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Toward Higher Bit Rate Transmission over PON

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I would like to dedicate this thesis to my loving parents

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Abstract

In recent years, the demand for higher bit rate and broader bandwidth never stopped, because of the requirements of some services, such like online gaming, big videos, cloud services, live broadcast and social applications. *Passive Optical Networks* (PON) is a very important telecommunication architecture which can support high speed *point-to-multipoint* (PtMP) transmission. The main issues for the high speed PON is to increase the bit rate which is above 10Gbps and have to keep the low cost at the same time, for example, to use the 10Gbps class optics or use the costly part in the in the optical line terminal (OLT) side to share the cost.

In this thesis, the performances of *Pulse Amplitude Modulation* (PAM)-2 and PAM-4 with different types of receiver (i.e., PIN, *Avalanche Photodiode* (APD), and *Semiconductor Optical Amplifier* (SOA) associated with PIN) are studied in terms of received optical power. The bit rate which is fixed to 25GHz is taken into account, which is the most interesting and attractive speed for the moment. Moreover, the adaptive equalizer is applied to improve the performance, and threshold optimization can enhance the performance of the adaptive equalizer, but it will also add additional complexity and cost to the system. Thus, the behavior of the case with and without the threshold optimization is analyzed and compared to identify whether the existing of the threshold optimization is necessary or not.

The software MATLAB and OptSim are combined to perform the simulation. The MATLAB is mainly to implement the data generation, *Digital to Analog Conversion* (DAC), *Analog to Digital Conversion* (DAC), *Least Mean Square* (LMS) based adaptive equalizer, BER computation based on counting the number of bits error, and obtain the required received optical power at receive side. The OptSim is mainly deals with the eye-diagrams, MZM, electrical transmitter and receiver filter, optical filter, PIN, APD, SOA, TIA, optical attenuator, received optical power measurement, and optical fiber simulation.

The simulation is divided into two parts, the first part is demonstrated in chapter 3, which is to obtain the received optical power at target BER equals to 10^{-3} by changing the normalized filter bandwidth which is normalized to the bit rate from 0.25 to 1, for three types of receivers which are mentioned above and with or without the adaptive equalizer, and then the performances of PAM-2 and PAM-4 are compared. The second part is analyzed in chapter 4, which is to obtain the received optical power at target BER equals to 10^{-3} by changing the total dispersion (i.e., fiber length), for three types of receivers which are mentioned above, with or without the adaptive equalizer, with or without threshold optimization, with or without filter bandwidth limitations (i.e., 7GHz and 0.75*Rs GHz), and two stages for *Mach-Zehnder Modulator* (MZM) are taken into account, one is ideal *Extinction Ration* (ER) with positive chirp and the other one is ER=6dB with negative chirp, and then the results of PAM-2 and PAM-4 are compared.

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1 Introduction

The *Passive Optical Network* (PON) based on power splitting distribution network is an important architecture which is required to keep peace with the demand for higher bit rate and broader bandwidth in the low loss and cost effective way. The PON variations has been developed continuously to cope with the increasing requirements of high speed and broadband applications, such as big video and virtual reality video, fifth-generation (5G) wireless , online gaming, social applications, live broadcast and cloud services [1] and it will never stop evolving to be adapted to the bit rate and bandwidth growth.

1.1 Passive Optical Networks

PON is an important telecommunication architecture which can support *point-to-multipoint* (PtMP) transmission, by using a simple unpowered (i.e., passive) optical splitter to serve multiple end-points which are individual customers, and only have to exploiting a single optical fiber, rather than individual fibers. PON is sometimes referred to as the “last mile” between *Internet Service Provider* (ISP) and the customer [2]. The transmission mode of downstream (i.e., from *Optical Line Terminal* (OLT) to *Optical Network Unit* (ONU)) is different from the transmission mode of upstream (i.e., from OLT to ONU). The transmission mode of downstream is broadcast, and for upstream, signals are combined by using multiple access protocol. There are also some variants of PONs, but they are not standardized and only could be supported by some companies. For example, *Wavelength Division Multiplexing PON* (WDM PON), which multiplexes a number of optical signals along a single optical fiber, each customer is assigned a different wavelength, exploiting the fiber low attenuation wavelength window from 1310nm to 1550nm (i.e., C band), WDM PON can provide a high capacity per user, high security and longer reach [2].

Up to now, all standardized PON generations have been based on bi-directional *Time-Division-Multiplexed/Time-Division-Multiple-Access* (TDM-TDMA) architecture with *Non-Return-to-Zero On-Off-Keying* (NRZ-OOK) modulation on single wavelength [4]. Current standardized *Next Generation PON stage2* (NG-PON2) was induced by the *Full Service Access Network* (FSAN) group in 2011. TWDM-PON has been selected by FSAN as a primary solution for NG-PON2, because it can be backward compatible with previous PONs, components can be reused and relatively mature in the technical aspect [5]. Contributions on NG-PON2 should consider both *Time and Wavelength Division Multiplexing* (TWDM) and point-to-multipoint *Wavelength Division Multiplexing* (WDM) architecture with several wavelengths and 10Gbps per wavelength, which towards the higher total bit rate that is beyond 10G by 2020 [1]. However, due to the increasing bit rate and bandwidth demands, for higher speed PON beyond 10G, there are two important bit rates needed to be focused, 40Gbps and 25Gbps, which are both interested to FSAN/ITU and IEEE PON. And 25Gbps is paid more attention with respect to 40Gbps due to several reasons, such as more *Chromatic Dispersion* (CD) tolerant, cost effective (e.g., 10G class optics can be reused) [4][5] and for line rates equal to 40Gbps or above require larger bandwidth or advanced modulation schemes (e.g., *Quadrature Amplitude Modulation* (QAM)) [1]. Therefore, the total capacity of 100Gbps with four wavelengths thus 25Gbps per wavelength is important for the next generation PON. The thesis mainly focus on the case that the bit rate equals to 25Gbps consequently.

The main goal of the higher bit rate PON beyond 10Gbps is to obtain the higher total bit rate and reduce the cost at the same time. The goal can be achieved by using cost-effective but high-performance transmitters and simple but effective modulation schemes [5]. However, when the bit rate increases, there are some issues are induced, such as the reduction in power budget, reduction in CD tolerant and higher bandwidth optical components are needed. Moreover, in order to reduce the cost, the main idea is to be backward compatible with the previous PONs on the same *Optical Distribution Network* (ODN) and maintain the same power budget at the same time. Therefore, the 10G class components should be able to be reused at the *Optical Network Unit* (ONU) side, because there is no cost sharing at ONU side, and the better and more costly components can be used at the OLT side, like optical amplifiers, due to the cost can be shared among all users [4].

1.2 Proposed modulation schemes

There are several modulation schemes are proposed to solve the above problems which are mentioned in section 1, by comparing the performances in terms of received optical power for a given target *Bit Error Rate* (BER) under different conditions, such as filter bandwidth, the chirp, and chromatic dispersion. And only *Intensity Modulation Direct Detection* (IMDD) modulation scheme is considered to speed-up the serial bit rate at the lowest cost [6].

1.2.1 Pulse Amplitude Modulation

The first proposed modulation scheme, also is the most common one to transmit data over the optical fiber, is NRZ (PAM-2). The advantage is that NRZ is very simple and can be kept in the low cost, it only needs a single threshold receiver to detect as shown in Figure 1.2 (a). But when the bit rate increases beyond 10G will require higher bandwidth photodiodes to reach the target BER [6], thus it is very bandwidth inefficient, and NRZ is the least CD tolerant scheme [4]. NRZ modulation is more suitable for the long haul, and dispersion compensation with slight negative dispersion fiber is needed [7]. Moreover, in the O band, for bit rate equal to 10Gbps, the *Directed Modulated Laser* (DML) with NRZ is suitable for 20Km transmission, and for 25Gbps or for longer wavelength band, such as S, C, and L band, the *Electro-absorption Modulated Laser* (EML) is required due to the CD . And in O-minus band, where has small negative dispersion, the directed modulated *Distributed Feed-Back* (DFB) with NRZ is suitable for 20Km transmission. The *Digital Signal Processing* (DSP) based equalization scheme can be exploited at the receiver side to compensate the dispersion and system bandwidth limitation, thus to allow the 25Gbps transmission by using the 10G class optics which can reduce the cost. But the DSP-assisted NRZ also implies the usage of the *Analog to Digital Conversion* (ADC) and *Digital to Analog Conversion* (DAC), which should be better used in the OLT side to share the cost [8].

The second proposed modulation scheme is PAM-4, it requires only half baud rate with respect to NRZ, and so the spectral efficiency is doubled. Thus it is more CD tolerant than NRZ, for example, the CD tolerance of PAM-4 with 12.5Gbps is four times of NRZ with 25Gbps. And for 25Gbps PAM-4, only 12.5Gbps EML, linear driver and the receiver with 12.5Gbps APD are needed, which implies the reusing of the 10G class optics [8]. However, the disadvantage of PAM-4 is that it is a multilevel signal and the extinction ratio will be limited at the transmitter side. Thus pam-4 needs the most linearity among the proposed modulation schemes [4] and a 3-level threshold receiver is needed, as shown in Figure 1.2 (c), and due to the limited extinction ratio, it will suffer the additional power penalty with respect to NRZ [4].

1.2.2 Duo-Binary Modulation

The third proposed modulation scheme is *Electrical Duo-Binary* (EDB), which is a three electrical level modulation format. It can be obtained by using a low pass filter to an NRZ signal, thus for example, for bit rate at 25Gbps only 7GHz system bandwidth is needed [6]. And the receiver side is relatively simpler because of only a 2-level threshold as shown in Figure 1.2 (b), and an XOR gate are needed, this implies a pre-coding (differential coding) at the transmitter side to avoid error propagation [9]. EDB is more CD tolerant than NRZ. And at 25Gbps, the lowest cost proposal for next-generation high-speed PON is to exploit EDB at 25Gbps reusing 10Gbps *Avalanche Photo-Diod*e (ADP) receiver [4]. The CD tolerant of EDB is greatly enhanced by approximately a factor of 2 due to the frequency spectrum of EDB is half that of NRZ. But with the advantages of the higher coding complexity, and less sensitivity (because it is a 3-level signal) [8].

Another proposed modulation scheme is *Optical Duo-Binary* (OBD), which is a 3-level signal in terms of electric filed, that is, '-1, 0, +1', thus *Inter-Symbol-Interferences* (ISI) is reduced as shown in Figure 1.1, which can improve the CD tolerant. And OBD is a 2-level signal in terms of optical power, thus the complexity of the receiver can be reduced with respect to the case of EDB, which can also increase the CD tolerant [8]. At the transmitter side, a wider (i.e. 15GHz) low pass filter is needed to drive the *Mach-Zehnder Modulator* (MZM) but the MZM is too expensive to be used it OLT side, and the pre-coding is also needed (same as the case of EDB). And ODB does not reduce the bandwidth requirement of the receiver with respect to NRZ [6]. On the other hand, OBD has some great properties, such as only needs a single level threshold at the receiver side like the case in NRZ as shown in Figure 1.2 (d), and it is more CD tolerant than NRZ [4].

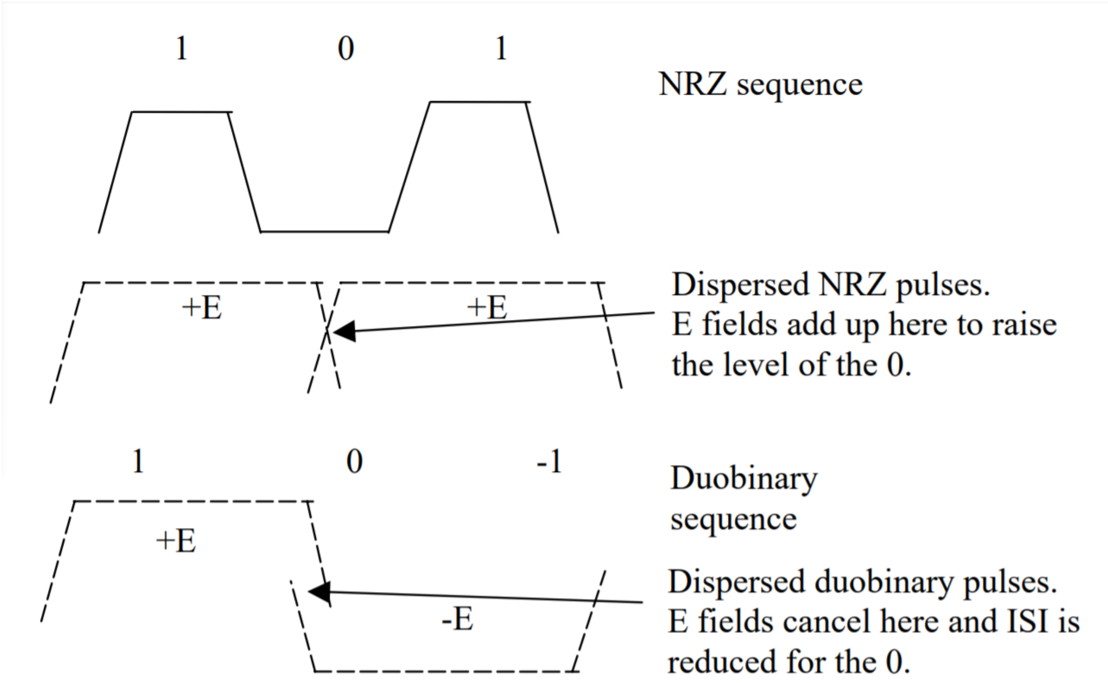


Figure 1.1: Effect of dispersion on NRZ and duo-binary sequences [7]

For uncompensated *Single Mode Fiber* (SMF), duo-binary modulation is a better choice with respect to NRZ modulation. Duo-binary is a modulation scheme that can transmit at bit rate R_b bps by using bandwidth smaller than $\frac{R_b}{2}$ Hz. According to the Nyquist's rule, duo-binary pulses have ISI for sure, but ISI is under control and the original values can be recovered. So the transmitted pulses can be longer in the time domain due to the smaller bandwidth, thus fewer distortion effects of the channel, hence duo-binary modulation is more resilient to the dispersion [7]. And as shown in Figure 1.2 which shows the received eye-diagrams of different modulation schemes with detection threshold. It is obvious that there is only a single threshold receiver is needed to detect for NRZ and ODB, a 2-level threshold and 3-level receiver is needed to detect for EDB and PAM-4 respectively.

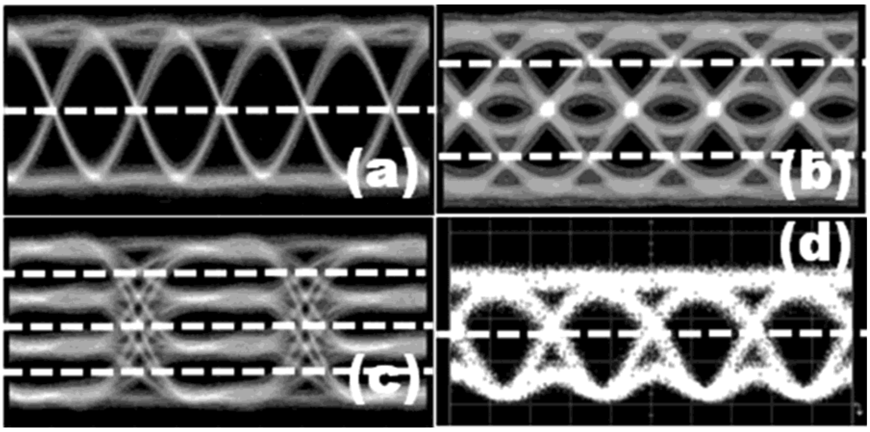


Figure 1.2: Eye-diagrams of modulation schemes with threshold of detection ((a): NRZ, (b): EDB, (c): PAM-4 and (d): ODB) [4]

1.2.3 Carrier-less Amplitude\Phase Modulation

The last proposed modulation scheme is *Carrier-less Amplitude\Phase* modulation (CAP). It is demonstrated recently that the bandwidth of each channel can be broadened for high-speed short-reach transmission by exploiting the *multi-level multi-band CAP* (MM-CAP), and the short distance is because of the spectrum fading effect which is caused by CD [10]. The principle of MM-CAP signal based WDM-CAP-PON for multi-user access in downstream is shown in Figure 1.3. The two dimensional CAP can be generated by using a filter pair, which is combined by two orthogonal filters at the transmitter side, and using a matched filter pair at the receiver side. Thus for a single channel, N sub-bands can be assigned to N users without interferences. CAP modulation is paid a lot of attention to be used in high-speed WDM-CAP-PON, because of the simple implementation and low cost, and the number of users increase when MM-CAP is applied. For example, MM-CAP based WDM-CAP-PON can support 11 channels, 55 sub-bands, that is, for 55 users with 10Gbps for each along 40Km SMF in the downstream [10]. But the CAP modulation suffers from spectrum fading effect, power fading, and *Self-Phase Modulation* (SPM) effect, which can cause the reduction of the *Optical Signal to Noise Ratio* (OSNR) [10], [11], [12].

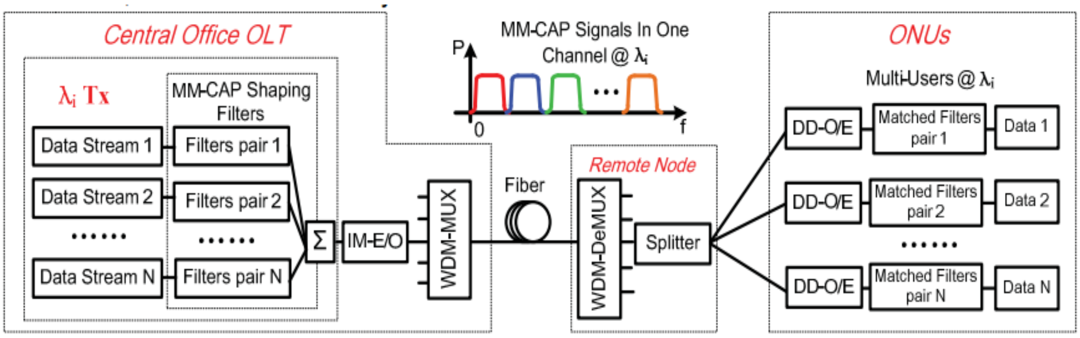


Figure 1.3: Principle of MM-CAP signal based WDM-CAP-PON for multi-user access (IM: Intensity Modulation, DD: Direct Detection) [10]

1.3 Digital signal processing and dispersion compensation

When the serial bit rate increases, the main issues are CD and system bandwidth limitations.

Digital Signal Processing (DSP) is very important nowadays in high-speed PON, which can greatly reduce the requirements for optics to reduce the cost, such as the complexity and bandwidth requirements to obtain a high throughput PON. For example, 10Gbps class optics can be used at the ONU when the bit rate is increased up to 40Gbps by using DSP [13]. And using 10Gbps class optics when the bit rate is 25Gbps, the receiver sensitivity for EDB and NRZ associated with DSP is very similar to NRZ [4]. Moreover, DSP associated with PAM-4 and NRZ are suitable for 25Gbps downstream transmission when using 10G class [14]. Moreover, DSP can be used to enhance the recovery capability of the upstream signal in the *Burst Mode* (BM) [13].

The CD compensation or equalization is necessary when the serial bit rate is above 40Gbps [4]. The linear and non-linear equalizer are more and more attractive in the high speed PON, for example, the *Feed-Forward Equalizer* (FFE) combines with *Decision Feedback Equalizer* (DFE) which is called *Electronic Dispersion Compensation* (EDC) can be exploited at the receiver side to cope with the bandwidth limitations [13], which is a very strict constraint for PAM-2, and to relax the chromatic dispersion [4]. For example, at 25Gbps bit rate and NRZ modulation, without a pre-emphasis FFE/DFE equalizer can reach a good performance at bandwidths between 11.25 to 16.25 GHz, but with an FFE/DFE can reach a good performance at bandwidth 6.25 GHz [15]. However, the disadvantages of using DSP are it requires ideally high-speed ADC and DAC which are expensive, and it is more power consumption than by using EDC [16]. Other CD compensation technologies are, for example, tight optical filtering using a *Delay Interferometer* (DI) [17] which is not possible to be exploited in the burst mode as well as DSP-based equalization and EDC [4], and dispersion pre-compensation by exploiting a *Fiber Bragg Grating* (FBG) [18] or a *Dispersion Compensation Fiber* (DCF) [19]. For example, the CD can be compensated by using the FBG with negative dispersion up to 40Km reaches [20]. But FBG and DCF should be used in a cost-effective way by using them only in the OLT side to share the cost.

The *Least Mean Square* (LMS) based adaptive equalizer can automatically adapt to the time-varying properties of the channel, related to the least mean square of the error signal, that is, the differences between the desired and the actual signal. And it is exploited in the following simulation in this thesis.

1.4 Wavelength plans

For now, the 25Gbps is the most attractive, interesting and mature bit rate among which are higher than 10Gbps [2], [21]. For these new bit rate systems, the upstream wavelength can be re-used, but the downstream wavelength must be assigned again, thus several wavelength plans needed to be compared and analyzed. The most of S, L and C band are occupied, as well as the left side of O band, which is occupied by XG(S)-PON and GPON upstream [21]. Thus the wavelength plans mainly focus on the remaining part of the O band, the O band has a good property which is the low dispersion coefficient for G.652 fiber, that is, CD requirements is relatively low in the O band [22]. However, the fiber reach is limited because the fiber attenuation is relatively high in the O band [4].

The two basic requirements of wavelength plan which must be satisfied, one is that it is must be compatible with the previous PON systems, for example, XG(S)-PON and NG-PON2 are based on 10Gb/s line rate which are must be compatible with. And for the downstream, the wavelength must be different from the existing downstream wavelength of previous PONs, but for the upstream, the existing upstream wavelength can be reused if the TDM is chosen. The other one is that the existing industry must be able to be used in the future to keep the low cost [21].

