MASTER

Implementation of optical amplification in a national-scale SDH network

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Implementation of Optical Amplification in a National-Scale SDH Network

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Preface

This report describes the ten months of work done at COMSAT Argentina and the Instituto Tecnológico de Buenos Aires (ITBA) as part of my MSc graduation thesis and concludes my five and a half years of study at Eindhoven University of Technology (TU/e). Furthermore the report serves as a recommendation for network changes in COMSAT's national SDH ring network.

I greatly enjoyed working at COMSAT and this project added a most valuable practical experience to my educational trajectory. My special thanks go out to Dr. Diego F. Grosz from the Instituto Tecnológico de Buenos Aires who guided me with everlasting enthusiasm during these ten months of work.

From COMSAT I wish to thank the employees who welcomed me with great enthusiasm and in special I would like to name my direct guide ing. Leonardo A. Zandanel and the Program Management Engineers Gabriel A. Vaschchuk and Gustavo E. Piñeyro for providing me with all the SDH network related details, teaching me 'Lunfardo' (slang spoken in Buenos Aires) and for taking me along on field work in downtown Buenos Aires with the climax being the deployment of a fiber network connection in the 'Casa Rosada' (The Argentinean President's working residence).

I would like to acknowledge the TUE International Relations Office and the KIVI NIRIA for providing me with a scholarship.

Finally, I wish to thank Prof. ir. A.M.J. Koonen and Dr. I. Tafur Monroy who closely observed my progress from within TU/e.

Buenos Aires, February 28, 2006

Joris Steinberg

Contents

Assignment

COMSAT Argentina operates a 3400-km national SDH STM-16 (2,5 Gb/s) optical ring network running from Buenos Aires to Mendoza and back. The fiber traces are indicated on the map shown in Figure 1.

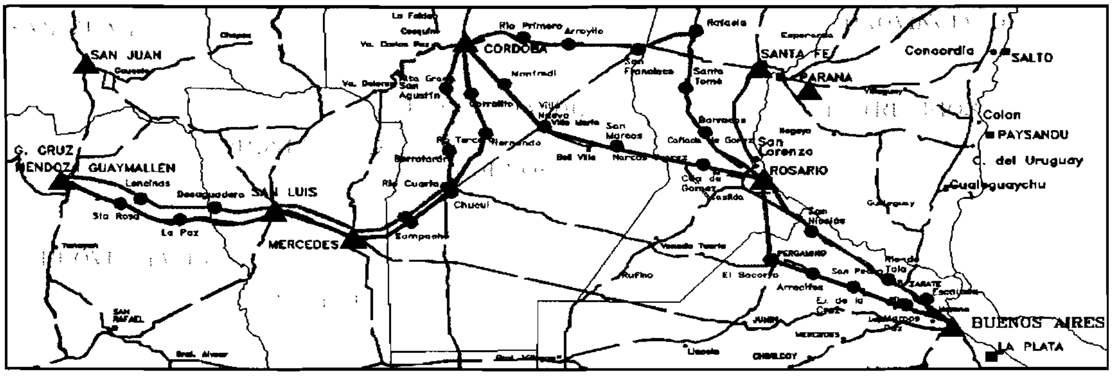

Figure 1: SDH optical ring network operated by COMSAT in Argentina

Signals propagating through the fiber need to be amplified approximately every 90 km due to signal attenuation. This is done by so-called *Add/Drop Multiplexers* (ADM) which have a 3R[1] regeneration function. These ADMs convert the received optical signal to the electrical domain, add and/or drop sub-signals, multiplex the new aggregate and convert it back to the optical domain where it is then transmitted over the fiber to the next ADM. However, most ADMs in COMSAT's network are solely used for 3R regeneration where 1R regeneration (just Re-amplification) would suffice since no sub-signals are added and/or dropped. These ADMs are costly devices which could be used in COMSAT's growing metropolitan networks where signals *do* need to be added and/or dropped. COMSAT wants to remove at least four ADMs from its national SDH network so they can be deployed in the Buenos Aires metropolitan SDH network.

Removing ADMs and connecting the 'loose' fiber ends is not an option because of the increased propagation distance that would lead to a non-acceptable *Bit-Error-Rate* (BER) performance. Somewhere along the line of this increased propagation distance the signal would need to be amplified. The network is using a single wavelength at approximately 1550 nm (the third transmission window). COMSAT has no current plans for an upgrade to a *Wavelength Division Multiplexing* (WDM) scheme. Neither is there a request for switching to higher bit-rates like 10 Gb/s. However, it would be interesting to know to what extent the network changes researched/implemented are compatible with future plans to upgrade the network capacity.

Cost of a possible network change needs to be below the price of a new ADM to make the solution financially feasible. My task was to:

Find and test a financially feasible solution to remove an ADM from COMSAT's national SDH network without impairing the network's functionality.

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[1] 3R stands for Re-amplification, Re-shaping and Re-timing.

Abstract

The report is divided as follows:

- Chapter One serves as an introduction to the *Synchronous Optical NETwork* (SONET) and the *Synchronous Digital Hierarchy* (SDH). SDH is the transport standard that is used in the optical ring network that COMSAT deploys. History and the background of SONET/SDH are presented. Technical aspects such as architecture, multiplexing, frame structures, overhead, network components, protection & rings and clocking are also discussed.

- Chapter Two describes the SDH network operated by COMSAT. The following features are presented: geographical details and distances, fiber types and losses, optical power levels, details on the Lucent *WaveStar*^{TM} ADM 16/1 that is used and the clients that are connected with their corresponding line-speeds. With this latter feature the occupation percentage of the network is calculated.

- Chapter Three presents attenuation and dispersion calculations for the situation where an ADM is removed and the neighboring sites are connected. The distance that would need to be bridged is calculated for any ADM removed and the fact if any traffic is added and/or dropped at that site is indicated with that. A couple of attenuation calculation examples are given for both worst-case and real-case scenarios. The BER vs. *Optical Signal-to-Noise Ratio* (OSNR) for system metrics performance is then introduced followed by dispersion calculations for a 2,5-Gb/s *Non Return-to-Zero* (NRZ) bit sequence with a non-ideal extinction-ratio.

- Chapter Four elaborates on various general solutions making use of both *Erbium-Doped Fiber Amplifiers* (EDFA) and Raman Amplifiers. Technical aspects with advantages and disadvantages are discussed for each general solution followed by a short financial analysis.

- Chapter Five presents various solutions proposed by optical equipment vendors. A standard solution offered by Lucent Technologies is derived from *WaveStar*^{TM} ADM 16/1 technical documentation. Detailed solutions offered by Padtec and Meriton Networks are presented.

- Chapter Six deals with the implementation of a solution chosen by COMSAT for removing an ADM from their SDH network. Schematic setups and measurement results are shown and discussed.

- Chapter Seven includes recommendations and elaborates on future network capacity upgrades.

- Chapter Eight (in English) and Nine (in Spanish) present the conclusions of this report.

Resúmen en Castellano

El informe está dividido de la siguiente forma:

- El Capítulo Uno sirve como introducción al *Synchronous Optical NETwork* (SONET) y el *Synchronous Digital Hierarchy* (SDH). SDH es el estándar de transporte usado en la red de anillo óptica de COMSAT. Se presentan las características más relevantes de SONET/SDH. Se discuten, también, aspectos técnicos como arquitectura, multiplexación, estructuras de trama, overhead, componentes de red, protección & anillos y sincronización.

- El Capítulo Dos describe la red SDH operada por COMSAT. Se presentan los siguientes aspectos: detalles geográficos y distancias, tipos de fibra y pérdidas ópticas, niveles de potencia óptica, detalles del sistema Lucent *WaveStar*™ ADM 16/1 y los clientes que están conectados con sus correspondientes velocidades de línea. Por último, se calcula el porcentaje de la ocupación de la red.

