To my family...
Abstract

Over the years, optical communication systems have been seen as one of the attractive solutions to the increasing high data rate in telecommunication systems. There also has been a tremendous increase in usage of transferring information like Internet and multimedia applications.

The scientific research in optic and/or photonic area is in continuous evolution. While students formation in this field is, in many cases, insufficient and, often, too much theorist. The purpose of my thesis is to allow to approach, particularly Telecommunications Engineering students, to the optic communications world. First of all, already from the simple academic courses, it can be a launch pad to create more and more people interest in this field. For a long time term, there will be a great number of potential researchers in order to increase the technological progress. This can now seem only a banality. However, during my university studies, I observed that the practical study is becoming very important to learn targets, obviously accompanied by good theoretical bases.

Overall, this thesis illustrates a student lab practice with a previous theoretical explanation. Students job is based on the one system of measure of Synchronous Digital Hierarchy (SDH) pseudo-real and high speed traffic. This traffic is produced to a high-performance and expensive device. The device made up of Tektronix, labeled with ST2400A. In reality, it is an electric/optic transceiver of traffic SDH at 2.5 Gb/s. The receiver is able to monitor directly system performances. Through this system of measures BER, eye-diagram, jitter, control of bias, to different distance (25 and 50 km) are calculated and other factors typical of the optic communications.
Thesis is composed of seven chapters in total, divided into three parts: Theoretical (first four chapters), Practice (Chapter 5), and Results and Conclusions (Chapters 6 and 7), as summarized below.

**Chapter 1**
A short introduction on optic communications and their principal losses.

**Chapter 2**
Synchronous Digital Hierarchy base characteristics, in particular the frame structure that it is generated by ST2400A.

**Chapter 3**
Optical transceiver types and functions. Optical sources such as lasers and how they can affect system performance varying parameters.

**Chapter 4**
Theoretical explanation of digital transmission on optical carrier measurements.

**Chapter 5**
Student practice structure.

**Chapter 6**
Data results relative plots and comments.

**Chapter 7**
Final conclusions and future aspects.

This final work is part of LLP/Erasmus contest. It is developed in collaboration with Politecnico di Torino in Turin (Italy), has been projected in the laboratories of the Optic Communications Group of the signal theories and communications department of Universitat Politècnica de Catalunya in Barcelona (Spain), under special supervision of Prof. Josep Prat Gomà.
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Part I

Theoretical
Chapter 1

Overview of Optical Fiber Communications

1.1 Introduction

In a basic optical fiber transmission link, the key sections are a transmitter consisting of a light source and its associated drive circuitry, a cable offering mechanical and environmental protection to the optical fibers contained inside, and receiver consisting of a photodetector plus amplification and signal restoring circuitry.

One of the principal characteristics of an optical fiber is its attenuation as a function of wavelength. Early technology made exclusive use of the 800 to 900 nm wavelength band, since, this region, the fibers made at that time exhibited a local minimum in an attenuation curve. This region is referred to as the first window. By reducing the concentration of hydroxyl ions and metallic impurities in the fiber material, in the 1980s manufacturers were able to fabricate optical fibers with very low loss in the 1100 to 1600 nm region. This spectral band is referred to as the long-wavelength region. Two windows are defined here: the second window, centered around 1310 nm and third window, centered around 1550 nm (Figure 1.1.1).

Once the cable is installed, a light source that is dimensionally com-
Figure 1.1.1: Attenuation in function of wavelength

patible with the fiber core\(^1\) is used to launch optical power into the fiber. Semiconductor light-emitting diodes (LEDs) and laser diodes are suitable for this purpose, since their light output can be modulated rapidly by simply varying the bias current at the desired transmission rate, thereby producing an optical signal, as we shall see in Chapter 3.

After an optical signal in launched into a fiber, it will become progressively attenuated and distorted with increasing distance because of scattering, absorption and dispersion mechanisms in the glass material. So, the design of an optical receiver is inherently more complex than that of the transmitter, since it has to interpret the content of the weakened and degraded signal received by the photodetector. The principal figure of merit

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\(^1\)The core of a conventional optical fiber is a cylinder of glass or plastic that runs along the fiber’s length. The core is surrounded by a medium with a lower index of refraction, typically a cladding of a different glass, or plastic. Light travelling in the core reflects from the core-cladding boundary due to total internal reflection, as long as the angle between the light and the boundary is less than the critical angle. As a result, the fiber transmits all rays that enter the fiber with a sufficiently small angle to the fiber’s axis. The limiting angle is called the acceptance angle, and the rays that are confined by the core/cladding boundary are called guided rays.
for a receiver is the minimum optical power necessary at the desired data rate to attain either a given error probability for digital system or a specifies signal-to-noise ratio for analog system.

Besides, an important aspect of an optical communication link is that many different wavelengths can be sent along a fiber simultaneously in the 1300 to 1600 nm spectrum. The technology of combining a number of wavelengths onto the same fiber is known as *wavelength division multiplexing* (WDM) that conceptually, it is the same as *frequency division multiplexing* (FDM) used in microwave radio and satellite systems.

An interesting and powerful part of the design and installation of an optical transmission are measurement techniques for verifying the operational characteristics of constituent components. Furthermore, when a link is being installed and tested, the work parameters of interest include bit error rate, timing jitter and signal to noise ratio as indicated by the eye pattern. During actual operation, measurements are needed for maintenance and monitoring functions to determine factors such as fault locations in fibers. These aspects will be deepened during this thesis, also seeing some practical cases[1, 2].

### 1.2 Digital Communication Links

Fig. 1.2.1 shows a diagram of a digital fiber-optic link. Signal waveforms are shown at several key points along the signal path. These waveforms illustrate some of the fundamental characteristics of a fiber optic link. In this example, the input electrical data stream to the optical transmitter is a non-return to zero (NRZ) digital pattern and it is converted to an optical signal through the electrical-to-optical (E/O) converter where ideally, every electron injected into the source should produce a single output photon. The optical transmitter is essentially a current-to-power converter. Semiconductor laser (light amplified by stimulated emission of radiation) diodes are predominant sources for long distance and high speed digital systems; besides, lasers provide high optical power, narrow spectral width and modulation rates beyond 10 Gb/s. LEDs are common lightwave sources for shorter distances and lower data rates.
Figure 1.2.1: A digital fibre-optic communication link[1]
International standards such as *Synchronous Optical Network* (SONET) and *Synchronous Digital Hierarchy* (SDH) specify data rates (from 51.84 Mb/s to 9.95 Mb/s) and formats used for digital modulation in telecommunication systems. Each of these high-speed channels contains lower data rate signals that have been time-interleaved using a method called *time division multiplexing* (TDM).

The same figure (Figure 1.2.1) shows that the output of the optical transmitter is not a perfect replica of the input electrical signal, so a significant test and measurement challenge is to characterize the waveform and signal-to-noise degradation present in E/O converters. The laser transmitter in this example has much *overshoot*\(^2\) during the transition from the zero to one state. This ringing of the laser output power is caused by interactions between the round-trip time of photons in the laser and the speed at which the optical gain can be changed by a step change in current. The characteristic frequency of raging is referred to as the relaxation oscillation frequency. It has a typical value between 2 to 30 GHz depending on laser parameters.

Figure 1.2.1 shows how the edges of digital waveform become more rounded after propagation through the fiber optic cable. This waveform spreading leads to distance limitations in an optical fiber link. The spectral width of an optical source is a major consideration for waveform spreading. Excess laser bandwidth is important due to chromatic dispersion in optical fibers. The different wavelengths contained in the optical signal travel at different velocities due to chromatic dispersion. After propagating through long fiber lengths, adjacent data bits start to overlap leading to intersymbol interference and error. Fabry-Perot lasers (Section 3.2.3.1) and LEDs are optical source examples that have wide spectral width. The spectral width of these sources may limit their usefulness for long fiber-optic links.

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\(^2\)overshoot refers to the transitory values of any parameter that exceeds its final (steady state) value during its transition from one value to another.
1.3 Types of Optical Fiber

Understanding the characteristics of different fiber types aides in understanding the applications for which they are used. Operating a fiber optic system properly relies on knowing what type of fiber is being used and why. There are two basic types of fiber: multimode fiber and single-mode fiber as showed in Fig. 1.3.1. Multimode fiber is best designed for short transmission distances, and is suited for use in LAN systems and video surveillance. Single-mode fiber is best designed for longer transmission distances, making it suitable for long-distance telephony and multichannel television broadcast systems.

1.3.1 Multimode Fiber

Multimode fiber, the first to be manufactured and commercialized, simply refers to the fact that numerous modes or light rays are carried simultaneously through the waveguide. Modes result from the fact that light will only propagate in the fiber core at discrete angles within the cone of acceptance. This fiber type has a much larger core diameter, compared to single-mode fiber, allowing for the larger number of modes, and multimode
fiber is easier to couple than single-mode optical fiber. Multimode fiber may be categorized as step-index or graded-index fiber (see sub-section 1.4.2).

1.3.2 Single-mode Fiber

Single-mode fiber allows for a higher capacity to transmit information because it can retain the fidelity of each light pulse over longer distances, and it exhibits no dispersion caused by multiple modes. Single-mode fiber also enjoys lower fiber attenuation than multimode fiber. Thus, more information can be transmitted per unit of time. Like multimode fiber, early single-mode fiber was generally characterized as step-index fiber meaning the refractive index of the fiber core is a step above that of the cladding rather than graduated as it is in graded-index fiber. Modern single-mode fibers have evolved into more complex designs such as matched clad, depressed clad and other exotic structures.

1.4 Loss Characteristics of Digital Communication Links on Optical Carriers

As the optical signal propagates over a long stretch of fiber, it becomes attenuated because of scattering, absorption by material impurities and other effects. The attenuation is measured in dBs ($10 \cdot \log \text{ of power ratio}$) and proportional to the length of the fiber. Fiber attenuation or fiber loss is therefore specified in dB/km. As shown in Fig. 1.1.1, silica glass has two low-loss windows, one around the 1310nm and one around 1550nm, which both are used for optical fiber communication. The popular single-mode fiber has a loss of about 0.25dB/km at 1550 nm and 0.4dB/km at 1310. Because the loss is lower at 1550 nm, this wavelength is preferred for long-haul communication. The third window around 850 nm, where the loss is about 2.5dB/km is used for short-reach (data) communication applications, mostly because low-cost optical sources and detectors are available for this wavelength.

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3Note that these wavelengths are defined in the vacuum. Thus, an optical signal at 1.55μm has a wavelength of about 1μm in a glass fiber, which has a refractive index of about 1.5.
1.4.1 Chromatic Dispersion in Single-mode Fiber

The loss characteristics of optical fiber often limit the distance that a signal can propagate. This is not always the case. In single-mode fibers, chromatic dispersion can limit the distance over which fiber optic signals can propagate.

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

\[ \text{Group Delay} = \frac{\partial \phi}{\partial \omega} \]

\[ CD = \frac{\partial^2 \phi}{\partial \omega^2} \]

where \( \phi \) is optical phase and \( \omega \) is the optical frequency.

Chromatic dispersion consists of both material dispersion and waveguide dispersion as illustrated in Fig. 1.4.1.

Both of these phenomena occur because all optical signals have a finite spectral width, and different spectral components will propagate at different speeds along the length of the fiber. One cause of this velocity difference is that the index of refraction of the fiber core is different for different wavelengths. This is called material dispersion and it is the dominant source of chromatic dispersion in single-mode fibers. Another cause of dispersion is that the cross-sectional distribution of light within the fiber also changes for different wavelengths. Shorter wavelengths are more completely confined to the fiber core, while a larger portion of the optical power at longer wavelengths propagates in the cladding. Since the index of the core is greater than the index of the cladding, this difference in spatial distribution causes a change in propagation velocity.
Chromatic dispersion can cause bit errors in digital communications or distortion and a higher noise floor in analog communications and, as shown in Fig. 1.4.2, can pose a serious issue in high-bit-rate systems if it is not measured accurately and some form of dispersion compensation is not employed.

1.4.2 Modal Dispersion

Modal dispersion is a distortion mechanism occurring in multimode fibers and other waveguides, in which the signal is spread in time because the propagation velocity of the optical signal is not the same for all modes.

In the ray optics analogy, modal dispersion in a step-index optical fiber may be compared to multipath propagation of a radio signal. Rays of light enter the fiber with different angles to the fiber axis, up to the fiber’s acceptance angle. Rays that enter with a shallower angle travel by a more direct path, and arrive sooner than rays that enter at a steeper angle (which reflect
Figure 1.4.2: Pulse broadening due to chromatic dispersion
many more times off the boundaries of the core as they travel the length of the fiber). The arrival of different components of the signal at different times distorts the shape (Figure 1.4.3). Modal dispersion limits the bandwidth of multimode fibers. For example, a typical step-index fiber (Figure 1.4.4) with a 50 µm core would be limited to approximately 20 MHz for a one kilometer length, in other words, a bandwidth of 20 MHz · km. Modal dispersion may be considerably reduced, but never completely eliminated, by the use of a core having a graded refractive index. The bandwidth of a typical off-the-shelf graded-index multimode fiber (Figure 1.4.5), having a 50 µm core, may approach 1 GHz · km or more. Multimode graded-index
fibers having bandwidths approaching 3 GHz \cdot km have been produced.

Purists insist on calling this effect an optical distortion, since dispersion is a wavelength-dependent phenomenon and multimode distortion may occur at a single wavelength. However, the term dispersion has become common for describing this effect.

A special case of modal dispersion is polarization mode dispersion (PMD) as described in the next sub-section.

1.4.3 Polarization Mode Dispersion (PMD)

Polarization mode dispersion is another cause of distortion in a communication link. It is caused by different polarization modes traveling at different speeds. Single-mode optical fiber and components support one fundamental mode, which consists of two orthogonal polarization modes. Ideally, the core of an optical fiber is perfectly circular, and therefore has the same index of refraction for both polarization states. However, mechanical and thermal stresses introduced during manufacturing result in asymmetries in the fiber core geometry. This asymmetry introduces small index of refraction differences for the two polarization states, a property called birefringence. External mechanical stresses and environmental conditions exacerbate the problem. Birefringence creates differing optical axes that generally correspond to the fast and slow axes. (These axes can also be thought of as corresponding to the Linear Polarization (LP) modes or Principal States of Polarization (PSP).) Birefringence causes one polarization mode to travel faster than the other, resulting in a difference in the propagation time called the differential group delay (DGD) as illustrated in Fig. 1.4.6. DGD is the unit that is used to describe PMD. DGD is typically measured in picoseconds.

When mode coupling is present, both the PSP and the DGD are also dependent on optical frequency. Mode coupling refers to an exchange of power among propagating polarization modes. This is usually seen in long lengths of single-mode fiber, and is sometimes observed even in short optical components. PMD effects resemble those of chromatic dispersion, but with
some key differences: Chromatic dispersion is a rather stable, linear effect, making compensation relatively easy, but PMD is a linear effect that is time-varying in fiber links, making compensation difficult. PMD is very stable in components. Unlike chromatic dispersion, the effects of PMD are dependent on the launched polarization state. In high-bit-rate systems, PMD may introduce errors as pulses spread into one another[2, 5, 6].

1.5 Wavelength Division Multiplexed (WDM) Systems

Figure 1.2.1 shows how a single wavelength digital waveform is sent through a fiber optic link. Increasing the data rate of a single wavelength channel is one strategy to increase the throughput on optical fibers. The data rate for a single channel will eventually reach its limits due to chromatic dispersion and/or polarization mode dispersion. An important strategy to further increase the available bandwidth is to add multiple wavelength channels. Multiple wavelength systems are referred to as being wavelength division multiplexed (WDM). Early WDM systems used a wide wavelength spacing. It was common to increase the bandwidth of 1310 nm link by adding a 1550 nm channel. The installation of WDM systems is often driven by economic reasons. It less expensive to update the terminal equipment to
WDM capability than to install new fiber optic cables. The introduction of the Erbium-doped fiber amplifier has moved nearly all WDM activity to the 1530 to 1565 nm wavelength window. More recent WDM installations are referred to as dense WDM (DWDM) systems due to the narrow spacing between optical channels.

