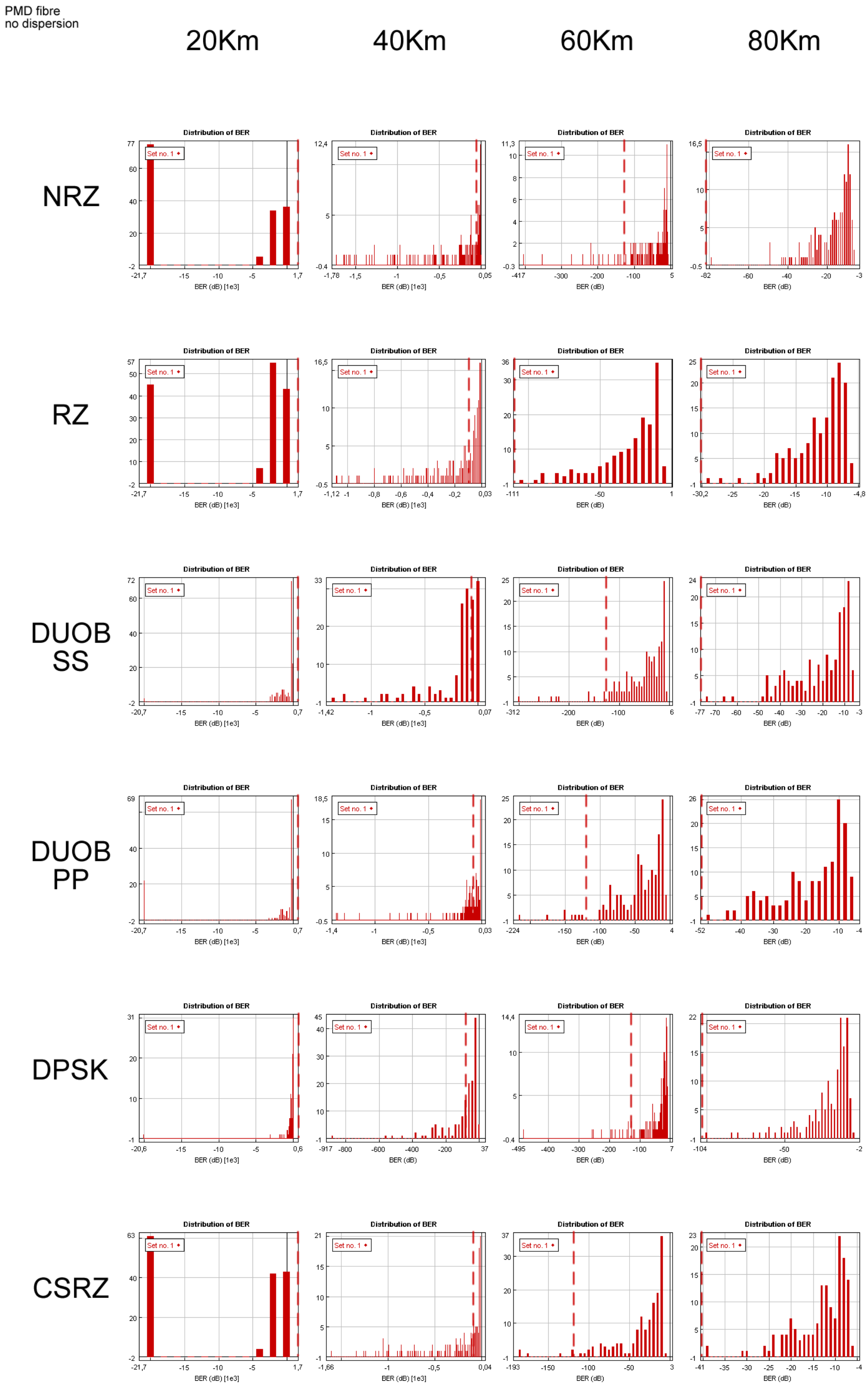


Fig. 5.11 Simulation results for FiberNLS_PMD at different lengths, without dispersion

5.5 PMD fibre simulation having PMD, attenuation and chromatic dispersion

Here nonlinear effects will be left out, and chromatic dispersion is added. Will chromatic dispersion reveal Duobinary's dispersion mitigating characteristics?

All except nonlinear effects will be simulated. Will chromatic dispersion finally affect NRZ so that its performance is hampered enough to allow it to be outperformed by another modulation format?

As seen in Fig. 5.12 these are the worst results so far, none of the simulated modulation formats is capable of achieving at least one simulation with BER below the threshold. Still Duobinary proves to be the best, and this means that Duobinary is far more resilient to chromatic dispersion than to PMD, which explains Duobinary's success for optic fibre communications. This conclusion is achieved by comparing histogram values or by simply compare central BER value in the histogram, both Duobinary modulators have far better results than all other modulators and modulations.

Now one simulation for this fibre remains, where this fibre is simulated with all impairments active. One thing is already clear, no modulation will be capable of a simulation with BER lower than 10^{-12} since adding nonlinear effects will only make matters worse. Yet one question arises, will there be any surprises?