The proposed wavelength plans are [21], [23], [24], [25]:

- All downstream and upstream wavelengths in O band:

  Plan A:

  It coexists with XG(S)-PON and NG-PON2 by WDM, and with the advantages of low fiber dispersion due to the O band, NRZ modulation formats without dispersion compensation, and low cost DML in upstream for ONU transmitter. But the disadvantages are the cooled ONU is needed which increases the cost, and it cannot coexist with GPON due to the usage of the same wavelength in upstream.

Plan B:

It is compatible with NG-PON2 by WDM, and XG(S)-PON by hybrid TDM and WDM, with advantages of the requirement of the uncooled DML, the WDM coexistence with GPON, and the reduction in the cost of the ONU burst mode transmitter due to the 3nm wide in all upstream channels. But with the disadvantages of the increment of *Dynamic Bandwidth Allocation* (DBA) due to the TDM coexistence with XG(S)-PON, and less uniformity among the four channels due to the different channel spacing and width.

- All downstream and upstream wavelengths in S/C/L band:

Plan C:

It is compatible with NG-PON2, XG(S)-PON and GPON by WDM, and the advantages is the lower fiber attenuation and mature amplification technology due to all wavelengths are in C band. And with the disadvantages of the requirement of dispersion compensation and DSP due to the higher dispersion in C band and the cooled EML in ONU.

- Downstream wavelength in S, C and L band, and upstream in O band:

Plan D:

All downstream wavelength are in C band with 5nm pass bandwidth and 20nm channel spacing, and upstream wavelength is same with plan A. It is WDM coexistence with NG-PON2 and XG(S)-PON, and not compatible with GPON.

Plan E:

All downstream wavelength are in C band with 5nm pass bandwidth and 20nm channel spacing, and upstream wavelength is same with plan B. It is WDM coexistence with NG-PON2 and TDM coexistence with XG(S)-PON, and compatible with GPON of the first channel.

Advantages:

It can reduce the cost of the optics at the OLT side due to the wide pass bandwidth and channel spacing, and the cost in the ONU due to the direct usage of the DML and NRZ modulation.

And the summary of the comparison among five proposed wavelength plans is represented in the Figure 1.4 [21], [23], [24], [25].

Item		Plan A	Plan B	Plan C	Plan D	Plan E
Coexistence with GPON	single wavelength system	No	Yes	Yes	No	Yes
	multiple wavelength system	No	No	Yes	No	No
ONU transmitter	single wavelength system	cooled DML	uncooled DML	cooled EML+DC	cooled DML	uncooled DML
	multiple wavelength system	cooled DML	cooled DML	cooled EML+DC	cooled DML	cooled DML
Dispersion compensation		No	No	Yes	Dn: Yes Up: No	Dn: Yes Up: No
Minimal upstream channel width		2nm	3nm	2nm	2nm	3nm
Minimal downstream channel width		3nm	3nm	2nm	5nm	5nm

Figure 1.4: Comparison among five proposed wavelength plans

1.5 XG(S)-PON and NG-PON2 enhancements

According to the FSAN Roadmap 2.0, for both XG(S)-PON and NG-PON2, the service rate must be above 10Gbps per wavelength by 2020.

- For XG(S)-PON contributions as following should be taken into account: [1], [25]

  1. Line rates and accessible service rates.

2. 20 and 40Km reach, and *Optical Path Loss* (OPL) classes from class N1 (i.e., loss with minimum value equals to 14dB and maximum value equals to 29dB) to class E2 (i.e., loss with minimum value equals to 20dB and maximum value equals to 35dB) [26].
3. Coexistence with legacy power split ODNs, and PON systems (i.e., GPON, XG(S)-PON, and NG-PON2).
4. Transceiver components.
5. Wavelength plans.
6. Requirements of amplification, and be compatible with WDM1r (*Wavelength Division Multiplexing*), CEx and CEMx.

- For NG-PON2 contributions as following should be taken into account: [1], [25]

  Contributions 1, 2, 4, 5, and 6 are the same as contributions on XG(S)-PON, and for contribution 3 on NG-PON2 is the coexistence with legacy power split ODNs and wavelength split ODNs, and PON systems (i.e., GPON, XG(S)-PON, and NG-PON2). And with additional contributions as following:

7. TWDM and *point-to-point* (PtP) WDM.
8. Channel bonding vs. higher line rates.
9. Fiber non-linearity.

1.6 Receiver types

There are three types of receivers are proposed in this thesis.

The first proposed receiver is the PIN receiver, it is not suitable to be used at ONU side, because it is very costly and power hungry optical pre-amplified higher bandwidth receiver, but it is possible to be used at OLT side [5].

The second proposed receiver is *Avalanche Photodiode* (APD) receiver, it is able to be used to detect 25Gbps NRZ data, but the APDs are very expensive and not mature. Present commercial available APDs are bandwidth limited to about 8GHz [5].

The third proposed receiver is PIN associated with *Semiconductor Optical Amplifier* (SOA) receiver. For bit rate above 25Gbps, for example 40Gbps, it is also a very interesting bit rate to be analyzed recently, but it is much less CD tolerant when the same modulation scheme is used, the theoretical factor is 2.5 between the dispersion tolerances of the two rates [5]. Without pre-amplification, it is very difficult to reach the target BER at the bit rates which are above 40Gbps. Thus, the PIN associated with SOA is also very attractive in the high-speed PON. For example, at bit rate equal to 25Gbps and SOA drive current equal to 160 mA for NRZ, it can reach sensitivity of -26.5dBm in *back-to-back* (B2B) case, and -24.7dBm when the fiber is 10Km, under a target BER equal to 10^{-3}, thus the power penalty is 1.8dB [27].

2 Overview of Simulation Conditions

In this thesis, the software MATLAB and OptSim are combined to perform the simulation.

The MATLAB is mainly to implement the data generation, *Digital to Analog Conversion* (DAC), *Analog to Digital Conversion* (ADC), LMS based adaptive equalizer, BER computation based on counting the number of bits error, and obtain the required received optical power at receive side. The OptSim mainly deals with the eye-diagrams, MZM, electrical transmitter and receiver filter, optical filter, PIN, APD, SOA, TIA, optical attenuator, received optical power measurement, and optical fiber simulation.

The general simulation parameters are as following:

- System simulation parameters:

  Implementing the simulation in OptSim environment, the VBS center frequency is 193THz (i.e., 1553.3nm) and the samples per bit equals to 8.

- Data generation parameters:

  The data generation process is performed in the MATLAB environment, *Pseudo-Random Binary Sequence* (PRBS) is generated, using the degree of PRBS equals to 16, and the number of simulated bit is 200000. $N_{sim\_bit} \geq \frac{100}{BER_{target}}$ to increase the simulation accuracy , where $BER_{target} = 10^{-3}$.

- Adaptive equalizer parameters:

Adaptive equalizer based on LMS, which is included in the DSP. The DSP section is implemented in the MATLAB, and the samples per symbol equals to two. The update coefficients for LMS algorithm, which is represented as 'mu' equals to 0.001, the number of training symbols for LMS algorithm equals to 4500, and the number of taps of equalizer filter equals to 20 in the simulation to reach a good performance.

- *Continuous Wave* (CW) laser:

The center emission frequency is set to 193THz, the CW power which is the output power of the laser is set to 5dBm, and the *Full Width Half Maximum* (FWHM) is set to its default value 10MHz.

- MZM:

The inputs of the MZM are optical signals which is to be modulated, and the electrical signal which is used to modulate the optical signal. In the simulation, two conditions are considered, the first one is set the *Extinction Ratio* (ER) equals to 'ideal' which means infinite, and the maximum transmissivity offset voltage equals to zero which means the positive chirp is used. The second condition is set the extinction ratio equals to 6dB, and the maximum transmissivity offset voltage equals to zero which means the negative chirp is used. Moreover, the chirp factor is set to the default value zero.

- Fiber:

The total dispersion is D*L [ps\nm], where D is the chromatic dispersion coefficient equals to 16.7 [ps\(nm*Km)] , and L is the fiber length [Km].

- PIN:

The PIN receiver is implemented by using the PIN receiver model in the OptSim. The reference frequency is set to 193THz, the -3dB bandwidth is set to 15GHz to free the bandwidth limitation, and the quantum noise is disabled which means no noise is added.

- APD:

The APD receiver is implemented by using the APD receiver model in the OptSim. The reference frequency is set to 193THz, the -3dB bandwidth is set to 50GHz to free the bandwidth limitation, the avalanche gain is set to 25 linear unit, and the noise figure F which is the amount of noise enhancement due to the avalanche multiplication process is set to the default value 10dB.

- SOA associated with PIN:

The SOA associated with PIN receiver is implemented by using the PIN receiver, a fixed gain amplifier, and an optical filter model in the OptSim. The block diagram to represent the SOA associated with PIN receiver is shown in Figure 2.1.

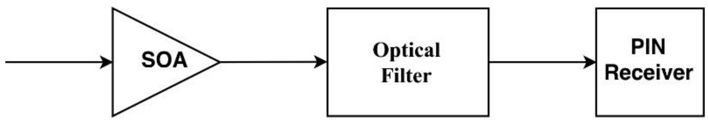


Figure 2.1: Block diagram of SOA associated with PIN

The SOA is implemented by using a fixed gain amplifier, the gain is set to 12dB where the gain shape is ‘flat’, and the noise figure is set to 9dB. And for the optical bandpass filter, the center frequency is set to 193THz, and the -3dB two-sided bandwidth is set to 60GHz which is 0.20nm.

The simulation is divided into two main parts. The first part is to obtain the required received optical power at the target BER equals to 10^{-3} when changing the normalized electrical filter bandwidth from 0.25 to 1 at both transmitter and receiver side, the filter bandwidth is normalized to the bit rate (that is 25Gbps for PAM-2 and PAM-4). The electrical filters are both 5-order Bessel low pass filter. And under the conditions of with and without the adaptive equalizer, and with threshold optimization. Finally, for all three types of receivers, namely PIN, APD and PIN associated with SOA, comparing the different conditions in terms of eye-diagrams and optical received power by plotting the figures of optical received power vs. electrical fiber bandwidths.

The second part is to obtain the required received optical power at the target BER equals to 10^{-3} when changing the fiber lengths (i.e., the dispersion). The bit rate is fixed at 25Gbps for both PAM-2 and PAM-4, thus the baud rates are 25Gbps for PAM-2 and 12.5Gbps for PAM-4. The electrical transmitter and receiver filters are both 1-order Bessel low pass filter when the electrical transmitter and receiver filter bandwidths equal to 7GHz, and both 5-order Bessel low pass filter when the electrical transmitter and receiver filter bandwidths equal to 0.75*baud rate [GHz], that is 18.75 GHz and 9.375 GHz for PAM-2 and PAM-4 respectively. And under the conditions of with and without the adaptive equalizer, and with and without threshold optimization. Finally, for all three types of receivers, namely PIN, APD and PIN associated with SOA, comparing the different conditions in terms of eye-diagrams and optical received power by plotting the figures of optical received power vs. total dispersion.

3 PAM-2 and PAM-4 vs. Bandwidth limitations

3.1 Simulation setup and basic simulation parameters

In this part, the required received optical power is obtained at the target BER equals to 10^{-3} when changing the normalized electrical filter bandwidth from 0.25 to 1 (for PAM-4 is from 0.25 to 0.8, because it is the maximum electrical filter bandwidth that can be reached in the OptSim software) at both transmitter and receiver side, which is normalized to the bit rate (that is 25Gbps for PAM-2 and PAM-4). The electrical filters are both 5-order Bessel low pass filter. And under the conditions of with and without the adaptive equalizer, and with threshold optimization. Finally, for all three types of receivers, namely PIN, APD and PIN associated with SOA, comparing the different conditions in terms of eye-diagrams and optical received power by plotting the figures of optical received power vs. electrical fiber bandwidths. The dispersion is assumed to equal to zero (the length of fiber equals to zero, which is the B2B case) and only the case ideal extinction ratio and positive chirp is taken into account.

The diagrams of the simulation environment are as following: Figure 3.1, Figure 3.2, and Figure 3.3 represent PIN receiver, APD receiver and SOA associated with PIN receiver respectively.

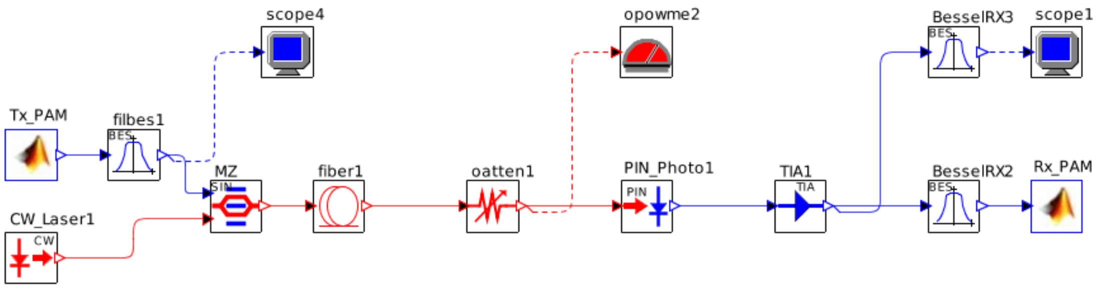


Figure 3.1: Diagram of PIN receiver when changing the filter bandwidth

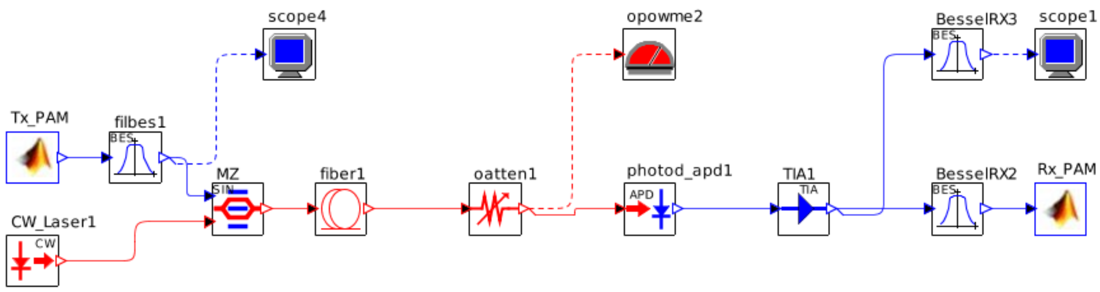


Figure 3.2: Diagram of APD receiver when changing the filter bandwidth

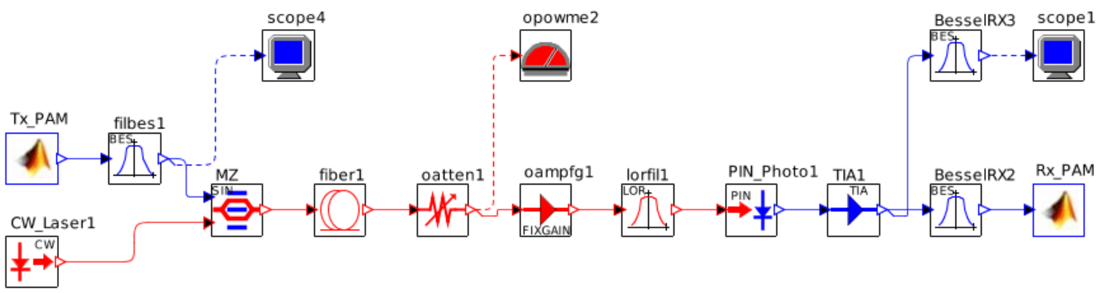
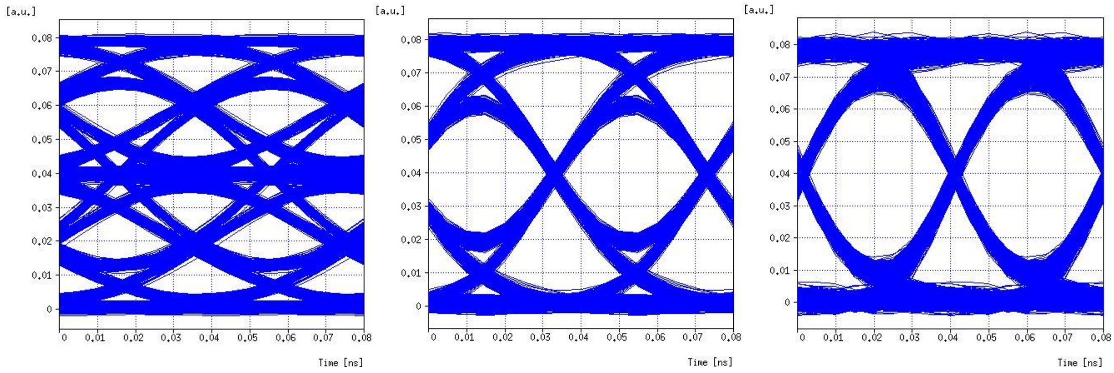


Figure 3.3: Diagram of SOA associated with PIN receiver when changing the filter bandwidth

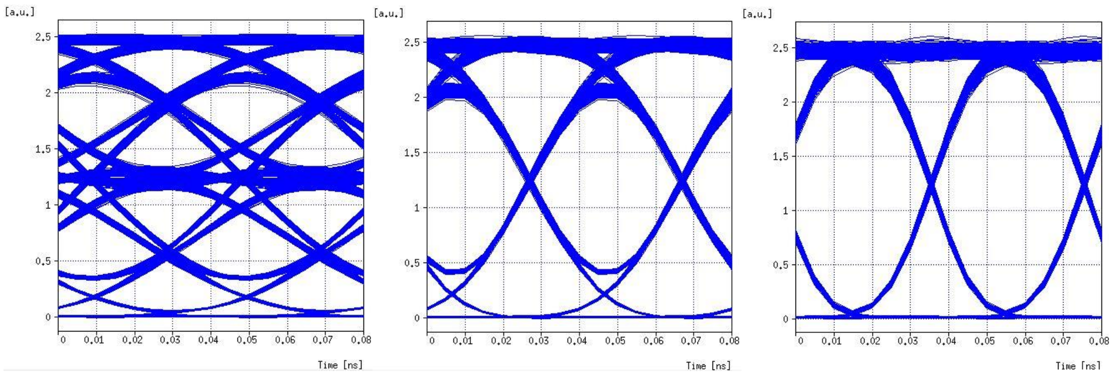
As shown in Figure 3.1 for PIN receiver, 'Tx_PAM' and 'Rx_PAM' are implementations in MATLAB, such as data generation and ADC were performed in 'TX_PAM' and LMS based adaptive equalizer, DAC and BER counting were implement in 'RX_PAM'. 'CW_Laser1' is the implementation of CW laser, which is connected to 'MZ', that is a MZM. 'filbes1' is the electrical filter at transmitter side, which is connected to 'scope4', which is used to observe the eye-diagrams at the transmitter side. 'fiber1' is the simulation of the optical fiber, with the fiber length is set to zero to simulate the B2B situation. 'oatten1' is the optical attenuator, and it is connected to 'PIN-Photo1' which is the implementation of the PIN photodiode and "opowme2", i.e., optical power meter, which is required to measure the received optical power. 'TIA1' represents for trans-impedance amplifier. 'BesselRX' is the simulation of the electrical filter at the receiver side, and 'scope1' is used to observe the received eye-diagrams. Moreover, as shown in the Figure 3.2 for APD receiver and Figure 3.3 for SOA+PIN receiver, everywhere are the same as the case with PIN receiver, except for 'photod_apd1' stands for APD photodiode in Figure 3.2 for APD receiver, and 'oampfg1' represents the fixed gain optical amplifier and 'lorfil1' simulates the optical filter in Figure 3.3 for SOA+PIN receiver.

3.2 Simulation results for PAM-2

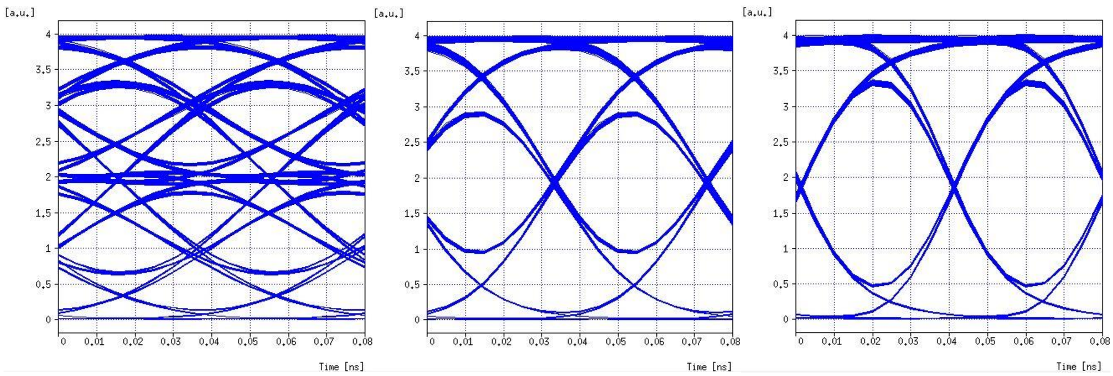
The bit rate equals to the baud rate, which is 25Gbps, and electrical filter bandwidths are from 0.25*25Gbps = 6.25Hz to 1*25Gbps = 25GHz for both transmitter and receiver filters, it is normalized to the bit rate. And all performing the ideal extinction ratio with the positive chirp. In the simulation, the situation with and without adaptive equalizer are both considered. From the eye-diagrams which are shown as following in Figure 3.4, when the normalized filter bandwidth equals to 0.25, the performance of the eye-diagrams are very poor, and the eye-diagrams are nearly ideal when the normalized bandwidth equals to 1. And it is obvious that when the bandwidth limitation is more relaxed, i.e., the normalized bandwidth from 0.25 to 1, the eye-diagrams are more wide open for PIN, APD and SOA+PIN receivers. Among all these three types of receivers, the eye-diagram of PIN receiver is the least clear and the amplitude is the smallest, due to there is neither EDFA nor avalanche gain existed. And there is only a single threshold receiver needed due to the PAM-2 modulation schemes.