Figure 1.5.1 shows the diagram of a DWDM fiber optic link. Lasers are combined in wavelength multiplexer to a single fiber. A common standard is a DWDM laser wavelength spacing of 100 GHz between channels. Systems use 4, 8, 16 or 32 channels.

Wavelength multiplexers are used to combine and separate the wavelength channels onto a single fiber with low loss. EDFA booster amplifiers are used to counteract the insertion loss\footnote{Insertion loss is the loss of signal power resulting from the insertion of a device in a transmission line or optical fiber, expressed in dBs. Insertion loss is a measure of attenuation but is a more precisely defined term. For instance, attenuation can include loss due to the source and load impedances not matching, but is not included in insertion loss since this is a loss that was already present before the "insertion" was made.} of the wavelength multiplexers at the transmitter and the receiver. A single EDFA can amplify all of the wavelength channels simultaneously.

With the introduction of WDM systems, new roles emerged for the use of fiber optics in telecommunication systems. Previously, when a set of signals needed routing to a particular location, the optical signal was detected and the routed electronically. The coming trend is to allow the optics to do some of the routing functions. The ability to add and drop certain wavelength channels from a fiber while sending on other channels undisturbed is an example of optical routing capability.

At the receiver, an EDFA is used to compensate for the loss of demultiplexer filters and to increase receiver sensitivity. The demultiplexer sorts the wavelengths out to the individual receivers for detection\footnote{\textsuperscript{1}}.

### 1.6 Characterization of Digital Fiber Optic Links

Section 1.2 introduced some of basic features of fiber optic links. It must be emphasized again that the primary purpose of a fiber optic link is to
Figure 1.5.1: A dense wavelength division multiplexed (DWDM) fiber optic link provide a low-loss data connection between two points. This section will outline techniques used to verify that acceptable end-to-end performance is achieved. This argument will be the key of this thesis, therefore it will be deepened in the next chapters.

1.6.1 Bit Error Ratio

The most important parameter of a digital system is the rate at which errors occur in the system. A common evaluation method is the bit error ratio test. A custom digital pattern is injected into the system. It is important to use a data pattern that simulates data sequences most likely to cause system errors. A pseudo random binary sequence (PRBS) is often used to simulate a wide range of bit patterns. The PRBS sequence is a “random” sequence of bits that repeats itself after a set number of bits. A common pattern is $2^{23} - 1$ bits in length (Appendix A). The output of the link under test is compared to the known input with an error detector. The error detector records the
number of errors and then ratios this to the number of bits transmitted. A bit error ratio of $10^{-10}$ is often considered the minimum acceptable bit error ratio for telecommunication applications. Data communication have more stringent requirements where $10^{-15}$ is often considered the minimum. A common measurement is to test the bit error ratio as a function of loss in the optical fiber.

1.6.2 Waveform Analysis

Bit error ratio measurements provide a pass/fail criteria for the system and can often identify particular bits that are in error. It is then necessary to troubleshoot a digital link to find the cause of the error or to find the margin in performance that the system provides. Digital waveforms at the input and output of the system can be viewed with high-speed oscilloscopes to identify and troubleshoot problem bit patterns.
Chapter 2

Synchronous Digital Hierarchy (SDH) Environment

2.1 Introduction

With the introduction of PCM technology in the 1960s, communications networks were gradually converted to digital technology over the next few years. To cope with the demand for ever higher bit rates, a multiplex hierarchy called the plesiochronous digital hierarchy (PDH) evolved. The bit rates start with the basic multiplex rate of 2 Mbit/s with further stages of 8, 34 and 140 Mbit/s. In North America and Japan, the primary rate is 1.5 Mbit/s. Hierarchy stages of 6 and 44 Mbit/s developed from this. Because of these very different developments, gateways between one network and another were very difficult and expensive to realize. The 1980s saw a start in the development of the synchronous digital hierarchy (SDH), with the intention of eliminating the disadvantages inherent in PDH. SDH brings the following advantages to network providers:

1. **High transmission rates.** Transmission rates of up to 10 Gbit/s can be achieved in modern SDH systems. SDH is therefore the most
suitable technology for backbones, which can be considered as being the super highways in today’s telecommunications networks.

2. **Simplified add & drop function.** Compared with the older PDH system, it is much easier to extract and insert low-bit rate channels from or into the high-speed bit streams in SDH. It is no longer necessary to demultiplex and then remultiplex the plesiochronous structure, a complex and costly procedure at the best of times.

3. **High availability and capacity matching.** With SDH, network providers can react quickly and easily to the requirements of their customers. For example, leased lines can be switched in a matter of minutes. The network provider can use standardized network elements that can be controlled and monitored from a central location by means of a telecommunications network management (TMN) system.

4. **Reliability.** Modern SDH networks include various automatic back-up and repair mechanisms to cope with system faults. Failure of a link or a network element does not lead to failure of the entire network which could be a financial disaster for the network provider. These back-up circuits are also monitored by a management system.

5. **Future-proof platform for new services.** Right now, SDH is the ideal platform for services ranging from POTS, ISDN and mobile radio through to data communications (LAN, WAN, etc.), and it is able to handle the very latest services, such as video on demand and digital video broadcasting via ATM that are gradually becoming established.

6. **Interconnection.** SDH makes it much easier to set up gateways between different network providers and to SONET systems. The SDH interfaces are globally standardized, making it possible to combine network elements from different manufacturers into a network. The result is a reduction in equipment costs as compared with PDH.

The trend is towards ever higher bit rates, such as STM-64 (time division multiplex, TDM). The current very high costs of such network elements are
a retarding factor, though. The alternative is so-called dense wavelength division multiplexing (DWDM). This is a technology that makes multiple use of single-mode optical fibers possible. Various wavelengths are used as carriers for the digital signals and are transmitted through the fibers simultaneously. Currently-available systems permit transmission of 16 wavelengths between 1520 nm and 1580 nm over a single fiber. One STM-16 channel is transmitted at each wavelength, giving a capacity of some 40 Gbit/s per fiber. Expansion to 32 and even 64 wavelengths has already been announced. Connected with the introduction of DWDM is the trend towards the “All Optical Network”. Optical add/drop multiplexers are already available commercially and the first field trials are in progress for optical cross-connects. In terms of the ISO-OSI layer model, this development basically means the introduction of an additional DWDM layer below the SDH layer (see Figure 2.1.1). Now, combine higher multiplex rates with the use of DWDM is a reality.

Now, will be illustrated the principal characteristics of SDH standard.

2.2 SDH Implementation Principles

This section describes the implementation principles for the Synchronous Digital Hierarchy (SDH), as a background for the detailed presentation of the SDH signal structures. In the following explanations, the following terms
are used to describe SDH networks:

- Network node. The SDH network node is a facility at which signals built in accordance with the SDH frame structure are generated and/or terminated. Therefore, a network node provides a convenient access point to add or drop payload signals, e.g., PDH tributary signals, for transmission over the SDH network.

- SDH transport system. An SDH transport system provides the technical means to transfer SDH signals between two network nodes.

- SDH network. An SDH network is formed by interconnecting the required number of network nodes by means of SDH transport systems.

### 2.2.1 Basic SDH Principles

SDH is implemented on the basis of two principles:

1. Direct synchronous multiplexing of individual tributary signals within the structure of the higher-rate multiplexed signal.

2. Transparent transporting of each individual tributary signal through the network, without any disassembly except at the two network nodes that exchange information through that particular signal. To enable synchronous multiplexing, SDH equipment is designed to permit efficient and reliable synchronization of the whole network to a single timing reference.

### 2.2.2 Direct Multiplexing Approach

Direct multiplexing means that individual tributary signals can be inserted and removed into the SDH multiplexed signal without intermediate multiplexing and demultiplexing steps. This capability results in the following characteristics:

- Efficient signal transport, as the same SDH transport system can carry various types of payloads (tributary signals).
• Flexible routing, because any tributary can be inserted and removed into the SDH signal as a single unit, without affecting in any way the other tributary signals carried by the same SDH signal. This permits to build cost-effective add/drop multiplexers, the key component of flexible networks, instead of implementing digital cross-connect systems as entities separated from multiplexing equipment.

In addition, the SDH signal structure includes sufficient overhead for management and maintenance purposes, and therefore provides the network operator full control over all the operational aspects of SDH networks and equipment units. This overhead permits the integration of the network management and maintenance functions within the transport network itself.

2.2.3 General Structure of SDH Signals

The SDH signal is a serial signal stream with a frame structure. Figure 2.2.1 shows the general structure of SDH signals. The SDH frame structure is formed by byte-interleaving the various signals carried within its structure.

Each SDH frame starts with framing bytes, which enable equipment receiving the SDH data stream to identify the beginning of each frame. The location of the other bytes within this frame structure is determined by its position relative to the framing byte. The organization of the frame can be easily understood by representing the frame structure as a rectangle comprising boxes arranged in N rows and M columns, where each box carries one byte. In accordance with this representation, the framing byte appears in the top left-hand box (the byte located in row 1, column 1), which by convention is referred to as byte 1 of the SDH frame. The frame bytes are transmitted bit by bit, sequentially, starting with those in the first row (see arrow in Figure 2.2.1). After the transmission of a row is completed, the bits in the next lower row are transmitted. The order of transmission within each row is from left to right. After transmission of the last byte in the frame (the byte located in row N, column M), the whole sequence repeats - starting with the framing byte of the following frame.
Figure 2.2.1: General structure of SDH signals
2.2.4 Frame Organization

As shown in Figure 2.2.2, an SDH frame comprises two distinct parts:

- Section Overhead (SOH)
- Virtual Container (VC)

2.2.4.1 Section Overhead

In SDH networks, the term section refers to the link between two consecutive SDH equipment units of the same type. Some signal carrying capacity is allocated in each SDH frame for the section overhead. This provides the facilities (alarm monitoring, bit error monitoring, data communications channels, etc.) required to support and maintain the transportation of a VC between nodes in an SDH network. The section overhead pertains only to an individual SDH transport system. This means that the section overhead is generated by the transmit side of a network node, and is terminated at the receive side of the next network node. Therefore, when several SDH transport systems are connected in tandem, the section overhead is
not transferred together with the payload (VC) between the interconnected transport systems.

2.2.4.2 Virtual Counter

The VC is an envelope (i.e., a special type of signal structure, or frame) that is used to transport a tributary signal across the SDH network. The path followed by a VC within the network may include any number of nodes, therefore the VC may be transferred from one SDH transport system to another, many times on its path through the network. Nevertheless, in most cases the VC is assembled at the point of entry to the SDH network and disassembled only at the point of exit. Since the VC is handled as an envelope that is opened only at the path end points, some of its signal carrying capacity is dedicated to path overhead. The path overhead provides the facilities (e.g., alarm and performance monitoring), required to support and maintain the transportation of the VC between the end points.

2.2.5 VC Assembly/Disassembly Process

The concept of a tributary signal being inserted into a virtual container, to be transported end-to-end across a SDH network, is fundamental to the operation of SDH networks. This process of inserting the tributary signal into the proper locations of a VC is referred to as “mapping”. In all the SDH signal structures, the carrying capacity provided for each individual tributary signal is always slightly greater than that required by the tributary rate. Thus, the mapping process must compensate for this difference. This is achieved by adding stuffing bytes, e.g., path overhead bytes, to the signal stream as part of the mapping process. This increases the bit rate of the composite signal to the rate provided for tributary transport in the SDH structure. At the point of exit from the SDH network, the tributary signal must be recovered from the virtual container, by removing the path overhead and stuffing bits. This process is referred to as “demapping”. After demapping, it is necessary to restore the original data rate of the recovered tributary data stream.
2.3 STM-1 Frame Structure

Base-level SDH signal is referred to as \textit{Synchronous Transport Mode Level 1} (STM-1).

2.3.1 Description of STM-1 Frame

STM-1 frames are transmitted at a fixed rate of 8000 frames per second\(^1\).

The STM-1 signal frame comprises 9 rows by 270 columns, resulting in a total signal capacity of 2430 bytes (19440 bits per frame). Considering the STM-1 frame repetition rate, 8000 frames per second, this yields a bit rate of 155.520 Mbps.

The STM-1 frame comprises the following parts:

\(^1\)At a transmission rate of 8000 frames per second, each byte supports a data rate of 64 kbps.
• Section Overhead. The STM-1 section overhead occupies the first nine columns of the STM-1 frame, for total of 81 bytes.

• Virtual Container. The remaining 261 columns of the STM-1 frame, which contain a total of 2349 bytes, are allocated to the virtual container. The virtual container itself comprises a container for the payload signal (260 columns), preceded by one column of path overhead. The virtual container carried in an STM-1 frame is referred to as a Virtual Container Level 4, or VC-4. VC-4, which is transported unchanged across the SDH network, provides a channel capacity of 150.34 Mbps. The VC-4 structure includes one column (9 bytes) for the VC-4 path overhead, leaving 260 columns of signal carrying capacity (149.76 Mbps). This carrying capacity is sufficient for transporting a 139.264 Mbps tributary signal (the fourth level in the PDH signal hierarchy). The VC-4 signal carrying capacity can also be subdivided, to permit the transport of multiple lower-level PDH signals.

2.3.2 Pointers

In Figure 2.3.1, the VC-4 appears to start immediately after the section overhead part of the STM-1 frame. Actually, to facilitate efficient multiplexing and cross-connection of signals in the SDH network, VC-4 structures are allowed to float within the payload part of STM-1 frames. This means that the VC-4 may begin anywhere within the STM-1 payload part. The result is that in most cases, a given VC-4 begins in one STM-1 frame and ends in the next. Were the VC-4 not allowed to float, buffers would be required to store the VC-4 data up to the instant it can be inserted in the STM-1 frame. These buffers (called slip buffers), which are often used in PDH multiplex equipment, introduce long delays. Moreover, they also cause disruptions in case a slip occurs.

2.3.2.1 Identifying VC-4 Beginning in the STM-1 Frame

When a VC-4 is assembled into the STM-1 frame, a pointer (byte) located in the section overhead of the STM-1 frame indicates the location of the
first byte (J1) of the VC-4 that starts in that STM-1 frame.

### 2.3.2.2 Using Pointers to Correct Timing Differences

SDH network are intended to operate as synchronous networks. Ideally, this means that all SDH network nodes should derive their timing signals from a single master network clock. However, in practical applications, network implementation must accommodate timing differences (clock offsets). These may be the result of an SDH node losing network timing reference and operating on its standby clock, or it may be caused by timing differences at the boundary between two separate SDH networks. The VC-4 is allowed to float freely within the space made available for it in the STM-1 frame, therefore phase adjustments can be made as required between the VC-4 and the STM-1 frame. To accommodate timing differences, the VC-4 can be moved (justified), positively or negatively three bytes at time, with respect to the STM-1 frame. This is achieved by simply recalculating and updating the pointer value at each SDH network node. In addition to clock offsets, updating the pointer will also accommodate any other adjustment required between the input SDH signal rate and the timing reference of the SDH mode. Pointer adjustments introduce jitter. Excessive jitter on a tributary signal degrades signal quality and may cause errors. Therefore, SDH networks must be designed to permit reliable distribution of timing to minimize the number of pointer adjustments.

### 2.4 SDH Overhead Data

In SDH networks, a transmission path can include three equipment functions:

- **SDH terminal multiplexer** – which performs the insertion/removal of tributary signals into SDH frames.

- **SDH cross-connect switch** – permits to change the routing of tributary signals carried in SDH frames.
• **Regenerator** – used to increase the physical range of the transmission path. The resulting structure of an SDH transmission path is shown below.

The resulting structure of an SDH transmission path is shown in Figure 2.4.1.

As shown above, a transmission path can comprise three types of segments:

- **Multiplexer section** – a part of a transmission path located between a terminal multiplexer and an adjacent SDH cross-connect equipment, or between two adjacent SDH terminal multiplexers.

- **Regenerator section** – a part of a transmission path located between a terminal multiplexer or SDH cross-connect equipment and the adjacent regenerator, or between two adjacent regenerators. A multiplexer section can include up to three regenerator sections.

- **Path** – the logical connection between the point at which a tributary signal is assembled into its virtual container, and the point at which it is disassembled from the virtual container.