- El Capítulo Tres presenta los cálculos de atenuación y dispersión que resultan de eliminar un ADM y conectar los sitios adyacentes. Se discuten casos de máxima atenuación y de atenuación real. Se calcula la tasa de error de bits en función de la relación señal-ruido óptica necesaria para el correcto funcionamiento del sistema. Se calcula, también, el efecto de la dispersión cromática para una secuencia NRZ de 2,5 Gb/s y para el caso de un transmisor con grado de extinción real.

- El Capítulo Cuatro se presentan soluciones ópticas generales utilizando amplificadores de fibra dopada con Erbio (EDFA) y amplificadores Raman. Aspectos técnicos, incluyendo ventajas y desventajas relativas, son discutidos para cada solución general, seguido por un breve análisis financiero.

- El Capítulo Cinco presenta las soluciones propuestas por diferentes vendedores de equipos ópticos. Se obtiene una solución estándar a partir de los manuales técnicos del *WaveStar*™ ADM 16/1. Se presentan en forma detallada, también, soluciones propuestas por Padtec y Meriton Networks.

- El Capítulo Seis detalla la implementación escogida por COMSAT para la eliminación de un ADM de la red SDH. Se presentan y discuten diagramas esquemáticos y resultados de mediciones.

- El Capítulo Siete incluye recomendaciones para futuras ampliaciones de la red.

- El Capítulo Ocho (en Inglés) y Nueve (en Castellano) presentan las conclusiones de este informe.

List of Symbols and Abbreviations

Constants

Physical Constants

c	speed of light in vacuum	$3{,}0\cdot 10^{8}$ m·s^{-1}
h	Planck's constant	$6{,}6256\cdot 10^{-34}$ J·s

Variables

Symbol	**Description**	**SI Unit**
α_p	fiber attenuation at Raman pump wavelength	[dB·km^{-1}]
α_s	fiber attenuation at signal wavelength	[dB·km^{-1}]
β_2	GVD-parameter	[rad·s·m^{-1}]
B	bit-rate	[bits·s^{-1}]
C	linear frequency chirp	-
σ	standard deviation	-
D	dispersion parameter	[ps·nm^{-1}km^{-1}]
ε_r	extinction-ratio	[dB]
G	optical amplifier gain	-
G_R	Raman gain	-
I	field intensity	-
λ	wavelength	[nm]
L_D	dispersion length	[m]
L_{span}	span loss	[dB]
N_{amp}	number of amplifier spans	-
NF	noise figure	[dB]
NF_{cq}	equivalent noise figure	[dB]
n_{sp}	spontaneous emission factor	-
P	average optical power level	[mW] or [dBm]
Q	Q-factor	-
T	1/e-intensity half width	[s]
v	optical frequency	[Hz]
v_m	vibrational frequency	[Hz]
z	propagation distance	[km]

Subscripts

Subscript	**Refers to...**
0	zero-bit
1	one-bit
ASE	amplified spontaneous emission
N	noise
out	output
S	signal
th	threshold

Abbreviations

ADM	Add/Drop Multiplexer
APD	Avalanche Photodiode
ASE	Amplified Spontaneous Emission
ATM	Asynchronous Transfer Mode
BER	Bit-Error-Rate
BERT	Bit-Error-Rate Tester
CC	Cross-Connect
CSA	Carrier Serving Area
DCM	Dispersion Compensation Module
DCN	Data Communication Network
DCS	Digital Cross Connect
DFB	Distributed Feedback Laser
DLC	Digital Loop Carrier
DPS	Data Packet Switch
DS	Digital Signal
D+R	Drop and Repeat Node
EDFA	Erbium Doped Fiber Amplifier
ETSI	European Telecommunication Standards Union
GVD	Group Velocity Dispersion
ISI	Inter-Symbol-Interference
ITU	International Telecommunications Union
LAN	Local Area Network
MN	Matched Node
NOC	Network Control Center
NE	Network Element
NRZ	Non Return-to-Zero
NSAP	Network Service Access Point
NZDSF	Non-Zero Dispersion-Shifted Fiber
OC	Optical Carrier
ODF	Optical Distribution Frame
OSNR	Optical Signal-to-Noise Ratio

OTDR	Optical Time-Domain Reflectometer
POP	Point of Presence
PPS	Path Protection Switching
PTU	Power and Timing Unit
SC	System Controller
SDH	Synchronous Digital Hierarchy
SEC	SDH Equipment Clock
SLM	Single Longitudinal Mode
SONET	Synchronous Optical Network
SPE	Synchronous Payload Envelope
SRS	Stimulated Raman Scattering
SSMF	Standard Single Mode Fiber
STM	Synchronous Transfer Module
STS	Synchronous Transport Signal
TDM	Time Division Multiplexing
TM	Terminal Multiplexer
TOH	Transport Overhead
VC	Virtual Container
WAN	Wide Area Network
WDM	Wavelength Division Multiplexing

1 Introduction to SONET/SDH

Telecommunication networks based on optical fiber technology have become a major information-transmission system, with high-capacity optical fiber links encircling the globe in both terrestrial and undersea installations. In the early days of optical fiber communications, the applications involved basically only the optical fiber, a light source and a photodetector. Now, there are numerous passive and active optical devices within a light-wave link that perform complex networking functions in the optical domain, such as signal restoration, routing and switching [1].

Due to the ever increasing need of sending more and more information, from and to businesses and residential users alike, higher bandwidth is required. Until now, several newer technologies have helped to remedy this situation in a *Local-Area Network* (LAN) environment. LAN-implementation today is faced with a wide range of choices for linking desktops. Technologies such as 100 Mb/s Ethernet, Fiber Channel, switched Ethernets, Gigabit Ethernet, and the much anticipated 10 Gigabit Ethernet have started to appear or be planned in many organizations needing faster connectivity between end systems.

Although faster LANs have addressed the need for desktop bandwidth within a building or campus environment, LANs do nothing to increase the bandwidth available for networking dispersed buildings or campuses over distances of more than a few miles. For this situation, a *Wide-Area Network* (WAN) is needed. Until relatively recently, there was no easy way to link even 10 Mb/s Ethernet LANs with so much as a fraction of the bandwidth that the LAN represented.

Fortunately, SONET/SDH provides welcome relief from this growing bandwidth problem in the WAN environment. SONET/SDH is capable of linking LANs at separate sites not at a mere fraction of 10 Mb/s, or even a full 10 Mb/s. Rather, SONET/SDH can link several 10 Mb/s Ethernets at a single site to other Ethernet LANs across the country. SONET/SDH links usually operate at speeds of 155 Mb/s or higher, and into the multi-Gb/s range.

This Chapter is about SONET/SDH, it explains where SONET/SDH came from, what it is used for, and how it is used. Most of it is based on the book *SONET/SDH, 3rd ed.* from Goralski [2].

1.1 Background

SONET is a North American standard for networking developed in the mid-1980s primarily by Bellcore and standardized by ANSI. It defines the interface between two SONET *Network Elements* (NEs). More specifically, it defines a digital hierarchy of synchronous signals, including their formats, and defines the electrical and optical characteristics of the interface. SDH is a closely related standard developed by the *International Telecommunications Union* (ITU).

SONET/SDH is a high-bit-rate-fiber-optic-based transport method that provides the foundation for linking high-speed *Asynchronous Transfer Mode* (ATM) switches and multiplexers and providing users with Broadband ISDN-compliant services.

As time went by, SDH became more important and SONET turned into more a variation of SDH. The differences between SONET and SDH are more a matter of terminology today and less in substance. So almost anything that applies to SONET also applies to SDH.

1.2 T-Carrier

Digital transmission systems are characterized by the fact that these communication links only carry information in the form of binary digits (universally known as bits). Binary digits can only represent a "0" or a "1". Strings of 0's and 1's can be constructed to represent almost anything from computer-based data to digitized voice to stereo audio on a music CD to the soundtrack of a movie, even potentially to the movie itself.

In the early 1960s a digital multiplexing trunk network was designed by engineers at Bell Telephone Laboratories called *T-carrier*. T-carrier was the basis of a whole family of digital trunking methods. The basic unit was the digitized voice channel, which produces a stream of bits at the constant rate of 64.000 bits per second, or 64 Kb/s. The 64 Kb/s digitized voice channel was designated *Digital Signal-0* (DS-0) in the T-carrier system. The "0" indicated the lowest level of what was to become the T-carrier hierarchy.

