PROJECTE FINAL DE CARRERA

LOW POWER SIGNALING IN
NEXT-GENERATION TWDM-PON

Estudis: Enginyeria de Telecomunicació

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To my dear family
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RESUM

Actualment la demanda per altes velocitats de transmissió dóna l’oportunitat d’estudiar profundament l’ús de les xarxes òptiques, les quals presenten altes tasses de transmissió així com transmissions a llargues distàncies i poques pèrdues. El nou estàndard de les Passive Optical Networks (PON), NG-PON2, està en procés d’estandardització. Aquest estàndard incrementa tant les tasses de transmissió com el número d’usuaris connectats a l’Optical Line Terminal (OLT) i permet la connexió d’un nou usuari sense haver de bloquejar les connexions actives, a través d’un senyal de senyalització que anomenem senyal de Control.

Per les transmissions de baixada, l’OLT utilitza Time Division Multiplexing (TDM) per comunicar-se amb cada usuari. D’altra banda, per les transmissions de pujada, TDM és usat com als estàndard anteriors, entre els usuaris, però l’increment en el nombre d’usuaris connectats és donat per l’ús de Wavelength Division Multiplexing (WDM) que agrupa 4 longituds d’ona centrals diferents, en les quals es poden connectar fins a 16 usuaris a cada una, arribant a un nombre d’usuaris total igual o major a 64. Per aquesta raó aquest estàndard és també anomenat TWDM-PON.

L’objectiu d’aquest projecte és estudiar la compatibilitat de dos senyals transmesos simultàniament durant una transmissió NG-PON2 de pujada. Aquests dos senyals són el de Dades d’una ONU que ja està transmetent i la de Control d’una nova ONU que vol establir la connexió amb la OLT. Aquests dos senyals interferiran en el punt en què el senyal de Control caigui a la banda del senyal de Dades, creant Crosstalk, que és l’obstacle a resoldre.

L’estudi de compatibilitat entre aquests dos senyals ha estat elaborat a través de mesures experimentals, obtenint la avaluació del Bit Error Rate (BER) en els dos senyals i les corresponents penalitats creades recíprocament. El projecte va ser iniciat amb una altra tesi focalitzada en la branca de les Dades, mentre que aquesta tesi està adreçada a la branca del Control. Finalment, som capaços de comparar els resultats obtinguts de les dues tesis i establir algunes conclusions sobre el funcionament del sistema sota les condicions proposades.
RESUMEN

Actualmente la demanda por altas velocidades de transmisión da la oportunidad de estudiar profundamente el uso de las redes ópticas, las cuales presentan altas velocidades así como transmisiones a largas distancias y pocas pérdidas. El nuevo estándar de las Passive Optical Networks (PON), NG-PON2, está en proceso de estandarización. Este estándar incrementa tanto las tasas de transmisión como el número de usuarios conectados al Optical Line Terminal (OLT) y permite la conexión de un nuevo usuario sin tener que bloquear las conexiones ya activas, a través de una señal de señalización que llamamos señal de Control.

Para las transmisiones de bajada, la OLT utiliza Time Division Multiplexing (TDM) para comunicarse con cada usuario. Por otro lado, para las transmisiones de subida, TDM es usado como en los estándares anteriores entre los usuarios, pero el incremento en el número de usuarios conectados es gracias al uso de Wavelength Division Multiplexing (WDM) que agrupa 4 longitudes de onda centrales diferentes, en las cuales se pueden conectar hasta 16 usuarios a cada una, llegando a un número total de usuarios igual o mayor a 64. Por esta razón este estándar es también llamado TWDM-PON.

El objetivo de este proyecto es estudiar la compatibilidad de dos señales transmitidas simultáneamente durante una transmisión NG-PON2 de subida. Estas dos señales son la de Datos de una Optical Network Unit (ONU) que ya está transmitiendo y la de Control de una nueva ONU que quiere establecer una conexión. Estas dos señales interferirán en el punto en que la señal de Control caiga en la banda de la señal de Datos, creando Crosstalk, que es el obstáculo a resolver.

El estudio de compatibilidad entre estas dos señales ha estado elaborado a través de medidas experimentales, obteniendo la evaluación del Bit Error Rate (BER) en las dos señales y las correspondientes penalidades creadas recíprocamente. El proyecto fue iniciado con otra tesis focalizada en la rama de los Datos, mientras que esta tesis está dirigida a la rama de Control. Finalmente, somos capaces de comparar los resultados obtenidos de las dos tesis y establecer algunas conclusiones sobre el funcionamiento del sistema bajo las condiciones propuestas.
ABSTRACT

Nowadays the demand for high transmission velocities brings the opportunity to deeply study the usage of optical networks, which present high bit rates moreover large distance budgets on the link. New standard on the Passive Optical Networks, NG-PON2, is on the standardization process. This standard increase both the bit rates on downstream and upstream communications, the number of users connected to one Central Office (CO) and provide the connection to a new user without stopping the active connections through a signalling signal we call Control signal.

For the downstream transmissions, the CO is having the entire band for its use and so there is only need to use Time Division Multiplexing (TDM) to communicate with each user. On the other hand, for the upstream communications, the TDM is used as on the former standards, between the users, but the increase on the number of connected users is given by the use of the Wavelength Division Multiplexing technique (WDM) which compiles 4 central wavelengths, in which at least 16 users can be connected at each one, making a total amount of users equal or bigger than 64. For this reason this standard is also called TWDM-PON.

The aim of this project is to study the compatibility between two signals transmitted simultaneously during an NG-PON2 upstream transmission. These two signals would be the Data signal from an already transmitting Optical Network Unit (ONU) and the Control signal from a new ONU that wants to establish a connection. These two signals might interfere on the point in which the Control signal falls into the Data signal creating a Crosstalk, the obstacle to solve.

The compatibility study between these two signals has been done through an experimental demonstrator, performing the BER evaluation on both signals and the relative reciprocal penalties. The project started with another thesis focused on the Data branch, while this thesis is addressed on the Control branch. As a final achievement we are able to compare the results obtained from the two theses and come up with some conclusions about the functioning of the system under the proposed conditions.
OUTLINE OF THESIS

This thesis is divided into 5 chapters.

Chapter 1 provides an overview of the Passive Optical Networks and its new standard NG-PON2 which is still under standardization process.

Chapter 2 explains part of the work carried out on the last thesis that started this project and from which study the current thesis continues. This chapter shows the analysis on the Data branch for the penalties caused by the Control signal interference and there are shown the results achieved at the last part of the work about the recovering of the Control signal affected by the Data signal.

Chapter 3 discusses the work carried out on the Control setup and describes all the optimization measures performed to accomplish with the requirements established on the previous chapter for the recovering of the Data signal and the Control signal simultaneously.

Chapter 4 shows the results obtained on the Control branch in terms of BER and Penalties caused by the Data signal and we find also the margin of work of the system for the recovering of both the signals.

Finally, Chapter 5 makes the confrontation between the Control and Data results to find the area at which both will work together respecting the Penalty constraint on the Data channel.
ACKNOWLEDGMENTS

This thesis was elaborated at the Istituto Superiore Mario Boella (ISMB), on the PhotonLab laboratory.

I would like to thank to my advisors, Roberto Gaudino and Valter Ferrero, the guidance they have provided me during this project, to Luca Bertignono, the knowledge he has shared and the patience to explain things many times and I render thanks to all the colleagues of the ISMB that offered me help when I needed it.

I want to appreciate also the good company of all my Erasmus friends, Elif, Didem, Cem, Hazal, Özge, Papiya and Joana, that walked with me through this adventure that is becoming emancipated and achieving the academic goals at the same time.

Finally I have to be grateful for having such an encouraging parents, Paco and Lucia, who made me believe in myself, which I think was the key element to reach the top of my career.
CHAPTER 1  INTRODUCTION

1.1 A growing demand

For some time, internet traffic volume has been growing tremendously, highlighting the lack of a proper access network capacity.

Nowadays, the existing broadband solutions are Digital Subscriber Line (DSL) and Cable Modem (CM). The first one, built on former communication infrastructures, the old copper cables, cannot provide high capacity services. On the other hand, CM network, that uses a Hybrid Fiber Coaxial (HFC) deployment, still has some limitations due to the fact that it was launched for analogue services and so the available band for the upstream communications is really restricted. To sum up, even the distances they can support neither bandwidths are enough for the amount of data traffic on demand.

The appearance of optical fibers, which allow propagations through long distances with little distortion and also with a high information-carrying capacity, brought the opportunity to provide exactly what we need.

These optical networks are appearing with competitive costs comparable to the ones of DSL and HFC. With speeds around the gigabit per second and larger covering distances, they appear to be a good solution.

In the frame of high bit rates and low loses on the path regarding optical fibers, there are many ways in which we can extend our network. The simplest solution would be the Point-to-Point network; which extends a fiber between the Central Office (CO) and each user, Figure 1.1.

- Having a single-mode fiber dedicated from the Central Office (CO) to each user makes possible to design and build a simpler optical transceiver.
- This structure provides also easier bandwidth upgrades as the whole bandwidth of the fiber is dedicated to one user.
- It facilitates the unbundling between the different telecommunication carriers
- The management of the network, seen from a system point of view, is simpler.
Even though, there are some disadvantages on this structure:

- It supposes a big deployment of fiber as we need to extend a fiber pair between the Central Office and each user.
- Therefore it is required a greater number of Optical Line Terminal (OLT) to manage all user’s connections.
- And accordingly to this a bigger number of transceivers.
- All of this leads to higher power consumption.
- Finally, the higher available bandwidth is debatable since the bottleneck regarding to this is found on the connection from the central office to the backbone network.

Another structure, shown in Figure 1.2, includes the use of a switch near the neighbourhood. This will suppose only one fiber between the CO and the switch, so we are saving in fiber deployment as in that part there is the largest link. From the switch to each user, \( N \) links of fiber are launched. Even though, this will still mean a big number of transceivers, as the network needs to send the signal between the OLT and the switch, and later between the switch and all the number of users, \( N \). In total we would need \( 2N \) transceivers, \( N \) on the switch, and one on each user. Another problem in this network is that the optical switch introduces delay on the transmissions due to the speed in switching.
Low power signaling in next-generation TWDM-PON

Another implementation expects to use passive optical splitters instead of switches. With this device we will both reduce the fiber deployment besides the number of transceivers since, with the use of multiplexing techniques, we can communicate from the CO to all the users with only one transceiver on the downstream case and with N on the upstream. This leads us to introduce the Passive Optical Networks. [1]

1.2 Why PON?

PON architecture presents a point-to-multipoint transmission, from the CO to the user’s home, done through the Optical Distribution Network (ODN). The ODN is comprised by the fiber deploy and passive optical devices that include splitters that divide the signal in several arms to connect the subscribers. These types of networks do not require extra power supply during the transmission path (Figure 1.3).
The communication is performed between the Optical Line Terminal (OLT), placed at the CO, and Optical Network Units (ONUs). These devices can be placed in many sites, depending on the fiber deployment we can afford. Some examples are found on Figure 1.4. [7]

As in this network we are sharing the infrastructure between many users, we have to take into account some considerations:

- Downstream and upstream communications are supported in the same fiber but transmitted at different wavelengths. See Figure 1.5.
- For downstream communications we have a point-to-multipoint network and so the OLT is having all the downstream bandwidth for its use.
- For upstream communications, we are having a multipoint-to-point network and so we have to deal with the fact that many ONUs will transmit at the same time to the OLT. This situation would cause collisions between the information sent and so we must use a multiplexing technique to avoid it.
Figure 1.4 Different fiber deployments depending on the placement of the ONU are presented, ordered by an increasing use of fiber. The placement of the ONU at more than 300 m from the building is called fiber-to-the-node (FTTN), it can use more deployment of the former copper cables than optical fiber. We can place the ONU at a curb, fiber-to-the-curb (FTTC), which is nowadays the most economic solution, at the building, fiber-to-the-building (FTTB) or at the end-user location, fiber-to-the-home (FTTH).

Figure 1.5 Simplified PON network formed by the OLT, ODN and ONU. On the OLT we can see a multiplexer/demultiplexer in wavelength for the correct emission and reception of the signal, as well as it is done on the ONU side. On the ODN we can see the same fiber used to support both downstream and upstream communications.
Some of the first architectures, Broadcast-PON (B-PON), Giga-bit capable-PON (G-PON) and Ethernet-PON (E-PON), were based in Time Division Multiple Access (TDMA-PON) [2].