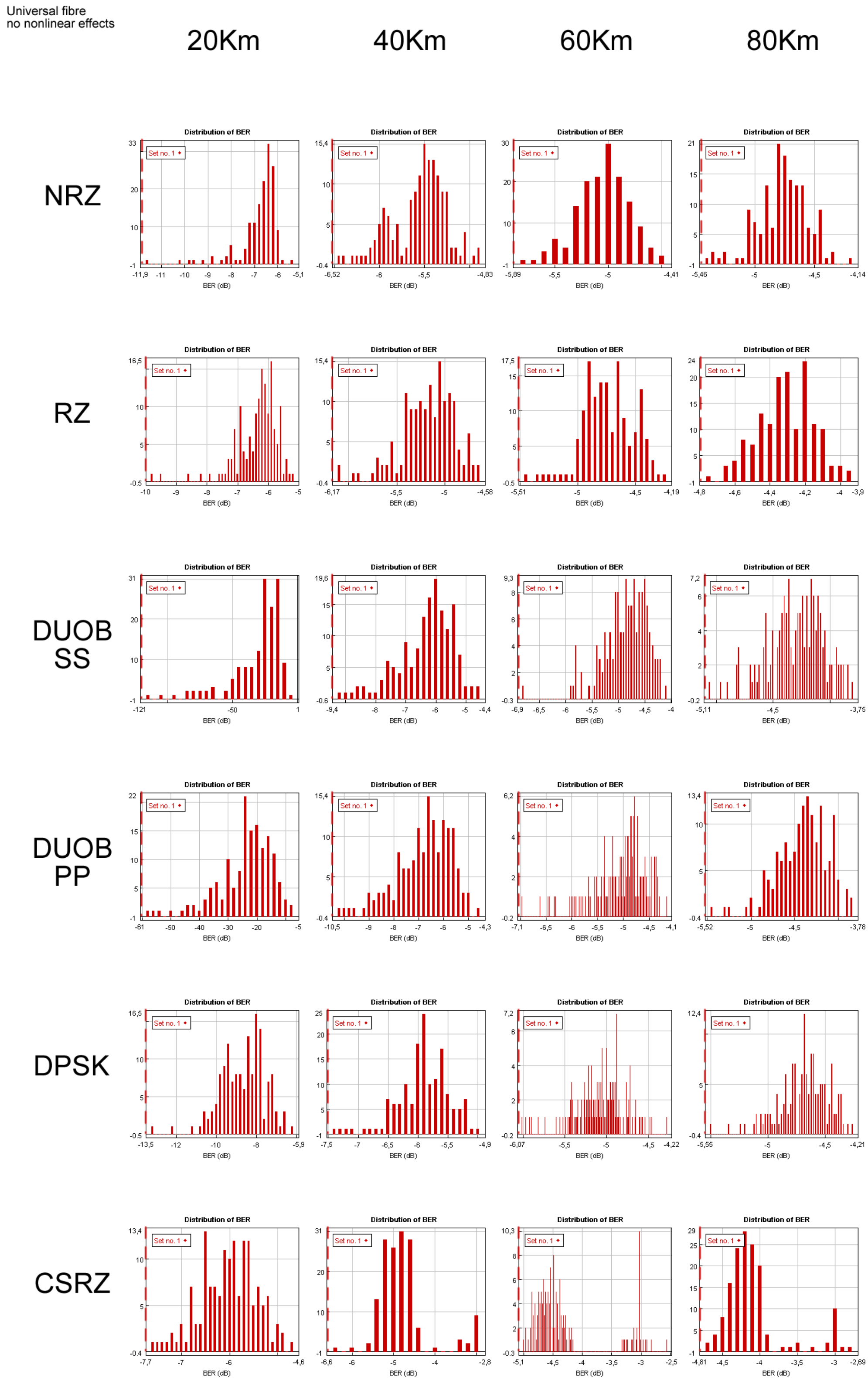


Fig. 5.12 Simulation results for FiberNLS_PMD at different lengths, without nonlinear effects

5.6 PMD fibre simulation having PMD, attenuation, chromatic dispersion and nonlinear effects

This simulation finalizes the first series of simulations, after this some conclusion can already be drawn, but lets see the simulation results first.

After looking at Fig. 5.13 one must conclude that nonlinear effects didn't affect Duobinary's performance; as a matter of fact, both figures: Fig. 5.12 and Fig. 5.13 are quite similar, not only for Duobinary but also for all modulation formats, in these figures, no iteration proved to achieve a BER under the threshold.

In a more global view, as surprising as it may seem, NRZ has proven to be the modulation format least affected by PMD.

One possible explanation can be the one stated before, the signal generated by NRZ modulator is cleaner, meaning that since the modulator is so simple, the signal modulation is straightforward having low distortion and other problems like chirp. For other modulations, the modulator is far more complex, as the modulator is not only modulating the signal, but is also adding extra information to it. Take the example of Duobinary modulation where the modulator not only modulates ones and zeros but also adds extra phase information to the modulation, this has the inevitable effect of adding distortions to the modulated signal.

PMD can be seen as a delay between modes, which will be somewhat mixed, and delayed again, and then mixed, and so on and so forth. This means that the most pure signal will be the one that will be less affected by PMD.

But does this mean that all systems should revert back to NRZ and that the new modulations simulated here should be abandoned as well? Of course not, NRZ although being a better choice for high PMD systems, will probably not be so for field implementation. The problem arises since PMD is a phenomenon that nowadays is posing a problem since most impairments have been somewhat mitigated, which means that PMD is the next impairment to tackle after all others have been dealt with. As NRZ is not renowned for its resilience against impairments such as chromatic dispersion, nonlinear effects and attenuation, this means that it will fall short of tackling this impairments and PMD won't be an issue since the system won't be able to have a transmission