(a) PIN



(b) APD



(c) APD

Figure 3.4: Eye-diagrams of PAM-2, from left to right the normalized filter bandwidth is 0.25, 0.5 and 1, respectively

First, for the situation with adaptive equalizer, from the plots of BER vs. the received optical power for the different value of normalized electrical filter bandwidth which are shown in Figure 3.5, it is obvious that when the electrical bandwidth increases, the received power is smaller, and the performances in terms of BER is better. And when the normalized bandwidth reaches nearly up to 0.5, the performance cannot be improved a lot when increasing the bandwidth. Moreover, similar to what are observed above from the eye-diagrams, it is also clear that the received power of PIN receiver is much worse than APD and SOA associated with PIN receiver because of no amplification.

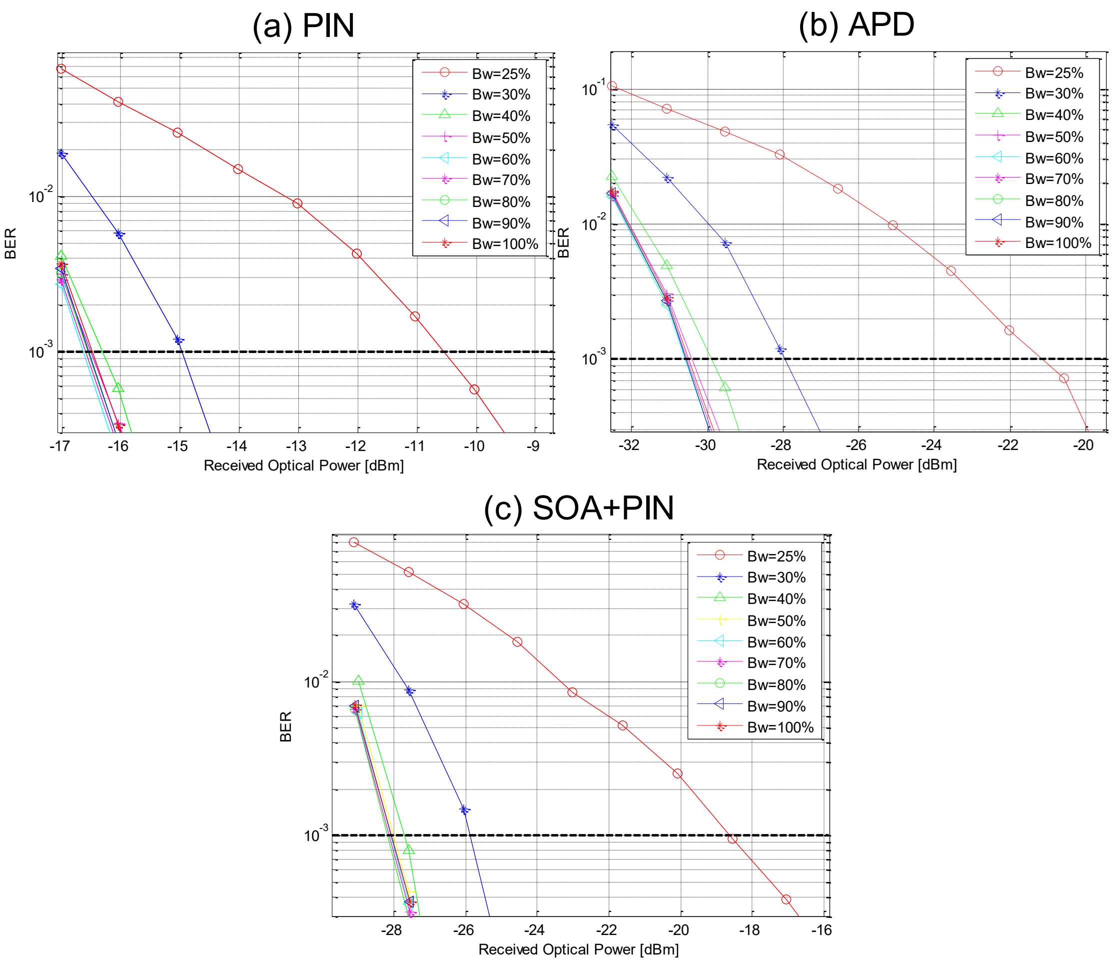


Figure 3.5: PAM-2, BER vs. the received optical power for the different value of normalized electrical filter bandwidth, with adaptive equalizer.

Second, for the situation without adaptive equalizer, from the plots of BER vs. the received optical power for the different value of normalized electrical filter bandwidth which are shown in Figure 3.6, it is shown that the behavior is similar to what was described in the section which is with the adaptive equalizer. Moreover, under the narrow bandwidth condition, the performance of the case without the equalizer is much worse than the case with the equalizer. When the normalized bandwidth equals to 0.25, the target BER even cannot be reached.

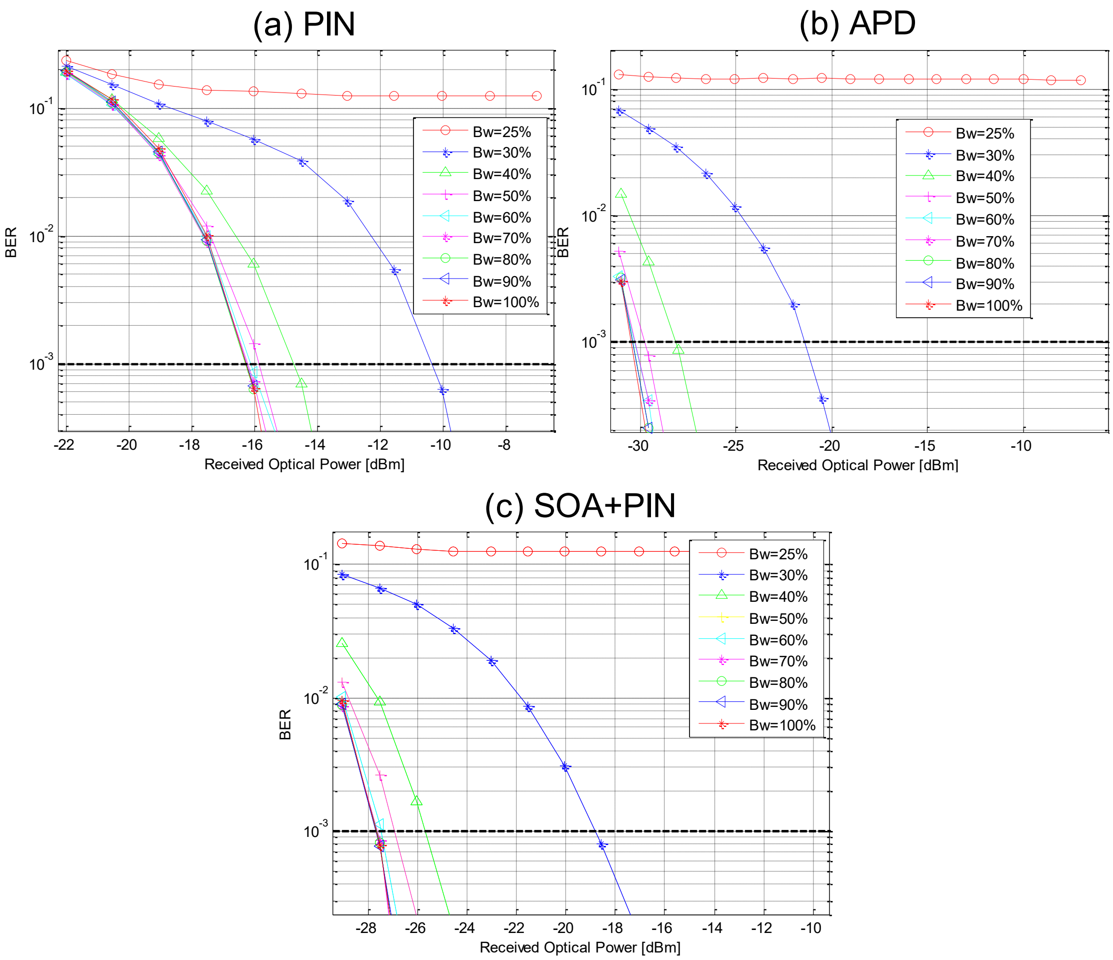


Figure 3.6: PAM-2, BER vs. the received optical power for the different value of normalized electrical filter bandwidth, without adaptive equalizer.

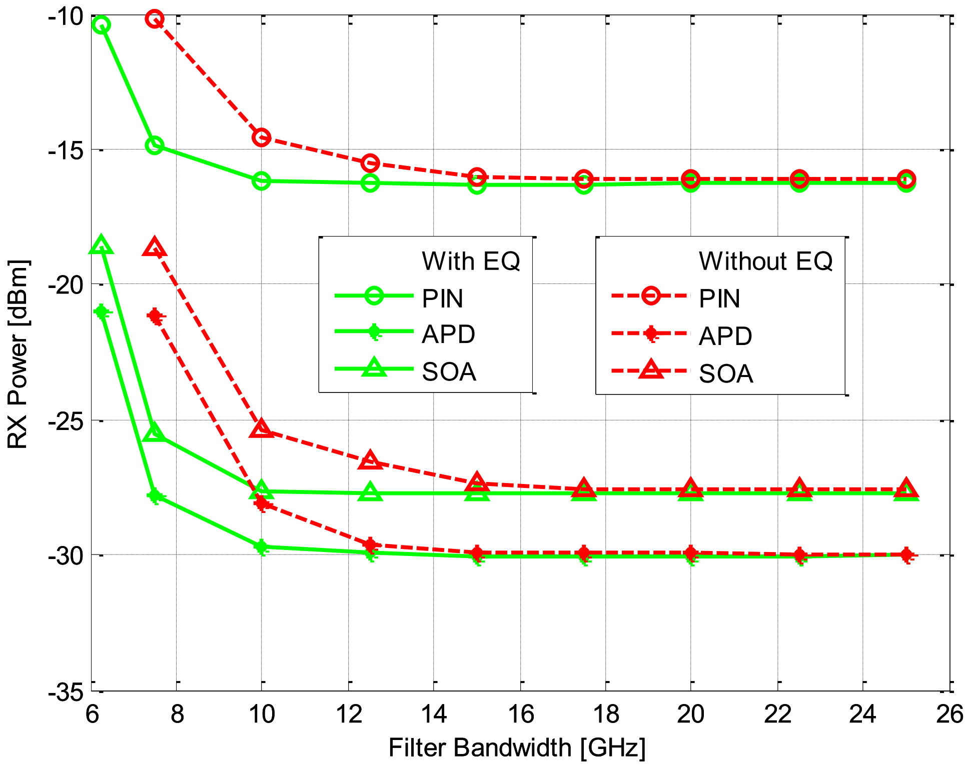


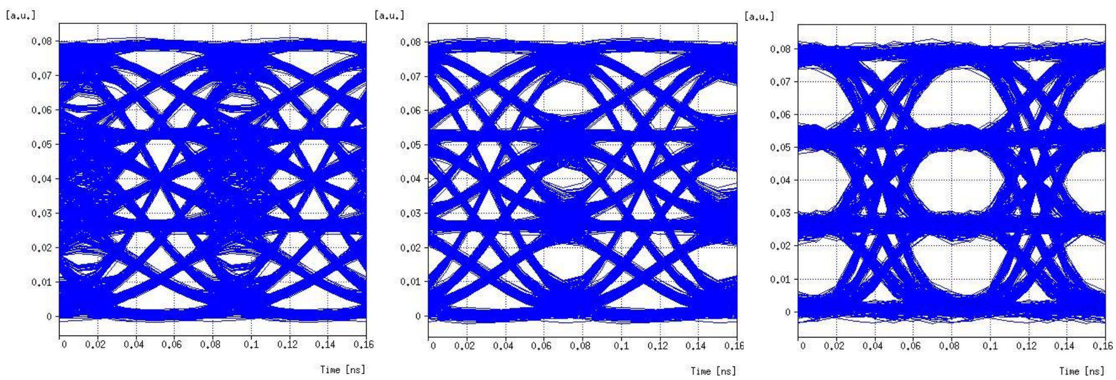
Figure 3.7: Optical received power vs. the electrical filter bandwidth for different types of receiver, with and without adaptive equalizer, for PAM-2

Figure 3.7 shows the optical received power vs. the electrical filter bandwidth for the PIN, APD and SOA+PIN receiver, where the received power is obtained at the target BER equals to 10^{-3}. The performance in terms of the received power of PIN receiver is the worst one, when the normalized filter bandwidth equals to 1 and with the equalizer, it has a power penalty of 13.78dB and 11.45dB with respect to APD and SOA + PIN receiver, respectively. If the adaptive equalizer is not applied, it suffers a power penalty of 13.91dB and 11.51dB with respect to APD and SOA+PIN receiver respectively, which is similar to the case with the adaptive equalizer. It is obvious that if there is no limitation of filter bandwidth (i.e., the normalized bandwidth larger than 0.6), the performance in terms of received power of the case without the equalizer is very similar to the case with the equalizer. However, if under the strict constraint of filter bandwidth, for example, the normalized bandwidth equals to 0.25, the case without the adaptive equalizer cannot reach the target BER. If the normalized bandwidth equals to 0.3, it has a power penalty of 4.69dB, 6.65dB, and 6.85dB with respect to the case with equalizer for the PIN, APD, and SOA+PIN receiver, respectively. Thus, the adaptive equalizer is more necessary if the filter bandwidth is too narrow, i.e., when it is smaller than 15GHz.

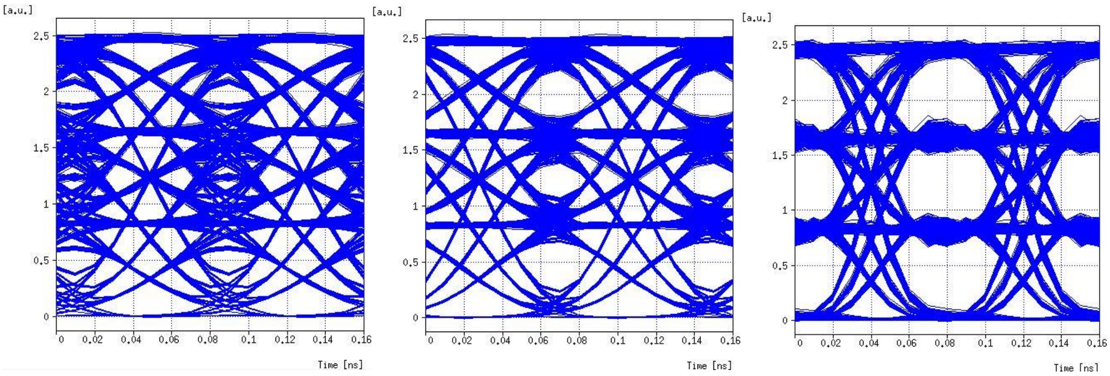
3.3 Simulation results for PAM-4

The bit rate equals to 25Gbps, and the baud rate is 12.5Gbps. And electrical filter bandwidths are from 0.25*25Gbps = 6.25Hz to 0.8*25Gbps = 20GHz for both transmitter and receiver filters, it is normalized to the bit rate. And all performing the ideal extinction ratio with the positive chirp.

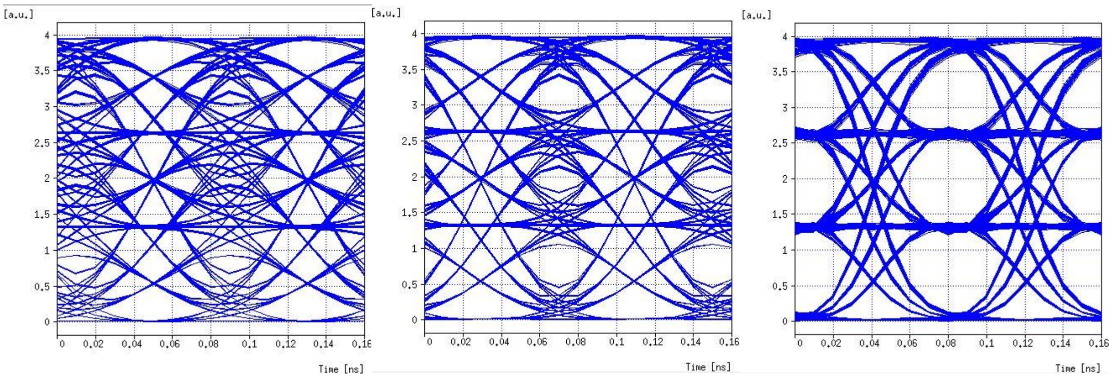
In the simulation, the situation with and without adaptive equalizer are both considered. From the eye-diagrams which are shown as following in Figure 3.8, when the normalized filter bandwidth equals to 0.25, the performance of the eye-diagrams are very poor, and the eye-diagrams are nearly ideal when the normalized bandwidth equals to 1. And it is obvious that when the bandwidth limitation is more relaxed, i.e., the normalized bandwidth from 0.25 to 1, the eye-diagrams are more wide open for PIN, APD and SOA+PIN receivers. Among all these three types of receivers, the eye-diagram of PIN receiver is the least clear and the amplitude is the smallest, due to there is neither EDFA nor avalanche gain existed. Moreover, a 3-level threshold receiver is needed to detect. Thus, it is more costly when using PAM-4 modulation scheme with respect to PAM-2 modulation.



(a) PIN



(b) APD



(c) SOA+PIN

Figure 3.8: Eye-diagrams of PAM-4, from left to right the normalized filter bandwidth is 0.25, 0.3 and 0.8, respectively.

First, for the situation with adaptive equalizer, from the plots of BER vs. the received optical power for the different value of normalized electrical filter bandwidth which are shown in Figure 3.9, the behaviors are similar to what was mentioned in section 3.2 for the PAM-2 case. And when the normalized bandwidth reaches nearly up to 0.3, the performance cannot be improved a lot when increasing the bandwidth. Moreover, for APD and SOA+PIN receiver, even for the case the normalized bandwidth equals to 0.25, the behavior is relatively good with respect to the case with larger filter bandwidth.

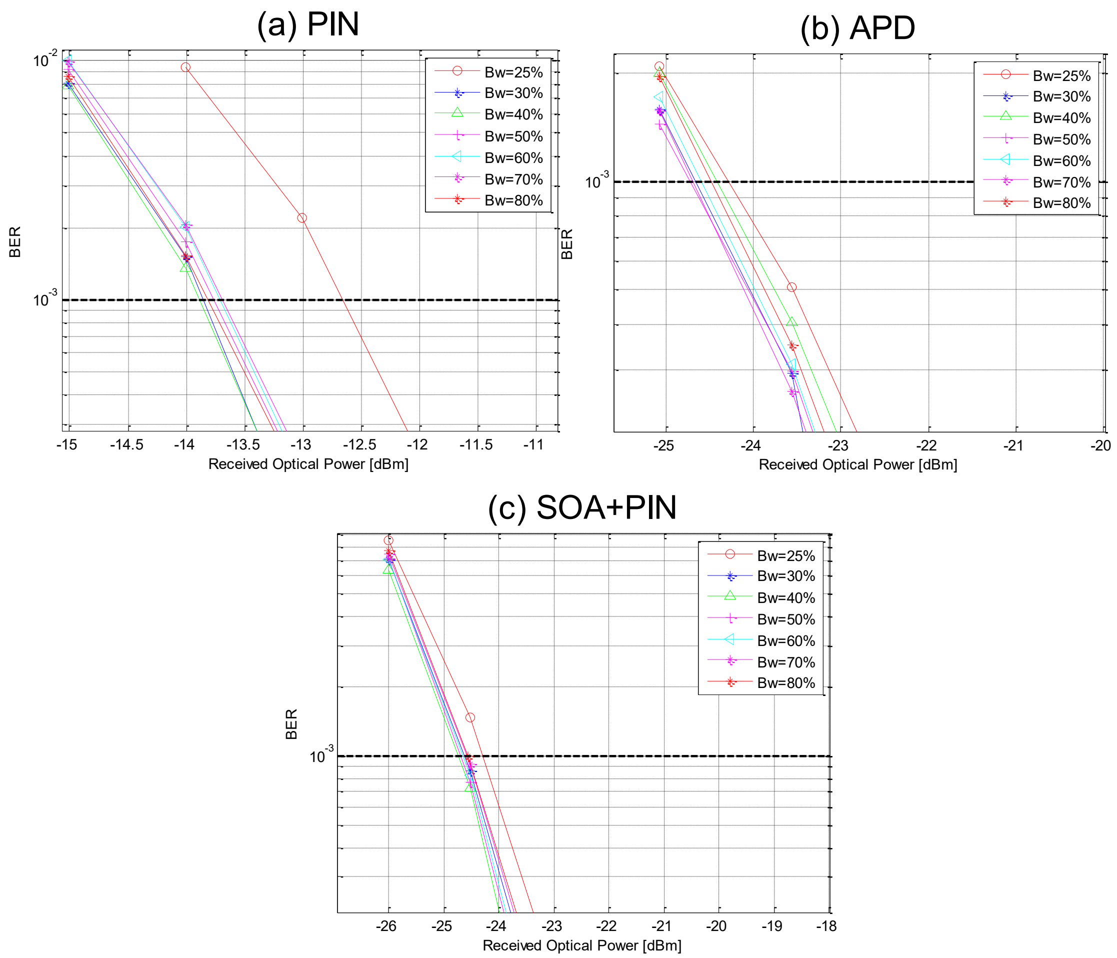


Figure 3.9: PAM-4, BER vs. the received optical power for the different value of normalized electrical filter bandwidth, with adaptive equalizer.