The procedure consists in informing the OLT that we want to transmit sending a signal. When it receives the requests from ONUs, it applies an algorithm to allocate each one in a timeslot. The OLT has the complete knowledge of the network and this makes the ONUs simpler by the fact that they no longer have to deal with the monitoring of it. This solution to avoid data collision is nowadays the most cost-effective.

Another solution adopted to differentiate ONUs upstream transmissions was the usage of a Wavelength Division Multiplexing (WDM). On this architecture we would be supposed to have a different wavelength for each ONU and so a specific receiver at the OLT for each one in order to distinguish them with this technique. This is not suitable because we will have a large number of users and so it will increase the complexity of our system as well as the cost. WDM was used in another standard, called Next Generation-PON1 (NG-PON1) or most popular XG-PON, to increase the capacity of a single fiber. Even though, on NG-PON2 this multiplexing technique will be used for another purpose, to separate between 4 XG-PON.

XG-PON achieves on the downstream until 10 Gbps and in the upstream 2.5 Gbps. It was the natural evolution of G-PON, but nowadays larger bandwidths are needed and it is necessary to evolve to another system that presents higher capacity.

This system is the Next Generation – Passive Optical Network 2 (NG-PON2), based on the Time and Wavelength Domain Multiplexing (TWDM). It piles 4 XG-PON using Wavelength Division Multiple Access (WDMA) and achieves downstream velocities up to 40 Gbps of aggregated capacity and 10 Gbps in the upstream.

All the standards mentioned are compatible with the predecessors to make possible the maintenance of former infrastructures, which are the most expensive part of the system. On Figure 1.6 we can see the comparison between the last three standards in terms of downstream and upstream bit rates. [14]
1.3 NG-PON2 / TWDM-PON

The use of TWDM allows us to avoid the utilization of high bit-rates per wavelength that will suppose big power consumption. The bit-rates given are an accumulated system capacity, this mean we are dealing with aggregated bit rates and so the amount of capacity offered to a central wavelength is the result of dividing the total, between the amounts of central wavelengths.

For instance, if the complete system capacity is 40 Gbps on the downstream and we have 4 central wavelengths for this standard, for each one the user will be able to achieve 10 Gbps. For the upstream, which the total capacity is 10 Gbps, there will be 2.5 Gbps per each central wavelength. This is the effect of using a WDM technique to separate between 4 XG-PON. See Figure 1.7.
1.4 Research bases

Until now, to make possible a new ONU connection to the network, former architectures used the ranging procedure that stopped the running transmissions. In this last architecture, the proposed solution is to have a particular transmission format, called Control signal, before starting the real transmission of data. Its purpose is to make possible this new connection without disturbing the already existing communications between active ONUs and the OLT.

This signal could be used then for:

- Exchange the useful information for the initialization stage of every ONU, in which we are dealing with the problem of establish a communication between the OLT and the ONU without interrupting or disturbing other transmissions already underway.
- Backup for control information, during the normal regime phase, between OLT and ONU.

On the first scenario, used for a first phase of the communication, the internal LASER of the ONU that wants to connect appears randomly inside the used wavelengths and starts to drift along them, provided for this standard in order to find the correct wavelength given by the instructions of the corresponding OLT.

The second usage of the Control signal is applied to an ONU correctly operating in the network. It will be an information exchange service that may be useful to make some adjustments on the ONU’s LASER wavelength position and on the Time Slot dimension for that user.

This Control signal will be also used during a multiple ONUs re-connection after a blackout situation, a very critical and time consuming scenario.

Politecnico di Torino in collaboration with Telecom Italia and under Full Service Access Network (FSAN) group guidelines, are carrying out a researching project over the NG-PON2 standard.

The aim of this investigation project is to find a solution that makes feasible the use of this Control signal. This project was already started by another thesis and on this one we will continue with the work focusing on the utilization of the Control signal on the first phase of the communication.

First of all, it is necessary to fix some important parameters to clarify the scenario in which we will work, to begin with, the ODN loss for NGPON2 will be the same standardized for XGPON. The standard expects four classes defined as follows (see Table 1.1) [8]

<table>
<thead>
<tr>
<th>‘Nominal1’ class (N1 class)</th>
<th>‘Nominal2’ class (N2 class)</th>
<th>‘Extended1’ class (E1 class)</th>
<th>‘Extended2’ class (E2 class)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Minimum loss</td>
<td>14 dB</td>
<td>16 dB</td>
<td>18 dB</td>
</tr>
<tr>
<td>Maximum loss</td>
<td>29 dB</td>
<td>31 dB</td>
<td>33 dB</td>
</tr>
</tbody>
</table>

*Table 1.1. NG-PON2 ODN Loss Standard*
Moreover a TWDM-PON system, with four pairs of wavelengths, will then be characterized for the parameters exposed in Table 1.2.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of wavelengths</td>
<td>4 (upgradable to 8)</td>
</tr>
<tr>
<td>WDM spacing between channels</td>
<td>100 GHz</td>
</tr>
<tr>
<td>Range of wavelengths for downstream</td>
<td>1595-1600 nm (up to 1605 nm with 8 wavelengths)</td>
</tr>
<tr>
<td>Range of wavelengths for upstream</td>
<td>1535-1540 nm (up to 1545 nm with 8 wavelengths)</td>
</tr>
<tr>
<td>Bit rate on upstream</td>
<td>10 Gbit/s (2.5 Gbit/s per wavelength)</td>
</tr>
<tr>
<td>Bit rate on downstream</td>
<td>40 Gbit/s (10 Gbit/s per wavelength)</td>
</tr>
<tr>
<td>Number of ONUs</td>
<td>64 (16 per wavelength)</td>
</tr>
<tr>
<td>Fiber length between the OLT and the ONU</td>
<td>40 km</td>
</tr>
<tr>
<td>Power budget on the ODN loses</td>
<td>35 dB</td>
</tr>
<tr>
<td>Compatibility</td>
<td>Full backward</td>
</tr>
</tbody>
</table>

Table 1.2 Characteristics for TWDM-PON Standard.

Basing our work on these constraints we can introduce the procedure to connect to the network for an ONU using the Control signal.

1.5 The bootstrapping phase

We have to take into account that this system is based on master-slave relation, and so the OLT controls the procedures to be followed by the ONU. When a transmission begins, the ONU starts to send the Control Signal in any wavelength to alert the OLT that wants to transmit. When the OLT starts to receive it, it tells to the ONU if it is the correct wavelength or no, and once it is on the assigned one, it helps the ONU to place itself onto the center.

After few communications, when the OLT receives the maximum power from the ONU, because it is on the center of the AWG filter of its corresponding OLT, the ONU can start the Data transmission.

All this process is called “Bootstrapping” phase. In the meanwhile of the wavelength displacement, the ONU can fall inside the band of other active ONUs and disturb them. This effect is called Coherent Crosstalk (Figure 1.8).
Low power signaling in next-generation TWDM-PON

Figure 1.8 Control signal of an ONU falling into the filter band of active ONUs. Coherent Crosstalk.

It can also occur that the ONU is not on the bandwidth of the active ONUs but inside the band of the optical filter of a certain wavelength, this is called Incoherent Crosstalk (Figure 1.9).

Figure 1.9 Control Signal Wavelength displacement of an ONU trying to establish the communication with the Optical Line Terminal. Incoherent Crosstalk because is inside the AWG filter band.
The case under study will be the first one, the Coherent Crosstalk between two ONUs. The Data and Control characteristics are:

- **DATA**: High transmission speed, $R_D = 2.5$ Gbps over a high frequency carrier, $f_D = 2.5$ GHz. NRZ-OOK modulation.
- **CONTROL**: Low speed signalling, $R_C = 2.5$ kbps, over a low frequency carrier, $f_C = 2.5$ MHz. BPSK modulation.

Accordingly to these values and the imminent appearance of interference, the electrical spectrum obtained will be like in **Figure 1.10**. There, the black signal is showing the Incoherent Crosstalk, which falls outside the band of the electrical filter, and so does not disturb us a lot. Another case would be when the beating falls inside the band of the electrical filter, being in that case Coherent Crosstalk, which would be the worse interference and is the base of our study. The Crosstalk is falling inside or outside depending on the difference between the optical frequencies at which the Data ($f_D'$) and the Control ($f_C'$) are sent by the LASERs. On our case we sent them at the same wavelength to have the Coherent Crosstalk.

**Figure 1.10** Electrical spectrum after the photo-receiver of the different signals taking part of the system: Control signal, Data signal and the crosstalk generated between them.
We evaluate the Data selecting a range of BER = [10^{-3}, 10^{-5}] and from this we extracted the Data power at which we achieve these values; then, taking into account all these considerations we evaluate the penalty versus the K parameter. K is defined like the ratio between the ONU2’s Control power ($P_C$) and the ONU1’s Data power ($P_D$). The definition of this parameter is done as shown on the Equation (Eq. 1.1).

$$K = \frac{P_C}{P_D} \quad \text{(Eq. 1.1)}$$

The correct value of K will allow us to recover both the signals, so the Data is not being disturbed by the new ONU that is trying to connect, the transmission is still satisfactory and, at the same time, the Control is not disturbed by the already transmitting ONUs and the new ONU can realize the connection successfully.
CHAPTER 2  

DATA SYSTEM

2.1 Introduction

My thesis work starts with the characterization of the ONU Control signal, affected by the Data signal transmitted by another ONU. The first apparatus will be used during its bootstrapping phase, during which will tune its optical frequency to the assigned one by the PON management.

This project was already started with a previous thesis that evaluated the penalties on the Data branch due to the Control signal presence. It was done by the built of an emulative system, in order to create the scenario in which two ONUs are trying to transmit simultaneously. The evaluation performed on the Control branch was based on the same scenario with some changes on the setup that will be explained on next chapters. On this chapter we will talk about the basics from which our work is based.

The scenario of interest is the one in which the ONU2 fall into the first ONU bandwidth and so create interference. Then it is studied how one signal is distorting the other one in order to find the power values necessary to work with both transmissions properly.

These measurements give us experimental results that help us to understand the real situation in which a system of this type will work, fixing some important constraints. The scheme is shown below and the measurements done were about BER and Penalties in the Data Channel due to the Control Channel crosstalk.

All the system is controlled by programmes built in MATLAB that can apply the changes automatically during the system measurements, thanks to the GPIB interface connecting a PC with all the apparatus. Some of the controlled aspects include the change of state of the apparatus (ON/OFF), the change in parameters and also the acquisition of the output values to analyze them.

2.2 Control signal transmission system

The system that generates the Control Channel is composed by an Arbitrary Waveform Generator (AWG), Agilent 33220A. It generates a Pseudorandom Binary sequence (PRBS)
with a period of 50.8 ms and order 7. This means \(2^7-1 = 127\) bits. In terms of bit rate we obtain \(R_C = 2.5\) kbps from the equation (Eq. 2.1).

\[
R_C = \frac{127\ \text{bits}}{50.8\ \text{ms}} = 2.5\ \text{kbps}
\]

(Eq. 2.1)

In order to obtain an electrical BPSK signal, the PRBS signal is sent to a second AWG, Agilent E4423B, which sinusoidal frequency can be set. On Table 2.1 we can find a numeric example to make more understandable the functioning of the two AWGs.

<table>
<thead>
<tr>
<th>PRBS (Modulating signal)</th>
<th>BPSK (Subcarrier)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Period (\rightarrow T = 50.8\ \text{ms})</td>
<td>Frequency (\rightarrow f = 500\ \text{kHz})</td>
</tr>
<tr>
<td>Order = (2^7) bits</td>
<td>(T = \frac{1}{500\ \text{kHz}} = 2\ \mu\text{s})</td>
</tr>
<tr>
<td>#bits/T = (2^7-1 = 128 - 1 = 127) bits</td>
<td>On each bit of the PRBS there are (\frac{400\ \mu\text{s}}{2\mu\text{s}} = 200) sinusoidal periods.</td>
</tr>
<tr>
<td>(f = \frac{1}{50.8\ \text{ms}} = 19.68\ \text{Hz})</td>
<td>Frequency (\rightarrow f = 2.5\ \text{MHz})</td>
</tr>
<tr>
<td>(\frac{50.8\ \text{ms}}{127\ \text{bits}} = \frac{400\ \mu\text{s}}{\text{bit}})</td>
<td>(T = \frac{1}{2.5\ \text{MHz}} = 400\ \text{ns})</td>
</tr>
<tr>
<td>On each bit of the PRBS there are (\frac{400\ \mu\text{s}}{400\text{ns}} = 1000) sinusoidal periods.</td>
<td></td>
</tr>
</tbody>
</table>

Table 2.1 Control Signal generation.