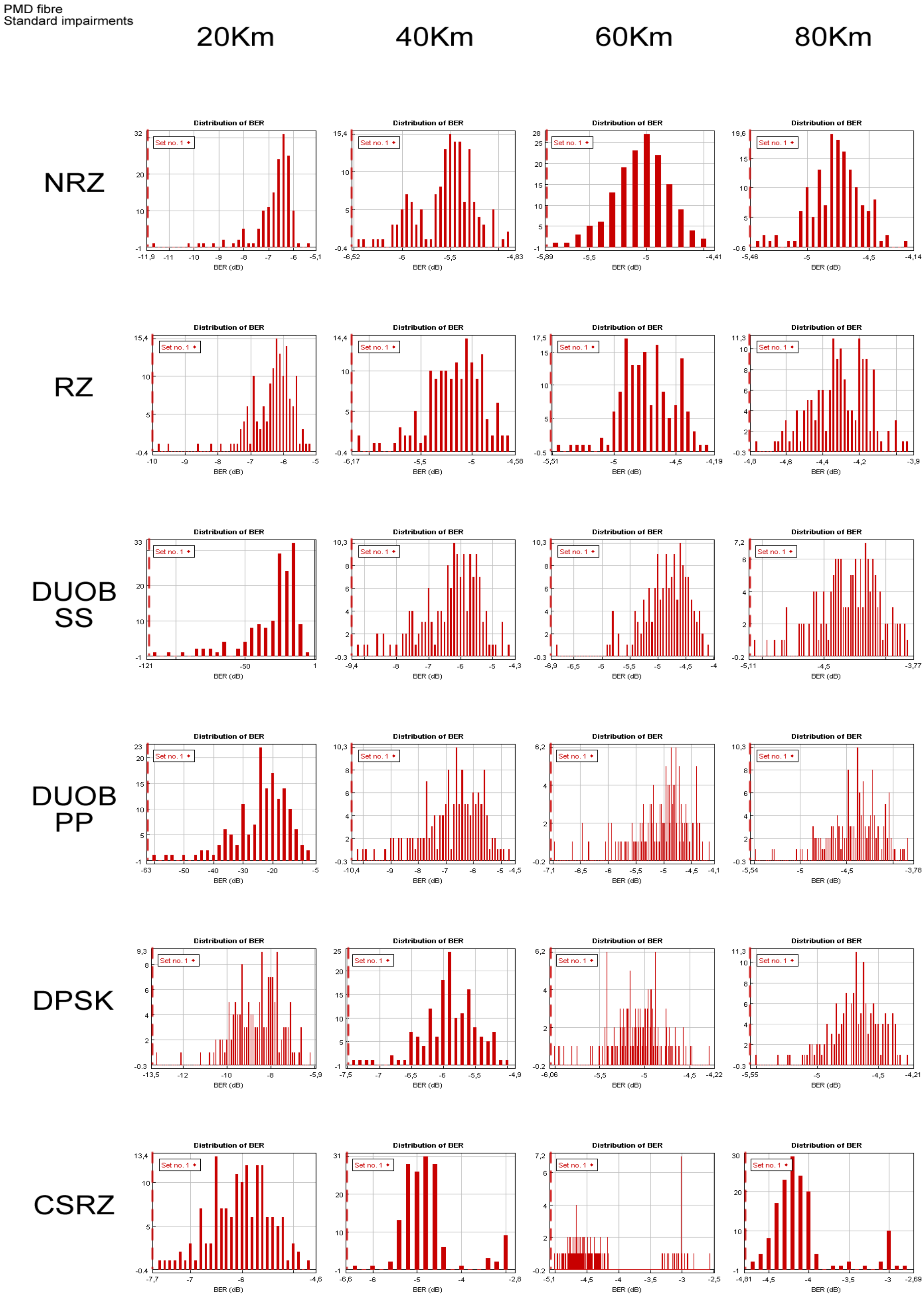


Fig. 5.13 Simulation results for FiberNLS_PMD at different lengths

length where PMD will be noticeable, as impairments that affect NRZ may never be completely removed.

But this does not explain why NRZ outperformed all other modulation formats; what explains it is that this fibre has very high PMD and the simulation it makes of other impairments is simplified, as seen in its description. This means that although these simulations allow us to reach some conclusions, these conclusions are, nevertheless, purely academic and not applicable to real world situations.

To finalise this dissertation there is still a need to perform some more realistic simulations as to infer which modulation format outperforms which, this will be accomplished by the use of what will be called “Universal Fibre”.

5.7 Universal fibre simulation without attenuation

The universal fibre simulates a realistic optical fibre in a more effective way; as a result of this, simulation time is over ten times greater, this fibre will allow final conclusion to be inferred as to which should be the elected modulation format. Please note that some influence will be felt for results concerning PMD's impact as this fibre has a much lower PMD value of merely $3.2\times10^{-15}(s/\sqrt{(m)})$ when compared to the previous fibre ($1581.3\times10^{-15}(s/\sqrt{(m)})$).

Without taking attenuation into consideration, simulated links can be longer, which enables us to have a look at the evolution of several modulation formats as the link distance increases.

And the first results are presented in Fig. 5.14, where one can clearly see that the hoped for opportunity to witness progressive link degradation as distance increases is not present as most links reveal themselves well above BER threshold values. There is a huge difference between Duobinary modulation and all others setting it apart. Duobinary presents itself as the best modulation format in this simulation, as all others prove useless even at a meagre 10Km of fibre. As a matter of fact, Duobinary does not achieve much longer links, succumbing to dispersion at the next simulated length, 20Km.

The next simulation will surely provide worse results as the added attenuation, although small, due to small fibre link size, can still make things worse.