Second, for the situation without the adaptive equalizer, from the plots of BER vs. the received optical power for the different value of normalized electrical filter bandwidth which is shown in Figure 3.10, the behaviors are similar to what was mentioned in section 3.2 for PAM-2. And when the normalized bandwidth reaches nearly up to 0.4, the performance cannot be improved a lot when increasing the bandwidth. Moreover, the performance of the case without the equalizer is much worse than the case with the equalizer if with the strict bandwidth constraint, that is, when the normalized filter bandwidth equals to 0.25 the target BER even cannot be reached.

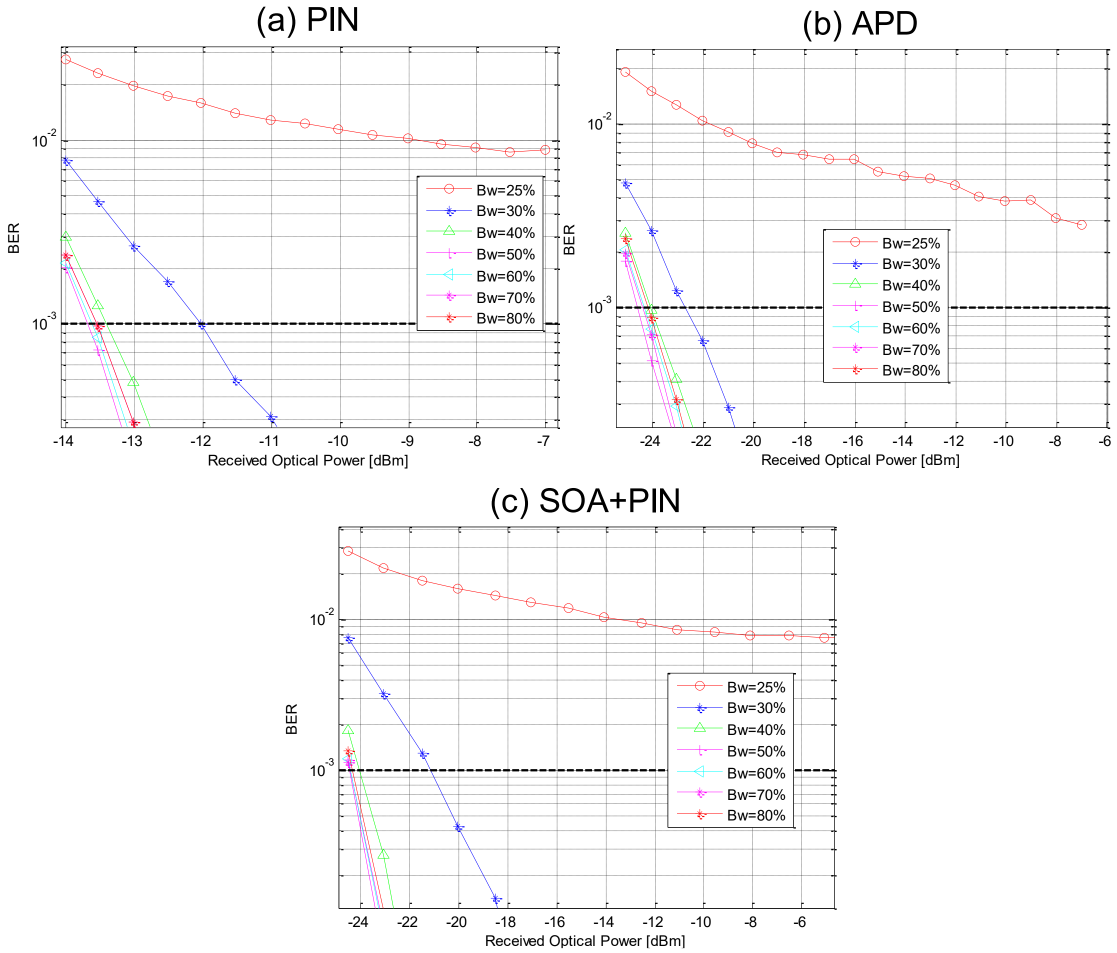


Figure 3.10: PAM-4, BER vs. the received optical power for the different value of normalized electrical filter bandwidth, without adaptive equalizer.

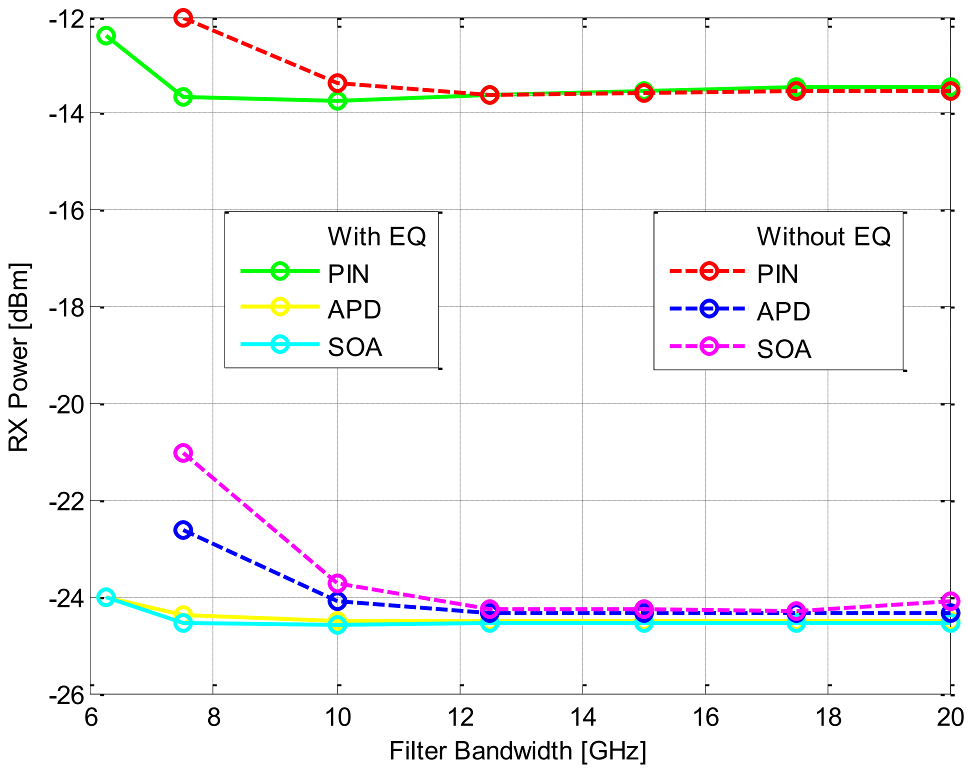
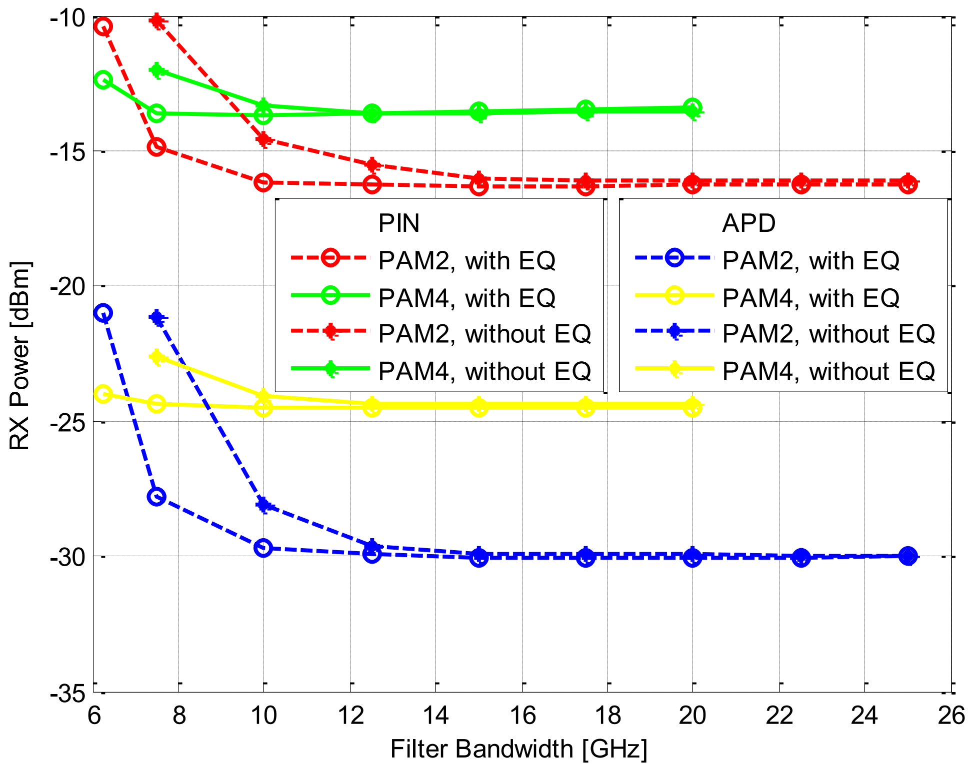


Figure 3.11: Optical received power vs. the electrical filter bandwidth for different types of receiver, with and without adaptive equalizer, for PAM-4.

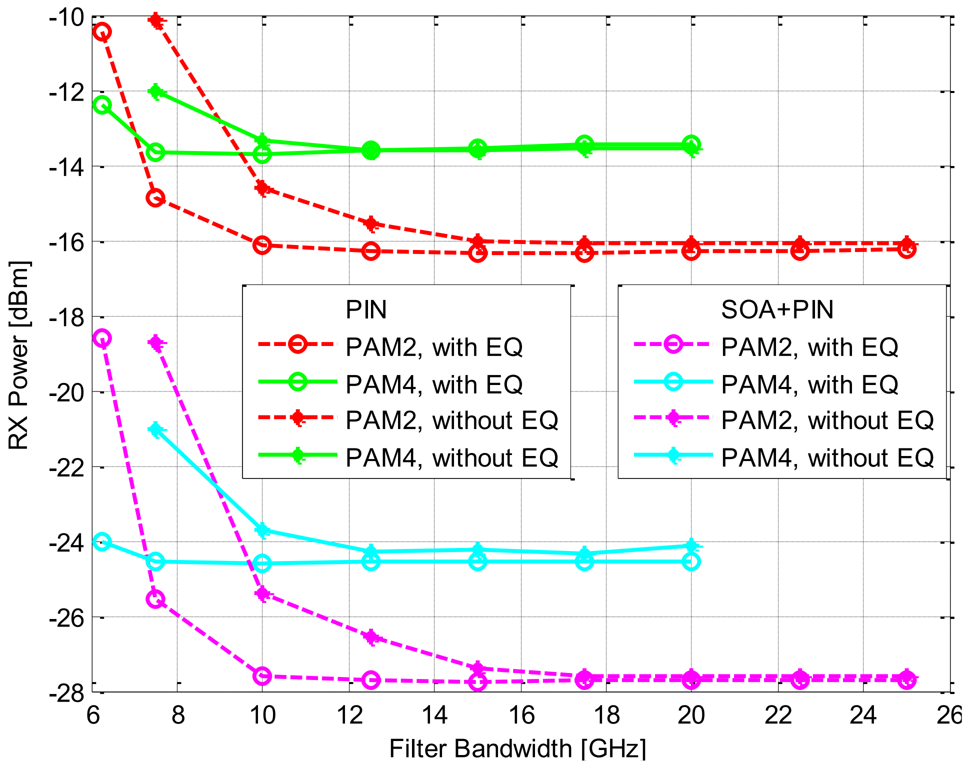
Figure 3.11 shows the optical received power vs. the electrical filter bandwidth for PIN, APD and SOA+PIN receiver, where the received power is obtained at the target BER equals to 10^{-3}. It is obvious that the performance of APD is very similar to the performance of SOA+PIN receiver. The performance in terms of received power of PIN receiver is the worst one, when the normalized filter bandwidth equals to 0.8 and with the adaptive equalizer, it suffers a power penalty of 11.07dB and 11.12dB with respect to APD and SOA associated with PIN receiver respectively. If the adaptive equalizer is not exploited, it has a power penalty equals to 10.81dB and 10.57dB. From the observation from the case of PAM-2, for both with and without the adaptive equalizer, it shows that for PAM-4 the power penalties between PIN and APD receiver, and PIN and SOA+PIN receiver are similar to case PAM-2. Moreover, it is obvious that if there is no limitation of filter bandwidth (i.e., the normalized bandwidth larger than 0.6), the performance in terms of received power of the case without the equalizer is very similar to the case with the equalizer. However, if under the strict constraint of filter bandwidth, for example, the normalized bandwidth equals to 0.25, it cannot reach the target BER. If the normalized bandwidth equals to 0.3, it has a power penalty of 1.62dB, 1.78dB, and 3.53dB with respect to the case with equalizer for the PIN, APD, and SOA+PIN receiver, respectively.

3.4 Comparison between PAM-2 and PAM-4

Figure 3.12 shows the optical received power vs. the electrical filter bandwidth, with and without the equalizer, for PAM-2 and PAM-4, where the received power is obtained at the target BER equals to 10^{-3}, for PIN, APD, SO+PIN receiver, respectively.



(a) PIN vs. APD



(b) PIN vs. SOA+PIN

Figure 3.12: Optical received power vs. the electrical filter bandwidth, with and without equalizer, for PAM-2 and PAM-4.

For the case with equalizer, the behaviour of PAM-4 exceeds the behaviour of PAM-2 when the filter bandwidth larger than 7.03GHz, 6.86GHz, and 7.37GHz for PIN, APD and SOA+PIN receiver respectively, that is around 7GHz. When the performance cannot be improved a lot by relaxing the filter bandwidth limitation, i.e., the normalized bandwidth equals to 0.4, that is 10GHz and it is larger than those exceeding bandwidths, PAM-4 suffers a power penalty of 2.44dB, 5.17dB, and 3.04dB for PIN, APD, and SOA+PIN receiver respectively, with respect to PAM-2. However, when the filter bandwidth less than those exceeding bandwidths, for example, the normalized bandwidth equals to 0.25, PAM-2 suffers a power penalty of 1.98dB, 3.01dB, and 5.41dB for PIN, APD, and SOA+PIN receiver respectively, with respect to PAM-4. For the case without the equalizer, the behaviour of PAM-4 exceeds the behaviour of PAM-

2 when the filter bandwidth larger than 8.97GHz, 8.21GHz, and 8.93GHz, which are larger than the case with the equalizer.

3.5 Conclusions

In this chapter, the performances of PAM-4 and PAM-2 vs. filter bandwidth for three types of receiver are studied, only the case with the adaptive equalizer and threshold optimization is considered. The filter bandwidth is normalized to the bit rate, which is 25GHz for PAM-2 and PAM-4.

It is observed that the performance of PIN receiver is much worse than APD and SOA+PIN receiver. When the normalized bandwidth reaches nearly up to 0.5 for PAM-2 and 0.4 for PAM-4, the performance cannot be improved a lot when increasing the bandwidth. And the adaptive equalizer is able to help relax the requirement of bandwidth limitation, but the performance cannot be improved when there is no filter bandwidth limitation by performing the adaptive equalizer, thus the equalizer is more essential under strictly bandwidth constraint. Moreover, PAM-4 is more suitable for the narrow filter bandwidth with respect to PAM-2, but the disadvantage is that when the filter bandwidth limitation is relaxed, the received power of PAM-4 is worse than PAM-2.

4 PAM-2 and PAM-4 vs. Dispersion

4.1 Simulation setup and basic simulation parameters

In this part, the required received optical power is obtained at the target BER equals to 10^{-3} when changing the fiber lengths (i.e., the dispersion). The bit rate is fixed at 25Gbps for both PAM-2 and PAM-4, thus the baud rates are 25Gbps for PAM-2 and 12.5Gbps for PAM-4. The electrical transmitter and receiver filters are both 1-order Bessel low pass filter when the electrical transmitter and receiver filter bandwidths equal to 7GHz (i.e., with filter bandwidth limitations), and both 5-order Bessel low pass filter when the electrical transmitter and receiver filter bandwidths equal to 0.75*baud rate [GHz] (i.e., without filter bandwidth limitations), that is 18.75GHz and 9.375 GHz for PAM-2 and PAM-4 respectively. And under the conditions of with and without the adaptive equalizer, and with and without threshold optimization. Finally, for all three types of receivers, namely PIN, APD and PIN associated with SOA, comparing the different conditions in terms of eye-diagrams and optical received power by plotting the figures of optical received power vs. total dispersion.

The diagrams of the simulation environment are as following: Figure 4.1, Figure 4.2, and Figure 4.3 represent the PIN receiver, APD receiver and SOA associated with PIN receiver respectively.

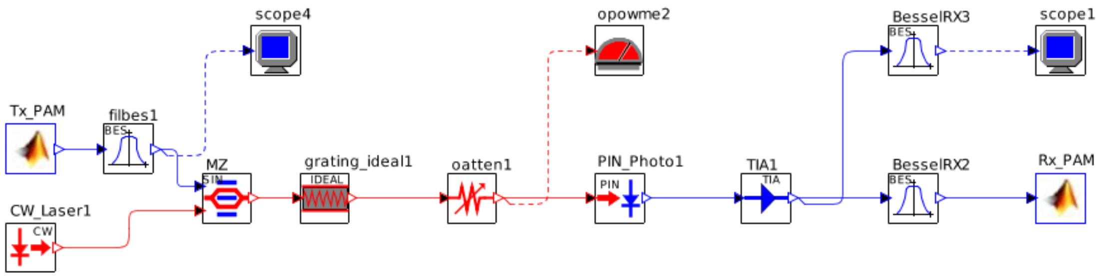


Figure 4.1: Diagram of PIN receiver when changing the fiber lengths

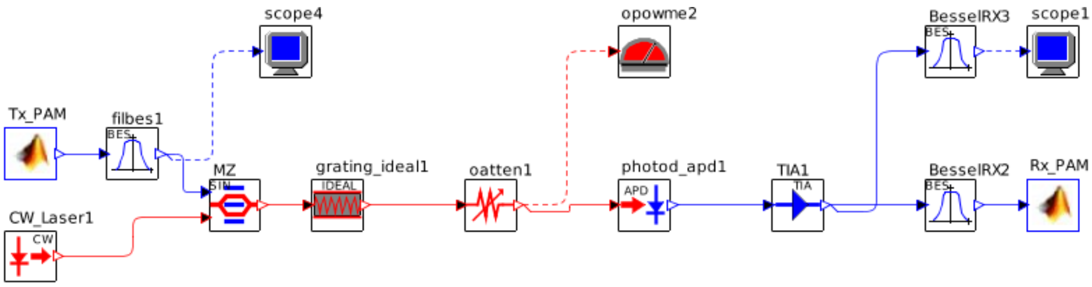


Figure 4.2: Diagram of APD receiver when changing the fiber lengths

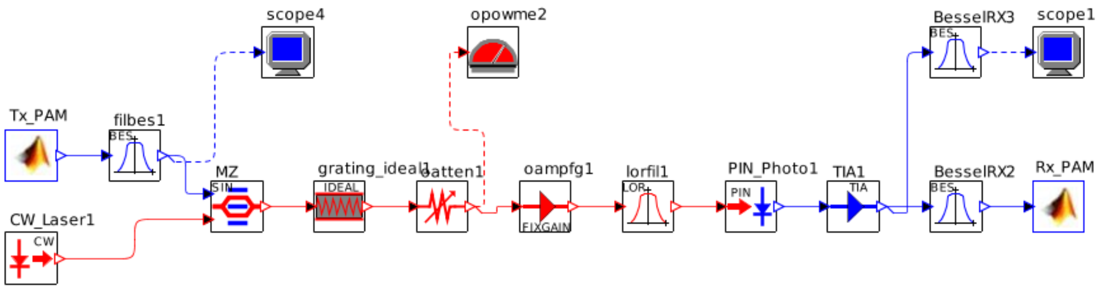


Figure 4.3: Diagram of SOA+PIN receiver when changing the fiber lengths

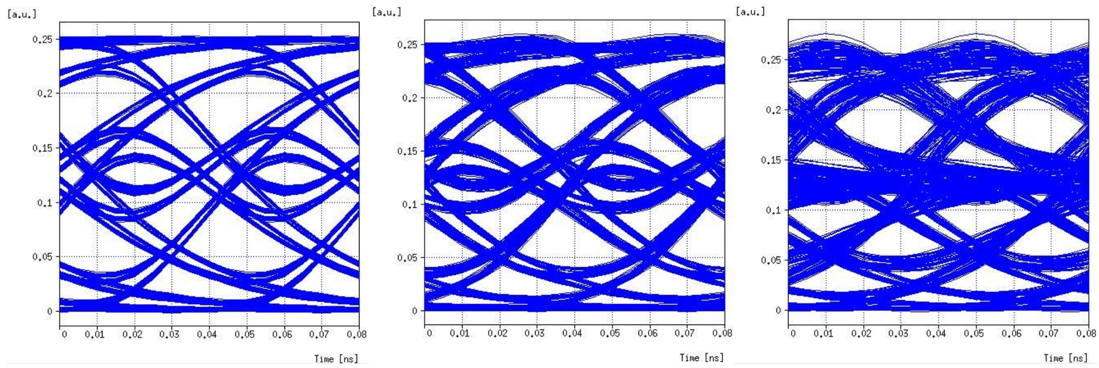
As shown in Figure 4.1 for PIN receiver, it is very similar with the case which is described in the section 3.1. In detail, 'Tx_PAM' and 'Rx_PAM' are implementations in MATLAB, such as data generation and ADC were performed in 'TX_PAM' and LMS based adaptive equalizer, threshold optimization, DAC and BER counting were implement in 'RX_PAM'. 'CW_Laser1' is the implementation of CW laser, which is connected to 'MZ', that is a MZM. 'filbes1' is the electrical filter at transmitter side, which is connected to 'scope4', which is used to observe the eye-diagrams at the transmitter side. 'fiber1' is the simulation of the optical fiber, with the fiber length is set to zero to simulate the B2B situation. 'oatten1' is the optical attenuator, and it is connected to 'PIN-Photo1' which is the implementation of the PIN photodiode and "opowme2", i.e., optical power meter, which is required to measure the received optical power. 'TIA1' represents for trans-impedance amplifier. 'BesselRX' is the simulation of the electrical filter at the receiver side, and 'scope1' is used to observe the received eye-diagrams. There is an additional block, it is 'grating_ideal1' which represents the ideal fiber grating, and it is performed to simulate the total dispersion. Moreover, as shown in the Figure 4.2 for APD receiver and Figure 4.3 for SOA+PIN receiver, everywhere are the same as the case with PIN receiver, except for 'photod_apd1' stands for APD photodiode in Figure 4.2 for APD receiver, and 'oampfg1' represents the fixed gain optical amplifier and 'lorfil1' simulates the optical filter in Figure 4.3 for SOA+PIN receiver.