Twenty-four DS-0 signals were multiplexed to yield a DS-1. The "1" indicated the first level of the T-carrier hierarchy. The DS-0 produced 64 Kb/s by generating 8 bits (1 byte) 8.000 times per second (= 125 μs per byte). The combined output of 24 DS-0s would require a way of sending at least 24 x 8 bits = 192 bits every 125 μs. To accomplish this, a DS-1 was organized into frames. Each frame was sent and received 8.000 times per second. An additional bit was added to help the receivers distinguish the beginning of one DS-1 frame from the end of the previous DS-1 frame. So the aggregate bit-rate of a DS-1 was 193 bits/frame x 8.000 frame/second = 1.544.000 bits per second or 1,544 Mb/s. The structure of a DS-1 frame is shown in Figure 1-1.

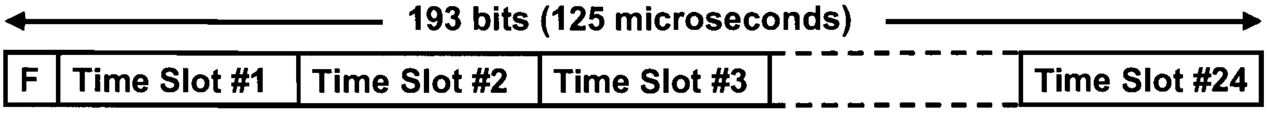

Figure 1-1: The DS-1 frame structure

Within the DS-1 frame, a DS-0 input channel always occupied the same position in the frame. For instance, a particular DS-0 channel may be the first 8 bits after the framing bit, or the next 8 bits after that, and so on. Because the DS-1 frame was thus divided by time and not by frequency, this method was referred to as *Time Division Multiplexing* (TDM).

A good deal of the initial work done that led to the development of SONET was done to address issues of DS-1 to DS-3 multiplexing. An M13 multiplexer combined 28 DS-1s (each with 24 DS-0s in most cases) to a single DS-3. This multiplexing was done in 2 stages; first 4 DS-1s (each 1,544 Mb/s) were combined to form a single DS-2 (6,312 Mb/s). In this process 136 Kb/s of overhead is added to the DS-1 signals to produce the DS-2 signal. Part of that overhead is added for DS-2 framing purposes. The second stage of the M13 multiplexing involved the combination of seven DS-2 signals to form a single DS-3 (44,736 Mb/s). Of the 552 Kb/s of overhead that is added to the DS-2 signals to produce the DS-3 aggregate, much of it consists of stuff bits which ensure rate and phase alignment of the incoming DS-2s.

1.3 Architecture

T-carrier, as mentioned in the foregoing section, does not conform to any standards. Most manufactures used proprietary transmission rates and protocols, making it impossible for equipment from different manufacturers to work together. With the deregulation of telecommunications in the U.S. and the increasing importance of international communications, this lack of standardization became a mayor problem. It was no longer certain that a transmitter in one city would be compatible with a receiver in another city operated by a different service provider.

To address this problem, the international telecommunications industry adopted two fundamental standards for fiber-optic systems, SONET and SDH, aimed at assuring the so-called *mid-span meet* of equipment from different manufacturers.

Table 1-1 shows the speeds of the SONET/SDH hierarchy, which consists of a few basic building blocks of terms and speeds. For SONET, each level has an *Optical Carrier* (OC) level and an electrical level transmission frame structure to go with it, called the *Synchronous Transport Signal* (STS). An STS-3 frame is sent on an OC-3 fiber optic link. An STS-1 frame (51,840 Mb/s) can carry a clear-channel DS-3 signal (44,736 Mb/s) or a combination of sub-DS-3 rate signals, such as DS-1 or DS-0.

SDH does not use this awkward STS/OC distinction, and almost always just uses a simpler *Synchronous Transfer Module-N* (STM-N) notation, as shown in the table. Table 1-1 also details the physical line bit-rate, the payload bit-rate, and the overhead bit-rate for each SONET/SDH level shown. The payload is merely the bit-rate remaining after the overhead bits, which cannot be used for customer data, are subtracted. The payload is carried inside an envelope, a special part of the transmission frame, in SONET/SDH. Finally, the table gives the SDH designations for each of the SONET levels. Obviously, the STS level divided by three (except for STM-1) gives the synchronous transport module (STM) level. In other words, SDH counts by threes, while SONET counts by ones. The SONET counting units are the basic 51,84 Mb/s bit-rate of OC-1. STM levels increase by units of 155,52 Mb/s (3 x 51,84 Mb/s).

Optical Level	Electrical Level	Line Rate (Mb/s)	Payload Rate (Mb/s)	Overhead Rate (Mb/s)	SDH Equivalence
OC-1	STS-1	51,840	50,112	1,728	STM-0
OC-3	STS-3	155,52	150,336	5,184	STM-1
OC-12	STS-12	622,08	601,344	20,736	STM-4
OC-24	STS-24	1244,16	1202,688	41,472	N.A.
OC-48	STS-48	2488,32	2405,376	82,944	STM-16
OC-192	STS-192	9953,28	9621,504	331,776	STM-64
OC-768	STS-768	39813,12	38486,016	1327,104	STM-256

Table 1-1: SONET/SDH digital hierarchy

Note that not all possible values of N are represented in SONET/SDH. For example, no OC-5 or STM-7 exists. Although the value of N can technically take on any value from 1 to some maximum, SONET/SDH standards define only a few of the levels. Otherwise, there would potentially be hundreds of different types of SONET/SDH equipment, making a joke of interoperability in spite of the presence of standards.

Sometimes there is a technical reason behind this preference for some levels and not others. For instance, early equipment vendors found that it was actually more cost effective to build SONET gear operating at the OC-12 level than at the OC-9 level because of laser chip costs and economies of scale. Little OC-9 SONET equipment was ever built, while the OC-12 equipment market has flourished.

It is absolutely crucial to remember that unless other arrangements are made in equipment configurations, *SONET/SDH will remain as canalized as a T-carrier.* That is, an STS-3 contains three STS-1s. An STS-12 contains twelve STS-1s, and so on. By default, all of the STS-1s inside an STS-48 on an OC-48 fiber optic link run at 51,84 Mb/s, the STS-1 rate. In the same fashion, in T-carrier, a DS-3 frame contains 28 T-1s, all operating at 1,544 Mb/s. Ironically, SONET/SDH, despite the incredible speeds available at the higher ends of the hierarchy, would seem to limit networking to channels operating at 51,84 Mb/s or 155,52 Mb/s from any individual user.

However, just as DS-3 (or DS-1 for that matter) is available as an *uncanalized* transport without a structure, so is SONET (SHD has its own channel structure). An uncanalized DS-3 merely offers a raw bit-rate (no more 28 DS-1s) at 45 Mb/s. In the same way, an uncanalized STS-12 would offer the user a raw bit-rate (no more 12 STS-1s) at approximately 622 Mb/s. The same applies to SDH canalizations. The terms used in Table 1-1 are of great importance throughout the rest of this chapter. Because these form the basis of the SONET/SDH architecture, a review of these terms will aid in the understanding of the architecture.

OC-N This notation refers to the SONET transmission characteristics of an N^{th} level transmission link. Within SONET, an OC-3 transmission link is assumed to have an STS-3 frame structure.

STS-N In this notation, STS refers to the SONET frame structure of an Nth level transmission link. This notation is analogous to the DS-1 notation in today's transmission network. Although most SONET links should properly be referred to as STS-N, it is much more common to speak of OC-N.

Payload The term used to indicate user data within a SONET/SDH frame.

Envelope The portion of the STS-1 frame used to carry payload and end system overhead. SDH sometimes calls this an Administrative Unit.

Overhead The portion of the STS-N/STM-N frame used to carry management data.

Concatenation A term that refers to the linking together of multiple STS-1/STM-1 frames to form an envelope capable of carrying higher bit-rate payloads, such as when SONET or SDH is used to carry ATM cells or IP packets. A concatenated SONET links is referred to as an STS-3c or an OC-3c, or whatever the SONET level happens to be. SDH has its own terminology for concatenation in the form of STM-Nc.