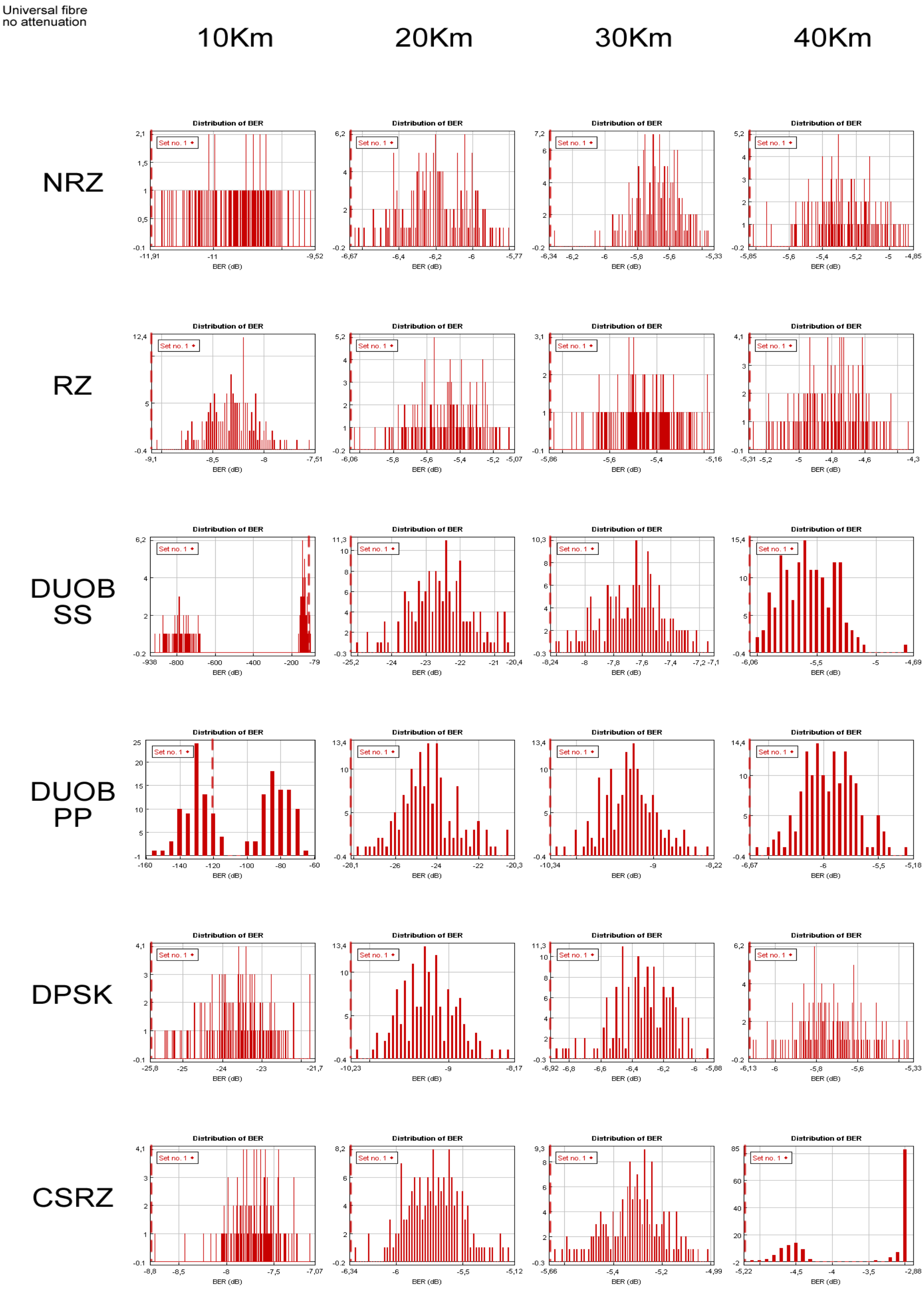


Fig. 5.14 Simulation results for Universal Fiber at different lengths, without attenuation

5.8 Universal fibre simulation

The simulation with the standard impairments should tell us how a realistic system would behave, since this fibre is the most realistic in VPI and all impairments are active, as in a real fibre.

These new results in Fig. 5.15 are very close to the ones in Fig. 5.14, proving that there is no significant attenuation in 10Km of modern fibres. The most accurate comparison is performed at 10Km and for Duobinary modulation, since at this distance and with this modulation the histogram presents better BER values, and these would easily be altered by slight changes in the link, whereas all other distances and modulations exhibit such poor values that even large changes might not affect the results and these depend on BER estimator accuracy, which at low BER values is poor.

These poor results for such short links are supported by [11] where a breakthrough is announced as links were established pass 10Km using 40Gbit/s in dispersion uncompensated fibre.

As up to this point, Duobinary is showing better results, one can take on the conclusions drawn before, where was seen that chromatic dispersion adversely affects Duobinary more than the other modulations. So to perform a fair comparison, chromatic dispersion should be compensated for, as the method to perform it is straightforward to implement. This takes us to the last simulation, where a dispersion compensating fibre will be used after the fibre, here, chromatic dispersion or very large amount of it will be compensated for, and hopefully, results will improve.

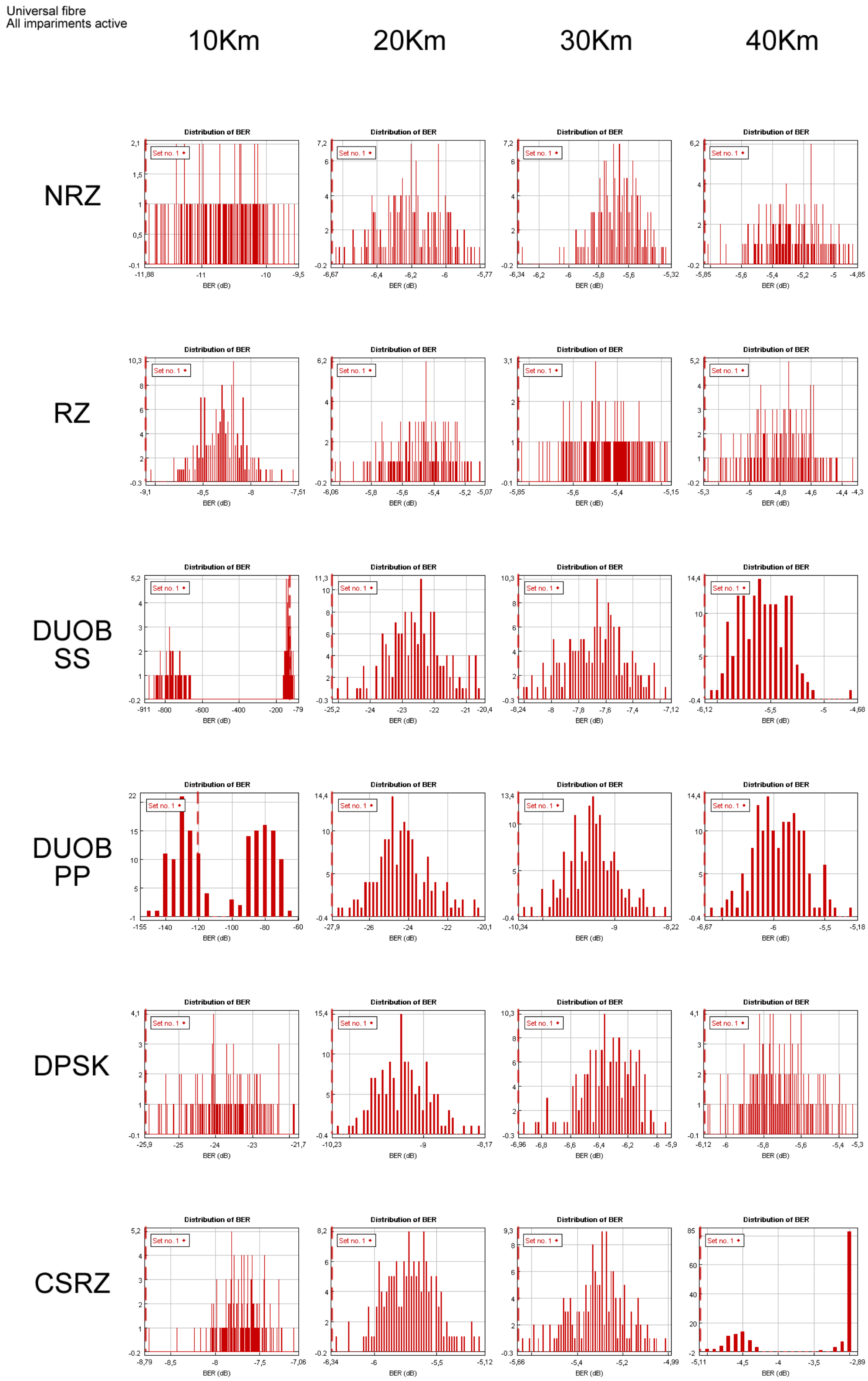


Fig. 5.15 Simulation results for Universal Fiber at different lengths

5.9 Dispersion compensating fibre length determination

To determine the length of the dispersion compensating fibre, one can start with a good educated