4.2 PAM-2

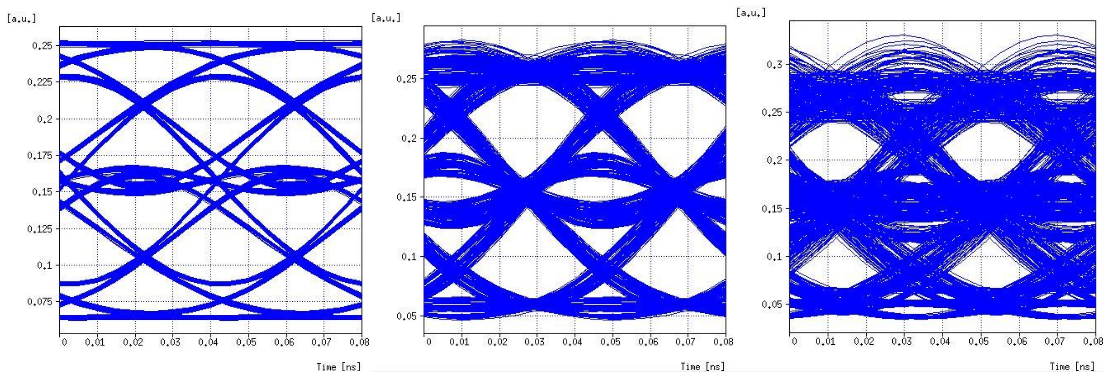
The bit rate equals to the baud rate, which is 25Gbps. The electrical filter is 1-pole when both transmitter and receiver filter bandwidths equal to 7GHz, and 5-pole when both transmitter and receiver filter bandwidths equal to 0.75*baud rate [GHz], that is 18.75 GHz. And two conditions are taken into account for MZM modulator, one is the ideal extinction ratio with positive chirp, the other one is the extinction ratio equals to 6dB with the negative chirp. For short distance optics using a silicon phonics device, the typical value of ER is 6dB [28].

4.2.1 Eye-diagrams comparison

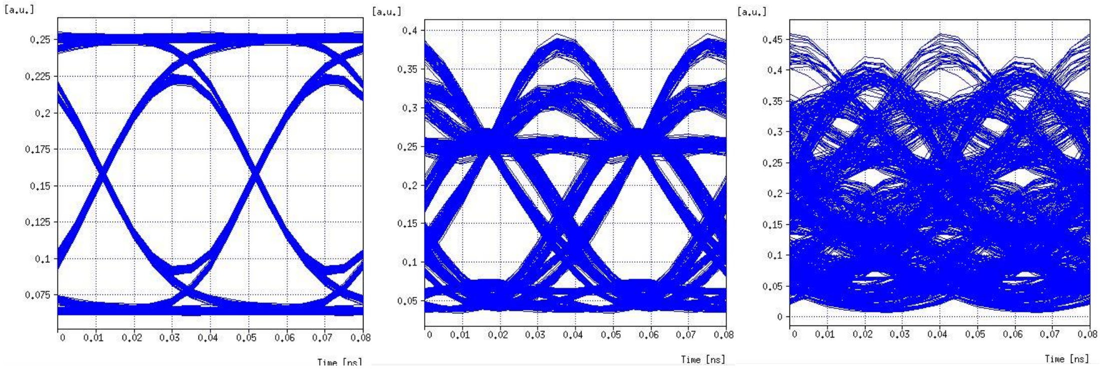
In the simulation, the situation with and without adaptive equalizer are both considered. From the eye-diagrams which are shown in Figure 4.4, it is obvious that when the length of fiber increases, i.e., the dispersion increases, the eye-diagrams are much more distorted. From Figure 4.4 (a) and (b) the eye-diagram of the case ER=6dB is clearer than the case with ideal ER and the same fiber length, and when the filter bandwidth is relaxed, that is, Bw=0.75*Rs, the eye-diagrams are widely open and it is nearly an ideal eye-diagram of PAM-2 modulation. Among all these three types of receivers, the eye-diagram of PIN receiver is the least clear and the amplitude is the smallest, as shown in Figure 4.4 (b), (c), (d) and (e). And there is only a single threshold receiver needed to detect. Moreover, the eye-diagram of filter bandwidth equals to 18.75GHz is better than the filter bandwidth equals to 7GHz as shown in Figure 4.4 (b) and (c).



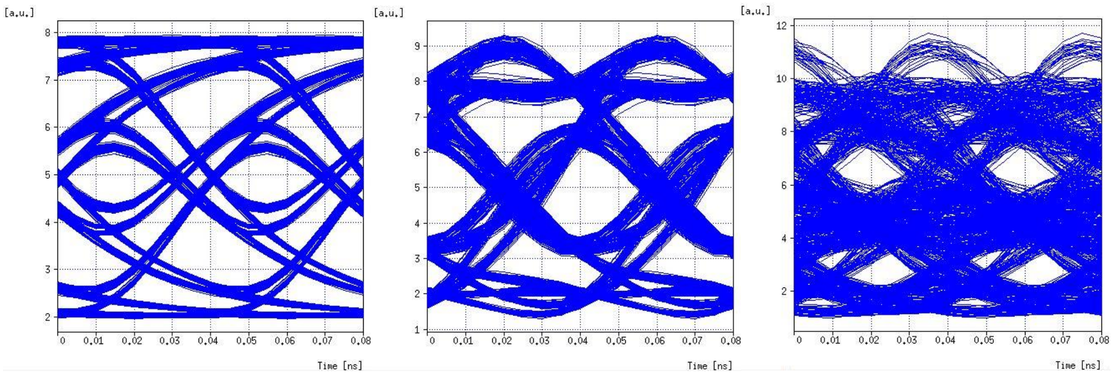
(a) PIN receiver, Ideal ER, filter bandwidth=7GHz, from left to right the fiber length is 0, 12 and 24Km (i.e., 0, 200.40, and 400.80 [ps/nm]), respectively



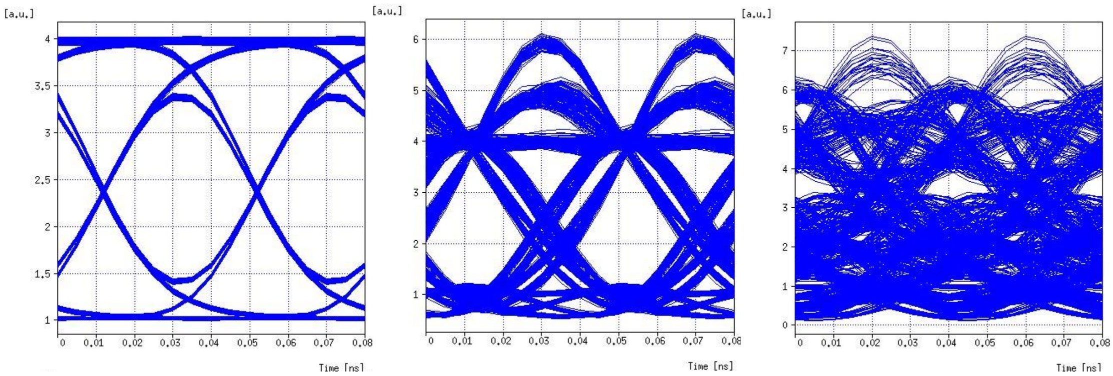
(b) PIN receiver, ER=6dB, filter bandwidth=7GHz, from left to right the fiber length is 0, 20 and 40Km (i.e., 0, 334.0, and 668.0 [ps/nm]), respectively



(c) PIN receiver, ER=6dB and filter bandwidth equals to 18.75GHz, from left to right the fiber length is 0, 20 and 40Km (i.e., 0, 334.0, and 668.0 [ps/nm]), respectively



(d) APD receiver, ER=6dB and filter bandwidth equals to 7GHz, from left to right the fiber length is 0, 20 and 40Km (i.e., 0, 334.0, and 668.0 [ps/nm]), respectively



(e) SOA receiver, ER=6dB and filter bandwidth equals to 18.75GHz, from left to right the fiber length is 0, 20 and 40Km (i.e., 0, 334.0, and 668.0 [ps/nm]), respectively

Figure 4.4: Eye-diagrams for PAM-2, for different fiber length

4.2.2 Simulation results for PAM-2

The case with and without the threshold optimization are both considered, without threshold optimization means that for PAM-2, the threshold is set to its theoretical value (i.e., zero) everywhere, as shown in Figure 4.5. For the condition with threshold optimization, using 500 equally spaced steps between the maximum and minimum of the received electrical signal and select the optimized threshold which is corresponded to the minimum BER. Threshold optimization can enhance the performance of the adaptive equalizer, but it will also add additional complexity and cost to the system. Thus, the behavior of the case with and without the threshold optimization is analyzed and compared to identify whether the existing of the threshold optimization is necessary or not.

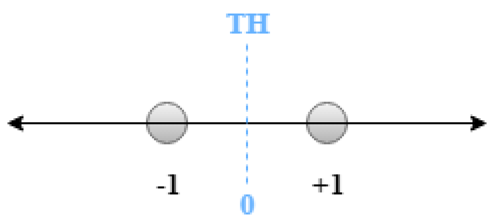
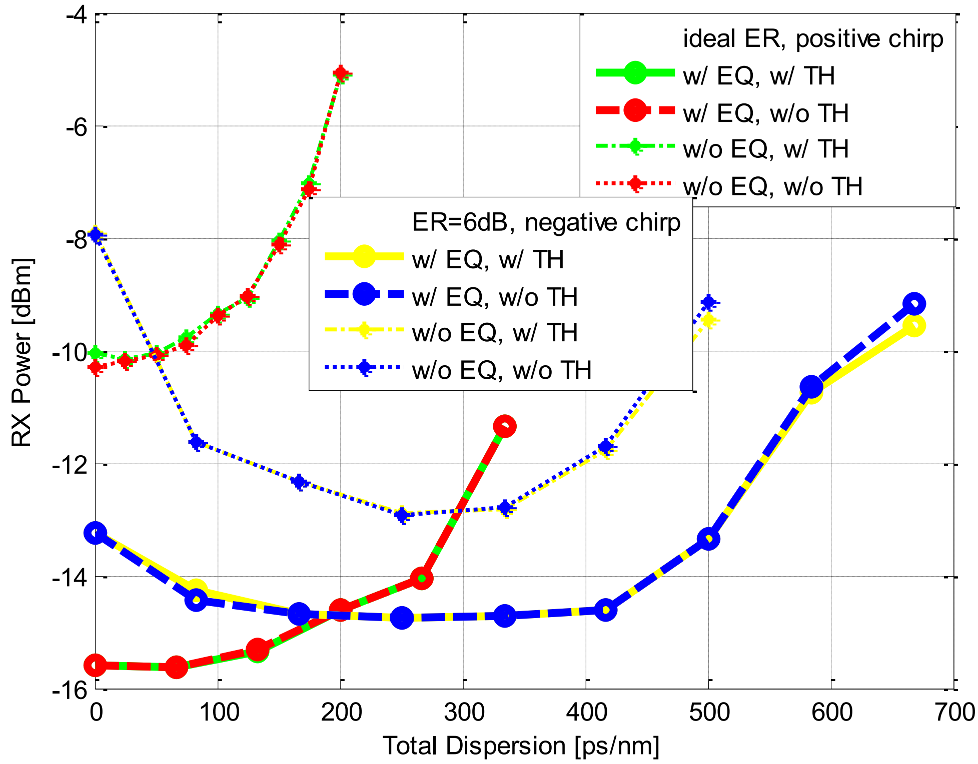
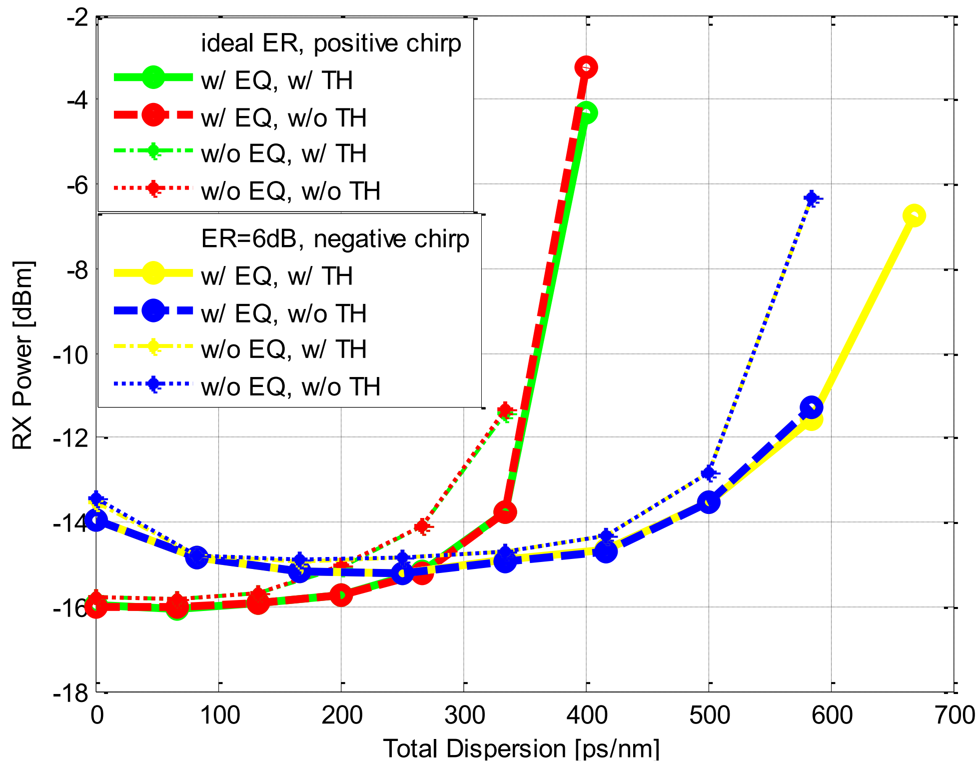


Figure 4.5: Constellation for PAM-2


ideal ER, positive chirp
w/ EQ, w/ TH
w/ EQ, w/o TH
w/o EQ, w/ TH
w/o EQ, w/o TH
ER=6dB, negative chirp
w/ EQ, w/ TH
w/ EQ, w/o TH
w/o EQ, w/ TH
w/o EQ, w/o TH
RX Power [dBm]
-4
-6
-8
-10
-12
-14
-16
0
100
200
300
400
500
600
700
Total Dispersion [ps/nm]

(a) Bw=7GHz



(b) Bw=75%*Rs GHz

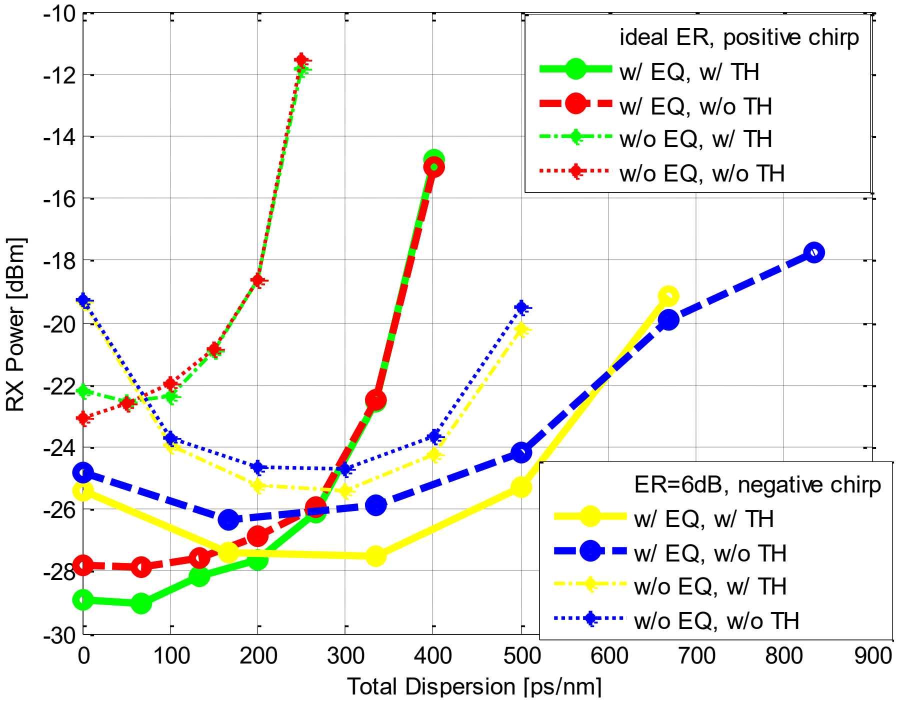
Figure 4.6: Received optical power vs. total dispersion, PIN receiver, PAM-2

As shown in Figure 4.6 for PIN receiver, the performance of the case without the threshold optimization is very similar to the case with the threshold optimization for both ideal ER with the positive chirp and ER=6dB with negative chirp, due to the quantum noise is disabled.

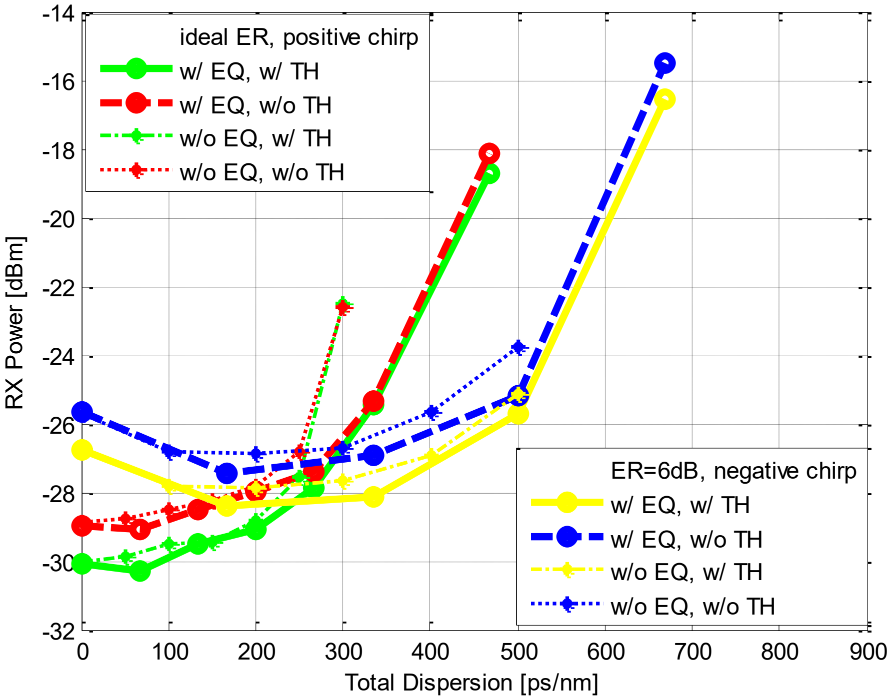
As shown in Figure 4.6 (a) for the case with threshold optimization and filter bandwidth equals to 7GHz, the case without the adaptive equalizer suffers a power penalty of 5.56dB at B2B (Back-to-Back) with respect to the case with the equalizer if with the ideal ER, if with ER=6dB it suffers a power penalty of 5.33dB at B2B, and at total dispersion equals to 250.5 [ps/nm] (i.e., 15Km) there exist a minimum power penalty equals to 1.82dB. Moreover, from the comparison between the case with ideal ER and ER=6dB for the case with the threshold optimization, at B2B the performance of the case with ER=6dB suffers a penalty of 2.35dB and 1.98dB for the case with and without the equalizer, respectively. However, the performance of the case with ER=6dB exceeds the case with ideal ER at total dispersion equals to 30.88 and 189.61 [ps/nm] (i.e., 1.85 and 11.35Km) for the case with equalizer and without equalizer respectively.

As shown in Figure 4.6 (b) for with threshold optimization and filter bandwidth equals to 75%*Rs GHz, the behavior of the case with the equalizer is very similar to the case without the equalizer, for both ideal ER and ER=6B. In addition, the performance of the case with ER=6dB suffers a penalty of 2.07dB and 2.35dB with respect to the case with ideal ER at B2B, for the case with and without the equalizer respectively, that is very similar to the case with filter bandwidth equals to 7GHz. And the performance of the case with ER=6dB exceeds the case with ideal ER at total dispersion equals to 212.86 and 269.30 [ps/nm] (i.e., 12.74 and 16.13Km) for the case with equalizer and without equalizer respectively.

As shown in Figure 4.6, from the comparison of the case with filter bandwidth equals to 7GHz and the bandwidth equals to 75%*Rs GHz both with the threshold optimization, if with the equalizer the case with bandwidth equals to 7GHz has a power penalty of 0.5dB and 0.7dB at B2B, for the case with ideal ER and ER=6dB respectively. And it suffers a penalty of 10.45dB and 10.54dB with respect to the case with bandwidth equals to 75%*Rs GHz for ideal ER and ER=6dB respectively if without the equalizer.