1.4 Multiplexing

It has already been pointed out that unless other configuration steps are taken, the basic, default structure for an STS-N link is as N STS-1s (the same is true in principle for SDH). So a basic STS-3 has 3 STS-1s, an STS-12 has 12 STS-1s, and so on.

But there is an *order* implied in the sequencing of STS-1s inside an STS-N. STS-1s will be loaded inside an STS-N in certain positions. The positions must well be known and fixed so that other multiplexing equipment can easily find them.

The positions of the three STS-1s inside an STS-3 are easy to understand. The bytes from the three STS-1s are just multiplexed together in the sequence 1-2-3-1-2-3-1-2-3.... and so on. This is called byte-interleaved multiplexing. However, in an STS-12, the twelve STS-1s must be ordered as if they were first made into an STS-3, and then four STS-3s were byte-interleaved multiplexed into an STS-12. The resulting STS-12 structure in terms of STS-1s is therefore 1-4-7-10-2-5-8-11-3-6-9-12....

In the same way, an STS-48 with forty-eight STS-1s must look like it came from 16 STS-3 multiplexers all running at the same time. Figure 1-2 shows the multiplexing of 12 STS-1s to form a single STS-12.

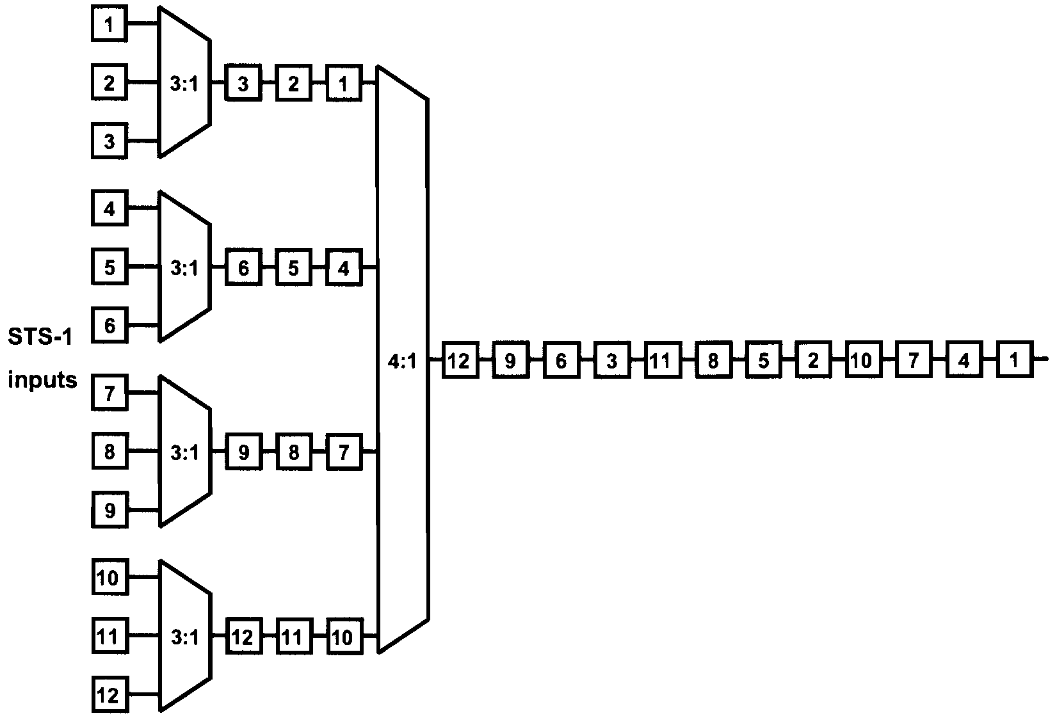

Figure 1-2: Multiplexing 12 STS-1s to form a single STS-12

1.5 Frame Structures

The basic building block of the SONET digital transmission hierarchy is called the STS level one, or STS-1 frame. In SDH, the SONET STS-1 frame is called the STM-0 frame. This sounds odd, but there is a good reason for the STM-0 designation. SDH originally contained no STS-1 equivalent frame. But since an STM-1 frame is quite complex, it was common even in SDH environments to speak of a "conceptual STM-0" frame identical to an STS-1 purely for educational purposes.

This basic, STS-1 SONET and STM-0 SDH frame consists of 810 bytes, transmitted 8.000 times per second (or once every 125 μs) to form a 51,840 Mb/s signal rate. This basic rate, the fundamental building block of SONET (but not SDH), is derived as follows:

810 bytes/frame x 8.000 frames/sec x 8 bits/byte = 51,840 Mb/s line rate.

In other words, the 810 bytes of the basic SONET frame structure are sent 8.000 times per second, and because each byte consists of 8 bits, the signaling rate on the link is 51,840 Mb/s.

Figure 1-3 shows the basic structure of the STS-1 SONET (and STM-0) frame in visual format. The STS-1 frame is 9 rows of 90 columns; it is always shown in this format, so that the overhead bytes will line up properly at the beginning of the frame. The STS-1 frame is transmitted one row at a time, from top to bottom, and from left to right within each row. Therefore, the byte in row 1, column 1 is sent first, and the byte in row 9, column 90 is sent last. After the 90th byte is sent at the end of row 1, the next byte sent is the first byte in row 2, the byte in column 1.

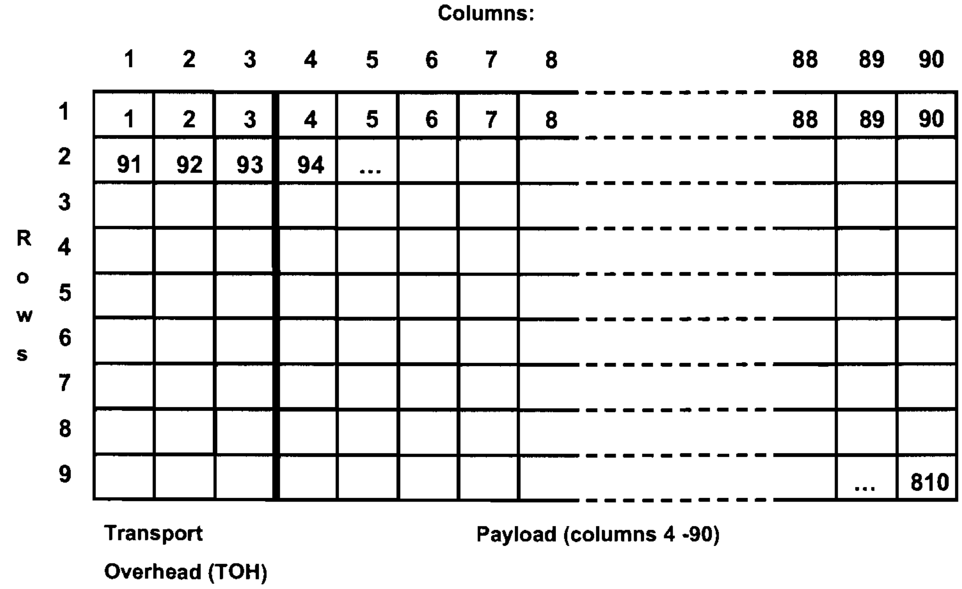

Figure 1-3: The SONET STS-1 (and STM-0) frame structure

An STS frame is composed of two main sections, each with their own structures. The first three columns of the STS-1 frame form the *Transport Overhead* (TOH) for the entire frame. All of the SONET overhead information that is used to manage defined parts of the SONET network and transported data (called a payload), is in the first three columns of the frame. This overhead section, therefore, consists of 27 bytes (9 rows x 3 bytes/row) sent as part of each and every SONET frame. This overhead cannot be eliminated or converted for user data.

The SONET payload is carried in the *Synchronous Payload Envelope* (SPE). The capacity of the SPE is 9 rows of 87 columns. This adds to 783 bytes of payload in each frame, giving a total user data rate of:

783 bytes/frame x 8.000 frames/sec x 8 bits/byte = 50,112 Mb/s payload rate.