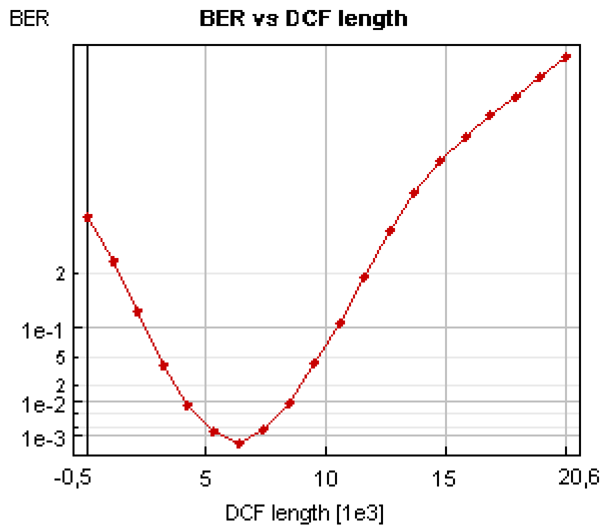


Fig. 5.16 First sweep to determine approximate DCF length

guess, as DCF fibres tend to have a high value of negative dispersion, it is straightforward to judge that DCF fibre will be considerably shorter that the fibre to be compensated for. The fibre used for this purpose is the same universal fibre used for simulation, but with some different characteristics that enable it to compensate for chromatic dispersion, namely negative chromatic dispersion. Having therefore a dispersion of $-90^{-6} s/m^2$ and a dispersion slope of $-0.21^3 s/m^3$. These values are not critical to the simulation, since one is not comparing DCF fibres, but merely finding means to compensate chromatic dispersion, would the dispersion values of the DCF fibre be different, its length would also be different, and no other considerable impact would be felt in the simulation. For all this, the simplest way to copy DCF fibre values from VPI examples, where we can find several that use DCF fibres. One problem exists though, the DCF fibres used are not the Universal Fibre model, and thus do not separate fast and slow axis simulation, therefore the values have to be copied to a new universal fibre, which will be the DCF fibre.

A simple sweep simulation performed for 40Km of universal fibre with a Duobinary modulator is enough to find out where the BER is lowest. Obviously the sweep factor is the DCF length. This first sweep yielded Fig. 5.16. So around 6Km of DCF for each 40Km of universal fibre is needed to

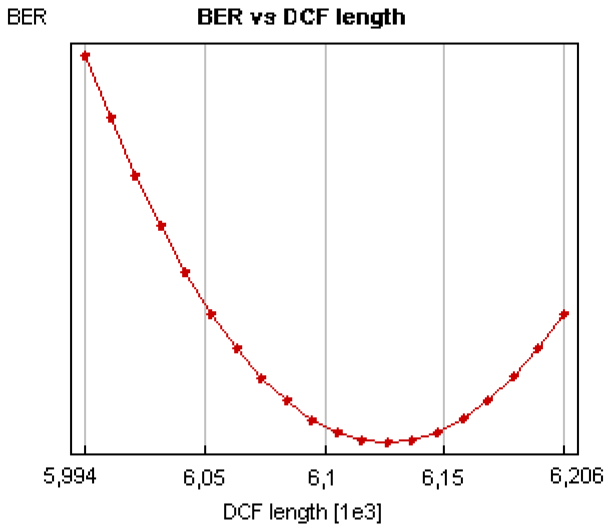


Fig. 5.17 Final sweep to determine precise DCF length

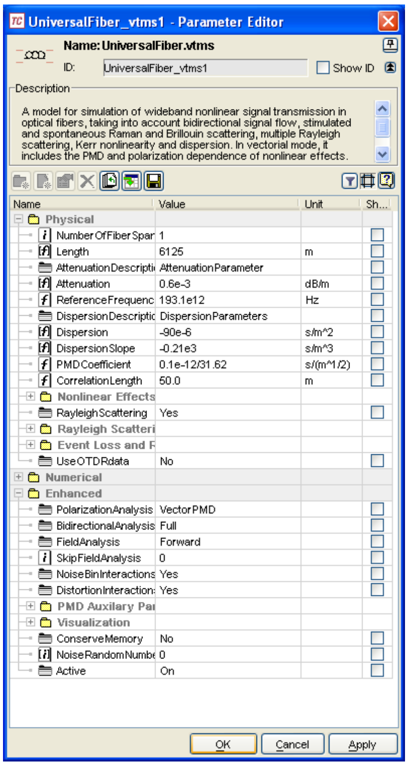


Fig. 5.18: Dispersion compensating fibre characteristics

minimize chromatic dispersion and, as a consequence, BER. This will only be true for this simulation setups and should not be considered as *de facto* standard values.

Fig. 5.17 shows a more accurate sweep, since the limits are narrow and there is a good amount of iterations. There were other simulations before this one, but the first coarser and latter finer simulations seem enough to illustrate the process. This will lead to Table 5.3.

From the simulation at 40Km, all others are calculated, this enables us to perform the next simulation with the required DCF length.

Universal fibre length (Km)	***DCF length (Km)***
40	6,125
30	4,59375
20	3,0625
10	1,53125

Table 5.3 DCF lengths needed to compensate the universal fibre in VPI

5.10 Dispersion compensated universal fibre simulation

This is the last, and taking the chance to use the jargon, not the least simulation. Here the compensated dispersion does not present itself as an impairment. One might argue that it would be easier just to alter fibre characteristic and use zero dispersion and dispersion slope. Although being a true argument, the point of these last simulations is to become ever so realistic and for as long as possible not use simulation domain problem solving; instead, realistic problem solving was used, as is the case of DCF.

The results are presented in Fig. 5.22 and most interestingly, they support the conclusion put forth in the first series of simulations. Here is why: first it was shown RZ, NRZ and CSRZ have advantage over Duobinary and DPSK, especially against PMD; here RZ, NRZ and CSRZ show the same results for 10Km. In spite of all modulations but DPSK being able to achieve all iterations with BER under the threshold, it is very clear that RZ, NRZ and CSRZ present perfect results, in

VPI represented by the lack of bars in the histogram, which means that BER is considered infinite by VPI, or more accurately $-\infty$. As an example, Fig. 5.19 is a depiction of the BER of all iteration points for the single sided Duobinary modulator simulated for 10Km of universal fibre. Careful examination of Fig. 5.19 shows some points in a shaded area under 1e-93 in the graph, this values are considered to be completely error free, for RZ, NRZ and CSRZ simulation at 10Km, all iterations share this characteristic of being completely error free.