(a) Bw=7GHz



(b) Bw=75%*Rs GHz

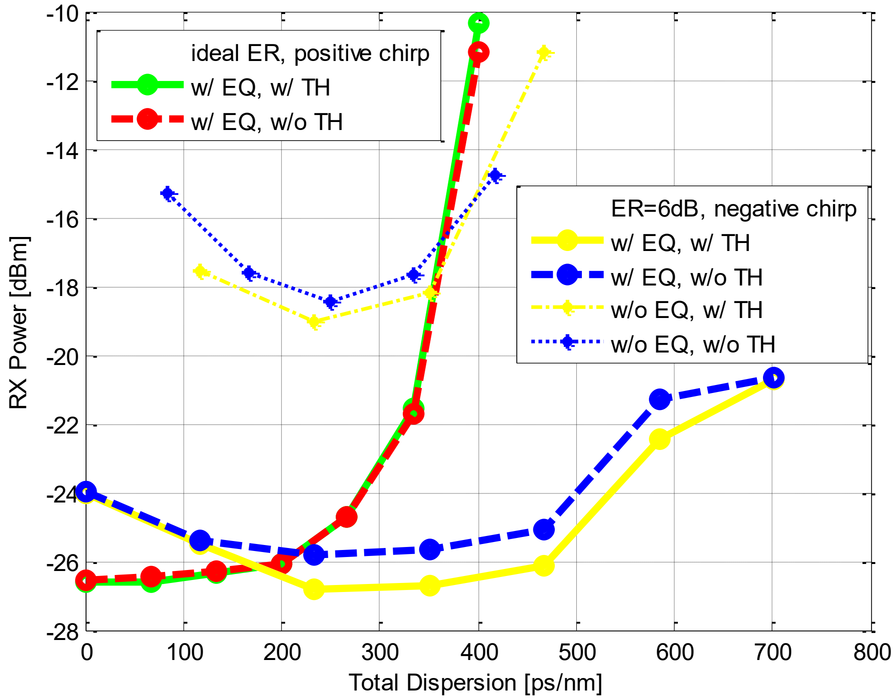
Figure 4.7: Received optical power vs. total dispersion, APD receiver, PAM-2

As shown in Figure 4.7, for APD receiver, the case without the threshold optimization suffers a slight power penalty which is about 1 to 1.5 dB with respect to the case with the threshold optimization, due to the noise figure F of APD is set to 10dB.

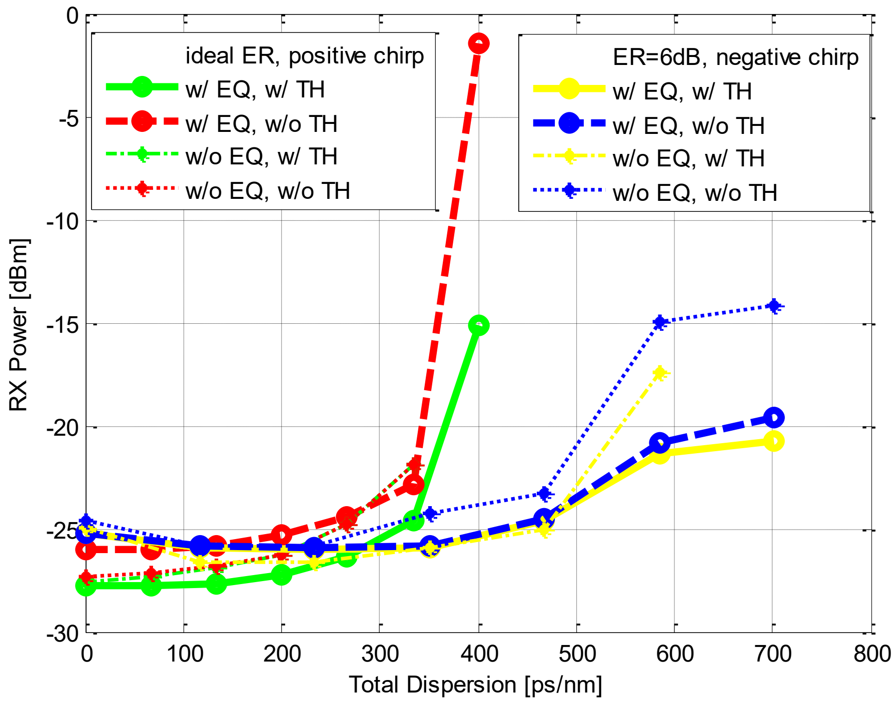
As shown in Figure 4.7 (a) for the case with threshold optimization and filter bandwidth equals to 7GHz, at B2B the performance of the case with ER=6dB suffers a penalty of 3.54dB and 2.90dB for the case with and without the equalizer respectively, the penalties are both slightly larger than the case with the PIN receiver. However, the performance of the case with ER=6dB exceeds the case with ideal ER at total dispersion equals to 71.30 and 210.48 [ps/nm] (i.e., 4.27 and 12.60Km) for the case with equalizer and without equalizer respectively. And the case without the adaptive equalizer has a power penalty equals to 6.74dB at B2B with respect to the case with the equalizer if with the ideal ER, and it suffers a power penalty of 6.09dB at B2B, and at total dispersion equals to about 300.6 [ps/nm] (i.e., 18Km) there exist a minimum power penalty equals to 2.11dB if with ER=6dB.

From Figure 4.7 (b), it is obvious that for the case with threshold optimization and filter bandwidth equals to 75%*Rs GHz, the behavior of the case with the equalizer is very similar to the case without the equalizer, for both ideal ER and ER=6B. Moreover, the performance of the case with ER=6dB suffers a penalty of 3.30dB and 3.34dB with respect to the case with ideal ER at B2B, for the case with and without the equalizer respectively, but the performance of the case with ER=6dB exceeds the case with ideal ER at total dispersion equals to about 240 [ps/nm] (i.e. 14.5Km) with the exceeding dispersion of the case with equalizer is slightly larger.

As shown in Figure 4.7, from the comparison of the case with filter bandwidth equals to 7GHz and the bandwidth equals to 75%*Rs GHz both with the threshold optimization, if with the equalizer, the case with the bandwidth equals to 7GHz has a power penalty of 1.1dB and 1.3dB at B2B, for the case with ideal ER and ER=6dB respectively. And it suffers a penalty of 6.68dB and 7.47dB with respect to the case with bandwidth equals to 75%*Rs GHz for ideal ER and ER=6dB respectively if without the equalizer.



(a) Bw=7GHz



(b) Bw=75%*Rs GHz

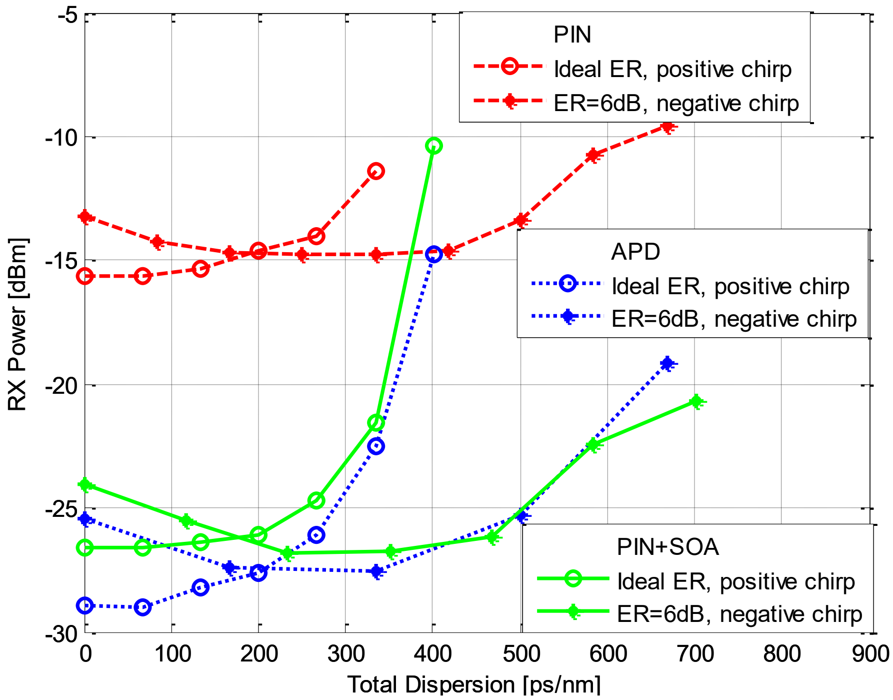
Figure 4.8: Received optical power vs. total dispersion, SOA+PIN receiver, PAM-2

As shown in Figure 4.8, for SOA+PIN receiver, the case without the threshold optimization suffers a power penalty which is about 1.2 to 1.8 dB with respect to the case with the threshold optimization, due to the noise figure of the EDFA is set to 9dB.

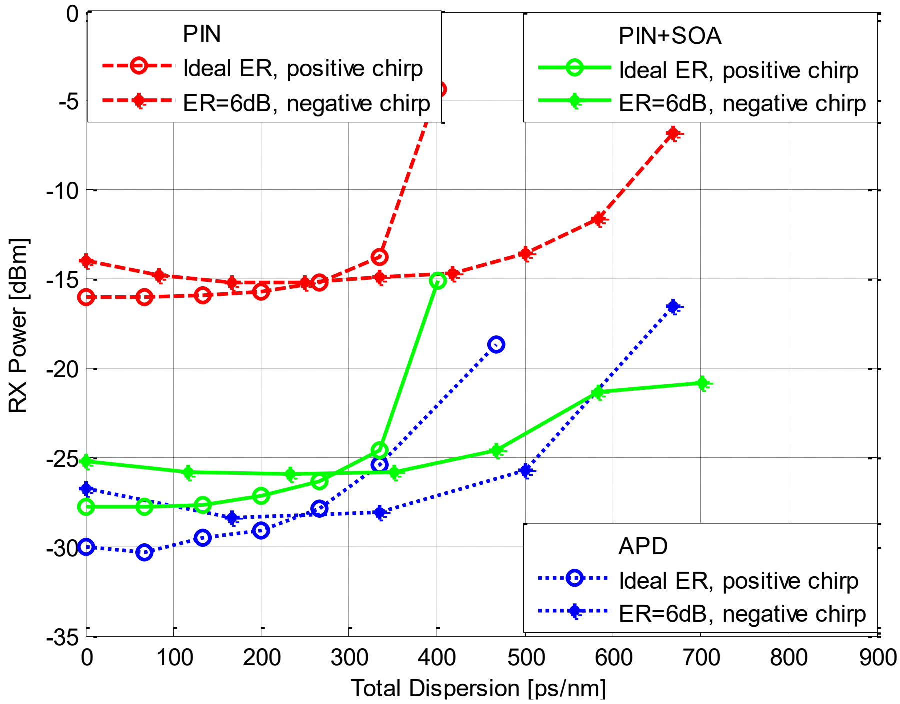
As shown in Figure 4.8 (a) for the case with threshold optimization and filter bandwidth equals to 7GHz, if the equalizer is applied, the performance of the case with ER=6dB suffers a penalty of 2.58dB at B2B, but the performance of the case with ER=6dB exceeds the case with ideal ER at total dispersion equals to 179.72 [ps/nm] (i.e., 10.76Km) with respect to the case with ideal ER. However, for the case without the equalizer and with the ideal ER, the target BER cannot be reached even at B2B. And the case without the adaptive equalizer and with ER=6dB, the target BER cannot be reached at B2B, it has a power penalty equals to 7.9dB at 7Km (i.e., dispersion equals to 116.9 [ps/nm]. From Figure 4.8 (b), it is obvious that for the case with threshold optimization and filter bandwidth equals to 75%*Rs GHz, the behavior of the case with the equalizer is very similar to the case without the equalizer, for both ideal ER and ER=6B. Moreover, the performance of the case with ER=6dB suffers a penalty of 2.51dB and 2.64dB with respect to the case with ideal ER at B2B, for the case with and without the equalizer respectively, but the performance of the case with ER=6dB exceeds the case with ideal ER at total dispersion equals to 283.49 and 137.76 [ps/nm] (i.e., 16.98 and 8.25Km) for the case with equalizer and without equalizer respectively.

As shown in Figure 4.8, from the comparison of the case with filter bandwidth equals to 7GHz and the bandwidth equals to 75%*Rs GHz both with the threshold optimization, if with the equalizer, the case with the bandwidth equals to 7GHz has a power penalty of 1.13dB and 1dB at B2B, for the case with ideal ER and ER=6dB respectively. And it suffers a penalty of 7.40dB with respect to the case with bandwidth equals to 75%*Rs GHz for ER=6dB respectively if without the equalizer.

The comparisons among three types of receiver are shown in Figure 4.9, only the case with the adaptive equalizer and with the threshold optimization is taken into account.



(a) Bw=7GHz



(b) Bw=75%*Rs GHz

Figure 4.9: Received optical power vs. total dispersion, PAM-2

As shown in Figure 4.9, only the case with the equalizer and threshold optimization is considered, it is obvious that the performance of PIN receiver is the worst one in both cases with and without filter bandwidth limitations.

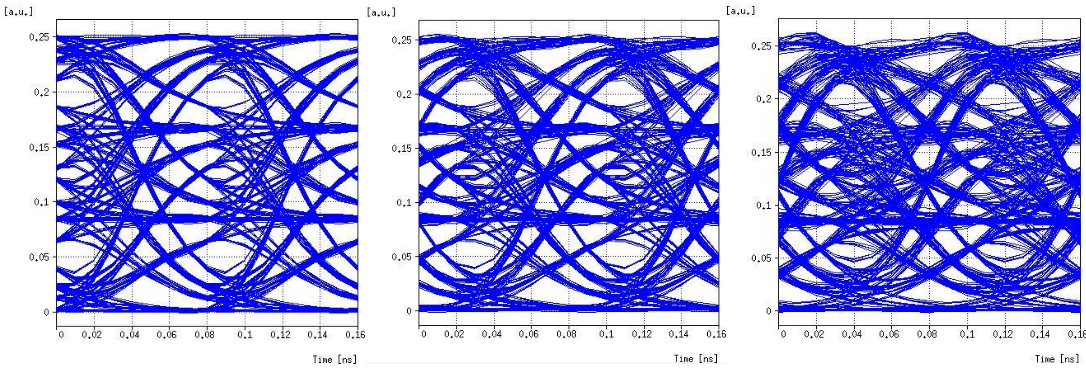
From Figure 4.9 (a) for filter bandwidth equals to 7GHz, when the ER is ideal and at B2B, the case with PIN receiver suffers a power penalty of 13.34 and 11.00dB with respect to the case with APD and SOA+PIN receiver respectively. When the ER equals to 6dB and at B2B, the case with PIN receiver suffers a power penalty of 12.15 and 10.78dB with respect to the case with APD and SOA+PIN receiver respectively, which is very similar to the case with ideal ER. From the Figure 4.9 (b) for without filter bandwidth limitations, the case with PIN receiver suffers a power penalty equals to 14.09 and 11.79dB at B2B when ER is ideal, and 12.82 and 11.31dB at B2B when ER equals to 6dB, with respect to the case with APD and SOA+PIN receiver respectively.

4.3 PAM-4

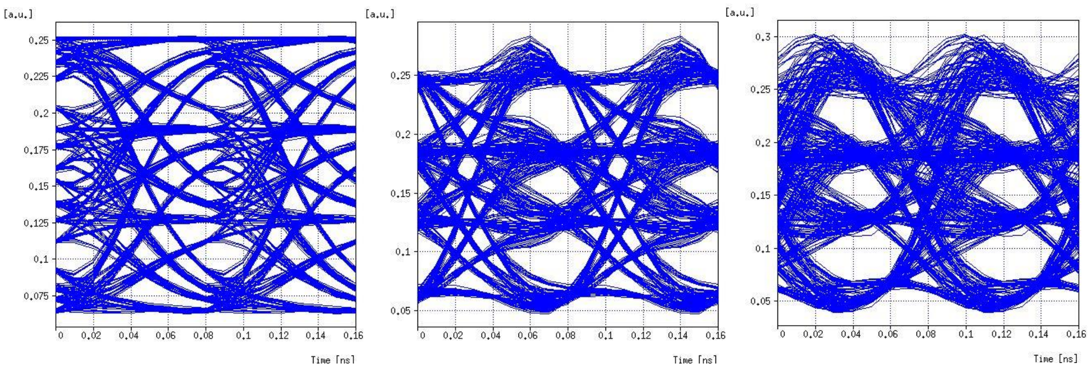
The bit rate equals to 25Gbps, thus the baud rate is 12.5Gbps. The electrical filter is 1-pole for both transmitter and receiver filter bandwidth equals to 7GHz (i.e. with filter bandwidth limitations), and 5-pole for both transmitter and receiver filter bandwidths equals to 0.75*baud rate [GHz] (i.e. without filter bandwidth limitations), that is 9.375 GHz. And two conditions are taken into account for MZM modulator, one is the ideal extinction ratio with positive chirp, the other one is the extinction ratio equals to 6dB with the negative chirp. For short distance optics using a silicon phonics device, the typical value of ER is 6dB [28].

4.3.1 Eye-diagrams comparison

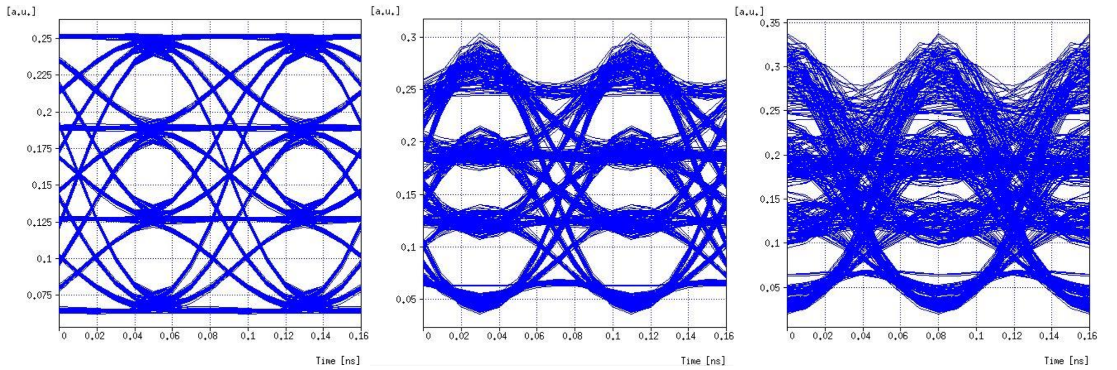
From the eye-diagrams which are shown in Figure 4.10, it is apparent that when the length of fiber increases, i.e., the dispersion increases, the eye-diagrams are more distorted. From Figure 4.10 (a) and (b) the eye-diagram of the case ER=6dB is clearer than the case with ideal ER and the same fiber length, and when the filter bandwidth is relaxed, that is, Bw=0.75*Rs, the eye-diagrams are widely open and it is nearly an ideal eye-diagram of PAM-4 modulation. Among all these three types of receivers, the eye-diagram of PIN receiver is the least clear and the amplitude is the smallest, as shown in Figure 4.10 (b), (c), (d) and (e). And there is a 3-level threshold receiver needed to detect. Moreover, the eye-diagram of the case without the filter bandwidth limitations is clearer than the case with the filter bandwidth limitations, and when the filter bandwidth is relaxed, that is, Bw=7GHz, the eye-diagrams are distorted and they are difficult to be recognized as the eye-diagram of the PAM-4 modulation, as shown in Figure 4.10 (b) and (c).



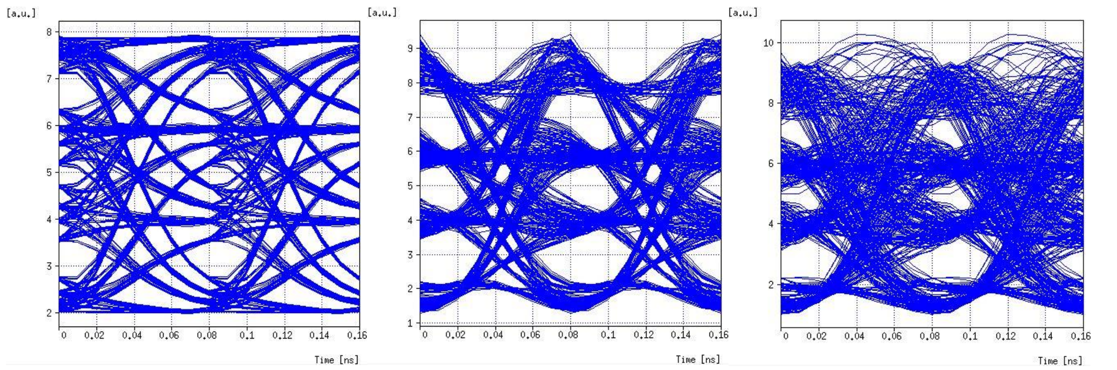
(a) PIN receiver, Ideal ER, filter bandwidth=7GHz, from left to right the fiber length is 0, 12 and 24Km (i.e., 0, 200.40, and 400.80 [ps/nm]), respectively



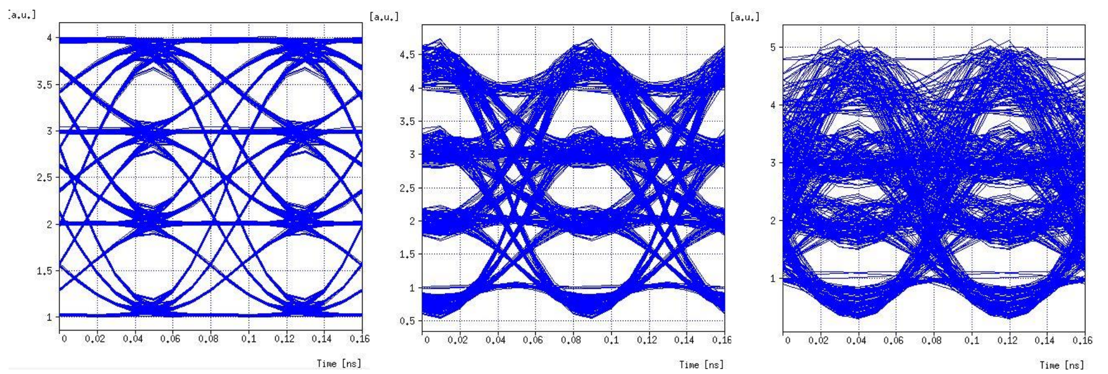
(b) PIN receiver, ER=6dB, filter bandwidth=7GHz, from left to right the fiber length is 0, 20 and 40Km (i.e., 0, 334.0, and 668.0 [ps/nm]), respectively



(c) PIN receiver, ER=6dB, filter bandwidth=9.375GHz, from left to right the fiber length is 0, 20 and 40Km (i.e., 0, 334.0, and 668.0 [ps/nm]), respectively



(d) APD receiver, ER=6dB, filter bandwidth=7GHz, from left to right the fiber length is 0, 30 and 60Km (i.e., 0, 501.0, and 1002.0 [ps/nm]), respectively



(e) SOA+PIN receiver, ER=6dB, filter bandwidth=75%* Rs GHz, from left to right the fiber length is 0, 24 and 48Km (i.e., 0, 400.80, and 801.60 [ps/nm]), respectively

Figure 4.10: Eye-diagrams for PAM-2, for different fiber length

4.3.2 Simulation results for PAM-4

The conditions with and without threshold optimization are taken into account. Without threshold optimization means that for PAM-4 the 3-level threshold is fixed everywhere at the theoretical value, as shown in Figure 4.11. For the case with threshold optimization, first, applying 500 steps between two levels of the received electrical signal and fixing the other two thresholds (i.e., TH1 and TH2) at their theoretical value, then the first optimized threshold where the minimum BER can be obtained is selected. Redoing the first step with fixed first optimized threshold and fixed threshold TH3, thus the second optimized threshold is obtained. Finally, the third optimized threshold can be selected by fixing the first and second optimized threshold. Threshold optimization can enhance the performance of the adaptive equalizer, but it will also add additional complexity and cost to the system. Thus, the behavior of the case with and without the threshold optimization is analyzed and compared to identify whether the existing of the threshold optimization is necessary or not.