It is easy to construct the overall structure of a frame at any level of the SONET hierarchy once the basic STS-1 format is understood. All SONET frames are sent 8.000 times per second. All SONET frames have exactly nine rows. The only variable is the number of columns.
For example, an STS-3 frame consists of 9 rows and is sent 8.000 times per second; however, an STS-3 frame is not 90 columns wide. The STS-3 frame is three times wider (N=3). Therefore, the STS-3 frame is 270 columns wide. The STS-3 overhead columns are multiplied by three as well, as are the SPE capacity columns. An STS-3 frame then is 270 columns wide,

of which the first 9 columns are TOH and the remaining 261 are payload capacity. The whole STS-3 frame is 2.430 bytes. The line rate for an OC-3, therefore, must be:

2.430 bytes/frame x 8000 frames/sec x 8 bits/byte = 155,52 Mb/s line rate.

Figure 1-4 shows some basic structures of other common SONET/SDH frame types.
The basic building block of the SDH digital transmission hierarchy is *not* the STM-0 frame. The STM-0 frame was used for years as an educational tool, mainly because jumping right in to the STM-1 frame was quite confusing for people new to SDH. Now STM-0 is an officially defined SDH frame.

The basic building block of the SDH digital transmission hierarch is the STM-1 frame and has 9 rows and 270 columns, the same as the SONET STS-3. The overhead is not really three times larger than the STM-0, since the STM-0 was more or less invented as a SONET STS-1 equivalent. The nine columns of overhead leading off the STM-1 frame technically stand on their own. The only real difference between SONET and SDH is in a part of the overhead called *path overhead.* It is beyond the scope of this chapter to explain this in more detail. The important fact to remember is that the basic building block of SDH digital transmission hierarchy is the STM-1 frame which runs at 155,52 Mb/s line rate.

1.6 Overhead

SONET/SDH adds no additional overhead at all at higher levels of the multiplexing hierarchy. All the overhead needed for synchronous, byte-interleaved multiplexing is present even at the lowest level of the hierarchy, at the STS-1 level. Of course, the trade-off is higher levels of overhead at the lower levels for no additional overhead at the higher levels. But this is not an insignificant advantage, especially when the need for higher and higher rate transports is considered, and this 'unused' overhead at higher levels of the hierarchy can be used.

The overhead percentage in SONET/SDH is fixed, while the overhead percentage continually rises in other, asynchronous multiplexing schemes. In SONET/SDH, the ratio of overhead to payload (1,728 Mb/s to 50,112 Mb/s) remains constant at 3,45 %, regardless of the value of N.

When several SONET/SDH data stream are multiplexing into one higher rate data streams (such as from three STS-1s to a single STS-3), the resulting SONET/SDH frame structure is called a *composite.* Every frame except a basic STS-1 frame (or STM-1 frame in SDH) is a composite frame of one form or another. Composites frames still retain all of the overhead bytes from each signal source. Obviously, an STS-3 frame that has nine columns of transport overhead, instead of just three from each of the STS-1s, still forms a unit and not just three frames traveling together. Thus, many of the "repeated" overhead bytes are essentially ignored ("undefined" in SONET/SDH talk) in composite frames. The full set of 27 transport overhead bytes is retained only in the first STS-1 or STM-0 of any composite. In the other levels of SONET/SDH, all of the transport overhead bytes may be present, but many of them are neither examined nor processed. These excessive overhead bytes can be used for other functions.

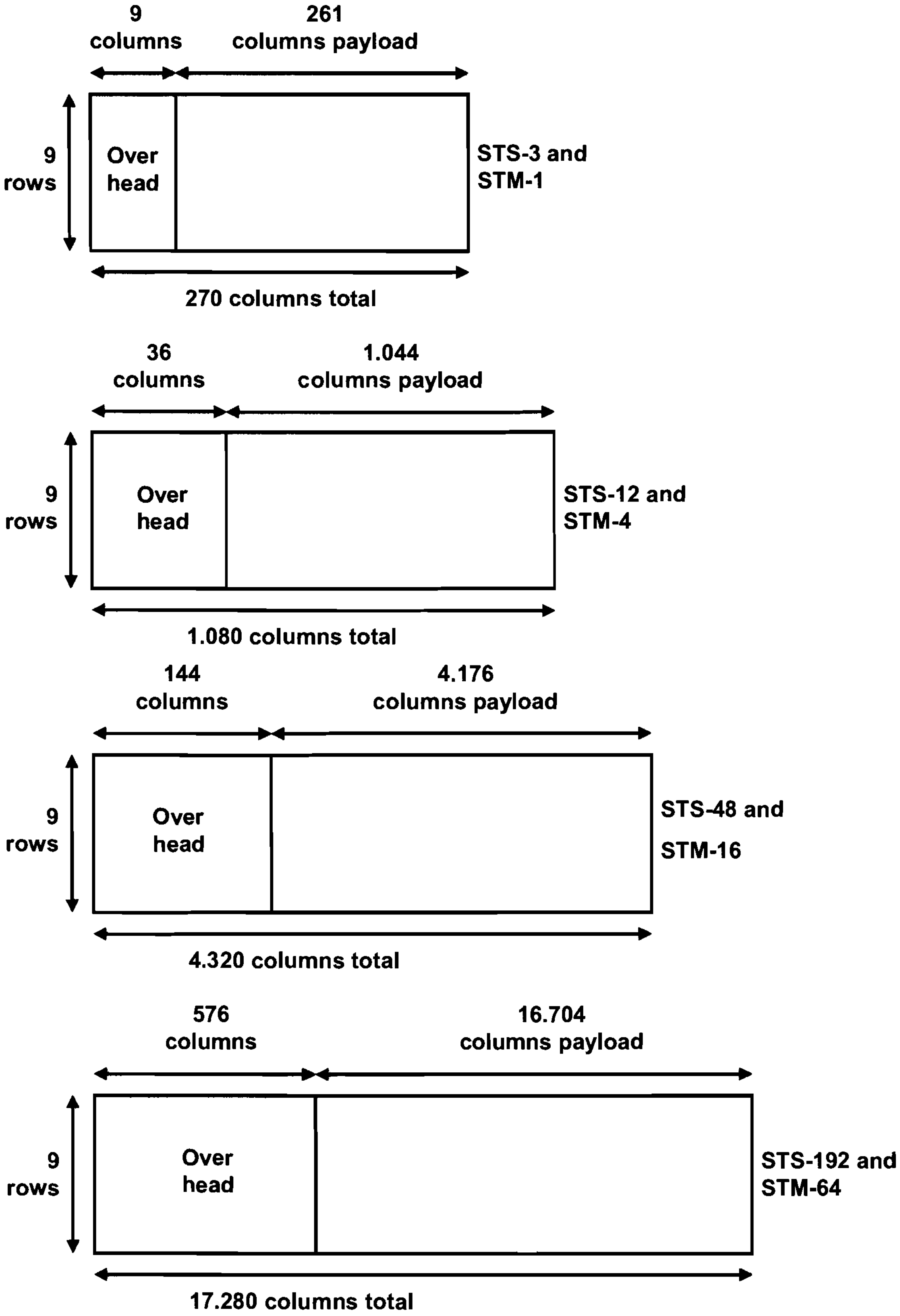

Figure 1-4: Structure of SONET/SDH frames (not to scale)

1.7 Network Components

SONET/SDH networks can be quite complex. This section introduces the overall components of a typical SONET/SDH network. Figure 1-5 shows the major components of a multiple-link SONET/SDH network, such as may be deployed by a major carrier in a metropolitan area today. Note that some of the SONET/SDH components form rings in the diagram. SONET/SDH rings have become a distinguishing feature of SONET/SDH, and they will be more extensively discussed in the next section.