To provide the support and maintenance signals associated with transmission across each segment, each of these segments is provided with its own overhead data, hence three types of overhead data:
• **Section overhead**, carried in the first nine columns of the STM-1 frame:
  
  – Multiplexer section (MS) overhead – carried in overhead rows 5 to 9.
  – Regenerator section (RS) overhead – carried in overhead rows 1 to 3.
  – AU pointers – carried in overhead row 4.

• **Path overhead**, carried in the first column of a VC-4. The path overhead carried in the VC-4 is called high-order path overhead; see Section 5 for a description of the low-order path overhead.

Figure 2.4.2 shows the detailed structure of the overhead data in STM-1 frames.

### 2.4.1 Regenerator Section Overhead (RSOH)

A regenerator section of an SDH network comprises the transmission medium and associated equipment between a network element and the adjacent regenerator, or between two adjacent regenerators. The associated equipment includes the aggregate interfaces and SDH processing equipment which either originates or terminates the regenerator section overhead. The functions of the various bytes carried in the STM-1 regenerator section overhead are described in Appendix B.

### 2.4.2 AU Pointers (H1, H2, H3 bytes)

The AU (Administration Unit) pointer bytes are used to enable the transfer of STM-1 frames within STM-N frames, and therefore are processed by multiplexer section terminating equipment. Separate pointers are provided for each STM-1 frame in an STM-N frame. AU pointer function is to link between the section overhead and the associated virtual container(s).
Figure 2.4.2: Organization of STM-1 Overhead Data
2.4.3 Multiplexer Section Overhead (MSOH)

A multiplexer section of an SDH network comprises the transmission medium, together with the associated equipment (including regenerators) that provide the means of transporting information between two consecutive network nodes (e.g., SDH multiplexers). One of the network nodes originates the multiplexer section overhead (MSOH) and the other terminates this overhead. The functions of the various bytes carried in the STM-1 multiplexer section overhead are described in Appendix B.

2.4.4 VC-4 Path Overhead Functions

The path overhead (POH) is contained within the virtual container portion of the STM-1 frame. The POH data of the VC-4 occupies all the 9 bytes of the first column. The functions of the various bytes carried in the VC-4 path overhead are described in Appendix B.

2.5 SDH Tributary Units

The VC-4 channel capacity, 149.76 Mbps, has been defined specifically for the transport of a fourth level (139.264 Mbps) PDH multiplex signal. To enable the transport and switching of lower-rate tributary signals within the VC-4, several special structures, called Tributary Units (TUs), have been defined. The characteristics of each TU type have been specifically selected to carry one of the standardized PDH signal rates. In addition, a fixed number of whole TUs may be mapped within the container area of a VC-4.

2.5.1 Tributary Unit Frame Structure

The structure of the tributary unit frame is rather similar to the SDH frame structure, described in Section 2.2.3. With reference to Figure 2, the tributary unit frame also includes a section overhead part and a virtual container part, which comprises a container and path overhead. In general, the tributary unit frame is generated in three steps:
• A low rate tributary signal is mapped into the TU “container”.

• Low-path path overhead is added before the container, to form the corresponding virtual container (VC-11, VC-12, VC-2 or VC-3, depending on the TU type).

• A TU pointer is added to indicate the beginning of the VC within the TU frame. This is the only element of TU section overhead.

The TU frame is then multiplexed into a fixed location within the VC-4. Because of the byte interleaving method, a TU frame structure is distributed over four consecutive VC-4 frames. It is therefore more accurate to refer to the structure as a TU multiframe. The phase of the multiframe structure is indicated by the H4 byte contained in the VC-4 path overhead.

2.5.2 SDH Multiplexing Hierarchy

Figure 2.5.1 shows a general view of the SDH multiplexing hierarchy. The hierarchy illustrates all the both the European and North American PDH multiplex levels.

Figure 2.5.1 also shows the utilization of additional SDH signal structures:

• TUG: tributary unit group, is the structure generated by combining several lower level tributaries into the next higher level tributary. For example, TUG-2 is generated by combining 3 TU-12 or 4 TU-11, and TUG-3 is generated by combining 7 TUG-2.

• AU: administrative unit, is a structure that includes a VC and a pointer to the beginning of the VC. For example, AU-3 contains one VC-3 and includes a pointer to the beginning of the VC.

• AUG: administrative unit group, is the structure generated by combining several lower level administrative units into the next higher level administrative unit. For example, AUG for the STM-1 level is generated by combining 3 AU-3 (several AUG can be combined for generating STM-N (N = 4, 16, etc.) structures).
The flexibility of the SDH multiplexing approach is illustrated by the many paths that can be used to build the various signal structures. For example, Figure 2.5.1 shows that the STM-1 signal can be generated by the following multiplexing paths:

- Each E1 signal is mapped into a VC-12, which is then encapsulated in a TU-12.
- Each group of 3 TU-12 is combined to obtain a TUG-2 (3 E1 signals per TUG-2).
- Seven TUG-2 are combined to obtain one TUG-3 (21 E1 signals per TUG-3). TUG-3 is carried in a VC-3.
- Three VC-3 are combined to generate one VC-4 (63 E1 signals per VC-4). The STM-1 signal carries one VC-4.
Chapter 3

Optical Transceivers

3.1 Introduction

An optical transmission link can be defined as the physical medium over which an information carrying optical signal propagates between a transmitter and a receiver. In the transmitter an optical carrier, generally the output of a laser, is modulated with a bit sequence. At the receiver, the optical signal is again converted into an electrical signal using one or more photodiodes. After a binary decision, ideally, the transmitted bit sequence is again obtained.

The first part (Section 3.2) of this chapter discusses optical transmitter specifications. Then, we focus on the devices used for electrical-to-optical conversion, namely, the laser and the modulator. Their characteristics are important for the driver design as well as the transmission system design.

At the output end of an optical transmission line, there must be a receiving device which interprets the information contained in the optical signal. The first element of this receiver is a photodetector that it must meet very high performance requirements. This will be dealt with in the second part of this chapter (Section 3.3).
3.2 Optical Transmitters

The transmitted signal is a two-level binary data stream consisting of either a 0 or a 1 in a time slot duration. This time slot is referred to as a bit period. Electrically, there are many ways of sending a given digital message. One of the simplest (but not necessarily the most efficient) techniques for sending binary data is amplitude-shift keying, wherein a voltage level is switched between two values, which are usually on or off. The resultant signal wave thus consists of a voltage pulse of amplitude relative to the zero voltage level when a binary 1 occurs and a zero voltage-level space when a binary 0 occurs.

The function of an optical transmitter is to convert the electrical signal to an optical signal. An electric current \( i(t) \) can be used to modulate directly an optical source (either a LED or a laser) to produce an optical output power \( P(t) \). Thus, in the optical signal emerging from the transmitter, a 1 is represented by a pulse of optical power (light) of the same duration of bit period, whereas a 0 is the absence of any light.[5]

3.2.1 Types of Modulation

Figures below illustrate two alternative ways to generate a modulated optical signal. In Fig. 3.2.1, the laser is turned on and off by modulating its current; this method is known as direct modulation. In Fig. 3.2.2, the laser is on at all times, a so-called continuous wave (CW) laser, and the light beam is modulated with a king of optoelectronic shutter, a so-called modulator; this method is known as external modulation. Direct modulation has the advantages of simplicity, compactness and cost effectiveness, whereas external modulation can produce higher-quality optical pulses, permitting extended reach and higher bit rates. Direct as well as external modulation can be used to produce non-return-to-zero (NRZ) or return-to-zero (RZ) modulated optical signal[2].
3.2.2 Extinction Ratio

Optical transmitters, no matter if directly or externally modulated, do not shut off completely when a zero is transmitted. This undesired effect is quantified by the extinction ratio (ER), which is defined as follows:

\[ ER = \frac{P_1}{P_0} \]  \hspace{1cm} (3.2.1)

\[ ER_{dB} = 10 \log ER \]  \hspace{1cm} (3.2.2)

where \( P_0 \) is the optical power emitted for a zero and \( P_1 \) the power for a one. Ideally ER is infinite. Typically, ERs for directly modulated lasers range from 9 to 14 dB, whereas ERs for externally modulated lasers can exceed 15 dB. SONET/SDH transmitters typically are required to have an ER in range of 8 to 12 dB, depending of the application [2].
So, a key indicator of the performance of an optical-fiber-based communications system is extinction ratio. The extinction ratio is used to describe the efficiency with which the transmitted optical power is modulated over the fiber-optic transport. The convention adopted for logic levels is that transmission of light (laser on) represents a logic “1” and no light transmission (laser off) represents a logic “0”.

$P_0$ is ideally equal to zero, making the optimum extinction ratio infinite. When the extinction ratio is not optimum, however, the transmitted power must be increased in order to maintain the same Bit Error Ratio. This increase in transmitted power due to non-ideal values of extinction ratio is called the “extinction-ratio power penalty”. It is demonstrated (ref. [5] pags. 303-305) that the ER power penalty is defined as the ratio of the average power required for a given value of ER to the average power required for the ideal case of $ER = \infty$. So, different values of ER produce a certain quantity of power penalty as illustrated in Figure 3.2.3.

In the experimental part of this thesis, will be illustrated how measure this important factor. The measurement system typically consists of
a digital storage oscilloscope or wideband digital-sampling oscilloscope and optical-to-electrical (O/E) converter. In practice, an accurate determination of extinction ratio is notoriously difficult to make. A common source of measurement error is the offset due to the dark current\(^1\) of the O/E converter’s photodiode. It’s the result of an output voltage generated by the photodiode in the absence of any optical signal power at its input. Failing to properly account for the dark current or any other minor measurement inaccuracies (particularly with respect to the \(P_0\) level) can result in significant error\([15]\).

### 3.2.3 Laser

In optical communications there are different types of sources what the LEDs and the Lasers. The seconds ones are the most commonly used thanks to its high performances.

The word laser is the acronym from Light Amplification by Stimulated Emission of Radiation. Laser is a mechanism for emitting electromagnetic radiation, often visible light, via the process of stimulated emission. The emitted laser light is (usually) a spatially coherent, narrow low-divergence beam, that can be manipulated with lenses. In laser technology, “coherent light” denotes a light source that produces (emits) light of in-step waves of identical frequency, phase and polarization\([16]\).

In data communication system the Fabry-Perot (FB) laser is preferred because of its lower costs. The FB laser is called semiconductor laser or laser diodes. In the following, there is a short description of the FB laser, in order to understand the basic concepts.

#### 3.2.3.1 Fabry-Perot Laser

Figure 3.2.4 illustrates a schematic model of a FB laser. It consists of a gain medium inside a highly reflective optical cavity, as well as a means to supply energy to the gain medium. The gain medium is a material with properties that allow it to amplify light by stimulated emission. It is formed

\(^1\)Typically, it is less than 5 nA for high-speed applications. So, this effect, in this thesis, is negligible.
Figure 3.2.4: The Fabry-Perot laser

by a forward biased p-n junction which injects carriers (electrons and holes) into a thin active region. These carriers “pump” the active region such that an incoming photon can stimulate the recombination of an electron-hole pair to produce a second identical photon. Thus, stimulated emission provides optical gain if the bandgap energy, that is, the energy released by the electron-hole pairs, matches the energy of the photons to be amplified. 1310 nm as well as 1550 nm lasers can be based on an InGaAsP active layer. The distance between p-type and n-type substrate, determines the wavelengths at which the laser can operate.

3.2.3.2 L/I Characteristics

The static relationship between the laser current, $I_L$ and the light output, $P_{out}$ is described by the curve in the Figure 3.2.5. Figure 3.2.5 shows the laser dependence of temperature and age. It is possible to note the parameter $I_{TH}$, it is called threshold current, a small amount of current due to incoherent light at output of laser. The current $I_{TH}$, is described by Equation 3.2.3.
Figure 3.2.5: L/I curves for a semiconductor laser

\[ I_{TH}(T) = I_{TH0} \exp \left( \frac{T}{T_0} \right) \]  \hspace{2cm} (3.2.3)

where \( I_{TH0} \) is the threshold current at 0 K and \( T_0 \) is a constant in the range of 50 to 70 K [2].

3.2.3.3 The Currents of Laser

There are two kind of laser’s currents:

1. **Bias current** \( I_B \): is the current supplied by the laser driver when transmitting a zero (laser off).

2. **Modulation current** \( I_M \): is the current added to the bias one when transmitting a one (laser on).

Figure 3.2.6 shows L/I curve where is illustrated the two currents. So, the laser current \( I_L \) varies depending on DC or AC coupling\(^2\) of the laser driver.

\(^2\)DC, Direct Coupling. AC, Alternative Coupling. AC coupling consists of using a capacitor to filter out the DC signal component from a signal with both AC and DC components. The capacitor must be in series with the signal. AC coupling is useful because the DC component of a signal acts as a voltage offset, and removing it from the signal can increase the resolution of signal measurements. AC coupling is also known as capacitive coupling.
\[ I_L = \begin{cases} 
  I_B \div (I_B + I_M) & \rightarrow \text{DC - Coupled} \\
  I_B - \frac{I_M}{2} \div I_B + \frac{I_M}{2} & \rightarrow \text{AC - Coupled} 
\end{cases} \quad (3.2.4) \]

In case of AC coupling, the bias current is defined as average current into the laser.

The bias and modulation currents of a laser driver are controlled either directly with (analog or digital) trim pots. One of the scopes of this thesis is understand how varying these currents is possible to improve the system performances. Besides, the bias current also, is controlled by an automatic power control (APC) circuit using feedback from the monitor photodiode.

Typically range available in commercial at 2.5 and 10 Gbit/s drivers for uncooled lasers is [2]

\[ I_M = 10 \ldots 100 \text{ mA} \quad (3.2.5) \]

\[ I_B = 0 \ldots 100 \text{ mA} \quad (3.2.6) \]
In the practice, bias current is used to indicate the operational point along the L/I laser curve as showed in Figure 3.2.7. This point is in the middle between zero level and one level. Besides, operational point is very important because it varies the extinction ratio. Ideally, zero level has to be a very low power level which, with a certain modulation current, increases ER value (8 dB are necessary in SDH applications). An numerical example can help to understand better.

Example

\[ BIAS_1 = 20 \text{ mA} \left\{ \begin{array}{l} P_0 = 0.1 \text{ mW} \\ P_1 = 3.1 \text{ mW} \end{array} \right\} \Rightarrow ER_{dB} = 10 \cdot \log_{10} \left( \frac{P_1}{P_0} \right) = 10 \cdot \log_{10} \left( \frac{3.1}{0.1} \right) \approx 15 dB \]
\[
B I A S_2 = 50 \text{ mA} \begin{cases} P_0 = 4 \text{ mW} \\ P_1 = 7 \text{ mW} \end{cases} \Rightarrow ER|dB = 10 \cdot \log_{10} \left( \frac{P_1}{P_0} \right) = 10 \cdot \log \left( \frac{7}{4} \right) \approx 2.5 dB
\]

### 3.3 Optical Receiver

At the end of any transmission system there is a receiver that store the information (either electric or light), processes it and it shows the result(s) at the final user(s). In optical field, the firts element of any receiver is the photodetector. This device is particularly important in the receiver operations, for example, its responsivity and noise properties, have a significant impact on the receiver’s performance. In the following two types of photodetector will shortly be explained: the \textit{p-i-n photodetector} and the \textit{avalanche photodetector} (APD). The last one is integrated in the Tektroniks ST2400A that will be used in lab’s practice (Part II - Practice).

The most meaningful criterion for measuring the performance of a digital communication system is the average error probability. The calculation of the error probability for a digital optical communication receiver differs from that conventional systems. This is because of discrete quantum nature of the optical signal and also because of this probabilistic character of the gain process when an avalanche photodiode is used. Various authors have used different numerical methods to derive approximate predictions for receiver performance. In this thesis [2, 5] will make as references.

#### 3.3.1 Photodetectors

##### 3.3.1.1 P-I-N Photodetectors

The most common detector is the \textit{p-i-n phototetector}, also called \textit{p-i-n photodiode}, shown schematically in Figure 3.3.1. This simplest device is consists of a p-n junction separated by a sub-strate of intrinsic region denominated \textit{i} . The junction must be reverse biased to create a strong electric field in the \textit{i} region. The light incident on intrinsic layer create electron-hole pairs,
which become separated by electric drift field. So, this gives rise to a current flow in an external circuit, known as the photocurrent expressed in Equation 3.3.1 in function of quantum efficiency\(^3\) \(\eta\) (Equation 3.3.2) and the electron charge \(q\),

\[
I_p = \eta q \quad (3.3.1)
\]

\[
\eta = \frac{I_p}{q} = \frac{P_0}{\eta q} \quad (3.3.2)
\]

In Equation 3.3.2 \(P_0\) is the optical power incident on the photodetector and \(h\nu\) is the photon energy.