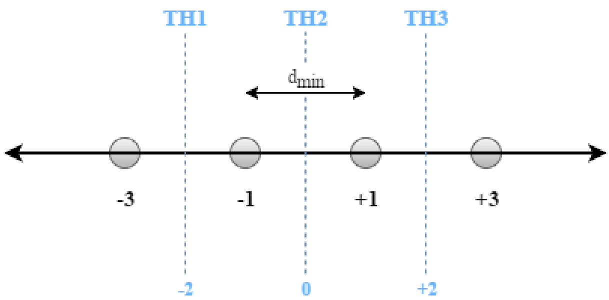


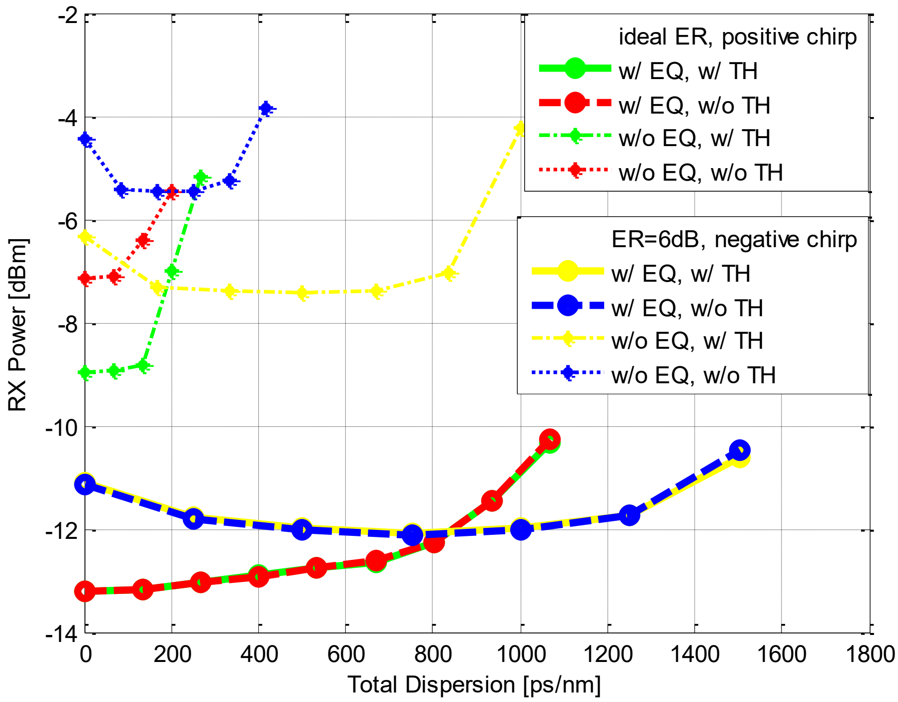
Figure 4.11: Constellation for PAM-4

As shown in Figure 4.12, for PIN receiver with the adaptive equalizer, the behavior of the case with the threshold optimization is very similar to the behavior of the case without the threshold optimization, due to the same reason which has been described in the section 4.2.2, in detail, for PIN receiver, the performance of the case without the threshold optimization is very similar to the case with the threshold optimization for both ideal ER with the positive chirp and ER=6dB with negative chirp, due to the quantum noise is disabled. However, if the equalizer is not applied, the performance of the case without the threshold optimization suffers a relatively large power penalty of 1.81 and 1,91dB with respect to the performance of the case with the threshold optimization at B2B, for with ideal ER and ER=6dB respectively, as shown in Figure 4.12 (a) for filter bandwidth equals to 7GHz. And it suffers a power penalty of 2.01 and 2.23dB with respect to the performance of the case with the threshold optimization at B2B, for with ideal ER and ER=6dB respectively, as shown in Figure 4.12 (b) for the case without the filter bandwidth limitations. These penalties are larger than the case with PAM-2 because it is a three-level threshold needed to be detected.

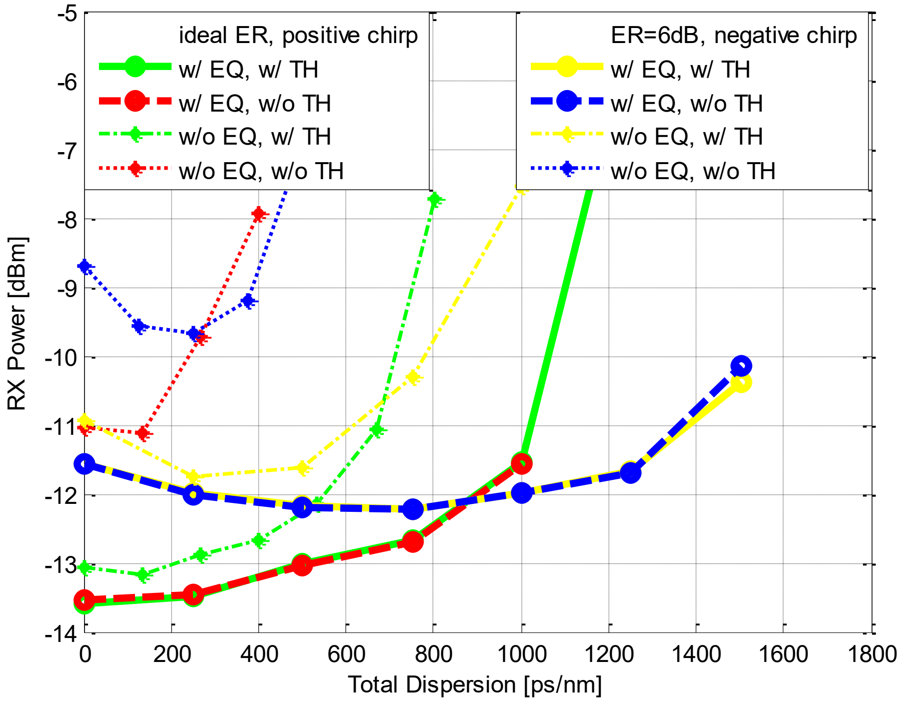
From Figure 4.12 (a) for Bw=7GHz, the performance of the case without the equalizer has a power penalty equals to 4.26 and 4.77dB with respect to the case with the equalizer at B2B, for ideal ER and ER=6dB respectively when threshold optimization is not applied. And for the case with the threshold optimization, the performance of the case with ER=6dB suffers a power penalty of 2.12 and 2.63dB with respect to the performance of the case with ideal ER at B2B for the case with and without the equalizer respectively, that are very similar to the penalties which have been described in the section 4.2.2 for PAM-2. But the performance of the case with ER=6dB exceeds at the total dispersion equals to 835.71 and 188.71[ps/nm] (i.e. 50.04 and 11.30Km) respectively.

And from Figure 4.12 (b) for the case without the bandwidth limitations, the performance of the case without the equalizer has a power penalty equals to 0.54 and 0.64dB with respect to the case with the equalizer at B2B, for ideal ER and ER=6dB respectively. These penalties are only slightly larger than the penalties which have been described in the section 4.2.2 for PAM-2, but the CD tolerant can be improved a lot by applying the equalizer. And for the case with the threshold optimization, the performance of the case with ER=6dB suffers a power penalty of 2.03 and 2.14dB with respect to the performance of the case with ideal ER at B2B for the case with and without the equalizer respectively, but the performance of the case with ER=6dB exceeds at the total dispersion equals to 885.48 and 686.41[ps/nm] (i.e. 53.02 and 41.10Km) respectively.

Moreover, as shown in Figure 4.12, from the comparison between the cases with and without the filter bandwidth both with the threshold optimization, for the case with the adaptive equalizer, the performance of the case with the filter bandwidth equals to 7GHz has a power penalty of 0.38 and 0.46dB with respect to the case without the filter bandwidth limitations for ideal ER and ER=6dB respectively, that are very similar to the penalties which have been obtained in the section 4.2.2 for PAM-2. And it suffers a penalty of 4.10 and 4.58dB if without the filter bandwidth limitations.



(a) Bw=7GHz



(b) Bw=0.75%*Rs GHz

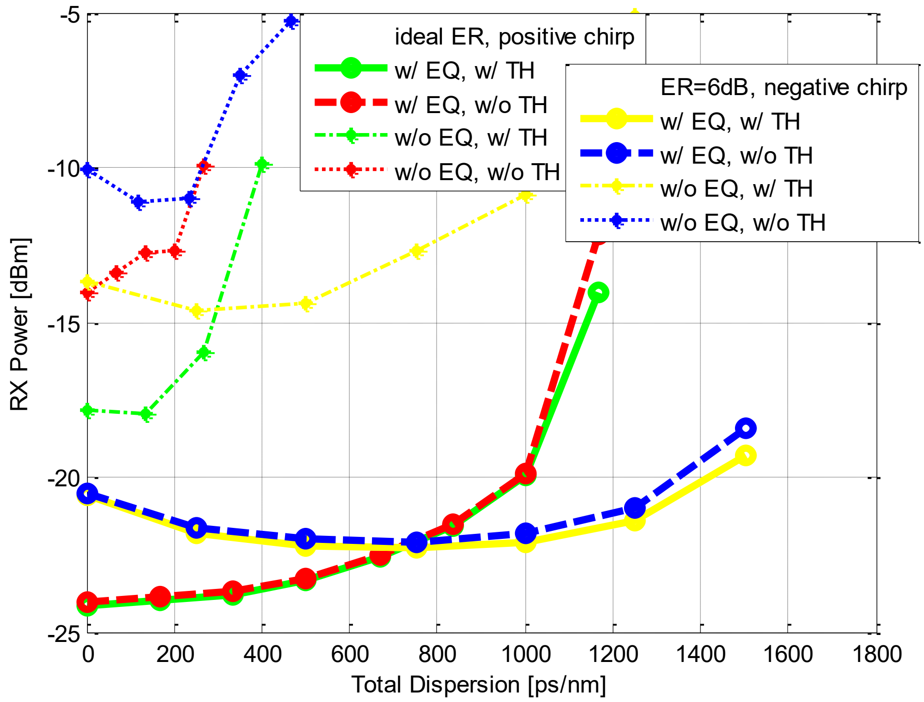
Figure 4.12: Received optical power vs. total dispersion, PIN receiver, PAM-4

As shown in Figure 4.13 for APD receiver, from the comparison between the performance of the cases with and without the threshold optimization, the behavior is very similar to what has been described for the case with PIN receiver, that is the performance of the case without the threshold optimization is very similar to the case with the threshold optimization if with the equalizer. But for the case without the equalizer, it suffers a power penalty equals about 3.7dB if Bw=7GHz, and about 5.3dB if without the filter bandwidth limitations, with respect to the performance of the case with the threshold optimization for both ideal ER and ER=6dB.

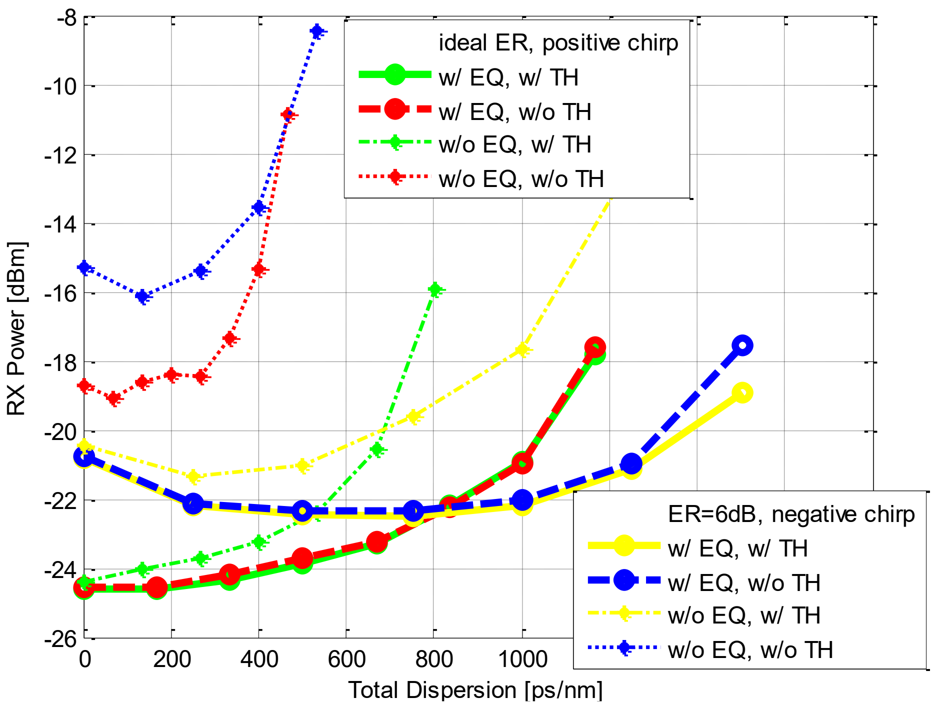
From Figure 4.13 (a) for Bw=7GHz, first the performance of cases with and without the equalizer are compared. The performance of the case without the equalizer suffers a power penalty of about 6.5dB when the threshold optimization is applied, and about 10.3dB without the threshold optimization, with respect to the performance of the case with the equalizer at B2B. Second, from the comparison between the performance of the case with ideal ER and ER=6dB when the threshold optimization is applied, the performance of the case with ER=6dB suffers a power penalty of 3.58 and 4.20dB at B2B, for the case with and without equalizer respectively. But the performance of the case with ideal ER is exceeded at the total dispersion equals to 715.44 and 292.40[ps/nm] (i.e. 42.84 and 17.51Km) respectively.

From Figure 4.13 (b) for the case without the filter bandwidth limitations, the performance of the case without the equalizer is very similar to the case with the equalizer at B2B when the threshold optimization is applied, but the performance of the case with the equalizer is more CD tolerant. However, when the threshold optimization is not applied, it suffers a power penalty equals about 5.6dB even at B2B with respect to the performance of the case with the equalizer. Second, from the comparison between the performance of the case with ideal ER and ER=6dB when the threshold optimization is applied, the performance of the case with ER=6dB suffers a power penalty of 3.77 and 3.95dB at B2B, for the case with and without equalizer respectively. But the performance of the case with ideal ER is exceeded at the total dispersion equals to 794.97 and 685.67[ps/nm] (i.e. 47.60 and 41.06Km) respectively.

As shown in Figure 4.13, from the comparison between the cases with and without the filter bandwidth both with the threshold optimization, for the case with the adaptive equalizer, the performance of the case with the filter bandwidth equals to 7GHz has a power penalty of 0.44 and 0.25dB at B2B with respect to the case without the filter bandwidth limitations for ideal ER and ER=6dB respectively. And it suffers a penalty of 6.52 and 6.77dB at B2B respectively if the equalizer is not applied.



(a) Bw=7GHz



(b) Bw=75%*Rs GHz

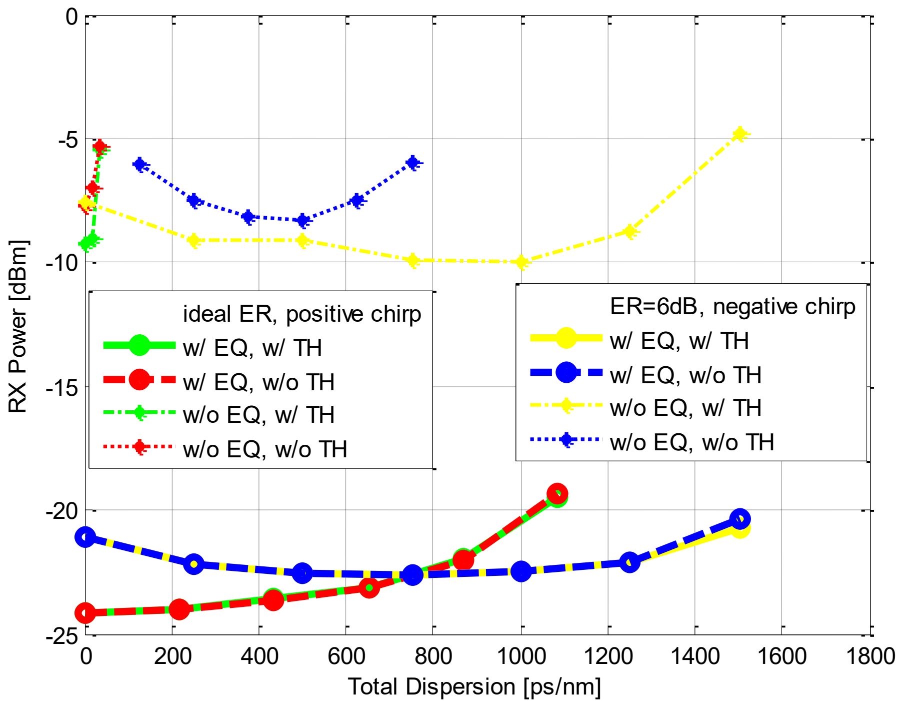
Figure 4.13: Received optical power vs. total dispersion, APD receiver, PAM-4

Figure 4.14 shows the received optical power vs. total dispersion (i.e., fiber lengths) for SOA+PIN receiver, it is apparent that the performance of the case with and without the threshold optimization is very much alike in performance when the equalizer is applied. However, if the equalizer is not applied, the results of the case without the equalizer suffers a larger power penalty equals to 1.54dB at B2B for the scenario with ideal ER, and 2.33dB at 7.5Km with ER=6dB (if the equalizer and the threshold optimization both are not applied, it is cannot reach the target BER even at B2B for the case with ER=6dB) with respect to the case with the threshold optimization, for the case with Bw=7GHz as shown in Figure 4.14 (a). And from Figure 4.14 (b) when there are no filter bandwidth limitations, it suffers a power penalty of 4.23 and 5.15dB at B2B for the case with ideal ER and ER=6dB respectively. It is obvious that the performance of the scenario which the equalizer is not applied, with ideal ER and under strictly filter bandwidth limitations (i.e., Bw=7GHz) is too poor to be used.

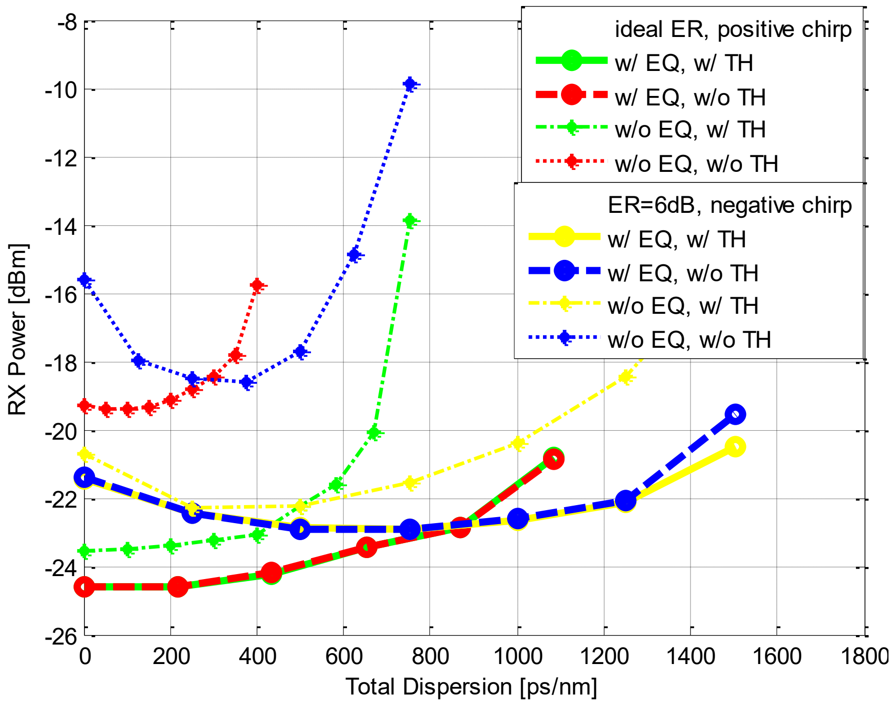
As shown in Figure 4.14 (a) for Bw=7GHz, first, the results of the case with and without the equalizer are compared, and only the scenario with the threshold optimization is taken into account. The performance of the case without the equalizer has a power penalty of 14.89 and 13.53dB at B2B for the case with ideal ER and ER=6dB respectively. Second, from the comparison between the case with ideal ER and ER=6dB, and only the scenario with the threshold optimization is considered, the performance of the case with ER=6dB suffers a power penalty equals to 3.07 and 1.71dB and at B2B for the case with and without the equalizer respectively, but it exceeds the case with ideal ER at dispersion equals to 23.06 and 743.74 [ps/nm] (i.e., 1.38 and 44.54Km) respectively.