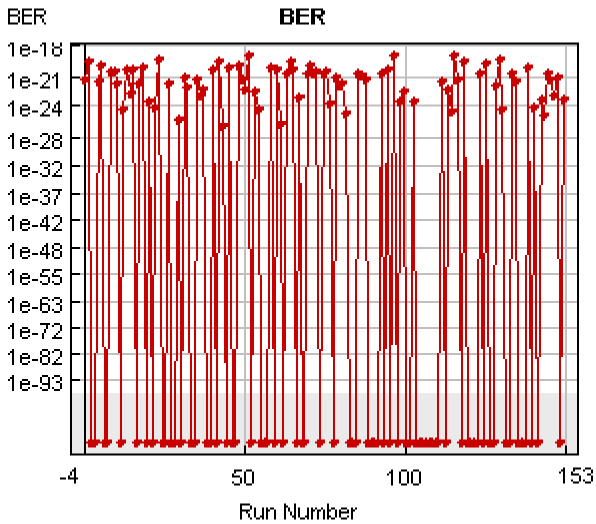


Fig. 5.19 BER values for all iteration points for single sided Duobinary modulator and a 10Km fibre span

As Duobinary is not completely error free, even though well under the BER threshold, one must conclude that artefacts added to the signal degrade it's performance, whenever dispersion is small enough that Duobinary high dispersion mitigating characteristics are not felt.

Also interestingly enough, NRZ still outperforms Duobinary for 40Km, only marginally though, but Duobinary is surpassed nevertheless, this will mean that Duobinary modulation at this length and for this bit rate is not better that NRZ, since the link length is short enough for any of its advantages, like reduced bandwidth, to be felt, especially when we have compensated dispersion, one thing Duobinary is somewhat insensitive but that affects NRZ a great deal.

One last simulation will be needed, to make final proof of which modulation format is indeed the best, not only for this length but as an overall best. The simulation is made using the same parameters but with a link length of 60Km and thus DCF length will be 9.1875Km.

5.11 Dispersion compensated universal fibre simulation at 60Km

Here will be presented the results pertaining a final 60Km simulation, made to assess or deny NRZ "better" performance over Duobinary. It has been shown in previous simulations that NRZ is better than Duobinary against PMD and low attenuation and nonlinear effects. This is why NRZ provided

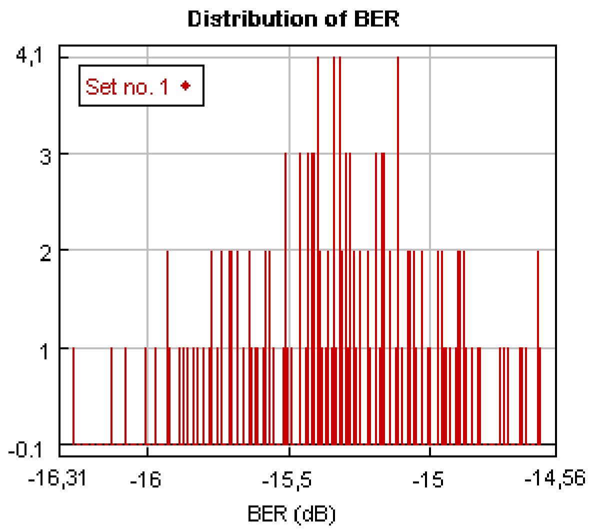


Fig. 5.20 Histogram of NRZ BER values for all iteration points for 60Km fibre span

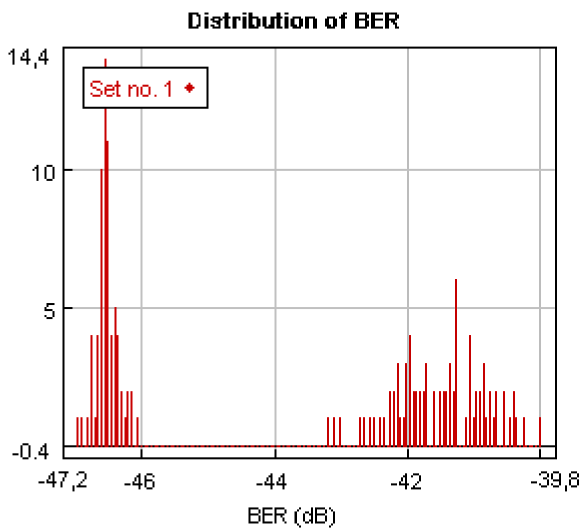


Fig. 5.21 Histogram of single sided Duobinary modulator BER values for 60Km fibre span