It will mean that for each bit change, we will have a change in the phase of the sinusoid. And if for instance we are using the second frequency, we can observe a change in phase each 1000 sinusoidal periods. In Figure 2.1 we can appreciate the modulation on the blue signal due to the bit change represented by the green one. In this case the frequency was 25 kHz and we are having 10 periods of the sinusoid for each bit.

Once we have our modulated signal, the output of this last AWG is connected to an Adapter of 25 Ω because the input impedance of the Distributed Feedback Laser (DFB) is 25 Ω and we have to adapt it to the output resistance of the AWG that is 50 Ω.
2.2.1 The DFB LASER

Our Control signal will be transmitted through the ODN by a DFB Laser. This LASER must work above its threshold to profit the linear behaviour in which we have stimulated emission. From its characterization, which will be showed on the next chapter we know that it is $I_{\text{Threshold}} \approx 10\, \text{mA}$.

We will directly modulate the LASER with our Control signal based on the sinusoidal subcarrier modulated in phase with the PRBS. For this we have to inject directly the RF signal on the LASER’s dedicated pins. This LASER is mounted on a circuit board that provides connected cables to each pin of the LASER’s butterfly package. On Figure 2.2 we can see the external and internal structure of the DFB LASER and the numbered pins. With the help of the Datasheet we chose the correct ones for applying the direct modulation and apply the current and temperature control.

We have to take into account that changes in temperature or current on the LASER will affect our transmitted signal wavelength, so it is very important to use a Temperature and Current Controller (TEC ILX LDC-3744B) that stabilizes them.
The Control ONU has the necessity, during its “bootstrapping” phase, to tune the correct wavelengths, using different values of temperature and current on the LASER, so to find the correct point of work and wavelength for the next phase in which the Data transmission will be activated.

In this “bootstrapping” phase perhaps the Control ONU will fall on another Data ONU transmitting bandwidth, so reciprocal crosstalk interference will affect both signals. In order to decrease the amount of power that interferes we have decided to use a particular configuration.

We are interested in the use of a direct modulation on our DFB LASER, varying the output power of the two AWG’s that go into the RF signal input. With this we will spread the resulting optical bandwidth of the Control signal. We define this output power from the AWGs as the power dedicated to the modulation, given a certain working point of the LASER, and we call it \( m_{\text{index}} \).

With this parameter we will be able to spread the range of wavelengths in which the Control power is sent, which will benefit us on terms of interference as we will see on the following. On Figure 2.3 we can see how the range of currents of the DFB LASER is bigger when this parameter increases, which is directly related to the wavelengths in which the signal will be transmitted.
Low power signaling in next-generation TWDM-PON

First of all, we can obtain the margin with the equation (Eq. 2.2) in which the LASER can work when an input signal is applied with certain $m_{\text{index}}$. In our case, the $I_{\text{Bias}}$ of the LASER is set to 50 mA since with this point we can achieve all the points of the curve with the maximum $m_{\text{index}}$ without going out of the limits.

$$I_{\text{range}} = I_{\text{Bias}} \cdot [(1 - m_{\text{index}}), (1 + m_{\text{index}})] \quad (\text{Eq. 2.2})$$

In order to avoid the damage of the LASER, we cannot work with currents below 0 mA or above 150 mA due to the LASER’s characteristics, so we should choose carefully the values for current and modulation index. As an example, if we use a current of 100 mA and also a $m_{\text{index}} = 100\%$, we will run out of the LASER limits.

Once we know the current we are providing to the LASER, $I_{\text{Bias}}$, and the modulation index at which we want to work, we can calculate the output power of the BPSK Modulator, in order to obtain the desired DFB LASER’s dynamics. We can use the equation (Eq. 2.3), where $R \approx 50 \, \Omega$, $I_{\text{Bias}} = 50 \, \text{mA}$ and the $m_{\text{index}} = 100\%$. We obtain $V_{\text{pp}}^{\text{BPSK}} = 5 \, V_{\text{pp}}$. This BPSK signal is inserted on the LASER’s RF input port.

![P/I LASER Characteristic](image)

**Figure 2.3** Range of output power depending on the $m_{\text{index}}$ applied to the input current. It shows two examples, for $m_{\text{index}} = 20\%$, $I_{\text{Bias}} = [40,60] \, \text{mA}$, while with a $m_{\text{index}} = 100\%$ we are having a range of values of $I_{\text{Bias}} = [0,100] \, \text{mA}$. 

In our case, the $I_{\text{Bias}}$ of the LASER is set to 50 mA since with this point we can achieve all the points of the curve with the maximum $m_{\text{index}}$ without going out of the limits.
\[ V_{pp}^{BPSK} = 2 \cdot I_{Bias} \cdot m_{index} \cdot R \]  
(Eq. 2.3)

Since our key point is to spread the total amount of power of the Control signal as much as possible on the band, to set a lower value of power along the wavelength range where it falls, we must walk through all the range of input currents of the LASER as this is directly related with the wavelength in which we are transmitting. Using the Direct Modulation we can exploit this inner effect of the DFB LASER, called chirp effect, in which the output power of the LASER will be sent along a bigger band, which will mean a lower power and so a lower interference with the Data signal. This effect is shown on **Figure 2.4**.

![Figure 2.4](image.png)

*Figure 2.4 We can see the effect of the \( m_{index} \) on the wide of the spectrum of Control signal. On the top capture \( m_{index} = 20 \% \), while at the bottom \( m_{index} = 100 \% \).*

Finally, we connect the output of the LASER to a Variable Optical Attenuator (VOA) which with the programs will introduce variable attenuation values to generate a vector of different Control power values that will lead to different \( K \) parameters as we will see later.

To conclude with the Control part, the output of the VOA is connected to a Coupler 50/50 that will combine this signal and the Data Signal. On the following the generation of the Data signal will be explained.

### 2.3 Data signal transmission system

For the Data Channel branch description, we will start with the Pattern Generator that generates a PRBS at a \( f_D = 2.5 \) GHz, with \( R_D = 2.5 \) Gbps and a certain Extinction Ratio (ER),
an order for the sequence of $2^{15}$ and with Non Return Zero (NRZ) binary code, as we want
to create an On-Off Keying (OOK) modulation with the External Cavity LASER (ECL) used for
the Data.

On this branch, the signal will be externally modulated with the Mach Zehnder Modulator
(MZM). This modulator has three inputs and one output as shown on Figure 2.5.

![Figure 2.5 Schematic of the Mach Zehnder Modulator pins, Inputs and Outputs.](image)

At the input of the MZM we are introducing a continuous optical power (CW) generated by
our ECL. The first key point to study is the voltage of the bias. This parameter allows us to
achieve the maximum range of power at the output of the modulator, and for it we should
work at a $V_{bias}$ point that at the output of the modulator corresponds to the half of the
maximum output power, this means 3 dB below the maximum.

As we can see on the Figure 2.6 that represents the MZM electro-optical characteristics, at
this optimal point the variation of power is having a linear behaviour that gives us the
biggest range of output powers. In case the bias parameter is not correctly set, it will worsen
our ER. If the value that we check with the power meter is not the desired one, 3 dB below
the maximum measured, with a program in MATLAB, we change the output voltage of the
DC-AWG that supplies the voltage of the bias until we find the correct output power.
Figure 2.6 Electro-optical characteristics of the Mach Zehnder Modulator. It is shown how the correctly bias point permits to work at the maximum output power range of the Mach Zehnder Modulator. At the bottom there is an example of how the PRBS voltage is placed at the point at which the bias point has been set, obtaining at the output the maximum power range.

The next key point to analyze is the RF input voltage required. The Pattern Generator’s output, which is generating our PRBS that is introduced on the MZM’s RF input, have to be set with the correct voltage value. First of all, the output of the Pattern Generator goes into an amplifier to set the correct PRBS amplitude at the MZM’s RF input and then to avoid the noise at low frequencies a DC Block is introduced. The PRBS amplitude is defined in volts peak-to-peak, $V_{pp}$. It goes into the MZM’s RF input and defines our Extinction Ratio. This parameter is defined as the difference in logarithmic units between the optical power level.
of bit 1 and bit 0 of the sequence. This parameter will be measured at the modulator’s output.

In order to correctly measure the ER parameter we have to use a Wide Band Oscilloscope (Infinium DCA 86100A). First of all, this tool needs to be calibrated and later we select the proper function that calculates this parameter on the signal’s eye diagram. As said, to change this ER, we act on the power supplied by the BER Pattern Generator. If the PRBS given by this device has bigger amplitude, the range of voltages in which we will act on the characteristic of the MZM will be bigger and so the power range at its output, making it easier to distinguish between bit 1 and 0. We can see this effect on Figure 2.7.

![Figure 2.7](image)

*Figure 2.7 Effect of the Pseudo Random Binary Sequence voltage on the Extinction Ratio of the modulated output signal.*

Once the Bias point and the ER are fixed to the desired values, at the output of the external modulator, where we are having an NRZ-OOK signal, we include a splitter that separates the signal into 1% and 99%. The little amount of power goes to the Power meter that forms part
of the modulator’s bias point control, as seen before. The other 99% of the output goes
directly to a Polarization Maintainer.

The study done is focused on the worst case, when the Data and Control signals are causing
the maximum interference each other. This case would be given by both signals aligned in
wavelength and polarization. For the first condition, we have already aligned them making
both LASERs transmit at the same wavelength. For the polarization alignment condition, the
Polarization Maintainer acts on the Data signal’s polarization and with the help of a
Polarization Analyzer we monitor the Data and the Control polarization, so we can perform
the alignment desired.

The output of the Polarization Controller goes to a VOA, which we call VOA (B) (to not get
confused with the one used for the Control branch, VOA (A)), to generate different Data
power values as done with the Control signal, and the output of this device is going to the
50% coupler that mixes Control and Data together.

The coupler’s output is again partitioned by a splitter 20/80. The little fraction is used for
control purpose which includes a Multi-wavelength meter to assure that both the signals are
at the same wavelength so we have the biggest interference as mentioned before, two
Spectrum Analyzers, one Electrical (ESA) and one Optical (OSA), the first one used to see the
effect of the spread of the power due to the $m_{index}$ used; the second one to check if the
two signals are at the same wavelength seeing them simultaneously, so if they are aligned.
Notice that we are connecting an optical power to an Electrical instrument; we can do this
because the ESA has an inner Optical receiver in its configuration. Finally, a Polarization
Analyzer that helps us to align together with the Polarization Controller both LASERs
polarization. (See Figure 2.8).

The other 80 % of the signal is going to an Optical Receiver (Photodiode). At the output of it
we amplify the signal and eliminate the DC component. Finally, we insert a Low Pass Filter
(LPFF) and an electrical Splitter (50/50). So we can analyze our output signal in both
Oscilloscope (Eye diagram) and Error Detector (BER). (See Figure 2.8).
The devices forming part of the complete system are shown on Table 2.2. The schematic of the devices and its connections is shown on Figure 2.8. And on Figure 2.9 we can see the workbench mounted on the laboratory.