After that the responsivity of photodetector is defined by Equation 3.3.3

\[
\Re = \frac{I_p}{P_0} = \frac{nq}{h\nu} \quad (3.3.3)
\]

The width of intrinsic layer is an important factor, in fact the quantum efficiency is controlled by horizontal dimension, whereas the speed (band-

\(^3\)The fraction of photons that create electron-hole pairs with the total number of incident photons.
Figure 3.3.2: APD: basic structure

width) is controlled by the vertical dimension, as demonstrated by Equation 3.3.4,

$$BW = \frac{1}{2\pi} \cdot \frac{1}{W/v_n + R_{PD}C_{PD}}$$ (3.3.4)

where $W$ is the vertical dimension of $i$-layer, $v_n$ is the carrier velocity, $R_{PD}$ is the contact and spreading resistance and $C_{PD}$ is the photodiode junction capacitance. At 2.5 Gb/s or 10 Gb/s transmission systems, the reverse voltage\(^4\) should be chosen large in order to $v_n$ saturates at its maximum value and the transit time ($W/v_n$) is minimized [2, 5].

3.3.1.2 APD Photodetectors

Figure 3.3.2 shows the schematically structure of the *avalanche photodetector* (APD). At the contrary of p-i-n photodetector, there is an additional layer, called *multiplication region*. This newly provides gain through avalanche multiplication of electron-hole pairs generated in $i$-layer, now called the *absorption region*. This carrier multiplication mechanism is known as *impact ionization*, because electron-hole pairs are accelerated by the high electric

\(^4\)Typically 5-10 V.
The multiplication $M$ for all carriers generated in the photodiode is defined by Equation 3.3.5,

$$M = \frac{I_M}{I_p} \quad (3.3.5)$$

where $I_M$ is the average value of the total multiplied output current and $I_p$ is defined by Equation 3.3.1. So, the APD responsivity is

$$R_{ADP} = R \cdot M \quad (3.3.6)$$

But the reverse voltage of APD photodetector will be superior, in order of 40 - 60 V [2, 5].

### 3.3.2 Probability of Error

At the receiver measuring the rate of error is an aspect very relevant in the practice. A common method to measure how many errors occurring over a certain time is known as bit error rate (BER). This typical characteristic of a transmission system is defined by Equation 3.3.7

$$BER = \frac{N_e}{N_t} \quad (3.3.7)$$

where $N_e$ is the number of errors during a time interval $t$ and $N_t$ is the total number of bits transmitted in this time.

In digital/optical communication systems the acceptable minimal value of BER is $10^{-9}$. BER is strongly dependent on the signal noise ratio (SNR) or optical signal noise ratio (OSNR) at the receiver. The system error rate requirements and the receiver noise levels thus set a lower limit on the optical signal power level that is required at the photodetector.

These aspects are not very easy of as they seem. To calculate the BER at the receiver, know the probability distribution of the signal is necessary, because by means of this is possible to decide if 0 or 1 is sent. Figure 3.3.3 illustrates the relationship between signal, noise and bit error rate. The signal is a NRZ with noise (it is considered Gaussian). The noisy signal is sampled at the center of each bit period, producing two statistical Gaussian
Figure 3.3.3: Signal and probability distribution for received 0 and 1
distributions that have a standard deviation equal to the root mean square (\textit{rms}) of noise ripple. At midpoint between 1 and 0 level, there is a threshold voltage, that permit to distinguish where the distribution interferes with the other one. This area, (in the Figure 3.3.3, they are marked with orange and green lines) is the bit errors if an 1 is transmitted (orange zone) or if a 0 (green zone). \( P_0 \) and \( P_1 \) are the value of this area, i.e. the probability that a datum bit is received wrong.

Now, assuming that 0 and 1 occur with the same probability \( \frac{1}{2} \) imply that the two region (tail) of Gaussian distribution (orange and green) are equal in area, so the BER is defined by Equation 3.3.8

\[
BER = \int_Q^\infty Gauss(x) \, dx \quad (3.3.8)
\]

\[
Q = \frac{v_{pp}}{2 \cdot v_{rms}} 
\]

where in Equation 3.3.8 the function \( Gauss(x) \) is a normalized Gaussian distribution (zero mean and 1 of standard deviation), in Equation 3.3.9 \( v_{pp} \) is pick-to-pick value of signal received and \( v_{rms} \) is the rms of noise ripple (standard deviation). The lower bound of the integral \( Q \) is the difference between the one (or zero) level and the decision threshold \((v_{pp}/2)\) normalized in the standard deviation \( v_{rms} \) of Gaussian distribution [2]. The \textit{Q-factor} is very important in practice, it will often be used during the lab’s practice in Part II.

Overall, following passages the Equation 3.3.10 is obtained

\[
\int_Q^\infty Gauss(x) \, dx = \frac{1}{\sqrt{2\pi}} \int_Q^\infty e^{-\frac{x^2}{2}} \, dx = \frac{1}{2} \text{erfc} \left( \frac{Q}{\sqrt{2}} \right) \approx 
\]

\[
\approx \frac{1}{\sqrt{2\pi}} \cdot \frac{\exp\left(-\frac{Q^2}{2}\right)}{Q} 
\]

\( \text{erfc}(x) \) is an error function which is tabulated in various mathematical and technical books [2, 5, 6]. For example, the value \( Q \approx 7 \) corresponds
to a $BER = 10^{-12}$. Figure 3.3.4, shows the relationship between BER and Q-Factor.

How is possible to measure BER value in practice will be explained in the next chapter.
Chapter 4

Measurements and Tests over SDH Transmission Systems

4.1 Introduction

As with any communication systems, the basic performance measure for a fibre optic system is accuracy with which it can transmit information from one point to another. So, the quality and the issues of physical transmission, are very important to be known with the purpose to study and design a telecommunication network. This chapter is the most important for understanding better the lab’s practice that will be described in the Chapter 5. So, it introduces methods and techniques for analyzing the physical characteristics of digitally modulated optical carriers.

Physical level tests can be classified into three major areas:

1. Bit error ratio testing (BERT)
2. Eye diagram analysis
3. Jitter analysis

In the following, these three aspects will be described.
4.2 Bit Error Ratio Testing

In the Chapter 3 (Section 3.3.2) were introduced the concept of probability of error and bit error installments, observing above all the aspects mathematicians and theorists. Two types of bit error measurements can be conducted (Rec. [R2]):

1. In-service testing
2. Out-of-service testing

In-service testing is performed on the system during actual operation to give early warning of problems. In one approach, a single 64kb/s line is taken out of service and a known test pattern injected onto the line. The error performance of this line can be considered representative of all other lines on the system. Out-of service testing involves injecting a known test pattern onto the serial line. The system cannot carry live traffic during the test, so it is best suited for research and development or manufacturing test environments. The equipment used for out-of-service testing is known as a bit-error-ratio tester, or BERT.

The concept behind bit-error-ratio testing is shown in Figure 4.2.1.

The BERT consists of 2 sections: a pattern generator and an error detector. The pattern generator creates the test pattern together with a separate
clock signal at the selected data rate. This pattern is injected into the system under test and received at the error detector’s data rate input. The error detector includes its own pattern generator that produces an exact replica of the known test pattern and a comparator that checks every received bit against this internally generated pattern. Each time the received bit differs from the known transmitted bit, an error is logged. The pattern generator and the error detector must operate at identical clock rates and the phase relationship between them must be stable. The easiest way to ensure this is to use the pattern generator’s clock as the clock source for the error detector. This is straightforward enough when the two units are in close physical proximity a direct electrical connection can be made between them. When they are physically separated, for example at opposite ends of a transmission link, a direct connection may not be possible. In this case, the error detector’s clock signal must be recovered directly from the data.

The most common test pattern for out-of-service BER testing is the pseudo-random binary sequence, that it explains with details in the Appendix A. In the few words, PRBS pattern is generated by using a train of shift register with feedback. The pattern length is $2^N - 1$ ($N$ is integer$^1$).

In the [R1] and [R3] international recomandations, explains standards metrics of SDH transmission system.

4.3 Eye Diagram

4.3.1 Cocept

For evaluating the digital transmission systems, the eye diagram is the key tool to estimate the system reliability. The eye diagram is a composite of multiple pulses captured with a series of triggers based on data clock pulse fed separately into the scope. The scope overlays the multiple pulses to form the eye diagram. An eye diagram is a composite view of all the bit periods of a captured waveform superimposed upon each other. In other words, the waveform curve from the start of period 2 to the start of period 3 is overlaid

$^1$Typically $N$ is 7, 10, 15, 20, 23 or 31. Tektroniks ST2400A uses $2^{23} - 1$. 

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4.3.1: Concept of an eye-diagram [1]

on the curve from the start of period 1 to the start of period 2 and so on for all bit periods.

A properly constructed eye should contain every possible bit sequence from simple 101’s and 010’s, through to isolated ones after long runs of consecutive zeros and other problem sequences that often show up weaknesses present in system design (Figure 4.3.1)[12].

4.3.2 Useful Informations

Eye diagrams show parametric information about the signal (effects deriving from physics such as system bandwidth health, etc.). It will not show protocol or logical problems, if a logic 1 is healthy on the eye, this does not reveal the fact that the system meant to send a zero. However, if the physics of the system mean that a logic one becomes so distorted while passing through the system that the receiver at the far end mistakes it for a zero, this should be shown in a good eye diagram. Common ways of characterizing an eye are to
measure the rise times, fall times, jitter at the middle of the crossing point of the eye, the overshoot present and many other numerical descriptions of eye behavior in order to compare devices being measured. Instruments usually offer automated measurements that simplify and speed up the taking of such measurements.

### 4.3.3 Eye-Parameter Analysis

Different parameters are obtainable through the eye diagram. These parameters are directly results through statistic measures on the diagram, using the technique of the histogram directly on the oscilloscope. The histogram represents the mean of a distribution of values (Figure 4.3.3). This because the real data patterns consists of many different combinations of ones and zeros, so, it is impossible to base measurements on a single value waveforms.

Most eye parameters are referenced from four fundamental proprieties of the eye: one level, zero level, crossing time and crossing amplitude (Figure 4.3.2). Both the means and the standard deviations of these proprieties are important, so they must be measured using the histogram function of the oscilloscope [1].

**One/Zero Level.** This is measure of the mean logic one-level. It is found by construcion a vertical histogram in a narrow region about the center of the eye that includes only one-level data. Often, 40-60 window is used. The one level is the mean of the histogram and the standard deviation is the rms noise. The zero level corresonds to mean logic zero-value.

**Eye Crossing.** As shows Figure 4.3.2, there are two type of crossing: crossing time and crossing amplitude. The firts one defines the start (First Crossing Time) and the stop (Second Crossing Time) of bit period. To calculate this value, a horizontal histogram is made, and position
it where rising\textsuperscript{2} and falling\textsuperscript{3} edges of eye intersect. It is important to observe that the standard deviation corresponds to jitter, that it will described in detail more before.

\subsection*{4.3.4 Histogram Use Defects}

The problem with histograms is that the solutions vary with the chosen number of bins and bin sizes, and, thus, they yield no unique answer. Furthermore, the values of the performance metrics differ depending upon whether the mean, mode, or median of the histogram is utilized. The IEEE Standard on Transitions, Pulses, and Related Waveforms recommends using the mode

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{eye_diagram.png}
\caption{Fundamental properties of an eye diagram [14]}
\end{figure}

\textsuperscript{2}It refers to the time required for a signal to change from a specified low value to a specified high value. Typically, these values are 10\% and 90\% of the step height. In optical application 20\%-80\% is used for the presence of noise and jitter.

\textsuperscript{3}It refers to the time required for the amplitude of a pulse to decrease (fall) from a specified high value (usually 90\% of the peak value exclusive of overshoot or undershoot) to low value (usually 10\% of the minimum value exclusive of overshoot or undershoot).
or mean of a histogram, both of which depend on the distribution of the data. This is particularly important with respect to eye patterns, where the distribution is often not symmetric [12].

4.3.5 Calculating Extinction Ratio

The Section 3.2.2 have illustrated of the ER and his physical meaning to a system of transmission. Now, a method will be described for calculating it through eye diagram.

4.3.5.1 Histogram method

According to Equation 3.2.1, measure the mean value of one and zero levels making the histogram at both levels and calculate the ratio \( \mu_1 / \mu_0 \).\(^4\)

4.3.5.2 Example of ER Calculating without Histogram Use

This method is described according to reference [12], an IEEE publication. In the practice in Part II of this thesis, histogram method will be used.

ER is defined as the ratio of the average power used to transmit a logic level “1” to the average power used to transmit a logic level “0”. First,\(\)

\(^4\) \(\mu_0 \) and \(\mu_1 \) are the average of the zero and one level respectively.
calculate the central point $t_c$ of the eye diagram as follows:

$$t_c = \frac{\bar{t}_1 + \bar{t}_2}{2} \quad (4.3.1)$$

where $\bar{t}_1$ and $\bar{t}_2$ are the average first and second crossing times.

Extinction ratio can be computed from the mean of the data located in the central 20% of the eye diagram. Thus, the time span covers $t_c \pm 0.1T_B$.

Next, separate the data located in the central 20% of the eye diagram into top and bottom halves. This is done by using the value $(\mu_0 + \mu_1)/2$ as the horizontal separator. For each cluster, calculate the means $\mu_{\text{high}}$ and $\mu_{\text{low}}$. Finally, calculate the extinction ratio as follows:

$$ER = \frac{\mu_{\text{high}}}{\mu_{\text{low}}} \quad (4.3.2)$$

### 4.3.6 Calculating Q-Factor

The Q-Factor has been introduced in the Section 3.3.2 and it is an important characteristic of a transmission link. Finally, the Q-Factor is a measure of the digital signal eye-aperture; it adopts the concept of SNR in a digital signal and it is an a evaluation method that assumes a normal noise distribution. Now, a practice method to calculate it, is illustrated below through the use of an oscilloscope.

Figure 4.3.4 allows to value Q-Factor directly on the oscilloscope. Equation 4.3.3 is gotten from Equation 3.3.9,

$$Q = \frac{|\mu_1 - \mu_0|}{\sigma_1 + \sigma_0} \quad (4.3.3)$$

Instruments usually offer automated measurements that simplify and speed up the taking of such measurements. This will be described in during the experimental part of this thesis.

---

$^5$ $T_B$ is bit period.
4.3.7 Jitter Measurements

Jitter is basically a phase shift respect to the ideal position in time of a digital signal that travels in a transmission channel, and corresponds to the standard deviation experienced by the samples (Figure 4.3.5). The Jitter is a wholly undesirable effect in any communication system and therefore introduces a number of problems to the channel, which if not treated properly can completely degrade the quality and operation of the link. The jitter can cause errors in the reception of bits (BER degradation), because if not controlled it will confuse the recipient and cannot recover the clock synchronization on the receiving end, also can cause intersymbol interference (ISI) between pulses that propagate through the channel, because the jitter will produce a shift of the signals that make up the pulse and thus are mixed, thus precluding the recognition of the respective levels of the signal at the receiver.

Observing the eye-diagram, the jitter is the time interval around the crossing point. A traditional method of measuring it in an eye-diagram is placing a window around of this point and construct a histogram of samples taken only this region or automatically through the oscilloscope options.
A low jitter generation is desirable because it improves the horizontal eye-opening. Furthermore, in some types of regenerator, the clock signal recovered from the receiver optical signal is used to retransmit the data. Thus, to prevent excessive jitter accumulation along the chain, very tough jitter specifications are imposed on each generator. The jitter generation limits for a SDH transmitter prescribed by the standard [R5] and rewrite in Table 4.1 in case of 2.5 Gb/s transmission system (STM-16). Timing jitter as measured over a 60-second interval with a band pass filter with a lower cut-off frequency $f_1$ and a minimum upper cut-off frequency $f_4$ shall not exceed $B_1$ Unit Intervals (UI) peak-to-peak. Also, timing jitter as measured over a 60-second interval with a band pass filter with a lower cut-off frequency $f_3$ and a minimum upper cutoff frequency $f_4$ shall not exceed $B_2$ Unit Intervals (UI) peak-to-peak [R5].