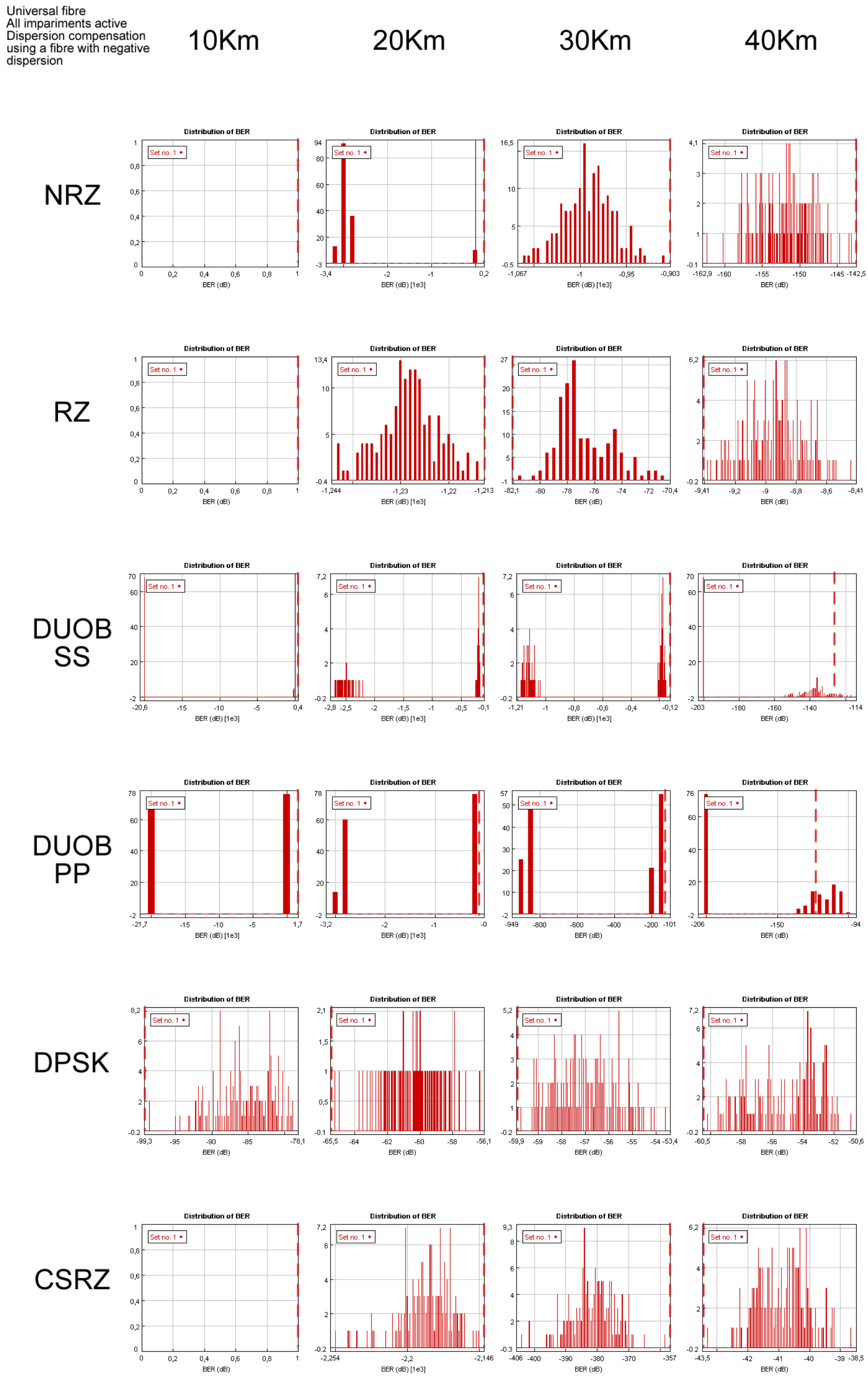


Fig. 5.22 Simulation results for Universal Fiber at different lengths, connected to a DCF

marginally better results for 40Km with DCF. If for 60Km NRZ is able to continue to show better results than Duobinary, it will definitely prove NRZ is still the modulation format to consider. If not, Duobinary will continue to be regarded the most promising format in high speed optical fibre communications.

Judging by Fig. 5.20, the increased distance took its toll in NRZ transmission, turning a perfectly working communications link in an unusable one, and just by adding an extra 20Km of fibre, and changing DCF length accordingly. Here no bar indicating the threshold is necessary to perform the comparison so it was not added.

Duobinary on its own, Fig. 5.21, proves to be far better than NRZ, although not being able to present simulated BER values above threshold, this in turn means that historical preference of Duobinary over NRZ is rightly justified.

This, in turn, represent the end of simulations in this dissertation, having reached some interesting results, especially when is comes to the NRZ *vs* Duobinary confrontation in selected conditions.

6 Final conclusions

Having performed such a plethora of simulations, it can be difficult to achieve one simple conclusion. Even though all simulations point to the same broad conclusion, there are still some misleading clues that can cause some confusion if not properly examined having in mind each simulation particularities.

The first simulation, served merely a trial to ensure some accuracy and to validate to some extent of the results in this dissertation, as these are based entirely on simulation.

The following simulation, considering only PMD started out by proving that Duobinary modulation is not well suited to counter PMD, as it presented surprisingly bad results. Although these might seem unexplainable, a very simple explanation can be proposed. It is based on the fact that both Duobinary modulators are more complex than the simple NRZ modulator. Not only this but NRZ is, in itself, a very simple and straightforward modulation, whereas Duobinary is not, as phase is encoded in the optical signal, this fact might explain Duobinary's poor performance as to add phase information to the signal, some artefacts are inevitably added, this, in turn, will cause a premature degradation of the signal, as it is mixed by the theoretical sections of the high PMD fibre. This comparison with NRZ modulation arises from the surprising fact that NRZ proved to be the best overall modulation format in this simulation. As Duobinary is a renowned modulation format, two possibilities arise here, one is the previous explanation, the other is that the computer model might not be simulating some physical property that would inevitably give Duobinary its advantage over all other simulated modulation formats. After having this insight on what were the best performing modulation formats for PMD mitigation, some other added impairments might bring some differences.

The next simulation has added two impairments in order to make a small but certain approach to a real fibre, these were attenuation and nonlinear effects. But these haven't really changed previously observed results in what concerns modulation format differences, these remain the same. Still there is a big difference in results under BER threshold as for 80Km no modulation is capable of at least one iteration with acceptable BER. This means that all modulation formats are affected by both attenuation and nonlinear effects, which was expected. What is still unexpected but again observed was that NRZ again outperformed Duobinary. As the differences are slight between to tables, a finer comparison can be achieved, this in turn allows us to infer that NRZ is still the best overall performant modulation format, but the margin it previously had to Duobinary has decreased, this will mean that NRZ is much better than Duobinary when high PMD is present and slightly better when nonlinear effects and attenuation are also present. This approach of NRZ and Duobinary performances can also be explained by the fact that Duobinary might be better than NRZ for attenuation and nonlinear effects, both together or separated, but this is a very slight difference, which could be explored, but, as this falls out of the scope of this dissertation it will not be explored any further.

Removing nonlinear effects and replacing them with chromatic dispersion revealed Duobinary's best qualities, especially for 20Km. Even though no iteration passed the threshold one can clearly see Duobinary's superiority in the histograms. This time the comparison had to be made using only histograms since no table is presented, and although this negates us a finer analysis, one can settle with a coarse one as the differences are vast, one especially evident is Duobinary's advantage. This will inevitably mean that Duobinary is by far the most resilient modulation format against chromatic dispersion, which explains in part why Duobinary is a modulation format of choice, since there will always be some degree of chromatic dispersion in a system, even when chromatic dispersion is compensated for. As much as the conclusion drawn from this set of simulations is in line with Duobinary's renowned performance, one can not yet rule out previous conclusions.