<table>
<thead>
<tr>
<th></th>
<th>Description of the devices taking part of the complete system.</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>BER Pattern Generator</td>
</tr>
<tr>
<td>2</td>
<td>External Cavity LASER</td>
</tr>
<tr>
<td>3</td>
<td>Mach Zehnder Modulator</td>
</tr>
<tr>
<td>4</td>
<td>Power Meter</td>
</tr>
<tr>
<td>5</td>
<td>Polarization Controller</td>
</tr>
<tr>
<td>6</td>
<td>AWG for PRBS</td>
</tr>
<tr>
<td>7</td>
<td>AWG for BPSK</td>
</tr>
<tr>
<td>8</td>
<td>T/C Controller</td>
</tr>
<tr>
<td>9</td>
<td>DFB LASER</td>
</tr>
<tr>
<td>10</td>
<td>VOA’s</td>
</tr>
<tr>
<td>11</td>
<td>Polarization Analyzer</td>
</tr>
<tr>
<td>12</td>
<td>Spectrum Analyzer</td>
</tr>
<tr>
<td>13</td>
<td>Optical Spectrum Analyzer</td>
</tr>
<tr>
<td>14</td>
<td>Wavelength meter</td>
</tr>
<tr>
<td>15</td>
<td>Optical Receiver</td>
</tr>
<tr>
<td>16</td>
<td>Digitizing Oscilloscope</td>
</tr>
<tr>
<td>17</td>
<td>BER Error Detector</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>BER Pattern Generator, Anritsu MP1763C</td>
</tr>
<tr>
<td>2</td>
<td>External Cavity LASER, Agilent</td>
</tr>
<tr>
<td>3</td>
<td>Mach Zehnder Modulator, Pirelli K05555</td>
</tr>
<tr>
<td>4</td>
<td>Power Meter, Agilent 8163</td>
</tr>
<tr>
<td>5</td>
<td>Polarization Controller, ThorLabs PL100S</td>
</tr>
<tr>
<td>6</td>
<td>AWG for PRBS, Agilent 33220A</td>
</tr>
<tr>
<td>7</td>
<td>AWG for BPSK, Agilent E4423B</td>
</tr>
<tr>
<td>8</td>
<td>T/C Controller, ILX Lightwave LDC-3744B</td>
</tr>
<tr>
<td>9</td>
<td>DFB LASER, Mitsubishi FU-68PDF-5</td>
</tr>
<tr>
<td>10</td>
<td>VOA’s, HP 8153A</td>
</tr>
<tr>
<td>11</td>
<td>Polarization Analyzer, Agilent 8509C</td>
</tr>
<tr>
<td>12</td>
<td>Spectrum Analyzer, HP 70004A + HP 70908A + HP 70810B</td>
</tr>
<tr>
<td>13</td>
<td>Optical Spectrum Analyzer, 86140B</td>
</tr>
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<td>14</td>
<td>Wavelength meter, HP 86120B</td>
</tr>
<tr>
<td>15</td>
<td>Optical Receiver, Newport 200ir</td>
</tr>
<tr>
<td>16</td>
<td>Digitizing Oscilloscope, HP 54750A</td>
</tr>
<tr>
<td>17</td>
<td>BER Error Detector, Anritsu MP1763D</td>
</tr>
</tbody>
</table>
**Figure 2.8** Data Evaluation Setup for the Acquisition of the BER and Data Penalties.

**Fig. 2.9** Laboratory Bench Set-Up Assembled In Istituto Superiore Mario Boella. Used To Obtain All The Experimental Results For The Crosstalk Interference.
2.4 Software

2.4.1 MZM’s Automatic Bias Control

This program is to adjust in real time the MZM’s bias. First, it queries for the power measured by the power meter at the 1 % branch of the MZM output. Then we measure the error between this power and the one that we want, the target that is the maximum we have previously measured. If this error is bigger than $10^{-5}$, we change the Voltage, supplied by the AWG to the Bias input of the MZM, adding or subtracting a value dependent on the error.

2.4.2 Data System BER Acquisition

For the acquisition of the BER on the Data branch, we counted with a program called **Repeated Data Acquisition** which also makes calls to several functions that control other parameters, to complete the acquisition.

- **Repeated Data Acquisition**

The acquisitions are done for no Control signal, which is the Reference case, and for Control signal at different power values, which is the case of using the $K$ parameter, defined as the ratio between the ONU2’s Control power ($P_C$) and the ONU1’s Data power ($P_D$), as shown on the equation ($Eq. \ 2.4$).

$$K = \frac{P_C}{P_D} \quad (Eq. \ 2.4)$$

We can also choose $m_{index} = 100 \%$ or different if necessary. First, it creates a structure, `Final_Values`, which contains all the useful data acquired; that is the parameters values achieved in each case. For example, the vectors of Data and Control power, the different $K$’s, the BER...Then it creates a vector in which there are the values for the x axis that will be the Data Power. And for these points we will acquire and save the corresponding BER values.

For each new point of Data Power we must change the Power of Control to maintain the power relation $K$ between the two signals. We should set a range of Data power in which we want to obtain the BER curve, then the $P^{START}_D$ is given by the power measured at the input of the Optical Receiver when the VOA’s attenuation is suppressed, and is a single value. The
different $Loss_B$ values are calculated depending on which power range we want our Data to vary, so $P_D$ and $Loss_B$ are vectors of the same length and are used in order to control our system in terms of received power. The $P_C$ values are calculated from the K introduced and the range of $P_D$ values set. So $P_C$ will be a matrix consisting on as many rows as K values and as much columns as $P_D$ values.

The different $Loss_A$ and $Loss_B$ values are introduced into the VOA_A and VOA_B to generate the desired value at the output. These two parameters, Loss_B and Loss_A, are two vectors obtained from the equations \((Eq.\ 2.4)\), \((Eq.\ 2.5)\) and \((Eq.\ 2.6)\).

\[
P_D = P_D^{START} - Loss_B \text{ dBm}
\]
\[
P_C = P_D + K \text{ dBm}
\]
\[
P_C = P_C^{START} - Loss_A \text{ dBm}
\]

Then the function `Ber_Threshold_Optimization` is called and run through all the points of the Data Power that we have set, acquiring the BER.

![Figure 2.10 Example of the internal structure of the variable Final_Values.](image)

- **BER Threshold Optimization**

This program, first of all, restarts some predefined values, as well as the synchronization between the BER Pattern Generator and the Error Detector before starting with the acquisitions.
On the main body the procedure consists on calling the function CPA Runner which queries the different Delay and BER in order to calculate the optimal delay value for the one we obtain the best BER on the eye diagram. For this process the Threshold is set to zero. Once we obtain the best value for the delay, we will no longer change it; we just will fix it to the best last value achieved. To move along the different delay values, we start doing big steps in the value in order to approach to the correct one faster and then we change it with little steps to obtain a more accurate value.

Then we call the function DTH Runner Decr to get the optimal Threshold point. We run this and no the Incremental one, because we already know that the most interfered level is the bit “1” as it is where we find more noise because everything is active, on the level “0”, we are not having power and so less noise. Then, the higher level of the eye will be lower and so the optimal threshold point will be below the centre of the eye. This threshold value will be calculated for each $P_D$ and $P_C$ couple of values along the all BER curve, and so for each $K$.

Once we have the optimal Threshold value, we make a query of the BER and then we set Threshold to zero to make another query of the BER and have the comparison between the two values with the optimization of the threshold and without it. The Delay is always fixed to the optimized one to save time as long as it does not change.
We are doing this BER Acquisition process while BER_OK is equal to 1, this is a flag that we change when the BER obtained is starting to overpass $10^{-5}$ as long as these will be very low values to consider for our application.

### 2.4.3 Data System Penalty Curves

- **BER Levels Plot**

We use this function to plot the values obtained and to control that everything is correct before launching more acquisitions to obtain later the media. We obtain 4 curves: two for the optimized threshold point and two with the threshold set to zero. The curves are the Reference, which is the BER of the Data signal without the Control signal activated, and the Data BER with the Control interference present.

- **Automatic Penalty**

We make an interpolation of the obtained BER values to have the complete curve of it. Then, the program looks for the nearest point to the “Target”, a variable we set to $10^{-3}$ or $10^{-4}$. Once we obtain the point, we take the Data power at which the reference curve cross this value of BER and the same procedure for the curve affected by the Control signal. This power difference is defined as the penalty with the equation (Eq. 2.5).

$$Penalty = P_D^{BER} = 10^{-3} (\text{Disturbed curve}) - P_D^{BER} = 10^{-3} (\text{Reference curve}) \quad (Eq. 2.5)$$

The two points are saved in a vector called BER, also with the K value at which we have obtained the BER curve. We will obtain the penalties for each value of K and then the plot will be depending on this K value as we will see later.

**Figure 2.12** Example of the internal structure of the variable BER. On the first cell we can see the value of the K parameter, on the second one the value of the Data power for the Reference Curve at a BER = $10^{-3}$ and the same on the third cell but for the Curve with the Control signal activated. The subtraction of these two values will result the penalty.
• **Automatic Plot Penalties**

On this program we make the subtraction between the two power values of Data that we have saved on the “BER” structure from the last program, for all the K values. Then we can plot the results having on the “x” axis the K values and on the “y” axis the penalties.

• **Automatic Repeatability**

We use it to plot all the Penalty curves we have obtained with the last program but all in one graphic. With this we can see if we are having some errors or they are following more or less the same behaviour. We can choose how many curves we want to see selecting the number of acquisitions. In *Figure 2.13* we can see an example.

![Penalties graph](image)

*Figure 2.13 Example of the repeatability of a Reference curve.*

• **Median BER**

Finally we can obtain the media of all the penalty curves and present a reliable result. The images presented below have pass all this process and are shown as we will see later as a media of 20 acquisitions.
2.5 Penalties on Data Channel

The graphics shown below are for BPSK subcarrier modulation with two different electrical subcarrier frequencies, 500 kHz and 2.5 MHz, of the Control signal and Data signal with two different extinction ratio values: 6 dB and 13 dB. Furthermore we apply the two cases: Continuous Wave (CW) and BPSK subcarrier modulation with $m_{index} = 100\%$. First of all, a group of examples of BER is presented (Figures 2.14 to 2.17), for a $K = -25$ dB, and later the penalties (Figures 2.18 to 2.21) calculated from the BER curves for all the values of $K$, which we cannot present in the BER curves for reasons of space, as well as all the curves were obtained also for a Median Threshold found in the middle of the eye diagram and for an Optimized Threshold, but the examples selected are presented with the Optimized one that is the best case.

On Figure 2.14 we can see a good result as the BER curve in which the Control is taking into account is so near to the one in which the Data signal is not disturbed. This means that we are not having penalties until a high value of powers at which the curves start to differentiate.

![Figure 2.14](image)

*Figure 2.14* Pair of curves that describe the behaviour of the BER of the Data signal with and without the interference of the Control signal for a power difference of $K = -25$ dB.

On Figure 2.15 we can see the behaviour when the frequency of the Control signal is higher and so there is less chirp effect and a worse case in comparison with the previous one.
Figure 2.15 Pair of curves that describe the behaviour of the BER of the Data signal with and without the interference of the Control signal for a power difference of $K = -25$.

On Figure 2.16 the curves are more distant as the Extinction Ratio is littler and so we are having more errors on the BER Data affected by the Control signal.

Figure 2.16. Pair of curves that describe the behaviour of the BER of the Data signal with and without the interference of the Control signal for a power difference of $K = -25 \text{ dB}$.

Finally on Figure 2.17 we are finding the worst case as long as we are using the highest frequency with the lowest Extinction Ratio.
With these four images we have demonstrated the effect of the E.R. and the frequency of the Control signal on the BER Evaluation.

On Figure 2.18 to Figure 2.21 we can find the penalty curves. In each graphic there are four curves that are described in the following:

- **CW [Median Threshold]:** We are not modulating the control signal and so the laser is working in Continuous Wave. This is the worst case as long as the signal is not spread and all the power falls into the peak. This makes the biggest interference with the Data signal as we have align them at the same wavelength and polarization.

  Median Threshold means that we are measuring the BER at the central point of the eye diagram, this means threshold at 0, which is not always the optimal one.

- **CW [Optimized Threshold]:** In this curve we are measuring the same but at the optimal point of the threshold of the eye diagram. We can see clearly an improvement. This optimization is carried out by a program run in MATLAB that measures the BER at different threshold points and chose the one that we get the best BER.
• $m_{\text{index}} = 100\%$ [Median Threshold]: In this curve we are applying a modulation on the Control signal and we can see the decrease in the penalties.

• $m_{\text{index}} = 100\%$ [Optimized Threshold]: We are having the same than in the point explained before but using the optimizing threshold process.

To obtain a reliable result, the curves are presented as a media of 20 acquisitions acquired in the same scenario. We expect to obtain a better result for a bigger Extinction Ratio since the bits are more distinguishable at the receiver and also when using a lower frequency on the control signal as we are spreading the signal power on the bandwidth, making the average power falling into the total band lower. Consequently this makes the interference on the Data lower.

---

*Fig. 2.18* Curves that describe the Penalties on the Data Branch due to the Control for an ER = 13 dB on the Data signal and $f_c = 500\ kHz$. 
Fig. 2.19 Curves that describe the Penalties on the Data Branch due to the Control for an ER = 13 dB on the Data signal and $f_c = 2.5 \, MHz$.