ST2400A Jitter Transfer\textsuperscript{7} is between 30 kHz and 300 kHz, so $f_1$ and $f_4$ frequencies are more appropriated (even if $f_3$ in under study at 2.5Gb/s but, according to recommendation a value of 1 MHz has been suggested).

\textsuperscript{6}It is the phase deviation of one clock period.

\textsuperscript{7}Jitter Transfer is the ratio of the amplitude of an equipment’s output jitter to an applied input sinusoidal component. This characteristic is specified in ST2400A User Manual.
Figure 4.3.6: Jitter measurement

<table>
<thead>
<tr>
<th>STM level</th>
<th>$f_1$ [Hz]</th>
<th>$f_3$ [kHz]</th>
<th>$f_4$ [MHz]</th>
<th>$B_1(UI_{pp})$</th>
<th>$B_2(UI_{pp})$</th>
</tr>
</thead>
<tbody>
<tr>
<td>STM-16</td>
<td>5000</td>
<td>1000</td>
<td>20</td>
<td>1.5</td>
<td>0.15</td>
</tr>
</tbody>
</table>

Table 4.1: SDH jitter limits from recommendation [R5]
So, in STM-16 transmission each UI equals to 0.4 ns and the maximum timing jitter (peak-to-peak) accepted is of:

\[
Jitter_{pp}^{\text{max}} = 1.5 \cdot 0.4 \times 10^{-9} = 600 \times 10^{-12}
\]

\(Jitter_{pp} < 600\) ps

### 4.3.8 Eye-Parameter Summary

Table 4.2 reassumes the eye-parameter definitions [1].

In the following, there is a description of the nomenclature used:

- \(\mu_1\) mean logic one-level
- \(\mu_0\) mean logic zero-level
- \(\mu_{95}\) 95th percentile of amplitude distribution extending upward from mean logic one-level to maximum data value
- \(\sigma_{\text{crossing}}\) standard deviation of time histogram about eye-crossing level
- \(\sigma_1\) standard deviation of amplitude histogram about one-level
- \(\sigma_0\) standard deviation of amplitude histogram about zero-level
- \(t_{\text{crossing}1}\) time location of first eye-crossing
- \(t_{\text{crossing}2}\) time location of second eye-crossing

### 4.4 Optical Power Budget

Another important measure used to in optic communication field is the *optical power budget*. It allow to know the complete scenery of all transmission link. Power budgeting for a digital optical fiber communication system is performed in a similar way to power budgeting within any communication system. When the transmitter characteristics, fiber cable losses and receiver

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<table>
<thead>
<tr>
<th>Eye Parameter</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Eye height / Eye opening</td>
<td>((\mu_1 - 3\sigma_1) - (\mu_0 + 3\sigma_0))</td>
</tr>
<tr>
<td>Eye width</td>
<td>((t_{crossing2} - 3\sigma_{crossing}) - (t_{crossing1} + 3\sigma_{crossing}))</td>
</tr>
<tr>
<td>RMS Jitter</td>
<td>(\sigma_{crossing})</td>
</tr>
<tr>
<td>Q-Factor</td>
<td>(</td>
</tr>
<tr>
<td>Overshoot</td>
<td>(\frac{\mu_1 + \mu_{95%}}{\mu_1 - \mu_0})</td>
</tr>
</tbody>
</table>

Table 4.2: Eye-Parameter definitions [1]
sensitivity are known, the relatively simple process of power budgeting allows the repeater spacing or the maximum transmission distance for the system to be evaluated [6].

So, the key to network distance is optical power budget: the amount of light available to make a fiber optic connection.

The first step is determining how much light is available for the electronic device themselves. Two measurements are needed from the manufacturer of the equipment. Minimum transmit power represents the worst case transmit power for a device (the device to guaranteed to provide at least that much power). The second piece of information required is the minimum receiver sensitivity. This figure represents the minimum amount of light required by the receiver to operate correctly (normally is $10^{-9}$ of BER).

Thus, if $P_s$ is the optical power emerging from the end of a fiber flylead attached to the light source, and if $P_R$ is the receiver sensitivity, then [5]

$$Optical\ Power\ Budget = P_S - P_R$$ (4.4.1)

However, it is important to add a system margin\(^8\) so that small variations in the system operating parameters do not demage system performance. So, Equation 4.4.1, can be rewrite in Equation 4.4.2

$$Optical\ Power\ Budget = P_S - P_R = 2l_c + \alpha_f L + M$$ (4.4.2)

where $l_c$ is connector loss, $\alpha_f$ is the fiber attenuation (dB/km), $L$ is the transmission distance and $M$ is the margin [5].

In conclusion, to know the optical power budget allow to determine the maximum link length without repeaters, it is also frequently used to aid decision in relation to combination of components required for a particular optical communication system. In Table 4.3 there is an example of optical power budget calculating with 25 km of optical fiber with an attenuation equals to 0.5 dB/km and results in a final power margin of 7 dB (i.e. an excess power of 7 dB).

\(^8\)Typically value is 5 - 8 dB [6].
<table>
<thead>
<tr>
<th>Component / loss parameter</th>
<th>Output / sensitivity / loss</th>
<th>Power margin (dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Min. Laser output</td>
<td>-5 dBm</td>
<td></td>
</tr>
<tr>
<td>Min. APD sensitivity</td>
<td>-32 dBm</td>
<td>27</td>
</tr>
<tr>
<td>Source and receiver connector loss</td>
<td>2 dB</td>
<td>25</td>
</tr>
<tr>
<td>Other connector losses</td>
<td>5 dB</td>
<td>20</td>
</tr>
<tr>
<td>Total splice loss</td>
<td>0.5 dB</td>
<td>19.5</td>
</tr>
<tr>
<td>Cable loss</td>
<td>$25 \times 0.5 = 12.5$ dB</td>
<td>7 (final)</td>
</tr>
</tbody>
</table>

Table 4.3: Example of optical power budget calculating
Part II

Practice
Chapter 5

Student Practice Realization

5.1 Introduction

This is the experimental part of this thesis. The principal purpose is to create a practice of laboratory for students, having as background all the first theoretical part. All work are based on a particular device made by Tektroniks, which name is ST2400A. The ST2400A is the first STM-16 (SDH)/OC-48 (SONET) test product optimized for testing 2.488 Gbit/s Dense Wavelength Division Multiplexed (DWDM) client systems. This high capacity and sensitivity equipment, generates SDH (or SONET) traffic at about 2.5 Gbit/s, which it is possible to perform testing on it directly. The ST2400A is a transceiver electric/optic, that produces a standard SDH frame with overhead and payload, according to international recommendations. Next section introduces this device with more details.

The lab’s practice is formed to two principal parts. The first one allows to study a point-to-point SDH transmission on fiber optics carriers. The traffic is generated and performed by ST2400A. As described in the Chapter 4, for evaluating the system performance (for example BER) is necessary to generate a pseudo-casual sequence of bits in order to simulate a pseudo-real SDH traffic. The most common test pattern for out-of-service BER testing is the pseudo-random binary sequence (PRBS) with $N = 23$ (Section 4.2). This first part of practice consists of three sub-parts too:
1. **BER.** Where a measure system will be make, that allows to read BER values on the ST2400A directly in different network conditions (zero-length, 25 Km and 50 Km). BER’s degradation is due to the *chromatic dispersion* on the optical fiber.

2. **Eye-diagram analysis.** Students will learn to read an eye-diagram and evaluate its parameters such as Q-Factor, overshoot, histogram technique, extinction ratio, etc., in different network conditions.

3. **Jitter measurement.** In this part, a method to calculate temporal jitter (RMS and peak-to-peak) by the oscilloscope will be introduced.

The second part is more advanced. The electrical output is used for allowing to vary the laser bias current and observe how it is important for the system performance. Bias current is an important parameter necessary to optimize the performance. In fact, editing bias current, transmission parameters like Q-Factor or Optical Power change. The traffic is the same, i.e. SDH 2.5 Gbit/s, but now it is modulated by an external laser which lightwave is 1550 nm. Laser output is monitored by the oscilloscope. The target is to find a bias value to optimize the system performance. How does extinction ratio vary in function of bias current? And Q-Factor? These questions will be sharpened during the practice.

The second step is to fix optimum bias current and determine the system sensitivity (for example $Q \simeq 6 \rightarrow BER \simeq 10^{-9}$) and optical power budget.

After a short introduction of ST2400A, practice will be explained in details. In Appendix A, it is possible to find the complete practice, where there are all testing procedures. Besides, in Chapter 6 there are the results of these measurements.

### 5.2 Tektronix ST2400A

Tektronix ST2400A (Figure 5.2.1) is special test equipment that allow to generate SDH/SONET traffic at 2.5 Gbit/s, working as transmitter and receiver in the same time. It is possible to analyze BER in the each SHD
overhead section (RSOH and MSOH) in particular LOS, LOF, byte B1 and B2, etc. as illustrated in Appendix B. This section described user interface, hardware characteristics, and its principal operations. The device is very complex and in the case of a practice of laboratory dedicated to students, only base aspects will be considered. In Appendix C is illustrated commands description of this device.

5.2.1 Operating Characteristics

Figure 5.2.2 and 5.2.3 show two sections of ST2400A, transmitter and receiver section respectively. This structure is very simplified but it allows to understand the functions of this device. Outside of outlined line, there are user choices. Users can select the multiplexing type if 155 Mbps or 622 Mbps (i.e. 16 x STM-1 or 4 x STM-1 respectively) and the test pattern. When the different signals are multiplexed, it is possible to transmit electric signal directly or optical modulated by a laser at 1310 or 1550 nm with a bit rate of 2.5 Gbit/s. The receiver is consists of an ADP photodetector that receive the optical signal and send it to error detector. Error detector counts data errors that occur by parity bits (B1 for RSOH and B2 for
Figure 5.2.2: Block diagram of ST2400A: transmitter side

![Block diagram of ST2400A: transmitter side](image1)

Figure 5.2.3: Block diagram of ST2400A: receiver side

![Block diagram of ST2400A: receiver side](image2)
MSOH) include in the overhead sections of SDH frame. Errors counting are showed on the display. The output is available to user in 16xSTM-1 at 155 Mbps or 4xSTM-1 at 622 Mbps mode thanks to a demultiplexer.

The ST2400A provides electrical input and output clock and data interfaces operating at 2.488 Gb/s. The signal that inputs/outputs in electrical mode is \textit{ECL}\textsuperscript{1} type. This signal requires connection to an AC-coupled 50 Ohm termination through a \textit{bias-tee}\textsuperscript{2} network supplying.

If users select optical mode, the signal is directly modulated onto laser and transmitted on standard fiber at 0 dBm of power. The user can individually enable/disable laser \#1 (1310 nm), laser \#2 (1550 nm), and electrical outputs. Multiple outputs can be simultaneously active.

Receiver can be electrical or optical too. The optical one is a 1550 nm input at max -10 dBm of power which is connected to ADP photodetector. The electrical one (composed only data and clock) has to need a bias-tee termination (only data connector), like input.

Where payload testing is not required, or an external 155 or 622 Mbit/s tributary signal is not available, the ST2400A can operate independently. An internally-generated 2.488 Gbit/s test signal provides full error performance analysis and reporting of the 2.488 Gbit/s signal. \textit{Internal mode} (also it is available Through and External Mode, but not used in this practice) is ideal for DWDM SDH/SONET client system testing, where transmission quality test time and cost can be lowered through the use of a high-speed signal.

\textsuperscript{1}This is a differential signal that less susceptible to ground noise problems, as all noise becomes common-mode. Single-ended CMOS is much more susceptible, since ground bounce and other noise affect logic thresholds, degrading noise immunity. ECL signals remain unaffected, since noise rides on both signals as an average level. Logic levels are also less critical, since the threshold is the differential cross point, which can tolerate significant signal attenuation. Differential circuits also tend to generate less noise in the power supply.

\textsuperscript{2}A bias-tee is a three port network used for setting the DC bias point of some electronic components without disturbing other components. The bias tee is a diplexer. The low frequency port is used to set the bias; the high frequency port passes the radio frequency signals but blocks the biasing levels; the combined port connects to the device, which sees both the bias and RF. It is called a tee because the 3 ports are often arranged in the shape of a T.
5.3 BER and Dispersion Power Penalty Valuating

Measurement scenario includes a simple SDH at 2.5 Gbit/s point-to-point network, composed to a generator/receiver by ST2400A, Single Mode (SM) optical fibers, a variable optical attenuator, an optical coupler and an optical power meter. The test setup to measure the dispersion power penalty of a length of optical fiber is shown in Figure 5.3.1.

The experience starts with the calibration. The system must be cali-
brated before measuring the fiber. This involves determining the system sensitivity with no fiber in place \([1]\). With calibration procedure allows to measure an exactly power level \((P_{\text{cal}})\) at the outputs of optical power. The lightwave receiver must have high sensitivity. For SDH/SONET testing up to 2.5 Gbit/s, a sensitivity of at least -28 dBm is recomended \([R2]\). So, for calibrating this formula is used:

\[
P_{\text{cal}} = -28 - P_m
\]

where \(P_m\) is the optical power read at power meter. The calibration factor converts from the measured power meter reading in dBm to the optical power at the lightwave receiver.

After that, the system sensitivity is achieved using the jumper as showed in Figure 5.3.1. The scope is to set the optical attenuator to the level necessary to get a BER of about \(10^{-10}\) (or \(10^{-9}\) often is used), called \(P_{\text{ref}}\). Achieved this value, varing the optical attenuator and record more power level in BER range of \(10^8\) to \(10^4\). Plotting these values, zero-length curve is obtained. Now, for determining the dispersion power penalty, fiber spools at 25 and 50 km are used in this practice and repeating the same procedure like before, getting two other curves at 25 and 50 km. In order to estimate the dispersion power penalty, is necessary to draw a best-fit straight line through the data and determine the power level, \(P_{\text{fiber}}\), for \(10^{-10}\) BER. The dispersion power penalty will be:

\[
D = P_{\text{fiber}} - P_{\text{ref}}
\]

Figure 5.3.2 shows the ST2400A display format in order to read the BER. It is important to note that the device calculates other important parameters such as total errors (TOT), errored seconds (ES) and severely errored seconds (SES), defind in \([R2]\). Also ST2400A displays the overhead section considered and the bit error type. For each measurement is important to wait about 2 minutes in order to caputer an appropriate number of errors (at least 100 errors).

Figure 5.3.3 shows the real configuration which makes up in optical labo-
5.4 Eye-Diagram Analysis

For analyzing the eye-diagram is necessary to make this measurement configuration as showed in Figure 5.4.1. The optical signal output to the ST2400A at 1550 nm and about 0 dBm of power. The jumper is used to observe the eye in ideal situation at zero-length of fiber. An PIN photodetector allows to convert the optical signal into electrical and this signal is applied to the oscilloscope’s vertical input. A separate trigger signal at the data rate is applied to its trigger input. SYNCOUT connector at rear panel (Figure C.2.1) is clock trigger which output rate is $1/8^{th}$ transmit data rate (approximately 311 MHz). Ideally, the trigger signal is a sine or square wave at the clock rate of the data, although the data signal itself can be used when only qualitative analysis of the eye diagram is necessary. The oscilloscope triggers on the first clock transition after its trigger circuit is armed. Upon triggering, it captures whatever data waveform is present at the vertical input and display it on the screen. After a short deadtime, the trigger circuitry re-arms and triggers on the following clock transition. The data pattern at this instant will most probably be different from the previous pattern, so the display will now be combination of the two patterns. This process continues so that eventually, after many trigger events, all different one-zero combinations overlap on the screen.
Figure 5.3.3: Real lab setup
When eye-diagram is generated is possible to measure performance parameters (enumerated in Table 4.2) onto the oscilloscope directly in color grade mode\(^3\). Measurements demonstrate how eye-parameters vary in different network conditions and eye is degraded in function of dispersion penalty. Using the sweep function of the oscilloscope trigger, it is possible to see bit sequences that arrive to an ideal receiver.