The last simulation using the high PMD fibre with all impairments active brings nothing new to the previous conclusion, as the results are somewhat similar. This can be attributed to nonlinear effects small contribution in degrading link performance, or maybe chromatic dispersion contribution is too high for the adding of nonlinear effects to be noticed.

Even though a high PMD fibre was used in this first set of simulations, having all its limitations and simulation domain simplifications, some interesting conclusions were drawn. First NRZ modulation is not as limited as one might think since it was able to outperform Duobinary in the right conditions. But, perhaps the most interesting one is that Duobinary is not at all best suited to counter PMD's effects in link degradation, but it presents an exceptional performance when high chromatic dispersion is present. The proposed reason for NRZ dominance over Duobinary in a high PMD link is that, as previously shown, PMD in a optical link can be considered as a long sequence of small birefringent fibre sections randomly oriented in relation to each other. As the fast and slow components of the signal are subjected to different propagation speeds and then mixed an also random amount, these tend to spread optical ones to the place previously occupied by optical zeros, this dispersion obviously degrades the signal. Duobinary's strategy to counter this effect is based on the fact that when optical ones are separated by one or more optical zeros they have opposite phase, this in turn means that every time two optical ones overlap, they cancel each other, thus revealing the optical zero that would otherwise be undetectable. There are two problems with this approach, the first one is that PMD does not grow linearly with length, which means that after one birefringent section two overlapped optical ones cancel each other, after this, the next birefringent section may increase PMD or decrease it, depending on orientation or difference between fast and slow axis, this presents a problem as optical ones have cancelled some of their energy and now this signal will be subjected to a whole new PMD process, not only this, but artefacts present during Duobinary signal generation appear in different parts of the signal as these are dispersed in time, furthermore the cancellation process between optical ones may not perfect, as DPSK's poor performance shows us that phase information is easily lost for high amounts of PMD. The other problem is that there is a chance that two optical ones overlap only enough to cancel a small amount or close to that, which means that these optical ones have completely covered the optical zero, thus tricking the receiver and causing errors.

As much as the high PMD fibre results may be enlightening, an approach towards reality was needed, this was made possible by the use of the Universal Fibre, which enables a much finer simulation, having stimulated and spontaneous Raman and Brillouin scattering, multiple Rayleigh scattering, Kerr nonlinearity, just to name a few, obviously this comes at the cost of processing power.

The sequence of simulations using the Universal Fibre starts with some interesting results, as Duobinary presents some good results, especially when compared with the latest PMD simulation, one must remember though, that attenuation was off for this particular simulation. Being so an effort was made to infer on what where the differences between modulation formats discarding attenuation effects. This was made because, for 20Km at least, attenuation was not an issue, since fibre lengths were short and bit rates were high which accounts for added penalty from factors other than attenuation. Again Duobinary modulation stands out, but this time the difference is much greater, one might just justify this with the fact that this fibre, having less PMD, will allow Duobinary to excel as PMD was shown to be an impairment hard to tackle by Duobinary than by NRZ, one other possible explanation is that the Universal Fibre has effects that are better mitigated by Duobinary than by other modulations, thus increasing the performance difference between them.

One of these effects will be inevitably chromatic dispersion, as it was shown before to be the an easily tackled impairment by Duobinary modulation.

For the simulation of the universal fibre now with attenuation, results do not differ much since, as stated before, fibre lengths are not long enough for attenuation to have a harmful effect in BER.

Up to now, as far as simulation using Universal Fibre is concerned, Duobinary has excelled, as its performance is by far the best one, one question remained though, how would Duobinary compare against other modulation formats if chromatic dispersion would be removed by a chromatic dispersion compensation method? Would there be any difference to what was seen with high PMD fibre when compared to the Universal fibre?

The results are in line with was was seen before, as NRZ outperformed Duobinary marginally, this in itself called for another simulation at a distance greater than 40Km, this was performed at 60Km, having corrected the dispersion compensation fibre length.

At 60Km Duobinary shows a big difference when compared with NRZ, setting it apart as a modulation format of choice, when link conditions are less than adequate. Even though no modulation format achieved iterations having BER under the threshold, this conclusion still stands.

Being so, Duobinary modulation, regarded as a standard in resilience to impairments affecting fibre optic communications, here was shown not capable of surpassing NRZ's performance and simplicity when Duobinary's least bothering effect is compensated for, in this case chromatic dispersion by means of dispersion compensating fibre. Still this conclusion has to be taken lightly as it is applicable to short fibre spans near the limit of 40Gbit/s transmission. The explanation of NRZ surprising performance surely is related to short fibre length, which implies low attenuation and nonlinear effects, which Duobinary surpassed far easier than NRZ, as shown in the final simulation at 60Km, thus proving Duobinary as the modulation of choice. Nevertheless it was surprising to see NRZ outperform Duobinary in more than one simulated scenarios. This has steered the final part of this dissertation to some interesting conclusions.

7 Future work

Undoubtedly, in a dissertation devoted to simulations alone, future work will inevitably be real implementation of all modulators, demodulators and test setups, except from the ones that can not be performed like removing nonlinear effects from a fibre, or attenuation.

There are also other set-ups, especially having optical amplifiers, which could also yield interesting results, perhaps even different results from the use of Erbium Doped Amplification to the use of Raman Amplification, which could also lead to another title, since the comparison is being made against optical amplifier technology and not PMD.

As results point out, chromatic dispersion compensation plays an important role in extending link distance. The dispersion compensation scheme used in this dissertation although relatively simple to implement might be outclassed by more advanced dispersion compensation schemes. One other example of future work would be the use of different more complex chromatic dispersion compensation schemes.

Not only chromatic dispersion can be compensated for, but different modules for PMD compensation may be used, although very complex and hard to implement, these could cause different results.

The adding of modules will inevitably increase overall system budget and in turn, this increase might prevent the use of these modules. One question arises though, added complexity to transmitters, receivers and compensators can increase link lengths, therefore decreasing the amount of regenerator sections. Added system complexity increases the overall link budget, but fewer regenerator sections will decrease it, at what point is it preferable to stop adding complexity to the system trading it form more regenerator section? A study could be made as to check which modules could be added to the system while decreasing its budget.

There was also a noted difference between both Duobinary modulators, the differences of performance between the two could be explored as to determine which outperforms which and why.

Finally, some other modulation formats might be tried, and also a more in depth look at the differences presented by both Duobinary modulators.

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