Fig. 2.20 Curves that describe the Penalties on the Data Branch due to the Control for an ER = 6 dB on the Data signal and $f_c = 500 \, kHz$. 
Figure 2.21 Curves that describe the Penalties on the Data Branch due to the Control for an $ER = 6\, \text{dB}$ on the Data signal and $f_c = 2.5\, \text{MHz}$.

The results show that our assumptions were right and also we can make some comparison on Figure 2.22, where we can see four curves:

- The results obtained by the ITU-T organization.
- CW Curve, no interference signal.
- Interference signal active for $f_c = 2.5\, \text{MHz}$.
- Interference signal active for $f_c = 500\, \text{kHz}$. 
2.6 Conclusions

The study based in the Data penalty due to the Control signal in the scenario of Coherent Crosstalk arrived to some conclusions. To obtain a penalty lower than 0.2 dB at a $BER = 10^{-3}$, the difference power between the Control signal and the Data must be $K \leq -21$ dB for an E.R. on the Data single of 6 dB and using the lower frequency subcarrier.

This results support the idea of working with a Control signal to not disrupt the other transmissions. Now that we know that the Data can be recognized without problem respecting the difference power values seen before, we can continue our study on the other branch and see how this Control signal is affected by the Data transmission and if it is still possible to work with these two signals simultaneously. On next chapters it will be shown the works to evaluate the BER and the Penalties on the Control signal due to the Data one, and the results obtained.

On Table 2.3 we can find the Relative Crosstalk ($K$ dB) power values at which we obtain a $BER = 10^{-3}$ and a penalty $\leq 0.1$ dB on the Data signal. All the values presented were obtained for an optimized threshold as it appeared to be the best one. Notice that from the calculus of FSAN, using the IEEE standard, the original power difference between Data and Control to accomplish with the same requirements was around $K = 42$ dB. In the real case the penalties are reduced even with the Control signal sent without modulation. This result
is improved with the application of the modulation index on the Control signal as well as the use of lower subcarrier frequencies which both contribute on the spread of the Control signal’s power along the band, causing less interference, as seen before.

<table>
<thead>
<tr>
<th>Central Frequency of the Control signal</th>
<th>E.R.</th>
<th>Relative Crosstalk with Optimized Threshold</th>
</tr>
</thead>
<tbody>
<tr>
<td>500 kHz</td>
<td>13 dB</td>
<td>21 dB</td>
</tr>
<tr>
<td></td>
<td>6 dB</td>
<td>25,5 dB</td>
</tr>
<tr>
<td>2.5 MHz</td>
<td>13 dB</td>
<td>23,5 dB</td>
</tr>
<tr>
<td></td>
<td>6 dB</td>
<td>27 dB</td>
</tr>
</tbody>
</table>

*Table 2.3 Values of Data power at which we obtain a BER = 10^{-3} and a penalty ≤ 0.1 dB. We can observe that for little frequency on the Control signal the penalties are lower due to the spread of the signal. Also we obtain a better performance for bigger values of Extinction Ratio as the Data signal is more distinguishable.*

On the next chapter, we will deal with the evaluation of the Control signal and for that, we will delimitate the scenario to \( f_C = 2.5 \text{ MHz} \) on the Control signal.
CHAPTER 3  
CONTROL SYSTEM

3.1 Introduction

In this chapter we want to deal with a scenario that consists of two ONUs transmitting simultaneously but that are at different operation stage. The first one, the ONU1, is already transmitting its Data to the OLT while the other one, the ONU2, is on the bootstrapping phase, trying to find its corresponding wavelength by means of its Control signal.

We want to characterize the Coherent Crosstalk effect when the ONU1’s Data signal is overlapped with the ONU2’S Control signal bandwidth. This time, the penalty caused by the Data signal will be evaluated on the Control stream. It is the opposite case with respect to the previous chapter, where we measured the Data signal penalties due to the Control. The measuring process for the penalties on the Control stream and the results are explained and showed in the following.

3.2 Looking forward

In the real future system the same DFB LASER must be able to transmit at both two central frequencies of Control and Data stream. Due to that, we have to assure that our Data signal will work on the same DFB LASER than the Control signal before continuing with our work.

On the process of connecting the Data signal to the DFB Laser, we noticed that it was not able to work at proper conditions at the corresponding frequency, 2.5 GHz. The problem was due to the board in which the DFB LASER was mounted that induced capacitance and inductance effects to the butterfly package, cutting the high frequencies of the RF signal injected in the DFB LASER. Our solution was to connect directly the inputs to the corresponding pins of the butterfly package, avoiding the board filtering effects. The change of these connections made necessary the DFB LASER’s re-characterization, in order to know in detail how it will work.

3.2.1 LASER Characterization

First of all we obtained the linewidth of our DFB LASER (Figure 3.1) when modulation is not applied on the RF input, using just the Continuous Wave (CW) mode.
Figure 3.1 Linewidth of the DFB LASER. This acquired wave shape was obtained exploiting the heterodyne method, in order to translate close to the base band the working frequency of the DFB LASER.

Figure 3.1 Linewidth of the DFB LASER.

Then with the help of a MATLAB program, we check the output power of the DFB LASER for different input currents that we set between 0 and 100 mA, in order to plot the P/I characteristic of the DFB LASER. It is shown for different power units: dBm (Figure 3.2) and in mW (Figure 3.3).

Figure 3.2 P/I characteristic for DFB LASER with power units in dBm. We can observe the threshold point at 10 mA in which the power emission starts to grow faster. The difference power level between this point and the maximum is approximately 30 dB. We start to emit the maximum at 50 mA. This is the point at which we will work in the future setups.
Figure 3.3 P/I characteristic for DFB LASER with power units in mW. We can observe the point from which starts the stimulated emission and where the behaviour becomes linear, after the threshold point, at 10 mA.

The next step for the characterization was to observe its behaviour when a modulation is applied at the DFB LASER’s RF input port. The most important parameters to know were the input impedance and the passage of power of our device, which we can obtain directly through the S parameters. We used the Network Analyzer, a device that measures the reflection (S11) and transmission (S21) properties of an electrical signal.

Notice that at the former thesis it was demonstrated the need of using an adapter of 25 Ω for the input impedance of the LASER, in order to close the AWG output on a proper load and obtain a better performance. To improve the realization of the measurements, we add to this adapter a DC Block to eliminate the DC component that can damage the measure, creating a High Frequency Adapter (Figure 3.4) but for the study at low frequencies, we will add instead of a DC Block, a little capacitor that cut the low frequencies in a more accurate way, obtaining a Low Frequencies Adapter (Figure 3.5).
Figure 3.4 The adapter for high frequencies is composed by a DC Block that removes baseband signal and by a resistance that adapts the impedance of the system, $50 \, \Omega$, to the input impedance of the DFB LASER, $25 \, \Omega$, adding other $25 \, \Omega$.

Figure 3.5 Low Pass Filter Adapter. It is composed by a capacitance that cuts frequencies below $100 \, \text{Hz}$ and by a resistance that adapts the impedance of the system, $50 \, \Omega$, to the input impedance of the DFB LASER, $25 \, \Omega$, adding other $25 \, \Omega$.

At first glance this adapter (Figure 3.5) may seem a high pass filter, but this capacitor was designed to have a low cut-off frequency value in order to assure the pass of our signal at $2.5 \, \text{MHz}$ but cut the noise at very low frequencies. This adapter will be the one used in our system once we finish with the characterization measurements as long as we want to assure that our Control Signal, which is the currently one send onto the LASER, is not cut by the DC Block.

3.2.1.1 S11 Parameter

For measuring the S11 parameter, the connections between the devices of the system were established as shown in the Figure 3.6. And the devices taking part were:
- Network Analyzer: HP 8753D;
- T/C Controller: ILX Lightwave LDC-3744B;
- DFB LASER: Mitsubishi FU-68PDF-5;
- Optical Receiver: Agilent 11982A.

**Figure 3.6** System configuration for the measurement of the $S_{11}$ parameter.

First we measured the behaviour only of the adapter. We can observe in **Figure 3.7** that the reflections have a low value and don’t suffer abrupt behaviour changes. They remain almost stable.

**Figure 3.7** $S_{11}$ parameter for the Low Frequency Adapter. The device is almost stable and do not introduce distortion if we place it at the RF input of our DFB LASER. The high value of reflected power is due to the not matched impedance, in fact this adapter is a 25 Ω load and the Network Analyzer expects 50 Ω load to have the system normalized to that impedance.
Later we measure the S11 parameter for the complete system, Figure 3.8, and we can appreciate some changes within the only Adapter effect. The reflections are lower although the behaviour is no longer stable. Even though, the lowest value of the reflections are in the frequency band we will work, which is a positive aspect.

![System Spectrum Behavior](image)

*Figure 3.8* S11 parameter for the system at low frequency range. A positive point is the bigger attenuation effect falling into one of the bands we use: 2.5 MHz for the Control. The matched impedance reduce a lot the reflection of our system, unfortunately the lower frequencies are not so accurate, because of the Network Analyser limits.

### 3.2.1.2 S21 Parameter

On the other hand to measure the S21 parameter we used the configuration shown in Figure . Because of the characteristics of our Network Analyser, we cannot measure perfectly the frequencies below 30 kHz, and this is a very big problem for the characterization of the low frequency system. However, for the high frequencies characterization, where our Data signal will range around 2.5 GHz, this device will work properly and we can use it in order to characterize our system. See *Figure 3.10.*
Figure 3.9 System configuration for the measurement of the $S_{21}$ parameter. This schematic shows the use of the Network Analyzer, which is the one we use for the high frequencies characterization.

![System Spectrum Behaviour at High Frequencies](image)

Figure 3.10 $S_{21}$ parameter for large frequency range. We obtain losses around 10 dB at our working band, 2.5 GHz for the Data.

Finally, to measure the $S_{21}$ parameter at a low range of frequencies, we decided to use a different method that expects to change the devices used in order to launch and acquire our RF signal. This is because the Network analyzer is having a measurement capability comprised on the range of frequencies of 30 kHz to 6 GHz and so is no longer useful for our purpose at low frequencies.

Instead of using the Network Analyzer as a signal generator and a receiver, we used the oscilloscope to acquire the passage of power on the system and an AWG to generate the
input signal of the system at the adapter point. The configuration used is presented in the 
**Figure 3.11** and the devices taking part were:

- Arbitrary Waveform Generator: Agilent 33220A;
- T/C Controller: ILX Lightwave LDC-3744B;
- LASER: Mitsubishi FU-68PDF-5;
- Optical Receiver: Agilent 11982A;
- Real Time Oscilloscope: LeCroy Waverunner 104Xi

![Figure 3.11 Connections schematic for the measurements of the S21 parameter. Instead of the Network Analyser we are using an AWG in order to generate the RF input and an Oscilloscope to acquire the received signal.](image)

The process was to acquire the output signal with the oscilloscope for different frequency input signals generated by the AWG. Later we process the results with a MATLAB code that applies the equation (**Eq. 3.1**).

$$S_{21_{dB}} = 20 \cdot \log\left( \frac{P_tP_{final}}{P_tP_{initial}} \right)$$  \hspace{1cm} (**Eq. 3.1**)  

Where $P_tP_{final}$ is measured at the oscilloscope and $P_tP_{initial}$ is measured at the AWG. We compute the difference between them in dB and finally we obtain the next plot in **Figure 3.12**.
Figure 3.12 S21 Parameter for the system at a low frequency range. We can observe a fall of 4 dB respect to the predominant power level at 250 kHz. This is caused by the laser but don’t affect us as long as this is not the frequency at which we want to work with the Control signal, 2.5 MHz.

3.3 The new setup

For our purpose we needed to change some configurations of the former setup since the new measurements have to be taken on the Control branch.

First of all, as we need to recover the Control signal and evaluate the Penalties in it, we need to transmit a PRBS to measure the BER, so we recovered the first configuration in which we used the two AWG to generate this signal. In one AWG we are carrying the information and in the other one, we modulate the signal before entering in the LASER.

The power values for the Data and Control branch are generated by the two VOAs, which change the amount of attenuation they introduce in each channel to have a vector of different power levels. The difference between the two power levels is defined by the K parameter as before with the equation presented below (Eq. 3.2).

\[ K = \frac{P_C}{P_D} \quad (Eq. 3.2) \]

Another change is the no longer use of the BER Error Detector, which cannot be used for bit rates below 50 Mbps. Our Control Signal is transmitted at 2.5 kbps and so we found another
method in order to generate, acquire and evaluate it. Through the method explained in chapter number 2, we can generate our BPSK signal and using a real Time Oscilloscope we can acquire it. In order to evaluate a PRBS at the receiver, we use a BPSK demodulator before the Oscilloscope, moving to the baseband the received signal. Later, we process the results with a MATLAB program and we obtain the BER curves for different K values as done previously.