5.5 Jitter Measurements

The jitter measurement that is requested to make at students is very basic. Because it is a simple valuating of temporal jitter onto the oscilloscope directly using the same test setup in Figure 5.4.1. The procedure used is the same described in Section 4.3.7.

\(^3\)It is a type of oscilloscope visualization that allows recording all of eye lines on the screen. Different colors represent how often eye line pass in different points. For example, green is few times and white is too times.
5.6 Laser Bias Optimization

This experimental part is more advanced and it allows a special knowing in this subject. As illustrated in Section 3.2.3.3, lasers have got two kind of currents, bias and modulation current, that are the currents supplied by the laser driver when transmitting a zero and an one respectively. Modern lasers have got a special characteristic called automatic power control (APC) that allows to the transmitted optical power is automatically adjusted to ensure that the optimum power level is received at the remote terminal.

In the other words, the driver sets the laser modulation current to a preprogrammed value (operating temperature of about 23-25°C). The APC loop determines the bias current based on the monitor diode photocurrent, which is proportional to the average optical power. This approach requires part-to-part adjustment, and provides loose control accuracy of the modulation current. Students in this practice, will simulate this method manually, using a bias current adjusting, a photodetector, and an oscilloscope to monitor the system performance.

Figure 5.6.1 shows the experimental configuration for getting these measurements.

Now, the output signal at 2.5 Gbit/s is electric because ST2400A have not got an option to allow a bias adjusting. So, signal is taken on the real panel (DATA OUT connector). Figure 5.6.2 shows test setup. The electric signal outputs to ST2400A and it passes throught bias-tee circuit to adjust the signal. But, amplifier is necessary because the signal is too weak. Besides, before the amplifier an attenuator is connected in order to work in linear zone. Laser modulates directly signal at 1550 nm (Figure 5.6.3), but before there is another attenuator for no saturating or burning it.

5.6.1 Optical Power vs Bias Current

The first step of this practice is to determine characteristic between optical power and laser bias current, and verify if they have got a quasi-direct trend. Students will vary bias trimmer from 0 to 50 mA (Figure 5.6.4) and they
Figure 5.6.1: Practice setup for laser bias optimizing

Figure 5.6.2: Device configuration to modulate the electric signal
will record optical power value read onto the power meter at the output of laser. This bias trimmer not varies only bias current, but the operational point along the L/I laser curve.

### 5.6.2 Extinction Ratio/Q-Factor vs Bias Current

In this part of practice is requested to the students to valuating the extinction ratio in function of bias current. Now, the practice configuration is as in Figure 5.6.5, where optical output is at input of PIN photodetector, that convertes in electical signal for seeing it on the oscilloscope. Trigger is taken to ST2400A SYNC OUT connector. The extinction ratio is calculated by histogram method at one and zero level (mean value). Students record $\mu_0$ and $\mu_1$ values for each bias variation and calculate the ratio. After that plot these values.
Figure 5.6.5: Extinction Ratio and Q-Factor valuating
With the same equipment configuration, it is possible to determine the curve between Q-Factor and bias current. The optimum value is the maximum of this characteristic.

5.6.3 System Sensitivity

Finally, fixed optimum value of bias current and varying the optical attenuator in order to determine the system sensitivity. In the other hands, the minimum optical power to guarantee a Q-Factor of about 6. System sensitivity is calculated drawing a best-fit straight line at about $Q = 6$ ($BER \simeq 10^{-9}$) and reading the correspondent optical power value. Given this value of sensitivity it is possible to calculate the optical power budget, to determine how much fiber can use under these conditions of system. Figure 5.6.6 shows this experimental device setup.
Figure 5.6.6: System sensitivity configuration
Part III

Results and Conclusions
Chapter 6

Measurement Results

6.1 Introduction

This chapter will discuss and list out results of the measurements that they are experimented developing the practice. Measurements are organized in tables and in the most of case, there are their correspondent graphics or oscilloscope images. Near to each result, there is a comment for understandind better.

6.2 Dispersion Power Penalty Measurements

In the following there are measurements refered to the practice illustrated in Section 5.3. After the calibration, BER measurements of RSOH and MSOH (SDH overhead) are experimented on ST240A directly.

6.2.1 Calibration

\[ P_m = -28.4 \text{ dBm} \]

\[ P_{cal} = -28 - (-28.4) = 0.4 \text{ dBm} \]

This value is sumed to measured value during the measurements.
### 6.2.2 BER Results

#### Bit Error Ratio

<table>
<thead>
<tr>
<th>Optical Power [dBm]</th>
<th>RSOH</th>
<th>MSOH</th>
</tr>
</thead>
<tbody>
<tr>
<td>-32.25</td>
<td>$1.10 \times 10^{-11}$</td>
<td>$1.00 \times 10^{-11}$</td>
</tr>
<tr>
<td>-32.80</td>
<td>$1.40 \times 10^{-9}$</td>
<td>$1.30 \times 10^{-9}$</td>
</tr>
<tr>
<td>-33.21</td>
<td>$2.10 \times 10^{-8}$</td>
<td>$2.00 \times 10^{-8}$</td>
</tr>
<tr>
<td>-33.70</td>
<td>$3.80 \times 10^{-7}$</td>
<td>$3.80 \times 10^{-7}$</td>
</tr>
<tr>
<td>-34.30</td>
<td>$5.60 \times 10^{-6}$</td>
<td>$7.30 \times 10^{-6}$</td>
</tr>
<tr>
<td>-35.03</td>
<td>$1.30 \times 10^{-5}$</td>
<td>$1.00 \times 10^{-4}$</td>
</tr>
<tr>
<td>-36.14</td>
<td><em>signal lost</em></td>
<td><em>signal lost</em></td>
</tr>
</tbody>
</table>

Table 6.1: Zero-length fiber

<table>
<thead>
<tr>
<th>Optical Power [dBm]</th>
<th>RSOH</th>
<th>MSOH</th>
</tr>
</thead>
<tbody>
<tr>
<td>-31.22</td>
<td>$2.00 \times 10^{-11}$</td>
<td>$1.00 \times 10^{-11}$</td>
</tr>
<tr>
<td>-31.67</td>
<td>$4.50 \times 10^{10}$</td>
<td>$3.50 \times 10^{10}$</td>
</tr>
<tr>
<td>-32.22</td>
<td>$1.10 \times 10^{-8}$</td>
<td>$9.30 \times 10^{-9}$</td>
</tr>
<tr>
<td>-32.70</td>
<td>$1.40 \times 10^{-7}$</td>
<td>$1.50 \times 10^{-7}$</td>
</tr>
<tr>
<td>-33.22</td>
<td>$1.70 \times 10^{-6}$</td>
<td>$1.70 \times 10^{-6}$</td>
</tr>
<tr>
<td>-33.70</td>
<td>$8.00 \times 10^{-6}$</td>
<td>$1.30 \times 10^{-5}$</td>
</tr>
<tr>
<td>-34.20</td>
<td>$1.30 \times 10^{-5}$</td>
<td>$9.40 \times 10^{-4}$</td>
</tr>
<tr>
<td>-35.00</td>
<td><em>signal lost</em></td>
<td><em>signal lost</em></td>
</tr>
</tbody>
</table>

Table 6.2: 25 km of SMF fiber

97
<table>
<thead>
<tr>
<th>Optical Power [dBm]</th>
<th>RSOH</th>
<th>MSOH</th>
</tr>
</thead>
<tbody>
<tr>
<td>-28.30</td>
<td>1.40 × 10^{-11}</td>
<td>1.00 × 10^{-11}</td>
</tr>
<tr>
<td>-29.20</td>
<td>4.40 × 10^{-10}</td>
<td>4.00 × 10^{-10}</td>
</tr>
<tr>
<td>-30.12</td>
<td>7.30 × 10^{-8}</td>
<td>7.70 × 10^{-9}</td>
</tr>
<tr>
<td>-31.26</td>
<td>2.80 × 10^{-6}</td>
<td>3.10 × 10^{-6}</td>
</tr>
<tr>
<td>-31.97</td>
<td>1.00 × 10^{-5}</td>
<td>1.00 × 10^{-4}</td>
</tr>
<tr>
<td>-32.41</td>
<td>1.00 × 10^{-3}</td>
<td>1.00 × 10^{-3}</td>
</tr>
<tr>
<td>-33.00</td>
<td>signal lost</td>
<td>signal lost</td>
</tr>
</tbody>
</table>

Table 6.3: 50 km of standard fiber

Table 6.1 shows the BER values for each variation of optical power in the case of a “short fiber”, connecting the transmitter and the receiver directly. From these values, evaluate system sensitivity is possible. If an acceptable value of BER is chosen, for example $10^{-9}$ or $10^{-10}$, the sensitivity is about -32.50/32.80 dBm. This value is very satisfy because it was used a high efficiency ADP photodetector.

The errors in the two sections of overhead (RSOH and MSOH) are not too much different among them and follow the same order of magnitude. At about -36 dBm the signal is lost and LOS LED in the front panel (receiver part) of the ST2400A is turn on.

Next, trends of BER for 25 km (Table 6.2) and 50 km (Table 6.3) is evaluated. Note that, even if optical power is relatively low, 50 km of distance can be achieved with error free and without a signal regeneration block.
Figure 6.2.1: Optical Power vs BER: RSOH
Figure 6.5.1 and 6.2.2 represent BER characteristics in function of optical power. Each straight lines are a tendent line, i.e. computers calculate mean value automatically and make this linear characteristic.

It is possible to note that at 25 km of distance dispersion is acceptable because its value is of only 0.8 dB. At 50 km this value increase to 3.4 dB, taking with BER reference $10^{-10}$. Obviously, if this reference value is smaller then dispersion power penalty will increase.
6.3 Eye-Diagram Analysis

Figure 6.3.1: Eye-Diagram: zero-length fiber

Figure 6.3.2: Eye-Diagram: 25 km of SMF
Figure 6.3.3: Eye-Diagram: 50 km of SMF

<table>
<thead>
<tr>
<th>Eye-Parameter</th>
<th>Unit</th>
<th>zero-length fiber</th>
<th>25 km of SMF</th>
<th>50 km of SMF</th>
</tr>
</thead>
<tbody>
<tr>
<td>Eye height/opening</td>
<td>mV</td>
<td>340.00</td>
<td>80.42</td>
<td>4.97</td>
</tr>
<tr>
<td>Eye width</td>
<td>ps</td>
<td>291.92</td>
<td>272.79</td>
<td>129.31</td>
</tr>
<tr>
<td>Q-Factor</td>
<td>-</td>
<td>10.03</td>
<td>7.09</td>
<td>3.89</td>
</tr>
<tr>
<td>Overshoot</td>
<td>-</td>
<td>2.20%</td>
<td>4.10%</td>
<td>11.80%</td>
</tr>
</tbody>
</table>

Table 6.4: Eye-Diagram parameter measurements

These three eye-diagrams show how changes system performances in function of the distance. The first one is a very regular diagram with a good opening and defined one and zero level. The second (at 25 km) is closer, but Q-Factor is excellent yet. At the end of this image sequence, there is an eye-diagram at 50 km of distance very corrupted of dispersion power penalty. At 50 km, high overshoot is present with 11.80% and a lot of jitter. Besides, at low level, there is a double zero, that compromise an exact sampling at the receiver. In the other hands, ST2400A transmit 0 dBm of optical power, but 15 dB of attenuation is necessary to protect it. So, before fiber spool there is a maximum optical power of -15 dBm. If 0.22 dB/km of optical dispersion along the fiber is considered, at the receiver about -27.5 dBm is possible to measure. According to Table 6.3, this value is satisfactory if always an
ADP photodetector is used. As a matter of fact, is necessary -33 dBm of power to lose the signal. Using a PIN photodetector this is not acceptable.

6.3.1 Histogram Technique

![Histogram oscilloscope display and Eye-Diagram with histogram](image)

Table 6.5: Q-Factor evaluation using histogram method for 25 km of SMF

<table>
<thead>
<tr>
<th>zero level mean $\mu_0$</th>
<th>one level mean $\mu_1$</th>
<th>zero level standard deviation $\sigma_0$</th>
<th>one level standard deviation $\sigma_1$</th>
<th>Q-Factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.32 mV</td>
<td>17.63 mV</td>
<td>1.30 mV</td>
<td>1.17 mV</td>
<td>6.61</td>
</tr>
</tbody>
</table>

6.3.2 Extinction Ratio Measurements

Figure 6.3.5 shows that in a SDH transmission at 2.5 Gb/s, it is possible to arrive to 50-55 km in order to get an acceptable value of extinction ratio (at least 8 dB). After that, a regenerator system is necessary.
<table>
<thead>
<tr>
<th>Unit</th>
<th>zero-length fiber</th>
<th>25 km of SMF</th>
<th>50 km of SMF</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\mu_0$</td>
<td>mV</td>
<td>2.63</td>
<td>0.55</td>
</tr>
<tr>
<td>$\mu_1$</td>
<td>mV</td>
<td>113.09</td>
<td>17.69</td>
</tr>
<tr>
<td>Dark Offset</td>
<td>mV</td>
<td>0.20</td>
<td>-</td>
</tr>
<tr>
<td>ER</td>
<td>-</td>
<td>43.00</td>
<td>32.16</td>
</tr>
<tr>
<td>ER</td>
<td>dB</td>
<td>16.33</td>
<td>15.07</td>
</tr>
</tbody>
</table>

Table 6.6: Extinction ratio measurements

Figure 6.3.5: Extinction ratio vs Distance
It is important to note that, although the mean value of zero and one level is expressed in Volts, ER formula does not change (i.e. not use $20 \cdot \log ER$ instead of $10 \cdot \log ER$). Because, photodetector PIN generates a signal proportional to mean power.

### 6.4 Jitter Measurements

![Timing jitter measurements](image)

**Figure 6.4.1: Timing jitter measurements**

<table>
<thead>
<tr>
<th>Jitter Type</th>
<th>Unit</th>
<th>zero-length fiber</th>
<th>25 km of SMF</th>
<th>50 km of SMF</th>
</tr>
</thead>
<tbody>
<tr>
<td>RMS</td>
<td>ps</td>
<td>19.28</td>
<td>22.16</td>
<td>35.09</td>
</tr>
<tr>
<td>peak-to-peak</td>
<td>ps</td>
<td>113.23</td>
<td>133.24</td>
<td>260.51</td>
</tr>
<tr>
<td>Fall Time</td>
<td>ps</td>
<td>165.21</td>
<td>245.52</td>
<td>295.32</td>
</tr>
<tr>
<td>Rise Time</td>
<td>ps</td>
<td>117.91</td>
<td>191.83</td>
<td>245.63</td>
</tr>
</tbody>
</table>

**Table 6.7: Jitter measurements**

The jitter values measured is quite good and respect the international limits prescribed by the standard [R5]. These measurements are got by an automatically option of oscilloscope. Naturally, it is possible to make a vertical
histogram around the eye crossing, and valuating the mean coefficient (Figure 6.4.2).

6.5 Laser Bias Optimization

6.5.1 Optical Power vs Bias Current

First of all, L/I characteristic is extracted for each value of bias (meant as operational point) the optical power by optical power meter. Figure 6.5.1 shows this L/I curve where is possible to observe that threshold current is about 7 mA. The linear zone, where is possible to position the input data, start to about 17.5 mA which corresponds an optical power of about 0.75 mW (-0.125 dBm).

6.5.2 Extinction Ratio/Q-Factor vs Bias Current

In the following there are ER and Q-Factor in funcion of bias measurements. For these measurements is important to find out a trade-off between these parameters.

Table 6.8 shows zero and one values (in Volts) and the correspondent ER calculate in linear and dB mode (in case of negative value, it consideres in absolute terms). Figure 6.5.2 is the plot of $I_{BIAS}$ and $ER_{dB}$. Observing the graph, ER is excellent with lower values of current. As the current increases, the curve trand decreses. For the Figure 6.5.1 is known that only
Figure 6.5.1: Optical Power vs Bias Current
current value from about 17.5 mA allow to work in the linear zone, so the first values of ER are rejected. The attention will be focus from this value. It is particularly to note that in Figure 6.5.2 around 18 dB of ER, there is a quasi-constant zone. This happens when there is a transition between saturated (clipping\(^1\)) and linear zone.