As shown in Figure 1-5, there are six main network elements that can be used in SONET/SDH networks. These are labeled in the figure as follows:

1. **Terminal multiplexer (TM):** An "end point" device on the SONET/SDH network. This device gathers bytes to be sent on the SONET/SDH network link and delivers bytes on the other end of the network.
2. **Add/drop multiplexer (ADM):** Really just a "full-featured" TM. However it is more accurate to refer to the TM as an ADM operating in what is known as "terminal mode". This device usually connects to several TMs and aggregates or splits SONET/SDH traffic at various speeds.
3. **Digital loop carrier (DLC):** This SONET/SDH device is used to link serving offices with ordinary analog copper-twisted-pair local loops in order to support large numbers of residential users in what is know as a *carrier serving area* (CSA).
4. **Digital cross-connect (DCS):** This SONET device can add or drop individual SONET/SDH channels at a given location. It is basically an even more sophisticated version of the SONET/SDH ADM.
5. **Matched nodes (MN):** These SONET/SDH devices interconnect SONET/SDH rings. They provide an alternate path for the SONET/SDH signals in case of equipment failure.
6. **Drop and repeat nodes (D+R):** These devices are capable of "splitting" the SONET/SDH signals and sending copy bytes onto two or more output links. The devices will be used to connect DLC devices for residential video (or even voice) devices.

The equipment found in this network is separated into central office terminal equipment and outside plant equipment.

The central office equipment consists of a SONET/SDH-compatible switch (i.e., digital cross-connect switch) and digital loop carrier equipment. This equipment forms the network terminating point for SONET/SDH transport services.

The outside plant equipment consists of a fiber ring topology for survivability, and access multiplexers to this ring. The multiplexers are functionally separated into two categories, TMs and ADMs. TMs provide conversion from the non-SONET transmission media to the SONET format. Add/drop multiplexers are an integral component of the SONET/SDH architecture; they allow access to the SONET/SDH transmission network without fully demultiplexing the SONET/SDH signal. Non-SONET/SDH signals may be added to or taken from the SONET/SDH transmission signal via this equipment. The difference between SONET/SDH TMs and ADMs is often only a difference in network location and in function, rather than a fundamental or intrinsic difference.

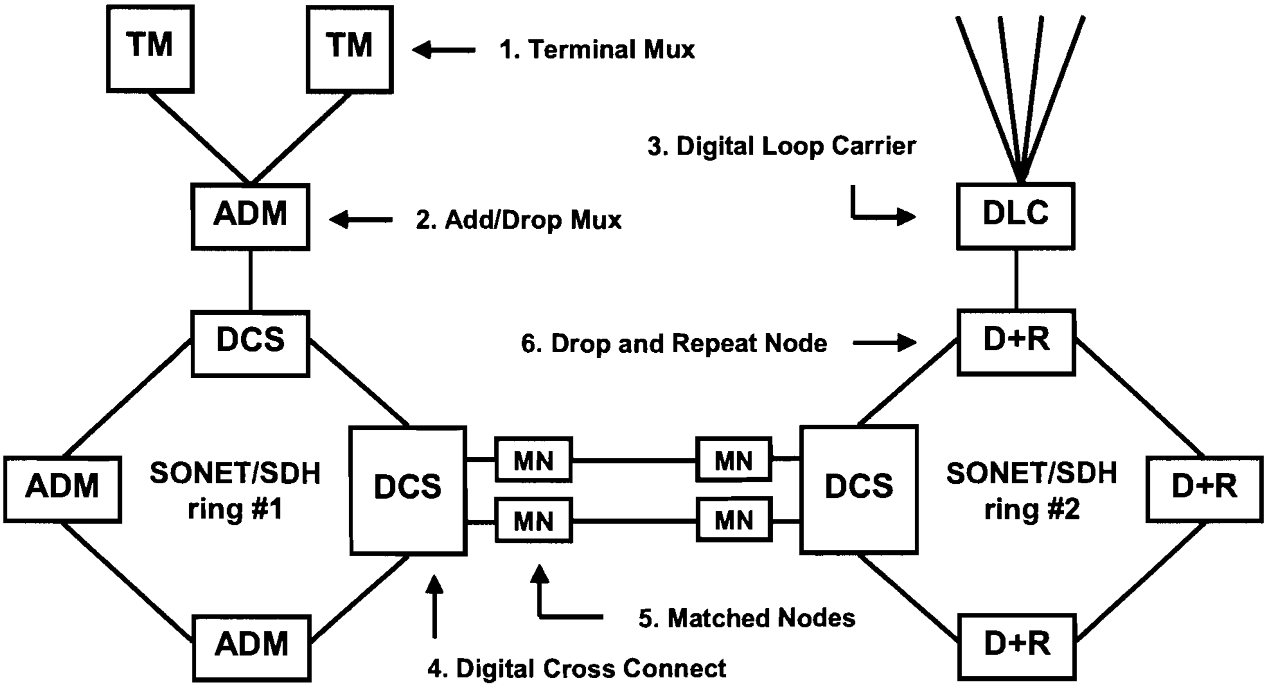

Figure 1-5: Major SONET/SDH components

Physically, the SONET/SDH equipment described is of quite modest size. The solid-state electronics that characterize SONET/SDH result in components that are typically rack-mounted in standard communications cabinets. The power requirements are correspondingly modest as well.

1.8 Protection and Rings

A distinguishing characteristic of SONET/SDH links is their capability to be deployed in a ring topology and configuration. Fiber optic links are inherently unidirectional and not full duplex. All SONET/SDH fiber links consist of a transmit fiber and a receive fiber. SONET/SDH ADMs have a minimum of four fiber interfaces: one for *upstream* and *downstream* transmission in each direction. When the loose “ends” of the last ADM in a chain of ADMs are looped around, a closed loop or ring results.

In Figure 1-6, the simple SONET/SDH ring consists of several ADMs linked by their upstream and downstream fibers. The ring may span only a few miles, or stretch to literally thousands of miles, depending on its purpose. Note that there are still SONET/SDH TMs, with users attached to feed the ring with traffic. Naturally, the aggregate traffic from the TMs cannot exceed the capacity of the SONET/SDH ring.

What is the advantage of deploying SONET/SDH in a ring configuration? Quite simply, rings provide greater reliability by furnishing two separate paths for digital signals between ADMs. Even this simple SONET/SDH ring provides what is known as *path protection switching* (PPS), or just *path switching*, between the SONET/SDH ADM nodes.

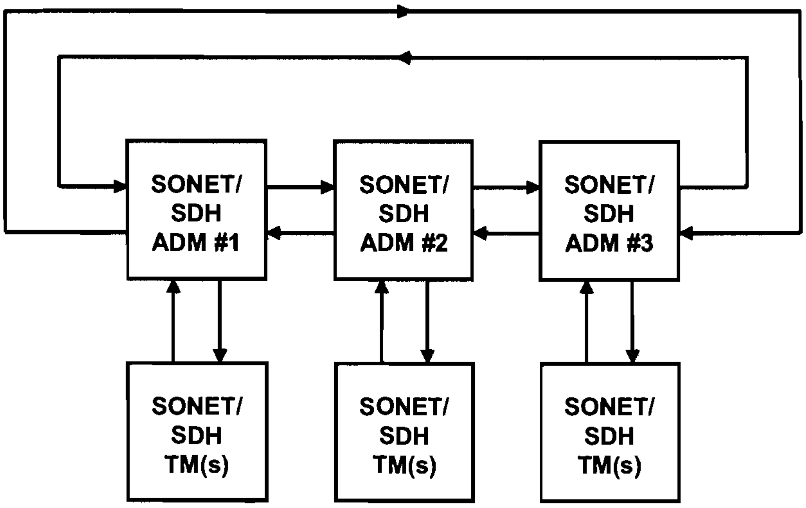

Figure 1-6: A simple SONET/SDH ring

Typically, the two fibers are deployed in the same cable sheath and are laid in the same conduit. Consider what would happen if the fibers between SONET/SDH ADM #2 and ADM #3 in the figure were severely damaged by some environmental disaster or even a construction "incident". Signals can still travel between ADM #2 and ADM #3 through ADM #1. There is still a fiber path between ADM #2 and ADM #3.