### 3.4 The acquisitions

Thinking about our received signal, we have at the receiver side a BPSK signal centered around 2.5 MHz. To obtain reliable BER values around $10^{-3}$, we require having 100 bit error over 100,000 bits. If our PRBS sequence is comprised by 127 bits, we need to acquire 788 sequences. Each sequence has duration of 50.8 ms and so the total amount of sequences will be 40 s. At the oscilloscope screen we only can acquire the results for a scale of 20 ms/div. In the screen there are 10 div, which mean 200 ms per screen. As we want to acquire 40 s, we should acquire 200 times the screen.

If we scale this issue to a complete acquisition that is composed by a certain number of points, is easy to realize that become really hard to obtain it in a reasonable period of time. Because this procedure is time consuming, we propose another solution. It consisted on using a heterodyne receiver to translate our band to a lower one what automatically mean demodulate our PRBS if we chose the proper values. On Figure 3.13 we can see a simple schematic of the mixer that accomplish with the equation (Eq. 3.3).

![Figure 3.13 Simple mixer schematic, the variables take these values: $f_{RF} = 2.5$ MHz; $f_{LO} = 2.5$ MHz; $f_{IF} =$ Baseband.](image)

Figure 3.13 Simple mixer schematic, the variables take these values: $f_{RF} = 2.5$ MHz; $f_{LO} = 2.5$ MHz; $f_{IF} =$ Baseband;
In our case the interesting frequency is the one subtraction obtained that translate our signal to the baseband, where our signal is with $R_c = 2.5 \text{ kbps}$.

To generate the signal for the Local Oscillator (L.O.) we introduce at the former system a new AWG generating a sinusoidal signal at $2.5 \text{ MHz}$. The RF input is the output of our entire system, the signal we want to transfer in band to low frequencies. And finally, the Intermediate Frequency (IF) output is the signal measured with the Real-Time Oscilloscope.

As we can see on Figure 3.14, comparing it with the Data system, the BER Error Detector is no longer on the schematic as we have substituted it by the Real Time Oscilloscope: LeCroy Waverunner 104Xi. Another new incorporation is what we have called BPSK Receiver and which element composition is explained later.

\[
f_{IF} = f_{LO} \pm f_{RF} \quad (Eq. 3.3)
\]

An important thing to take into account is the alignment of the RF and LO signals, both in frequency than in phase, to obtain at the output the best performance of the PRBS. In the specific, the phase has some drifts and we have to check and adjust it before launching the

---

**Figure 3.14** Control Evaluation Setup, including the BPSK Receiver and the Real-time Oscilloscope as the new devices incorporated to the system.
measurements. However, this parameter is stable and after have been fixed it we are sure of the phase matching.

Having moved the acquired signal to the baseband, the acquisitions are faster as long as we can use a scale of 5 s/div, having a total of 50 s for screen. Now in this case we are having 125.000 bits in each screen and so enough bits for our BER target, $10^{-3}$. Even though, we acquire a certain number of repetitions of the screen to reach better BER targets, for instance $10^{-4}$.

In order to maintain the same power constraints established during the Data signal evaluations, we have decided to acquire two different set of measurements.

The complete characterization of our Control branch was done using a fixed range of Control Power, changing the Data power to obtain the different $K$ cases. After this preliminary sensing step, we selected a sub-range of Control power for which our signal can be reached, even for Control than for Data, trying to demonstrate the surviving of our complete NGPON2 system solution. The post-processing was done with a MATLAB program that compared the launched PRBS by the ONU with the one received at the OLT side.

The first results we obtained were not as good as we needed. On the one hand, the Control was sent with a high level of power that allowed us to recover it but, on the other hand, it is at the same time the reason that causes penalties on our Data, as seen on the former study of the Data Penalties. In addition, the $K$ parameter at which we find little penalties on the Control signal is not big enough, $K = -10$ dB. This value would cause lots of penalties on the Data of the transmitting ONU as long as is not a remarkable difference between the powers. We found from the last study that we need $K \leq -21$ dB.

The first curve for the BER of the Control signal without Data interference is shown on Figure 3.15, its Control Power is comprised in a range of $P_C = [-45, -35]$ dBm and at $P_C = -40$ dBm is where we achieve a BER $= 10^{-3}$.
A possible solution to improve the system performance can be introduce after the BPSK receiver a band-pass filter at 2.5 MHz with a little bandwidth, very narrow, to eliminate the noise around it. Later we translate in band our signal and pass it through an amplifier.

At first we were trying to develop a Butterworth Filter of order 8 and PI section. We found this was the best solution thanks to the simulation of the circuit with the Simulink tool of MATLAB. Although on the implementation of the Band-Pass Filter we find some difficulties:

- The obtained values for the components were very little for the capacitors and big for the inductances, it was hard to find them even because are not so realistic and we could not find them as normalized values, and because of the budget we should build the inductances with the Nagaoka method, having a handmade Butterworth filter.

- Due to these lower values, the tolerances of the components really affect us on setting the proper central frequency and its bandwidth; also we do not find the exact values we need because the standardization is different.
- The parasite components, due to the metalized base where the circuit should be mounted, are comparable to our component values and so it would be required to be built in an air structure.

- We could change the values making the capacitors ten times bigger while the inductances ten times lower, but then the characteristic impedance of the circuit would change.

After all this considerations, the next step was to design the filter with another implementation, a simpler one but still useful in order to eliminate the useless signal around our BPSK: HPF + LPF. The HPF was built with two capacitances in parallel with values of $C_1 = 1 \text{ nF}$ and $C_2 = 330 \text{ pF}$, which parallel results in a total $C = 1.33 \text{ nF}$ and an $R = 51 \Omega$. On the LPF we used the same methodology and used two capacitances in series with values of $C_1 = 680 \text{ pF}$ and $C_2 = 220 \text{ pF}$ and an $R = 51 \Omega$. Then the characteristic using both the filters in cascade mode is shown on Figure 3.16.

![Figure 3.16](image)

*Figure 3.16 On this figure we can see the parameter S21 for the High Pass Filter + Low Pass Filter. We have an attenuation of 10 dB at our frequency $f_c = 2.5 \text{ MHz}$ and approximately the bandwidth is 7 MHz.*

After the demodulation stage, when we have a base band PRBS signal, we filter out the residual noise with another LPF at 2.5 kHz. Using $R = 51 \Omega$ and $C = 1 \mu\text{F}$, the theoretical cut frequency for our filter was $f_c = 3.12 \text{ kHz}$. On the image below, Figure 3.17, we can see that we obtain a bandwidth $B = 5 \text{ kHz}$. 
Figure 3.17 On this image we can see the response of the Low Pass Filter. We can see that at our demodulated Control signal frequency, $f_{\text{dem}} = 2.5 \text{ kHz}$ we are having an attenuation of 4 dB and the cut frequency is at $f_{\text{cut}} = 5 \text{ kHz}$.

As a final caution, to achieve a reasonable BER, we will send our Control signal with a power comprised in [-40,-60] dBm so as not to create a big crosstalk on the Data channel. For this reason, we need to amplify our control signal at the receiver to recover it properly, as these low values of power are comparable with the internal noise of the oscilloscope and it can worsen our BER.

The amplifier setup was done with a TL081, using a non-inverting configuration to achieve 20 dB of gain. See Figure 3.18. Using the equation (Eq. 3.4) we obtained the values shown:

$$ G = \frac{V_{\text{out}}}{V_{\text{in}}} = 1 + \frac{R_1}{R_2} \quad \text{with } R_1 = 2 \text{ k}\Omega, R_2 = 100 \text{ }\Omega \quad (\text{Eq. 3.4}) $$

Figure 3.18 Non-inverting configuration of Operational Amplifier.
To obtain the gain we wanted, we could use different values for the resistances as long as we respect the relation between them, so, we chose lower values to avoid excessive thermal noise. As we can see on Figure 3.19, we obtained a gain of 28 dB in the band we are transmitting, specifically at our frequency: 2.5 kHz.

![Amplifier Behavior](image)

*Figure 3.19 Amplifier Behaviour for a Low Frequency range. At the interesting frequency, 2.5 kHz, we have an amplification of, approximately, 28 dB.*

All the blocks introduced after the optical receiver are shown in the next block diagram, Figure 3.20 and the setup on the laboratory is shown on Figure 3.21.

![Block diagram](image)

*Figure 3.20 Block diagram with the components that comprehend the BPSK Receiver placed after the Optical receiver and before the Real-time Oscilloscope.*
With all these changes we expect to obtain a notorious improvement in our BER Reference Curve, which is obtained only sending the Control Signal. The programmes used for the acquisition and the post-processing of the results are explained on the following.

In the following the spectrum of the signals at different points of the schematic are presented. On Figure 3.22 we find the spectrum at the input of the Receiver, on Figure 3.23, at the output, on Figure 3.24, the spectrum after the BPF and finally, on Figure 3.25 the Spectrum after the BPSK Demodulator.
Figure 3.22 Spectrum of the Data and Control signals at the input of the optical receiver. The Data signal is centered at $f_D = 192.56 \text{ THz}$ where the ECL is transmitting. The shape of the Data spectrum is given by the NRZ, and its bandwidth by the frequency at which the NRZ is transmitted.

Figure 3.23 Spectrum of the Data and Control signals at the output of the optical receiver. The Data has been cut by the filter of the receiver but the biggest amount of information is conserved.
Low power signaling in next-generation TWDM-PON

**Figure 3.24** Spectrum of the Control signal at the output of the Band Pass Filter. This filter is centered at the frequency at which the Control signal is, and eliminate the Data signal on its major part.

**Figure 3.25** Spectrum of the Control signal at the output of the BPSK Demodulator. This Demodulator translates into the baseband the Control signal, recovering the information carried in it with a low bit rate.
3.6 The Software

3.6.1 Acquisition on the laboratory

- **Control Acquisition**

  Thanks to this program we will set the range of values in which we want that the power of Data vary and the K values that differentiates Data and Control, which can have many values as it is a vector. From this it calculates the different power values, which results a Matrix. One row for each K difference, and the number of columns depending on the values of Data we want to sweep. We always assure that the range of Data powers is inside the one used on the previous measurements on the Data penalties as for a future confrontation we need to be on the area in which we know the Data signal can work.

  Once we have the values set, we will repeat the acquisition procedure as many times as we need for obtain a reliable result. The process consists on create a directory on the oscilloscope, to save the screens and then, once the power values are adjusted with the VOA’s, we call the function “Waveform Save”, which is explained in the following. All the values set for the parameters are save on the *Final_Values* structure for the post-processing use.

- **Function Waveform Save**

  This program is in charge of saving the waveform that we see on the oscilloscope screen. The scale selected for the horizontal axis that is Time, is fixed to a low value, 50 ms/div for the adjustment of the “y” axis. It applies changes on the offset and the amplitude to take profit of the dynamics of the device. We start with little amplitudes and adjusting the offset, and then it increase the amplitude with the corresponding adjustment of the offset until it finds the maximum affordable range without going outside the screen. Once this value is found, we set the Time axis to 5s/div.

  The Sample rate is set to 10 kS/s as long as this is the minimum sampling time we can use on the screen to watch the waveform correctly, as to plot a square signal we need 4 points and our signal is at 2.5 kbps. See equation (Eq. 3.5)
\[ \text{Sampling rate} = 2.5 \, \text{kbps} \cdot 4 \cdot \frac{s}{b} = 10 \, \frac{\text{ks}}{s} \quad (\text{Eq. 3.5}) \]

It results a total of 500 [kS] for each screen. See equation (Eq. 3.6)

\[ \text{Number of samples} = 10 \, \frac{\text{ks}}{s} \cdot 5 \, \frac{s}{\text{div}} \cdot 10 \, \text{div} = 500 \, \text{kS} \quad (\text{Eq. 3.6}) \]

The screen is saved as many repetitions we select depending on the BER values we want to achieve, as many little more repetitions we need to have a reliable result as it has been explained.