Second step is to draw Q-Factor vs Bias characteristic. Data and graph are in Table 6.9 and Figure 6.5.3 respectively. This characteristic is bell-shaped curve. With low bias values (work point is place before the threshold current), the input signal is saturated at a low level. The ER is very small and the eye diagram closes at zero. This can be noted by switching oscilloscope into normal mode in order to show the signal in real-time. Increasing laser current and moving the work point in linear region, Q-Factor increases to an optimal point, which is the maximum of the curve. The maximum corresponds to \( Q = 9.45 \) with \( I_{Bias}^{Optim} = 30 \text{ mA} \). Then, continuing to increase \( I_{Bias} \) the signal tends to saturate at one level, because Q-Factor decreases sharply. Observing another time the Figure 6.5.2, with this current amount implies a bad extinction ratio of about 6.91 dB.

Finally, the trade-off is to take \( I_{Bias} = 22 \div 23 \text{ mA} \) that corresponds to \( ER \simeq 15 \text{ dB} \) (good) and a \( Q = 7.59 \div 8.26 \) that are a very good values (\( BER = 1.4 \times 10^{-14} \div 5.5 \times 10^{-17} \)).

6.5.3 System Sensitivity

The last measurement is to search system sensitivity. Table 6.10 describes a list of measurements with keeping bias current constant and varying the optical attenuator. Considering \( I_{Bias} = 22.5 \text{ mA} \), these values are obtained:

In conclusion, system sensitivity corresponds to red row in Table 6.10, with \( P_R = -19.56 \text{ dBm} \). This value is not very high because a PIN photodetector is used. When ADP photodetector has used (Section 6.2.2), it is important to note that sensitivity was about 10 dB larger than a PIN.

\(^1\)Clipping is a form of waveform distortion that occurs when an amplifier is overdriven and attempts to deliver an output voltage or current beyond its maximum capability. Driving an amplifier into clipping may cause it to output power in excess of its published ratings.
<table>
<thead>
<tr>
<th>$I_{\text{BIAS}}$ [mA]</th>
<th>zero mean [V]</th>
<th>one mean [V]</th>
<th>ER</th>
<th>ER [dB]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>$-2.40 \times 10^{-5}$</td>
<td>$1.24 \times 10^{-2}$</td>
<td>516.67</td>
<td>21.13</td>
</tr>
<tr>
<td>5</td>
<td>$1.70 \times 10^{-4}$</td>
<td>$1.54 \times 10^{-2}$</td>
<td>90.59</td>
<td>19.57</td>
</tr>
<tr>
<td>10</td>
<td>$4.29 \times 10^{-4}$</td>
<td>$2.87 \times 10^{-2}$</td>
<td>66.92</td>
<td>18.25</td>
</tr>
<tr>
<td>15</td>
<td>$7.62 \times 10^{-4}$</td>
<td>$4.53 \times 10^{-2}$</td>
<td>59.41</td>
<td>17.74</td>
</tr>
<tr>
<td>20</td>
<td>$9.32 \times 10^{-4}$</td>
<td>$5.25 \times 10^{-2}$</td>
<td>56.33</td>
<td>17.50</td>
</tr>
<tr>
<td>25</td>
<td>$7.74 \times 10^{-3}$</td>
<td>$5.68 \times 10^{-2}$</td>
<td>7.84</td>
<td>8.94</td>
</tr>
<tr>
<td>30</td>
<td>$1.42 \times 10^{-2}$</td>
<td>$6.99 \times 10^{-2}$</td>
<td>4.91</td>
<td>6.91</td>
</tr>
<tr>
<td>35</td>
<td>$2.30 \times 10^{-2}$</td>
<td>$7.98 \times 10^{-2}$</td>
<td>3.46</td>
<td>5.40</td>
</tr>
<tr>
<td>40</td>
<td>$3.23 \times 10^{-2}$</td>
<td>$8.94 \times 10^{-2}$</td>
<td>2.77</td>
<td>4.42</td>
</tr>
<tr>
<td>45</td>
<td>$4.13 \times 10^{-2}$</td>
<td>$9.92 \times 10^{-2}$</td>
<td>2.40</td>
<td>3.80</td>
</tr>
<tr>
<td>50</td>
<td>$5.10 \times 10^{-2}$</td>
<td>$1.08 \times 10^{-1}$</td>
<td>2.12</td>
<td>3.27</td>
</tr>
</tbody>
</table>

Table 6.8: Extinction ratio vs bias current

Figure 6.5.2: Extinction ratio vs bias current
<table>
<thead>
<tr>
<th>$I_{BIAS}$[mA]</th>
<th>Q-Factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1.67</td>
</tr>
<tr>
<td>5</td>
<td>2.41</td>
</tr>
<tr>
<td>10</td>
<td>3.51</td>
</tr>
<tr>
<td>15</td>
<td>4.75</td>
</tr>
<tr>
<td>20</td>
<td>6.40</td>
</tr>
<tr>
<td>22</td>
<td>7.59</td>
</tr>
<tr>
<td>23</td>
<td>8.26</td>
</tr>
<tr>
<td>25</td>
<td>8.96</td>
</tr>
<tr>
<td>30</td>
<td>9.45</td>
</tr>
<tr>
<td>35</td>
<td>9.03</td>
</tr>
<tr>
<td>40</td>
<td>7.65</td>
</tr>
<tr>
<td>45</td>
<td>5.62</td>
</tr>
<tr>
<td>50</td>
<td>3.65</td>
</tr>
</tbody>
</table>

Table 6.9: Q-Factor vs bias current

Figure 6.5.3: Q-Factor vs bias current
<table>
<thead>
<tr>
<th>Attenuation [dB]</th>
<th>Optical Power [dBm]</th>
<th>Optical Power [mW]</th>
<th>Q-Factor</th>
<th>BER Estimation (Eq. 3.3.10)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>-10.46</td>
<td>8.99 × 10^{-2}</td>
<td>7.59</td>
<td>1.60 × 10^{-14}</td>
</tr>
<tr>
<td>5</td>
<td>-15.38</td>
<td>2.90 × 10^{-2}</td>
<td>7.03</td>
<td>1.03 × 10^{-12}</td>
</tr>
<tr>
<td>7</td>
<td>-17.44</td>
<td>1.80 × 10^{-2}</td>
<td>6.45</td>
<td>5.59 × 10^{-11}</td>
</tr>
<tr>
<td>9</td>
<td>-19.56</td>
<td>1.11 × 10^{-2}</td>
<td>5.81</td>
<td>3.12 × 10^{-9}</td>
</tr>
<tr>
<td>11</td>
<td>-21.54</td>
<td>7.01 × 10^{-3}</td>
<td>4.97</td>
<td>3.35 × 10^{-7}</td>
</tr>
<tr>
<td>13</td>
<td>-23.48</td>
<td>4.49 × 10^{-3}</td>
<td>4.14</td>
<td>1.74 × 10^{-5}</td>
</tr>
<tr>
<td>15</td>
<td>-25.36</td>
<td>2.91 × 10^{-3}</td>
<td>3.87</td>
<td>5.54 × 10^{-5}</td>
</tr>
<tr>
<td>17</td>
<td>-27.41</td>
<td>1.82 × 10^{-3}</td>
<td>3.25</td>
<td>5.77 × 10^{-4}</td>
</tr>
<tr>
<td>19</td>
<td>-29.37</td>
<td>1.16 × 10^{-3}</td>
<td>0</td>
<td>0.50</td>
</tr>
</tbody>
</table>

Table 6.10: System sensitivity
Chapter 7

Conclusions and Future Developments

Overall I concluded that this digital fibre optic link can serve as a good and useful educational tool for students studying the physics of optic link. The various measurement techniques carried out in this thesis will help them enhance their knowledge and gain better understanding in making an efficient digital fibre-optic link system.

The optical-fiber transmission is looming as a major innovation in the field of telecommunications. Its technical feasibility is being demonstrated in many on-going field experiments and trials. The impact of this new technology upon the communications field will depend on the economic viability of fiber systems compared to conventional and alternative systems in various applications.

This project gave me the opportunity to get to the heart of optical communications and touch that I already knew and most of all learn a lot. The practical impact study has allowed me to meet many problems typical of an experimental activity. For example, the careful cleaning of the fiber, which seems to be a banality, in the practical world can degrade system performances. Regulation ISO/IEC 14763-3, relating to procedures for verifying the performance of optical fiber connections: “Cleaning shall be repeated every time a test cord is connected to the cabling or component

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Connections should be inspected with a microscope after cleaning, to verify that they are uncontaminated”.

A major problem encountered during the practice has been to adapt the external laser to electrical SDH signal. Laser driving circuit consists mainly of RC circuit that creates time constant. At a determined frequency, which in our case was 2.5 Gb/s, this time constant may be too short and the frame bits can not reach the appropriate level.

It is appropriate, before using a laser to ensure that it is linear in frequency (without any ripple). So, a frequency analysis is needed, using a network analyzer (or spectrum), as HP8702.

Another key aspect is the ISI (Intersymbol Interference). At this data decision point, the signal is significantly degraded by the accumulation of random noise and ISI, resulting in erroneous decisions due to eye closure. In a practical receiver implementation, ISI exists due to receiver bandwidth limitation, baseline wander, or nonlinearity of the active components. If we monitor the signal eye diagram before the data decision, we find that, in addition to random noise, the signal has a certain amount of bounded amplitude fluctuation caused by ISI, which exhibits strong pattern dependence, as shows in Figure 7.0.1. To estimate the ISI penalty on optical sensitivity, a simple solution is to consider a worst-case amplitude-noise distribution. This is done separately by shifting the mean value of the Gaussian distribution from $V_1$ and $V_0$ to the lower amplitude boundary ($V_1 - V_{ISI}$) and
(V_0 + V_{ISI}). It is assumed that V_{ISI} is the vertical eye closure caused by ISI (Figure 7.0.2).

Further comment is important about the use of attenuators (electrical or optical). As well as a means of equipment protection (in the case of laser or ST2400A), but attenuators allow the amplifier (used in the second part of the practice), to work in the linear region without saturating the signal.

In conclusion, students when remake this lab practice can obtain different results. It is normal (if values are not too different) because measurements strongly depend on instrumentation (i.e. calibration, type of fiber, cables, etc.) which is used and the environment characteristic (i.e. temperature, humidity). So, this thesis has to be a practice guide and it can be modified according to each demands.
7.1 Future Developments

All devices used in practice can be interfaced via GPIB\textsuperscript{1} port to a personal computer. So, managing input / output is done directly through a user interface. For the simulation of optical transmission is often used LabVIEW. This is a software which can be set and display results automatically ST2400, digital optical attenuator, optical power meter and oscilloscope.

LabVIEW (short for Laboratory Virtual Instrumentation Engineering Workbench) is a platform and development environment for a visual programming language from National Instruments. The programming language used in LabVIEW, also referred to as G, is a dataflow programming language. Execution is determined by the structure of a graphical block diagram (the LV-source code) on which the programmer connects different function-nodes by drawing wires. These wires propagate variables and any node can execute as soon as all its input data become available. Since this might be the case for multiple nodes simultaneously, G is inherently capable of parallel execution. Controls and indicators on the front panel allow an operator to input data into or extract data from a running virtual instrument. The front panel can also serve as a programmatic interface. Thus a virtual instrument (VI) can either be run as a program, with the front panel serving as a user interface, or, when dropped as a node onto the block diagram, the front panel defines the inputs and outputs for the given node through the connector pane. This implies each VI can be easily tested before being embedded as a subroutine into a larger program. One benefit of LabVIEW over other development environments is the extensive support for accessing instrumentation hardware. Figure 7.1.1 shows LabVIEW environment and a possible user interface\textsuperscript{2}.

In conclusion, automating measurements, better results are achieved. For example, to calculate the Q-Factor, see the eye-diagram with precision onto oscilloscope is necessary for a good measurement. The eye must be

\textsuperscript{1}General Purpose Interface Bus. Standard IEEE-488. a short-range digital communications bus specification. It was created for use with automated test equipment in the late 1960s, and is still in use for that purpose.

\textsuperscript{2}Pictures for illustration purposes only.
Figure 7.1.1: LabVIEW environment
opened so that it covers well the whole screen. This is possible to get with much more precision. In addition, students can also learn to use this program widely used for optical transmission simulations.
Bibliography


International Recommendations

[R1] ITU-T G.821, “Error performance of international digital connection operating at a bit rate below the primary rate and forming part of an integrated services digital network”, 08/96

[R2] ITU-T G.826, “Error performance parameters and objectives for international, constant bit rate digital path at or above the primary rate”, 02/99

[R3] ITU-T M.2100, “Performance limits for bringing-into-service and maintenance of international PDH path, section and transmission systems”, 07/95


[R5] ITU-T G.825, “The control of jitter and wander within digital networks which are based on Synchronous Digital Hierarchy (SDH)”, 03/93
Appendixes
Appendix A

Pseudo Random Binary Sequences (PRBS)

Pseudo random binary sequences (PRBSs) are widely used for testing hardware for digital communication. Testing of hardware for digital communication requires transmission and reception of a signal that subjects the transmission channel to the characteristics of random digital signal. A PRBSs is a random bit sequence that repeats itself, thus not truly random, as the name implies. A truly random sequence never repeats itself, but truly random sequences are difficult to generate, and would have very little use in practical systems. However PRBSs with long sequence lengths (several billion bits) show close resemblance to truly random signals, and are sufficient for test purposes. PRBSs have well known properties, and the generation and acquisition of them are simple. Knowing how a PRBS is generated, makes it possible to predict the sequence. This is a very desirable feature when testing hardware for digital communication, as it allows you to predict how an incoming sequence is supposed to look. This makes it possible to register and count any errors that might occur in the sequence.
Figure A.1.1: General LFSR. The switches $a_1$ to $a_N$ make out the tap sets, and can be either closed (1) or open (0). The coefficients $X_K$ to $X_{K-N}$ represent the bits being shifted through the LFSR. The output of the LFSR is shown as $X_K$, but could be taken from any of the $N$ register outputs.

A.1 Shift Register Generation of Pseudo Random Binary Sequences

PRBSs can be generated by shifting bits through a number ($N$) of cascaded registers, where some of the register outputs (referred to as tap sets) are added modulo-2 and fed back to the input of the first register. The maximal length of the sequence is determined by the number of possible states that the shift register can assume, and the properties of the sequence is determined by which tap sets that are modulo-2 added and feed back to the first register. This type of PRBS generator is called a linear feedback shift register (LFSR), and figure 2.1 shows a general LFSR. Mathematically, the LFSR shown in figure Figure A.1.1 on page 123 can be described as shown in equation (A.1.1).

$$X_K = a_1X_{K-1} \oplus a_2X_{K-2} \oplus \ldots \oplus a_NX_{K-N} \quad \text{(A.1.1)}$$
The coefficients $a_1$ to $a_N$ can assume the values ‘1’ (switch closed) or ‘0’ (switch open) and make out the tap sets. $X_K$ to $X_{K-N}$ are the bits being shifted through the registers. $X_K$ is shown as the LFSR output on figure A.1.1 on page 123, but the output from the LFSR can be taken from any of the N register outputs.

It can be shown that for a LFSR of length N, one or several tap sets exists that will result in the generation of a maximal length sequence. Maximal length sequences have a period length of $2^N - 1$ bits, and have many useful properties. A table containing tap sets that result in the generation of maximal length sequences. In the remainder of this chapter focus will be on maximal length sequences. As indicated in figure Figure A.1.1 on page 123, the bits in the shift register are shifted from the left to the right. Each time the bits in the register are shifted, a new state will appear in the register. The number of states that the shift register can assume, is equal to the length of the sequence. In a LFSR like the one in figure 2.1, configured to generate a PRBS, all possible states of the register will appear exactly once (except the all zeroes state). The all zeroes state consisting of only zeroes is not included, as this state would cause the LFSR to output zeroes indefinitely.