From Figure 4.14 (b) when there is no filter bandwidth is applied, the performance of the case without the equalizer has a power penalty of 1.08 and 0.7dB at B2B for the case with ideal ER and ER=6dB respectively. And the performance of the case with ER=6dB suffers a power penalty of 3.19 and 2.82dB and at B2B for the case with and without the equalizer respectively, but it exceeds the case with ideal ER at dispersion equals to 520.02 and 883.78 [ps/nm] (i.e., 31.14 and 52.92Km) respectively.

In addition, as shown in Figure 4.14, from the comparison between the scenario with Bw=7GHz and Bw=75%*Rs GHz, and only the case with threshold optimization is taken into account, the results of the case with Bw=7GHz has a power penalty of 0.45 and 0.33dB at B2B for the case with ideal ER and ER=6dB respectively when the equalizer is applied. And for the scenario without the equalizer, it suffers a power penalty equals 14.27dB at B2B and 13.22 at 7.5Km respectively, with respect to the results of the case with Bw=75%*Rs GHz.



(a) Bw=7GHz

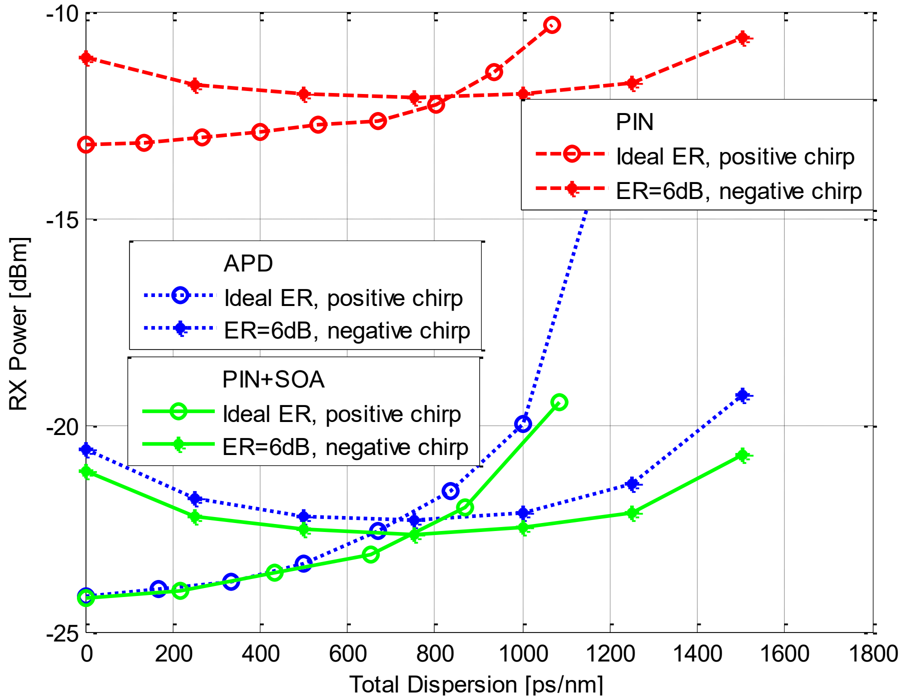


(b) Bw=75%*Rs GHz

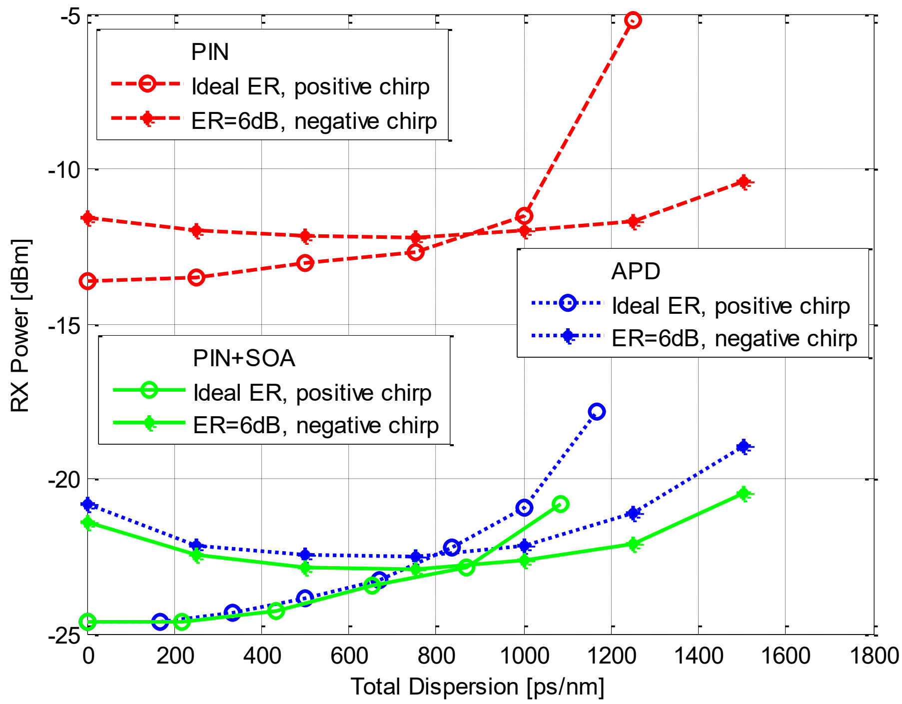
Figure 4.14: Received optical power vs. total dispersion, SOA+PIN receiver, PAM-4

As shown in Figure 4.15, only the case with the equalizer and threshold optimization is taken into account, it is apparent that the result of the case with PIN receiver is the worst one in both cases with and without filter bandwidth limitations, and the performance of the case with APD and SOA+PIN receiver are very much alike, which is similar to the behavior of PAM-2.

From Figure 4.15 (a) for filter bandwidth equals to 7GHz, when the ideal ER is applied, the case with PIN receiver suffers a power penalty equals to about 10.9dB at B2B with respect to the case with APD and SOA+PIN receiver. When the ER equals to 6dB, the case with PIN receiver suffers a power penalty of about 9.7dB at B2B, which is very similar to the case with ideal ER. From the Figure 4.15 (b) for without filter bandwidth limitations, the case with PIN receiver suffers a power penalty equals to about 11dB at B2B when ER is ideal, and 9.6dB at B2B when ER equals to 6dB, with respect to the case with APD and SOA+PIN receiver.



(a) Bw=7GHz

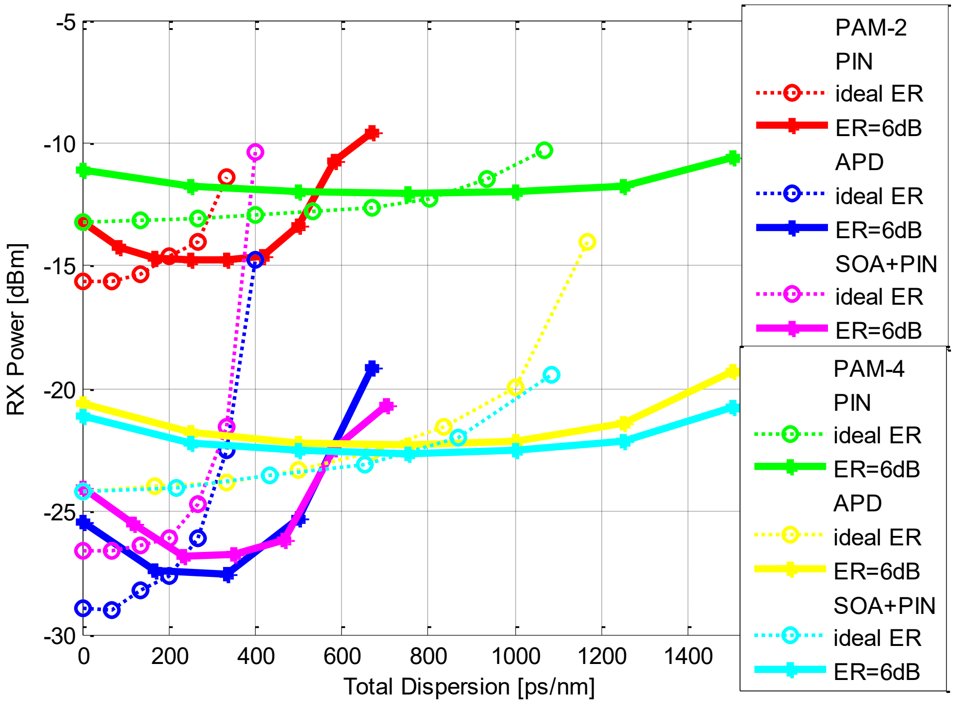


(b) Bw=75%*Rs GHz

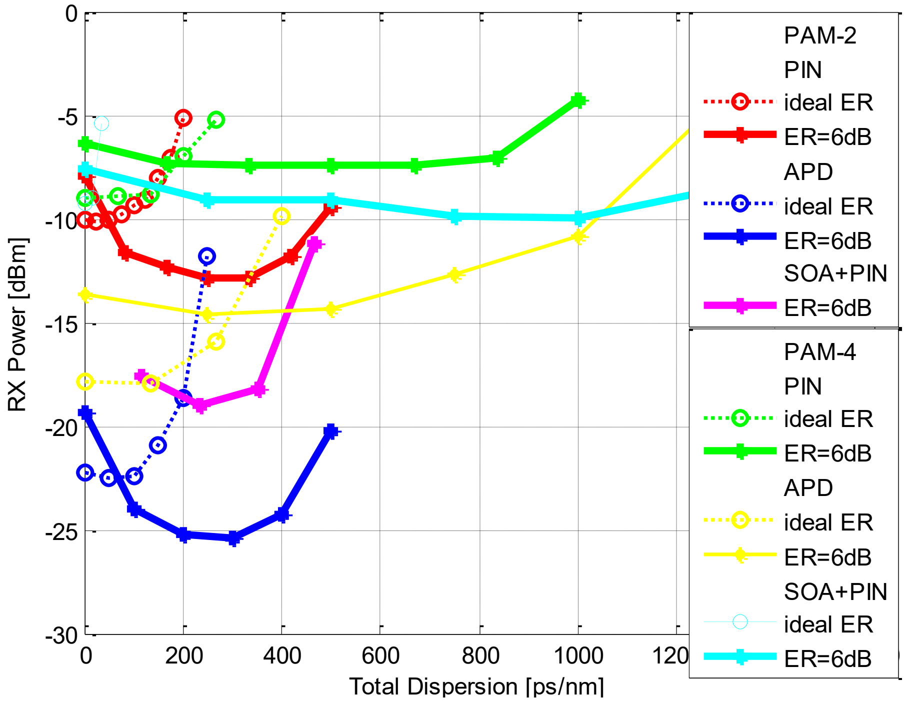
Figure 4.15: Received optical power vs. total dispersion, PAM-4.

4.4 Comparison between PAM-2 and PAM-4

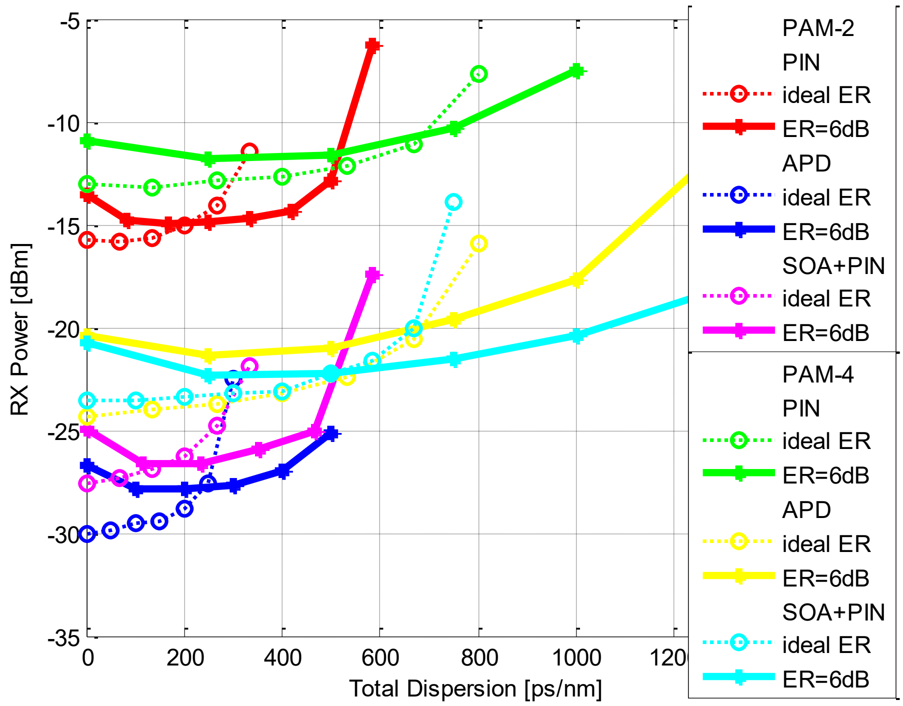
The conditions PAM-2 and PAM-4 are compared, only the case with Bw=7GHz and with the threshold optimization is considered if the adaptive equalizer is applied, because the performances of the case with Bw=7GHz suffers a little power penalty with respect to the case with Bw=75%*Rs GHz. And if the adaptive equalizer is not applied, both cases with BW=7GHz and Bw=75%*Rs GHz are taken into account.



(a) With equalizer and Bw=7GHz



(b) Without equalizer and Bw=7GHz



(c) Without equalizer and Bw=75%*Rs

Figure 4.16: Received optical power vs. total dispersion, for PAM-2 and PAM-4

As shown in Figure 4.16, it is obvious that PAM-4 is much more chromatic dispersion tolerant than PAM-2, for all the cases with or without the equalizer, with or without threshold optimization, ideal ER or ER=6dB, and with or without filter bandwidth limitations. Even though the performance of the case with PAM-4 suffers some power penalty when the chromatic dispersion is low (i.e., short distance transmission), up to a specific relative higher chromatic dispersion (i.e., longer distance transmission) it exceeds the performance of the case with PAM-2.

In detail, from Figure 4.16 (a) for the scenario with equalizer and Bw=7GHz, the results of the case with PAM-4 has a power penalty equals to 2.38, 4.79 and 2.44dB at B2B with respect to the case with PAM-2, but it exceeds at dispersion equals to 291.18, 309.96 and 284.35 [ps/nm] (i.e., 17.44, 18.56 and 17.03Km) for PIN, APD, and SOA+PIN receiver respectively, when ER is ideal. If ER equals to 6dB, it suffers a power penalty equals to 2.14, 4.83, and 2.93dB at B2B, which are very similar to the case with ideal ER, and exceeds the performance of the case with PAM-2 at dispersion equals to 547.34, 584.91, and 581.50 [ps/nm] (i.e., 32.78, 35.02 and 34.82Km) for PIN, APD, and SOA+PIN receiver respectively.

As shown in Figure 4.16 (b) for the scenario without equalizer and Bw=7GHz, when ER is ideal the performance of the case with PAM-4 has a power penalty equals to 1.08 and 4.34dB at B2B with respect to the case with PAM-2, but it exceeds at dispersion equals to 128.27 and 216.32dB [ps/nm] (i.e., 7.68 and 12.95Km) for PIN and APD receiver respectively, and for SOA+PIN receiver it cannot reach the target BER even when dispersion equals to zero. If ER equals to 6dB, it suffers a power penalty equals to 1.58 and 4.83dB at B2B for PIN and APD receiver, and the target BER cannot be reached at B2B for SOA+PIN receiver with PAM-2, then it exceeds the performance of the case with PAM-2 after dispersion is larger than 501.0, 467.6 and 501.0 [ps/nm] (i.e., 30.0, 28.0 and 30.0Km) for APD, and SOA+PIN receiver respectively.

And as shown in Figure 4.16 (c) for the scenario without equalizer and Bw=75%*Rs GHz, the results of the case with PAM-4 has a power penalty equals to 2.70, 5.66 and 4.06dB at B2B with respect to the case with PAM-2, but it exceeds at dispersion that equals to 301.33, 287.67 and 305.88 [ps/nm] (i.e., 18.04, 17.23 and 18.32Km) for PIN, APD, and SOA+PIN receiver respectively when ER is ideal. If ER equals to 6dB, it suffers a power penalty equals to 2.60, 6.27, and 4.24dB at B2B, and exceeds the performance of the case with PAM-2 at dispersion that equals to 521.44, 601.20, and 512.33 [ps/nm] (i.e., 31.22, 36.00 and 34.82Km) for PIN, APD, and SOA+PIN receiver respectively.

4.5 Conclusions

In this chapter, the performances of PAM-4 and PAM-2 vs. chromatic dispersion for three types of receiver are studied, the cases with or without the adaptive equalizer, with or without the threshold optimization, Bw=7GHz or Bw=75%*baud rate, and ideal ER with the positive chirp or ER=6dB with negative chirp are taken into account.

It is observed that:

- The performance of the PIN receiver is much worse with respect to APD and SOA+PIN receiver.

- The case with ER=6dB and negative chirp is more dispersion resilient, but it suffers a little power penalty under the low dispersion circumstances, and it can exceed the case with ideal ER and positive chirp when the total CD is larger than a specific value. The total CD where the performance of the case with ER=6dB exceeds the case with ideal ER increases when the filter bandwidth increases, and increment for the case without the adaptive equalizer is much more than the case with the equalizer. When Bw=75%*Rs, the exceeding point of the case without the equalizer is closer to the case with the equalizer.

- The case with the equalizer is more CD tolerant with respect to the case without the equalizer. The performance can be improved a lot by using the adaptive equalizer under the strict bandwidth constraint, but not in the case without the filter bandwidth limitation, that is, the equalizer is more necessary if the bandwidth is too narrow. The performances can be improve a lot by increasing the filter bandwidth if the equalizer is not applied, but not for the case with the equalizer.

- The case with the threshold optimization is more CD tolerant when the equalizer is not applied, especially for PAM-4. And if the filter bandwidth limitation is relaxed, the performances can be improved by applying the threshold optimization, and the improvement of the case without the equalizer is much larger than the case with the equalizer.

- PAM-4 is more CD tolerant than PAM-2, but it suffers a little power penalty when the total CD is low. The adaptive equalizer is more required for PAM-2 than PAM-4 under the strict filter bandwidth limitations, but for PAM-4 even without bandwidth limitations, the CD tolerant can be improved a lot by applying the equalizer.

5 Conclusions and future work

PON based on power splitting distribution network is an important telecommunication architecture which can provide PtMP transmission. It can support higher bit rate, low loss probability and keep the cost down at the same time.

In the thesis, the performance of PAM-2 and PAM-4 vs. filter bandwidth limitations are studied in Chapter 3, for different conditions, namely, three different types of receivers, with or without the adaptive equalizer, with the threshold optimization, and ideal ER with positive chirp. It is observed that the performance of PIN receiver is much worse than APD and SOA+PIN receiver. When the normalized bandwidth reaches nearly up to 0.5 for PAM-2 and 0.4 for PAM-4, the performance cannot be improved a lot when increasing the bandwidth. And the adaptive equalizer is able to help relax the requirement of bandwidth limitation, but the performance cannot be improved when there is no filter bandwidth limitation by performing the adaptive equalizer, thus the equalizer is more essential under strictly bandwidth constraint. Moreover, PAM-4 is more suitable for the narrow filter bandwidth with respect to PAM-2, but the disadvantage is that when the filter bandwidth limitation is relaxed, the received power of PAM-4 is worse than PAM-2.

And the performance of PAM-2 and PAM-4 vs. total dispersion are studied in Chapter 4, for different conditions, namely, three different types of receivers, with or without the adaptive equalizer, with or without the threshold optimization, with or without the bandwidth limitations, and ideal ER with positive chirp or ER=6dB with negative chirp. It is observed that the performance of the PIN receiver is much worse with respect to APD and SOA+PIN receiver. In addition, the case with ER=6dB and negative chirp is more dispersion resilient, but it suffers a little power penalty under the low dispersion circumstances, and it can exceed the case with ideal ER and positive chirp when the total CD is larger than a specific value. The case with the equalizer is more CD tolerant with respect to the case without the equalizer. The equalizer is more necessary if the bandwidth is too narrow. And the performances can be improve a lot by increasing the filter bandwidth if the equalizer is not applied, but not for the case with the equalizer. The case with the threshold optimization is more CD tolerant when the equalizer is not applied, especially for PAM-4. And if the filter bandwidth limitation is relaxed, the performances can be improved by applying the threshold optimization. Moreover, PAM-4 is more CD tolerant than PAM-2, the adaptive equalizer is more required for PAM-2 than PAM-4 under the strict filter bandwidth limitations, but for PAM-4 even without bandwidth limitations, the CD tolerant can be improved a lot by applying the equalizer.

Future work:

- The performance can be improved by exploiting some advanced modulation schemes, such as EDB which can relax the system bandwidth requirement, and ODB which only needs a single threshold receiver to be detected.
- In the thesis, the ideal DAC, ADC, CW laser, and MZM modulator are applied, but they could not be implemented in a cost efficient way in the real world.
- Similar research when the bit rate is above 25Gbps, i.e., 40Gbps, which is much less CD tolerant.

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