### 3.6.2 Post-processing at the computer

- **PRBS Allignment and BER**

This program is in charge of computing the BER results. It means to extract from the correct sampling time, the value of the bit, and compare it with the original signal sent. It counts all the errors and makes the division between this number of errors and the total amount of bits that we have acquired on that point.

This program calls to a function called **BER Evaluation**. This function is in charge of computing all the number of errors along all the repetitions to decide which BER corresponds to a point. At the beginning this function have to align the PRBS captured from the screen with the original one and for this it has to remove some bits at the beginning to assure that the first bits coincide and so the rest of the sequence.

From each screen we acquire the partial number of errors over the partial number of bits, which result in the partial BER of that screen (See **Figure 3.26**). To make the results more reliable, as said before, we repeat this process for many screens and accumulate the number of errors and bits until we obtain the final BER for that point after 10 repetitions.
The Partial BER is: 9.191953e-02 With Errors: 11487 Over 124968 Bit Acquired
****
The Partial Number of bit is: 409872
The Partial Number of errors is: 37788
****

**Figure 3.26** Example of the partial BER obtained at a certain number of repetitions. We can know the number of the repetition by taking a look at the partial number of bits, in this case would be the repetition 4.

The procedure is repeated for all the points of a curve. And then for each group of these repetitions we are obtaining a point. The number of points depends on the range of power we want to evaluate and the steps we are using to pass from one value to another. For instance, if we are having $P_d = [-27, -20]$ dBm with steps of 0.5 dB, we will have 15 points, what means 150 screens in total, and this is for one curve. If later we want to obtain a media we will repeat all this process as many times as the magnitude of media needed.

- **BER Plot**

With this program we can plot the BER curve of an acquisition or all the curves simultaneously to see the repeatability of the results. On the “x” axis we will have the power of the Control signal, while on the “y” axis we will have the BER values obtained from the file “BER BEST Evaluation Phase Filtered ST2”, in this case because we find that for this sample time we obtain the best results. This optimal sampling time will range between 2 and 3, but just change when we disconnect the oscilloscope from the system. Once we launch a set of measurements it remains stable.

- **Median BER Plot**

With this program we can plot the media of all the BER curves obtained for each acquisition in order to obtain a smoother curve. The media is calculated with the MATLAB function “median”. To this function we pass a matrix formed by as many rows as acquisitions and as many columns as points of a curve. We read and save these values on the matrix from the files obtained with the program PRBS alignment.
and BER. On Figure 3.27 we see an example of the repeatability of a curve and how the media fits on the center of all the curves obtained.

![Control BER Evaluation](image)

**Figure 3.27** Confrontation of the different BER curves obtained at each acquisition, repeatability, with the media of all the curves. On this graphic we took 5 acquisitions, as we can see the values are smooth with the media.

- **Penalties**

  It is in charge of making the subtraction between the power values at which the Ref BER curve and the different K BER cross the BER level $10^{-3}$.

- **Penalties Plot**

  It plots along an “x” axis formed by the K’s and “y” axis formed by the penalties in dB, the results obtained with the previous program.
CHAPTER 4  BER AND PENALTIES

4.1 Introduction

On this chapter it is shown the first studies in which we acquire Bit Error Rate (BER) curves for a fixed Control power range and for a Data power that varies in order to achieve different K values so in terms of power ratio between the two signals. All this acquisition procedure was done using the optimized setup obtained from the previous evaluations, the one that filter out, as much as possible, the noise introduced by our system and later by the data channel. Lately, we obtain some specific BER curves for one fixed point of Control power, varying the Data Power in a range in which the well-known Data Branch will work. The goal of this final evaluation is to demonstrate directly that exist a certain range of power values for which both transmission (Control and Data signals) systems can be detected at the same time.

4.2 Reference BER

As seen before, we take as a reference BER, the curve obtained without any interfering signal on the one we want to recover. In this case, we are recovering the Control signal without any Crosstalk induced by the Data signal.

After the optimizations the expected result would be a really low BER for a $P_C = -40$ dBm and a worse recovering of the signal, and so bigger BER values, when we run into lower values of $P_C$. But, in a first time, the obtained curves showed that we had more or less the same BER values for $P_C = -40$ dBm than for $P_C = -60$ dBm. Meanwhile, approximately on the center of the power values, we were achieving the worst BER case. This strange behaviour was not certainly the one expected for our system and after a deep study of the results and the revision of the work bench, we found out the problem. It was caused by a conduced modulating electrical signal that was entering in our system.

Our recovered PRBS was being reinforced by the original one since it was transmitted through the metallic workbench table which was connected to the ground sharing the connection with the signal generation device. A setup subset was mounted on the
workbench table, so the modulating signal was captured by some of the components of the receiver. To understand the curves presented on the following, we have to think how this conducted signal was affecting to the results.

For a high value of $P_c$, this modulating electrical signal, as was having a low power level, was not predominant and so we see its effect just like a low disturbance that don’t affect so much our original signal, the curve is going to low BER values as expected.

The central point of our characterization, the one that shows the bigger BER value, is the one in which the two signals, the original and the conducted, are at the same power level and their interfering cause the high number of errors.

After this point, the conducted modulating BPSK electrical signal becomes the relevant one as long as the control power is getting low values, and we recover the signal as we were doing before but from the conducted one. Due to all of this we are observing this behaviour on the graphic. We have to find in which point this conducted signal is entering in our system and distorting our measurements.

The first results we obtained after carrying out the assembly of the setup explained on the third chapter are shown on Figure 4.1. The different graphics correspond to different sampling times (ST). On a first assumption we launched the measurements on a big range of Control power comprised between $P_c = [-60 \text{ dBm}, -40 \text{ dBm}]$. 
Figure 4.1 Reference BER curves for Control signal showing a wrong behaviour due to the conduced signal entering in our system.

After some tests we understood that the principal reason of our conduced signal was the ground plain created by the workbench. The solution adopted in order to remedy the problem was to isolate all the components from the workbench table. From now on, the transmitted PRBS was insulated from the chain of amplifier of our system and cannot reinforce or damage the results. Then, having already selected the best Sampling Time, the BER obtained was correct.

We want to highlight the fact that a BER = $10^{-3}$ is achieved for a Power of the Control Signal of $P_c = -52.5$ dBm, while in the past it was at $P_c = -40$ dBm. In the next images (Figure 4.2 and Figure 4.3) we can see an improvement of approximately 12.5 dB. Considering the less power required by the Control signal to reach the desired BER is now desirable to have a point of work common for both the two branches.
Figure 4.2 Reference BER comparison between the curve obtained with the former system and the one after the optimization process in which we add the BPF and the amplification stage.

Figure 4.3 Zoom on the interesting area, at a BER = $10^{-3}$, the difference is 12.5 dB.

This fact, as we will see later, will allow us to accomplish with the requirements established on the previous thesis for the correct functioning of the complete system with a certain margin.

The improvements acquired were thanks to first of all the use of the Band Pass Filter in confrontation with the former Low Pass Filter. Remember that the Data spectrum is occupying a big band and so it is important to filter it out as much as possible, so the use of a BPF was more suitable for our case.
Also it was important to use an amplification stage before entering into the LeCroy Oscilloscope as a low power signal will be distorted by the inner noise of the device of measurement as happened before. With this we reach the BER curves with less power needed on the Control branch, which is an advantage for the recovering of the Data signal.

4.3 Complete BER Curves

To obtain the curves that show the BER on the Control branch affected by the Data signal we run the corresponding program in MATLAB. Before launching the measurements for a big number of acquisitions to obtain the media, in order to save time, we took some proofs to see in which range of K’s we will get interesting results. The first setup measurement used was designed in order to obtain results about the Control signal behaviour when our Data signal is present with an ER of 6 dB.

On Figure 4.4 were launched the Reference Curve and some curves affected by the Data signal, at a 6 dB extinction ratio, with different power difference parameter, \( K = [-11,-17] \) dB. As long as this difference means \( K = \frac{P_C}{P_D} \), in this case we are varying the Data power to obtain the different relation parameter between the two power levels of Control and Data.

We should pay attention on the BER graphics in which, even the curves are achieving BER values below \( 10^{-4} \) values, it is not so reliable. This is owing to the fact that we have designed the program for the BER obtainment to acquire a certain number of repetitions of the oscilloscope screen, which make possible to obtain the necessary number of bits for the proper calculation of BER values bigger \( 10^{-4} \).
Figure 4.4 Control BER curves for the reference case, in which no Data signal is applied, and with K difference power applied between Control and Data with values from [-11, -17] dB and an Extinction Ratio on the Data of 6 dB. Notice that the BER points below $10^{-4}$ are not so reliable as the number of repetitions of the screen we acquire are for obtaining the necessary number of bits for computing BER values bigger than $10^{-4}$.

The plots obtained are so close that we can consider that in all cases we are recovering the disturbed Control signal as for the case of the reference curve. These results are quite important because confirm that our BPSK signal can survive at the presence of the Data, at least for some points of power values. On the next measurements we want to increase this power difference to see some penalties on our signal under study, the Control one. The Data signal has the same Extinction Ratio than before, 6 dB.

In Figure 4.5 we start to see the separation between the K curves and the reference one. Since we are increasing the difference between the Data Power and the Control, it is been harder to recover it.
From these two plots we considered interesting the points from $K = [-17, -27]$ dB since are starting to have some penalties but not passing 2 dB of it what we consider too much for our system.

To have an overall idea about how much it took to obtain the results, we made some calculations along the equations (Eq. 4.1), (Eq. 4.2), (Eq. 4.3) and (Eq. 4.4).

1 screen acquisition = 50 s (acquisition) + 20 s (guard time to save the plot)  
(Eq. 4.1)

Each screen is acquired 10 times to have the necessary number of bits to consider reliable the measurement over the BER targets.

$70 \times 10 \text{ repetitions} = 700 \text{ s (to obtain a point of the curve)}$  
(Eq. 4.2)

The number of points of the curve depends on the range of power we are using and the length of the step between the points. For instance, if we use a range of $P_C = [-54, -48]$ dBm and a step of 0.5 dB between the points, we will have 13 points.

$700 \frac{s}{\text{point}} \times 13 \text{ points} = 9100 \text{ s}$  
(Eq. 4.3)
With this we will obtain a curve, but as we want to do a media to avoid errors and smooth the results, if we want to obtain 10 curves it will finally take:

\[ 9100 \cdot \frac{s}{\text{curve}} \cdot 10 \text{ curves} \approx 25 \text{ h} \quad \text{(Eq. 4.4)} \]

If we are having 7 curves, the reference and the 6 with the different values of the K parameter applied, we spend a total time of 177 hours.

Finally, the first results obtained for an Extinction Ratio on the Data signal of 6 dB are shown on Figure 4.6.

![Figure 4.6 Control BER curves obtained for an Extinction Ratio on the Data signal of 6 dB. The interference curves are plotted for a K = [-17,-27] dB with steps of 2 dB.](image)

For an E.R. of 13 dB applied on the Data signal, we decided not to obtain the curve at \( K = -27 \) dB as on the previous image for E.R. = 6 dB it is not crossing the point of \( \text{BER} = 10^{-3} \) and because with this setup we expect having worse results on the Control branch performance as the Data signal is causing more interference due to the higher voltage value to achieve the E.R. desired, we will obtain the curves for \( K = [-17,-25] \) with steps of 2 dB. See Figure 4.7.
Control BER curves obtained for an Extinction Ratio on the Data signal of 13 dB. On the red colour we can find the reference curve for no Data signal applied, while the interference curves are plotted for a $K = [-17, -27]$ dB with steps of 2 dB.

On the results we can check how the sensitivity has not changed as on the Reference curve no Data signal is applied and is on this one where we change the E.R. For the curve with a Relative Crosstalk of 25 dB we are not crossing the BER value $10^{-3}$.

### 4.4 Control Penalties

As we had defined the penalties for the Data, on the Control branch will be the same, the difference of power values at which the two different curves, the Reference and the Disturbed one, with a certain Relative Crosstalk $K$, cross the $BER = 10^{-3}$. See the equation (Eq. 4.5).

$$Penalty = P_{C}^{BER} = 10^{-3} (\text{Disturbed curve}) - P_{C}^{BER} = 10^{-3} (\text{Reference curve})$$

(Eq. 4.5)

In order to confront (compare) both the penalties on the Data and on the Control, we have to be aware that the new curve, for the Control penalties will have approximately the same shape but the curve will grow on the opposite direction than the ones obtained for the Data signal.