SONET/SDH rings allow for repairs to be made without disrupting customer service. This is a valuable capability that justifies the added expense of the extra fiber needed to "close the ring" of SONET/SDH ADMs. Today, it is rare to see a SONET/SDH deployment of any size without rings.

1.9 Clocking

A key feature, if not *the* key feature, of SONET/SDH is its synchronous operation. When detecting a bit stream it is very important for the receiver to know when to sample the incoming bit stream. This sampling is done by means of a clock which indicates the receiver when to sample. A clock running too fast will oversample the incoming bit stream and within a string of bits a certain bit will be sampled twice. A clock running slow will undersample the incoming bit streams and cause bits to be dropped or missed.

Usually in SONET/SDH systems the primary reference clock is known as Stratum 1 clock for the whole service provider's network. A Stratum 1 clock is the most accurate in the entire network.

The network Stratum 1 clock uses regular leased lines to distribute these clock pulses directly to other devices in the network. These are Stratum 2 clocks, and they are directly connected to the Stratum 1 clock. It would be too expensive too hook everything up directly to the Stratum 1 clock, so yet another set of network devices gets clock not from the Stratum 1 clock, but from a Stratum 2 clock. These are, not surprisingly, Stratum 3 clocks. Yet other devices, the Stratum 4 clocks, get their timing from the Stratum 3 clocks. Stratum 1 clocks are the most accurate of all, better than 0.00001 parts per million. This corresponds to losing a second every 300.000 years.

The Stratum 2 clocks are "only" accurate to 0.016 parts per million. The important thing about Stratum 2 is that if the reference link were lost to the Stratum 1 clock, the Stratum 2 clock would not wander off of the mark far before the link would be restored. Stratum 3 and 4 clocks on their turn are less accurate than a Stratum 2 clock.

1.10 Advantages

SONET/SDH is more than just a lot of bandwidth and to conclude this chapter a list of numerous advantages in a number of areas is listed below:

• Technology	Unprecedented speeds available on fiber-optic networks
• Economics	Best interface for fiber-optic networks
	Economical adding and dropping of channels
• Flexibility	Modular equipment design
	Adequate overhead for network management
	Standardization of management
• Compatibility	Works well with existing network hierarchies
	Allows multiple vendors' equipment to interoperate
	Worldwide standard

2 SDH network operated by COMSAT

2.1 POPs and Distances

The SDH optical ring network is schematically shown in Figure 2-1. The ring consists of two fiber traces leased from Silica Networks and Global Crossing. A circle indicates the *Point of Presence* (POP) of an ADM. Overlapping Global Crossing and Silica Networks POPs are not interconnected and located in different buildings. At the end-points of both fiber traces (Buenos Aires and Mendoza) the situation is different. The ADMs in either one of these cities *are* interconnected although they are not located in the same building.

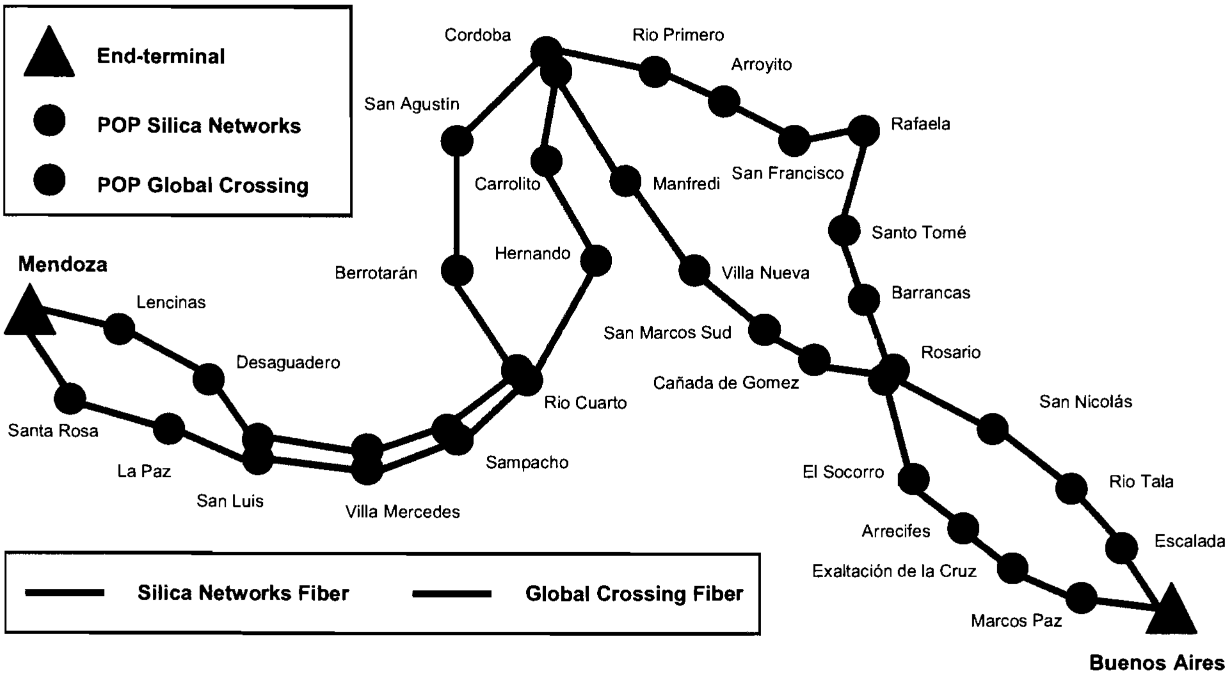

Figure 2-1: Schematic view of SDH network operated by COMSAT in Argentina

The network started out with just the leased fiber trace from Silica Networks. It is along this trace that signals are added and/or dropped. The Global Crossing fiber trace was later leased to create a ring network as means of protection to failures in the network. No signals are added and/or dropped along the Global Crossing fiber trace.

The length of the fiber trace between two POPs is listed in Table 2-1.

SILICA NETWORKS			**GLOBAL CROSSING**		
From	**To**	**Dist. [km]**	**From**	**To**	**Dist. [km]**
Buenos Aires	Marcos Paz	95,5	**Mendoza**	Lencinas	88,8
Marcos Paz	Exaltación de la Cruz	87,7	Lencinas	Desaguadero	90,5
Exaltación de la Cruz	Arrecifes	92,7	Desaguadero	San Luis	93,5
Arrecifes	El Socorro	86,3	San Luis	Villa Mercedes	97,3
El Socorro	Rosario	102,4	Villa Mercedes	Sampacho	81,9
Rosario	Cañada de Gomez	96,2	Sampacho	Rio Cuarto	48,3
Cañada de Gomez	San Marcos Sud	94,4	Rio Cuarto	Berrotarán	84,6
San Marcos Sud	Villa Nueva	88,8	Berrotarán	San Agustín	69,2
Villa Nueva	Manfredi	92,6	San Agustín	Cordoba	80,5
Manfredi	Cordoba	100,2	Cordoba	Rio Primero	78,2
Cordoba	Corralito	97,0	Rio Primero	Arroyito	60,2
Corralito	Hernando	92,6	Arroyito	San Francisco	96,9
Hernando	Rio Cuarto	91,5	San Francisco	Rafaela	96,1
Rio Cuarto	Sampacho	88,2	Rafaela	Santo Tomé	95,7
Sampacho	Villa Mercedes	90,8	Santo Tomé	Barrancas	72,1
Villa Mercedes	San Luis	86,3	Barrancas	Rosario	85,9
San Luis	La Paz	86,4	Rosario	San Nicolás	75,6
La Paz	Santa Rosa	90,2	San Nicolás	Rio Tala	82,6
Santa Rosa	**Mendoza**	89,9	Rio Tala	Escalada	81,7
			Escalada	**Buenos Aires**	97,1
Total		**1749,5**	**Total**		**1656,6**

Table 2-1: The length of a fiber trace between two consecutive POPs

2.2 Fiber types and Losses

Both Silica Networks and Global Crossing deployed fiber manufactured by Furukawa Electric. Silica Network uses *Standard Single Mode Fiber* (SSMF) compliant with the G.652 standard of the ITU whereas Global Crossing uses *Non-Zero Dispersion-Shifted Fiber* (NZDSF) compliant with the G.655 standard. A table of specifications for both fibers is shown in Table 2-2.