A.2 Properties of Pseudo Random Binary Sequences

A PRBS generated as shown in figure Figure A.1.1 on page 123, is a periodic sequence of ‘0’s and ‘1’s, where the length of each period can range from a few bits to several billion bits. Different sequences with equal lengths can be generated using different tap sets, and this can be used for testing the pattern dependant hardware often residing in digital hardware (for instance clock recovery circuits). Independent of the sequence length, the number of ‘0’s and ‘1’s in a sequence, will differ by only one, and the majority of bits will always be ‘1’s. Thus in a sequence that is 7 bits long, there will be four ‘1’s and three ‘0’s. This distribution of ones and zeroes is a consequence of all N bit states in the LFSR except one, appear exactly once. If all N bit states, including the all zero state, had appeared exactly once, the distribution of
A sequence of consecutive ‘1’s or ‘0’s is called a run, and the number of ‘1’s or ‘0’s in the run is called the run length. In a PRBS of length $2^N - 1$ bits there will be one run of $N$ ‘1’s, and one run of $N - 1$ ‘0’s. The number of runs of various lengths in a $2^N - 1$ bits long PRBS is given in Table A.1 on page 125. As Table A.1 on page 125 shows, about half of the runs will be of length 1, quarter will be of length 2, one eighth will be of length 3 etc.

An example of a LFSR generating a PRBS of length $2^4 - 1$ can be seen in figure Figure A.2.1 on page 126. The sequence generated by the LFSR in figure Figure A.2.1 on page 126 will be 111100010011010. The state diagram for the LFSR in figure Figure A.2.1 on page 126 consists of 15 different states of 4 bits. Each new state is obtained by shifting the previous state one bit to the right, and then replacing the left most bit by the result of a module 2 addition corresponding to the tap set used. Figure Figure A.2.2 on page 126 shows this state diagram. The LFSR in figure Figure A.2.1 on page 126 can be described by the polynomial:

$$1 + X^3 + X^4$$

where $X^3$ and $X^4$ refers to tap set used. For LFSRs generating maximal length sequences, this polynomial will be primitive. Each state in the LFSR
Figure A.2.1: LFSR generating a PRBS of length $2^4 - 1$

Figure A.2.2: State diagram for a LFSR generating a PRBS of length $2^4 - 1$
state diagram can be described by polynomials in a similar way, but these polynomials will not all be primitive. The polynomial describing the LFSR is often referred to as the parity check polynomial, as multiplication between this polynomial and any other polynomial that is part of the LSFR state diagram will yield the result of zero. Multiplication, addition, and division of such polynomials are done by counting coefficients module 2, and counting powers of $X$ modulo $N$. For instance, multiplying the parity check polynomial corresponding to the LFSR shown in figure A.2.1 on page 126, with one of the states (1001) from the LFSR state diagram (figure A.2.2 on page 126) yields

$$(1+X^3+X^4)(1+X^4) = 1+X^3+X^4+X^4+X^7+X^8 = 1+2X^3+3X^4 = 1+1 = 0$$

The polynomial description of the LFSR can be replaced by a description based on vectors if found appropriate. The LFSR in figure A.2.1 on page 126 can be described by the vector 0011, and the corresponding states of the LFSR state diagram can be described in the same way.

### A.3 Power Spectrum of Pseudo Random Binary Sequences

The power spectrum of a PRBS of length $2^N - 1$ has a $\left(\frac{\sin(x)}{x}\right)$ envelope as shown in figure A.3.1 on page 128 (the scale in figure A.3.1 on page 128 is not exact).

The spectrum null occur at $f = \frac{n}{T}$, where $T$ is the bit duration and $n$ is an integer.

The spacing between the line frequencies is $\frac{1}{(2^N-1)T}$, which means that in order to reduce frequency spacing, the length of the PRBS should be increased. The difference between the spectrum of a true random signal and that of a maximal length PRBS, is that the spectrum of the true random signal is continuous, while that of a PRBS is discrete. But by choosing a PRBS with a long period, close resemblance to a true random signal can be
Figure A.3.1: Power spectrum for a PRBS obtained. This property makes PRBSs ideal as test signals.
Appendix B

Further SDH Characteristics

B.1 Regenerator Section Overhead (RSOH) Bits

**Framing** A1, A2 Bytes. The six framing bytes carry the framing pattern, and are used to indicate the start of an STM-1 frame.

**Channel Identifier** C1 Byte. The C1 byte is used to identify STM-1 frames within a higher-level SDH frame (STM-N, where the standardized values of N are 4, 16, etc.). The byte carries the binary representation of the STM-1 frame number in the STM-N frame.

**Parity Check** B1 Byte. A 8-bit wide bit-interleaved parity (BIP-8) checksum is calculated over all the bits in the STM-1 frame, to permit error monitoring over the regenerator section. The computed even-parity checksum is placed in the RSOH of the following STM-1 frame.

**Data Communication Channel** D1, D2, D3 Bytes. The 192 kbps Data Communication Channel (DCC) provides the capability to transfer network management and maintenance information between regenerator section terminating equipment.

**Orderwire Channel** E1 Byte. The E1 byte is used to provide a local orderwire channel for voice communications between regenerators and remote terminal locations.
User Communication Channel  F1 byte. The F1 byte is intended to provide the network operator with a channel that is terminated at each regenerator location, and can carry proprietary communications. The information transmitted on this channel can be passed unmodified through a regenerator, or can be overwritten by data generated by the regenerator.

B.2  Multiplexer Section Overhead (MSOH) Bits

Parit Check  B2 Bytes. A 24-bit wide bit-interleaved parity (BIP) checksum is calculated over all the bits in the STM-1 frame (except those in the regenerator section overhead). The computed checksum is placed in the MSOH of the following STM-1 frame.

Protection Switching  K1, K2 Bytes. The K1 and K2 bytes carry the information needed to activate/deactivate the switching between the main and protection paths on a multiplexer section.

Data Communication Channel  D4 to D12 Bytes. Bytes D4 to D12 provide a 576 kbps data communication channel (DCC) between multiplexer section termination equipment. This channel is used to carry network administration and maintenance information.

Orderwire Channel  E2 Byte. The E2 byte is used to provide a local orderwire channel for voice communications between multiplexer section terminating equipment.

Alarm Signals  Alarm information is included as part of the MSOH.

B.3  VC-4 Path Bits

Path Trace Message  J1 Byte. J1 byte is used to repetitively transmit a 64-byte string (message). The message is transmitted one byte per VC-4 frame. A unique message is assigned to each path in an SDH network. Therefore, the path trace message can be used to check
continuity between any location on a transmission path and the path source.

**Parity Check** B3 Byte. An 8-bit wide bit-interleaved parity even checksum, used for error performance monitoring on the path, is calculated over all the bits of the previous VC-4. The computed value is placed in the B3 byte.

**Signal Label** C2 Byte. The signal label byte, C2, indicates the structure of the VC-4 container. The signal label can assume 256 values, however two of these values are of particular importance: The all “0”s code represents the VC-4 unequipped state (i.e., the VC-4 does not carry any tributary signals). The code “00000001” represents the VC-4 equipped state.

**Path Status** G1 Byte. The G1 byte is used to send status and performance monitoring information from the receive side of the path terminating equipment to the path originating equipment. This allows the status and performance of a path to be monitored from either end, or at any point along the path.

**Multiframe Indication** H4 byte. The H4 byte is used as a payload multiframe indicator, to provide support for complex payload structures, for example payload structures carrying multiple tributary units (TUs – see Section ??). If, for example, the TU overhead is distributed over four TU frames, these four frames form a TU multiframe structure. The H4 byte then indicates which frame of the TU multiframe is present in the current VC-4.

**User Communication Channel** F2 Byte. The F2 byte supports a user channel that enables proprietary network operator communications between path terminating equipment. Alarm Signals Alarm and performance information is included as part of the path overhead.
B.4 SDH Maintenance Signals

Loss of Signal (LOS) LOS state entered when received signal level drops below the value at which an error ratio of $10^{-3}$ is predicted. LOS state exited when 2 consecutive valid framing patterns are received, provided that during this time no new LOS condition has been detected.

Out of Frame (OOF) OOF state entered when 4 or 5 consecutive SDH frames are received with invalid (errored) framing patterns. Maximum OOF detection time is therefore $625\mu s$. OOF state exited when 2 consecutive SDH frames are received with valid framing patterns.

Loss of Frame (LOF) LOF state entered when OOF state exists for up to 3 ms. If OOFs are intermittent, the timer is not reset to zero until an in-frame state persists continuously for 0.25 ms. LOF state exited when an in-frame state exists continuously for 1 to 3 ms.

Loss of Pointer (LOP) LOP state entered when N consecutive invalid pointers are received where N = 8, 9 or 10. LOP state exited when 3 equal valid pointers or 3 consecutive AIS indications are received\(^1\).

Multiplexer Section AIS Sent by regenerator section terminating equipment (RSTE) to alert downstream MSTE of detected LOS or LOF state. Indicated by STM signal containing valid RSOH and a scrambled “all 1s” pattern in the rest of the frame. Detected by MSTE when bits 6 to 8 of the received K2 byte are set to “111” for 3 consecutive frames. Removal is detected by MSTE when 3 consecutive frames are received with a pattern other than “111” in bits 6 to 8 of K2.

AU Path AIS Sent by MSTE to alert downstream high order path terminating equipment (HO PTE) of detected LOP state or received AU

\(^1\)The AIS indication is an “all 1s” pattern in pointer bytes.
Path AIS. Indicated by transmitting “all 1s” pattern in the H1, H2, H3 pointer bytes plus all bytes of associated VC-3 and VC-4). Detected by HO PTE when “all 1’s” pattern is received in bytes H1 and H2 for 3 consecutive frames. Removal is detected when 3 consecutive valid AU pointers are received.

**TU Path AIS** Sent downstream to alert low order path terminating equipment (LO PTE) of detected TU LOP state or received TU path AIS. Indicated by transmitting “all 1’s” pattern in entire TU-1, TU-2 and TU-3 (i.e., pointer bytes V1-V3, V4 byte, plus all bytes of associated VC-1, VC-2 and VC-3 loaded by “all 1’s” pattern). Detected by LO PTE when “all 1’s” pattern received in bytes V1 and V2 for 3 consecutive multiframes. Removal is detected when 3 consecutive valid TU pointers are received.
Appendix C

Tektronix ST2400A
Commands Description

C.1 Front Panel

ST2400A principal characteristics will be illustrated, these part is useful for the lab’s practice.

In Figure C.1.1 ST2400A front panel is drowed, where there are some numbers that will describe in the following.

- Display (indicated with 1) and Display Controls (2): The LCD display is used to present main menus, submenus, and test results. The right

Figure C.1.1: Front Panel
and left arrows are used to position the LCD cursor. The INC (increment) and DEC (decrement) keys are used to change values. The ENTER key is used to insert the selected value. The SETUP key is located below the ENTER key on the front panel. Pressing the SETUP key at any time will start the menu sequence. Each additional press, represented by the black arrow, will access the next menu.

- Transmitter Controls and Connectors (Left-side of front panel): there are three connectors on the one electrical (155 electrical) and two optical. The electrical connector is an industry standard BNC that is marked 155/2.048 CLK IN. It provides a 75 ohm load impedance and direct coupling (DC) for the 155 Mb/s SDH electrical signal. This connection also accepts 2.048 Mb/s or 2.048 MHz input for internal signal generation using external timing synchronization (NOT used in this practice). On the right side of the Transmitter section are two industry standard FC/PC optical connectors— one input and one output. ST and SC connectors are available as an option. The input optical connector is marked 155/622 IN; it accepts either STM-1 or STM-4 signals, at 1310 nm (NOT used in this practice). The output optical connector is marked 2.4 Gb/s OUT (3); it outputs an STM-16 optical signal at 1550 nm. Both are equipped with screw caps to protect the optics from airborne contamination, such as dust.

- Receiver Controls and Connectors (Right-side of front panel): There are three connectors one electrical and two optical. The electrical signal connector is an industry standard BNC that is marked 155 OUT (NOT used in this practice). It provides the 75 ohm load impedance and direct coupling (DC) for the SDH electrical signal. The two industry standard FC/PC optical connectors are on the left side of the Receiver section, one input and one output. ST or SC connectors are available as options. The input optical connector is marked 2.4 Gb/s IN (4), it accepts the STM-16 signal, at either 1310 or 1550 nm. The output optical connector, marked 155/622 OUT, outputs STM-1 and STM-4 tributary signals at 1310 nm (NOT used in this practice).
Both are equipped with screw caps to protect the optics from airborne contamination, such as dust.

- Receiver Status Indicators (indicated with 5): The status indicators include the alarms and errors detailed below. The appropriate LED indicator will light for a minimum of 200 milliseconds when a corresponding alarm or error is detected. Detected errors and alarms are stored as historical data. The Receiver LOS (Loss Of Signal) alarm indicates that the 2.4 Gb/s Input signal has not been detected for more than 2 microseconds. The LOS alarm will be asserted no later than 127 microseconds after receiving the low signal (all zero) condition. The Receiver LOF (Loss Of Frame) alarm indicates that more than 3 milliseconds of an out of frame condition has occurred. The OOF (Out Of Frame) alarm indicates that more than 4 consecutive frames of the 2.4 Gb/s signal had frame alignment errors. The B1 and B2 LEDs indicate that Regenerator Section or Multiplexer Section (respectively) parity errors were detected. The REI/FEBE (Remote Error Indication or Far End Block Error) indicates that a non-zero value in the REI byte (M1 byte in MS-OH) was detected. The RDI/FERF (Remote Defect Indication or Far End Receive Failure) alarm indicates that bits 6, 7, and 8 of the K2 byte have been a binary 110, respectively, for three or more consecutive frames. The AIS (Alarm Indication Signal) indicates that bits 6, 7, and 8 of the K2 byte have been a binary 110, respectively, for three or more consecutive frames.

C.2 Rear Panel

In Figure C.2.1 is showed the rear panel of ST2400A. Other than electric power, there are few input/output or command connectors respect to front panel, but not all will be used in the lab’s practice. These are principal parts:

- LASER LOCKOUT (indicated with 6): LASER LOCKOUT is a safety device. The key switch disables the Transmitter’s 2.4 Gb/s laser out-
put when it is turned to the 0 (zero) position. The laser output can only be turned on when the key is in the 1 (one) position.

- CLK IN-OUT/DATA IN-OUT (labeled with 7 and 8): 2.488 Gb/s clock and data interface (electrical) inputs and outputs.

- SYNC OUT (9): clock trigger. The voltage level is 300 mV peak-to-peak minimum. This output requires an external 50 ohm termination to work properly. This output generates a sync output signal at 1/8 data rate (311 MHz), useful for triggering oscilloscope to measure the eye diagram of an STM-16 signal.
Appendix D

Difference between dB and dBm

A frequent problem found in technical communications, both written and verbal, is confusion between dB and dBm. This probably results from a fundamental lack of understanding, perhaps of the basic mathematics. This appendix note presents the fundamental definitions and illustrates some of their uses and it is strongly indicated for students that have not understood the difference yet.

D.1 dB

When a physical quantity, such as power or intensity, is measured relative to a reference level it is expressed in decibels (dB), which is a logarithmic unit. Decibel is considered as a dimensionless unit because it is a ratio of two quantities with the same unit thus cancellation takes place. It is used for quantifying the ratio between two values. The best example of this is extinction ratio.

The dB is a method for comparing two powers. The formal definition is:

\[ dB = 10 \cdot \log \left( \frac{P_1}{P_2} \right) \]
D.2 dBm

dBm is different but definitely related to dB. dBm stands for an absolute power level. It is in reference to another unit of power the milliwatt. Mathematically,

\[ dBm = 10 \cdot \log(P/1mW) \]

The value of “P” is power in watts. Then, with further calculation, you can convert the absolute power unit “P” into dBm. The value of power level “P” is now referenced to 1 mW. The unit dBm is devised because in practice, 1 mW is a convenient reference point from which to measure power. dBm is considered as an absolute unit, and it is an unit to measure power.

D.3 Summery

dB and dBm are different units and are used for different, although related measurements. dB relates to power ratios, while dBm describes an absolute power. Careful examination of the units that we use will not only avoid embarrassment, but will enhance our communications and, ultimately, our basic understanding of our circuits and measurements.
Appendix E

Practice Statement

In the next page, there is the practice statement to submit to students.