On the former graphics, when we incremented the value of $K$, we obtained less penalties on the Data channel as the Control was with lower power values. Now, when
we increment the $K$, we obtain worse results for the Control penalties as it is farer from the Data getting a lower power and so it is more difficult to recover it. On the other hand, with lower values of $K$, the Control has a similar power to the Data, which is enough to recover it. See Figure 4.8 and Figure 4.9.

![Figure 4.8](image1.png)

**Figure 4.8** Curve of penalties on the Control signal due to the Data signal for different $K$ parameter values. In this graphic the Extinction Ratio applied on the Data signal was 6 dB.

![Figure 4.9](image2.png)

**Figure 4.9** Curve of penalties on the Control signal due to the Data signal for different $K$ parameter values. In this graphic the Extinction Ratio applied on the Data signal was 13 dB.

While on the Data signal the penalty was an important requirement because of the NG-PON2 architecture constraints, on the Control signal we can afford more penalties as long as with this curve we achieve to receive the signal at a $10^{-3}$ BER. Because of
that, on the next chapter we focus the study on the demonstration of the work of the complete system, what means recover at the same time the Data and the Control signals, making our system work at a certain power values at which we already know the recover should be possible taking into consideration the already known penalties.

4.5 Subset of measurements

To prove that our system is working properly we decided to work for a single point of Control power and for different Data powers. With this we can see how the BER on the Control is around the desirable values between $10^{-2}$ and $10^{-5}$ for different K values generated with the different Data power values on the x axis. So, for higher Data power, we will have more power difference between the Control and the Data and so the BER performance on the Control branch will be worse as we can see on Figure 4.10.

Notice that on the second case, for an Extinction Ratio (ER) = 13 dB the BER is worst as the Data is being sent with more power. That is the contrary case to the former thesis, in which the penalties on Data where lower when the ER was bigger. This is because now Data is the interference and for a bigger ER the Data is more distinguishable as the bit power level is bigger, but this is at the same time distorting more the Control signal, and so we need lower Data power values to achieve the same Control BER target than on the ER = 6 dB case.
4.6 Margin of work for Data ER = 6 dB

While on the Data channel we afford a certain number of penalties, on the Control branch the constraint is not so limiting, and we fix to pass BER = $10^{-3}$ as the requirement.

For an ER = 6 dB on the Data signal, from the old measurements showed on the chapter 2, we obtained that we had to accomplish with the equation (Eq. 4.6) to obtain a penalty lower than 0.2 dB as shown on Figure 4.11.

$$\frac{P_C}{P_D} = K \leq -25 \text{ dB} \quad (\text{Eq. 4.6})$$
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Figure 4.11 Penalties on the Data signal due to the Control signal. Limit fixed at 0.2 dB of penalties.

On the other hand, as the important thing for the Control is using a Relative Crosstalk that allow us to recover the Control signal with at least a BER = 10^{-3}, we obtain a Contour of this BER value for the different power values of Data and Control. On the Figure 4.12 we can find two curves, because we obtain it also for 10^{-4}. And to obtain the Relative Crosstalk we have just to remember the equation (Eq. 4.7).

$$K = \frac{P_C}{P_D}$$

(Eq. 4.7)

Figure 4.12 BER Contour of the Control signal for an Extinction Ratio on the Data signal of 6 dB. The curves show the Control and Data power values to obtain BER of 10^{-3} and 10^{-4}.

If we take into account the constraint established by the Data branch, we should work with a $K \leq -25$. As the sensitivity found for the Data for this E.R. is
$P^{{BER=10^{-3}}}_{D} = -24.5 \text{ dBm}$. Defining the sensitivity as the Data power value at which we recover the signal with a $BER = 10^{-3}$ when there is no disturbing signal, Control signal, affecting. We can see it on Figure 4.13. We will obtain the equations (Eq. 4.8), (Eq. 4.9) shown on the following.

\[ K = P^{{Data\ constraint}}_{C} - P^{{BER=10^{-3}}}_{D} \leq -25 \text{ dB} \quad (\text{Eq. 4.8}) \]

\[ P^{{Data\ constraint}}_{C} \leq K + P^{{BER=10^{-3}}}_{D} = -25 \text{ dB} + (-24.5 \text{ dBm}) \leq -49.5 \text{ dBm} \quad (\text{Eq. 4.9}) \]

As for the sensitivity of the Control we have found that $P^{{BER=10^{-3}}}_{C} = -52.5 \text{ dBm}$, as shown on the images at the beginning of this chapter, there is no problem to recover at the same time both the signals as long as we respect the constraint establish by the Data study. And we obtain a margin shown on equation (Eq. 4.10).

\[ Margin = P^{{Data\ constraint}}_{C} - P^{{BER=10^{-3}}}_{C} = -49.5 \text{ dBm} - (-52.5 \text{ dBm}) = 3 \text{ dB} \quad (\text{Eq. 4.10}) \]
4.7 Margin of work for Data ER = 13 dB

For an E.R. of 13 dB on the Data signal, the results obtained on the Data branch where improved as we were distinguishing better this signal. On the equation (Eq. 4.11) we can find the constraint found on the Data branch obtained from the Figure 4.14.

\[
\frac{P_C}{P_D} = K \leq -21 \text{ dB} \quad \text{(Eq. 4.11)}
\]

![Graph showing median penalties on Data signal at 10^-3](image)

*Figure 4.14 Penalties on the Data signal due to the Control signal. In this case we do not arrive to the limit fixed at 0.2 dB of penalties.*

As on the last point, we obtain the BER Contour for different Data and Control power values combinations, choosing BER values of $10^{-2}$, $10^{-3}$ and $10^{-4}$, as shown on *Figure 4.15*. As the constraint for the recovering the Control signal is to use a Relative Crosstalk that allow us to recover the signal with at least a BER of $10^{-3}$. 
Figure 4.15 BER Contour of the Control signal for an Extinction Ratio on the Data signal of 13 dB. The curves show the Control and Data power values to obtain BER of $10^{-3}$ and $10^{-4}$.

As we have said this performance is better on the Data signal, and we can see it on the lower power of the sensitivity, which is $P_D^{BER=10^{-3}} = -26.5$ dBm, shown on the Figure 4.16. With the constraint on the Data and its sensitivity we can obtain the equations (Eq. 4.12), (Eq. 4.13) shown on the following.

![Figure 4.16](image)

Figure 4.16 Sensitivity of the Data signal, defining it as the power value at which we receive it with a BER $= 10^{-3}$ without the Control signal sent. The value obtained was $P_D^{BER=10^{-3}} \equiv -26.5$ dBm.

\[
K = P_C^{Data \ constraint} - P_D^{BER=10^{-3}} \leq -21 \text{ dB} \quad (Eq. 4.12)
\]
\[ p_{C}^{Data \ constraint} \leq K + p_{D}^{BER=10^{-3}} = -21 \text{dB} + (-26.5 \text{ dBm}) \leq -47.5 \text{ dBm} \]

\[ \text{(Eq. 4.13)} \]

On the contrary, for the recovering of the Control signal the use of this E.R. on the Data signal worsen the results on the penalties of Control as we have seen previously, but the sensitivity in this case remain the same value as for the Reference curve we are not applying Data signal, where the change of the E.R. is performed.

So, to avoid having more penalties, we can see that the margin of work here is bigger and so we can use bigger values of Control with which we can still recover the Data signal. Then, we can see on the equation \((\text{Eq. 4.9})\) the margin obtained in this case.

\[ Margin = p_{C}^{Data \ constraint} - p_{C}^{BER=10^{-3}} = -47.5 \text{ dBm} - (-52.5 \text{ dBm}) = 5 \text{ dB} \]

\[ \text{(Eq. 4.13)} \]
CHAPTER 5 CONCLUSIONS

5.1 Introduction

On the second chapter we found that the Data could be recovered for a certain Relative Crosstalk, $K$, between it and the Control signal, and so there were established the constraints for the future works on the Control branch.

On the third chapter we worked on the recovering of the Control signal, as at a first glance the results obtained do not were the best ones, and so we worked on the optimization of the setup, obtaining finally a better performance of the BER curve.

On the chapter 4 we obtained the BER and the Penalties for the Control evaluation and we could find the margin of work for the two signals recovering, taking also into account the constraints found on the second chapter.

So, through all this chapters we have seen the setup, the digital post-processing and the results achieved for the different evaluations on the BER and Penalties of Data and Control signals and we have found that they both can coexist as long as they accomplish with the mentioned constraints.

Finally, to see clearly the meaning of all these achievements, we present on this chapter 5 some images to clarify all the scenario and the values at which the system can work.

5.2 BER Contour at ER = 6 dB

In the following image, Figure 5.1, we can see both the curves for the BER values $10^{-3}$ and $10^{-4}$ for the Data and Control signal. These curves are showing how the BER values are achieved for certain combinations on Data and Control power values. On this case the E.R. of the Data signal will take a value of 6 dB.

At the point at which the lines are crossing and for higher values of Control and Data powers, respecting the values shown, we are obtaining the area for which both signals can be recovered, and so it is demonstrate the functioning of the standard.
Figure 5.1 BER Contour for ER = 6 dB on the Data signal. On the “x” axis the Data Power values are shown, while on the “y” axis there are the Control power values. The lines are showing for which values of power both channels are achieving BER $= 10^{-3}$ and $10^{-4}$. On the point they cross and for bigger values of both powers we are having the area in which the system will work.

To define the area for which the Control signal will be recovered, we can see on Figure 5.2, how for the curve at which the BER on the Control branch is having a value of $10^{-3}$ and higher values on the Control power, the Control branch will work.

Figure 5.2 Area of work of the Control signal. On this area the BER values will be $10^{-3}$ or more little.
On the other hand, for the recovering of the Data signal, we have to take into account the constraint fixed on the former thesis at which we want to recover it without penalties bigger than 0.2 dB. For this reason, the Data area of functioning will be delimited by the curve at which the BER is achieving $10^{-3}$ but also the maximum Control power for which we obtain 0.2 dB of penalties on the Data branch. See Figure 5.3.

**Figure 5.3** Area of work for the Data signal, respecting the constraint on the penalties, which fixes the maximum Control power to be $P_{C}^{max} = -49.5$ dBm.

Finally, we can see the area of work for the recovering of both the signals on Figure 5.4, in which we respect the requirements shown on the previous images.
Figure 5.4 Zoom on the area of work for obtaining a BER $\leq 10^{-3}$. The point at which both curves are crossing are at $P_c = -49$ dBm and $P_D = -24$ dBm, with which we obtain a $K = -25$ dB. Then, for maintaining this Relative Crosstalk we should increase both the powers with the same relation or with a different ratio but respecting the power values that make the system work inside the area.

Notice that the values shown are respecting the constraints established on the previous chapter about the maximum Relative Crosstalk affordable on the system and the corresponding sensitivities for each signal at the receiver.
5.3 BER Contour at ER = 13 dB

We obtained the same curves for an E.R. of 13 dB applied on the Data signal, showed on Figure 5.5.

Figure 5.5 BER Contour for ER = 13 dB on the Data signal. On the “x” axis the Data Power values are shown, while on the “y” axis there are the Control power values. The lines are showing for which values of power both channels are achieving \( \text{BER} = 10^{-3} \) and \( 10^{-4} \). On the point they cross and for bigger values of both powers we are having the area in which the system will work.

The area of work for the recovering of the Control signal would be the one shown on Figure 5.6. And the area for the Data recovering is shown on Figure 5.7, respecting the penalties constraint.
Figure 5.6 Area of work for the Control signal recovering. On this area the BER values will be $10^{-3}$ or more little.

Figure 5.7 Area of work for the Control signal recovering. On this area the BER values will be $10^{-3}$ or lower. Respecting the constraint on the penalties, which fixes the maximum Control power to be $P_C^{\text{max}} = -47.5$ dBm, we will obtain penalties below 0.2 dB.
Finally the area in which both the signals can be recovered with a BER $\leq 10^{-3}$ and penalties on the Data channel lower than 0.2 dB would be in the area shown on Figure 5.8.

Figure 5.8 Zoom on the area of work for obtaining a BER $\leq 10^{-3}$. The point at which both curves are crossing are at $P_C = -50.2$ dBm and $P_D = -26.4$ dBm, with which we obtain a $K = -23.8$ dB. Then, for maintaining this Relative Crosstalk we should increase both the powers with the same relation or with a different ratio but respecting the power values that make the system work inside the area.
REFERENCES