Specifications	**G.652**	**G.655**
Fiber attenuation at 1550 nm [dB/km]	≤ 0,25	≤ 0,22
Dispersion parameter D [ps/nm·km]	≤ 18	≤ 5
$A_{\text{effective}}$ [μm^2]	≈ 80	≈ 55

Table 2-2: G.652 and G.655 ITU compliant fiber specifications

The transmission wavelength used between POPs contained within the network lies at the third transmission window (around 1550 nm). An ADM located at a POP is connected with two fibers to each of its neighboring ADMs located at another POP. This way the traffic between POP X and POP Y is bi-directional. This is schematically shown in Figure 2-2.

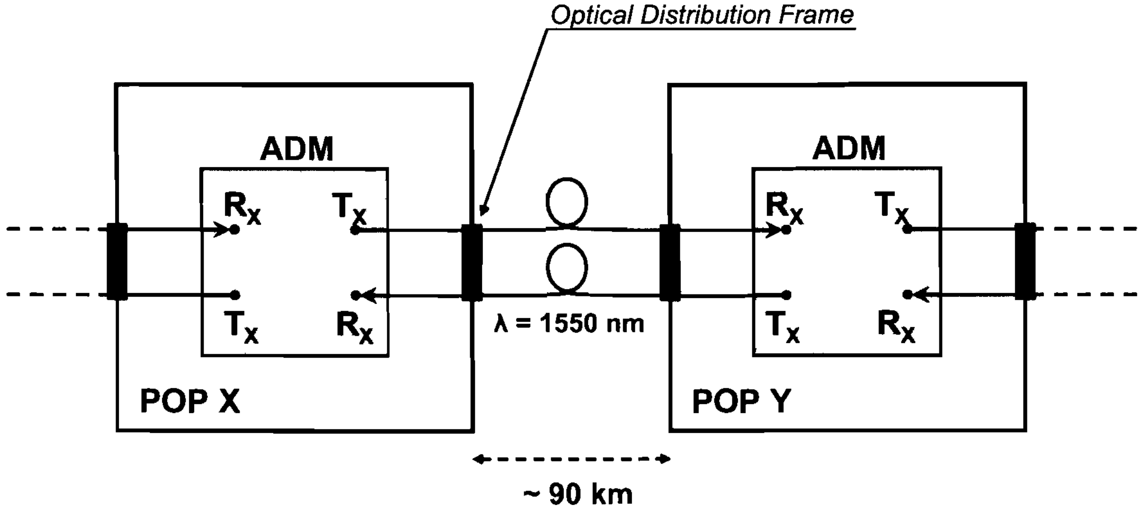

Figure 2-2: Schematic view of two connected POPs

Three different losses can be distinguished between a transmitter and a receiver:

- Fiber attenuation losses
- Splice losses (≈ 0,10 dB per splice)
- POP Connector losses (≤ 0,25 dB per connector)

This last loss needs some clarification. At a POP the fiber reaches an *Optical Distribution Frame* (ODF) from where it is connected to an ADM. These connections cause losses.

2.3 Optical Power Levels

Section 2.2 clarified the fact that every ADM located at a POP has two transmitters and two receivers. There is an optical power associated with each of these transmitters and receivers. These powers can be monitored from the *Network Control Center* (NOC) located in Buenos Aires and shown in Table 2-3. Buenos Aires (2) is connected to Marcos Paz (1), Marcos Paz (2) is connected to Exaltación de la Cruz (1), and so on. With this information the attenuation loss between two POPs can be calculated. This results in two attenuation losses since two fibers run between a pair of POPs (see Figure 2-2).
For instance, between *Villa Nueva* and *Manfred*, the following losses can be calculated:

Villa Nueva (2) T_x – Manfredi (1) R_x = 3 – (-25) dBm = **28 dB attenuation,**

Manfredi (1) T_x – Villa Nueva (2) R_x = 1 – (-20) dBm = **21 dB attenuation.**

SILICA NETWORKS			GLOBAL CROSSING		
Location	**Rx [dBm]**	**Tx [dBm]**	**Location**	**Rx [dBm]**	**Tx [dBm]**
Buenos Aires (2)	-20	+1	**Mendoza (2)**	-22	+1
Marcos Paz (1)	-22	+3	Lencinas (1)	-22	+1
Marcos Paz (2)	-23	+3	Lencinas (2)	-19	+1
Exaltación de la Cruz (1)	-21	+3	Desaguardero (1)	-19	+1
Exaltación de la Cruz (2)	-18	+3	Desaguardero (2)	-19	+3
Arrecifes (1)	-20	+3	San Luis (1)	-24	+3
Arrecifes (2)	-16	+3	San Luis (2)	-17	+3
El Socorro (1)	-17	+3	Villa Mercedes (1)	-17	+3
El Socorro (2)	-16	+3	Villa Mercedes (2)	-18	+1
Rosario (1)	-15	+3	Sampacho (1)	-19	+1
Rosario (2)	-21	+3	Sampacho (2)	-10	+1
Cañada de Gomes (1)	-21	+3	Rio Cuarto (1)	-10	+1
Cañada de Gomes (2)	-21	+3	Rio Cuarto (2)	-19	+1
San Marcos Sud (1)	-19	+3	Berrotarán (1)	-19	+1
San Marcos Sud (2)	-18	+3	Berrotarán (2)	-16	+1
Villa Nueva (1)	-19	+3	San Agostín (1)	-14	+1
Villa Nueva (2)	-20	+3	San Agostín (2)	-19	+1
Manfredi (1)	-25	+1	Cordoba (1)	-17	+1
Manfredi (2)	-21	+3	Cordoba (2)	-17	+1
Cordoba (1)	-21	+3	Rio Primero (1)	-16	+1
Cordoba (2)	-26	+3	Rio Primero (2)	-12	+1
Carrolito (1)	-22	+3	Arroyito (1)	-12	+1
Carrolito (2)	-17	+3	Arroyito (2)	-17	+3
Hermando (1)	-17	+3	San Francisco (1)	-19	+3
Hermando (2)	-17	+3	San Francisco (2)	-19	+3
Rio Cuarto (1)	-18	+3	Rafaela (1)	-18	+3
Rio Cuarto (2)	-15	+3	Rafaela (2)	-21	+1
Sampacho (1)	-15	+3	Santo Tomé (1)	-20	+1
Sampacho (2)	-16	+3	Santo Tomé (2)	-15	+1
Villa Mercedes (1)	-19	+3	Barrancas (1)	-18	+1
Villa Mercedes (2)	-23	+3	Barrancas (2)	-18	+1
San Luis (1)	-18	+3	Rosario (1)	-17	+1
San Luis (2)	-19	+3	Rosario (2)	-17	+1
La Paz (1)	-20	+3	San Nicolás (1)	-17	+1
La Paz (2)	-21	+3	San Nicolás (2)	-17	+1
Santa Rosa (1)	-18	+3	Rio Tala (1)	-17	+1
Santa Rosa (2)	-18	+3	Rio Tala (2)	-17	+1
Mendoza (1)	-18	+3	Escalada (1)	-17	+1
			Escalada (2)	-26	+3
			Buenos Aires (1)	-22	+1

Table 2-3: ADM receiver and transmitter power levels

2.4 WaveStar™ ADM 16/1

Every POP contains a Lucent *WaveStar*™ ADM 16/1 subrack which is housed in a *European Telecommunication Standards Institute* (ETSI) compliant rack. In these subracks there is room for:

- Two STM-16 line port units (Line Interface Units)
- Two *Power and Timing Units* (PTU)
- Two *Cross-Connect* (CC) *Units*
- One *System Controller* (SC)
- 9 additional slots for tributary interface units

Figure 2-3 shows the frontview of a *WaveStar*™ ADM 16/1 subrack. The elements listed above are indicated in the figure and will be explained individually below. Observe that two tributary slots are empty and can be used for future insertion of tributary interface units.

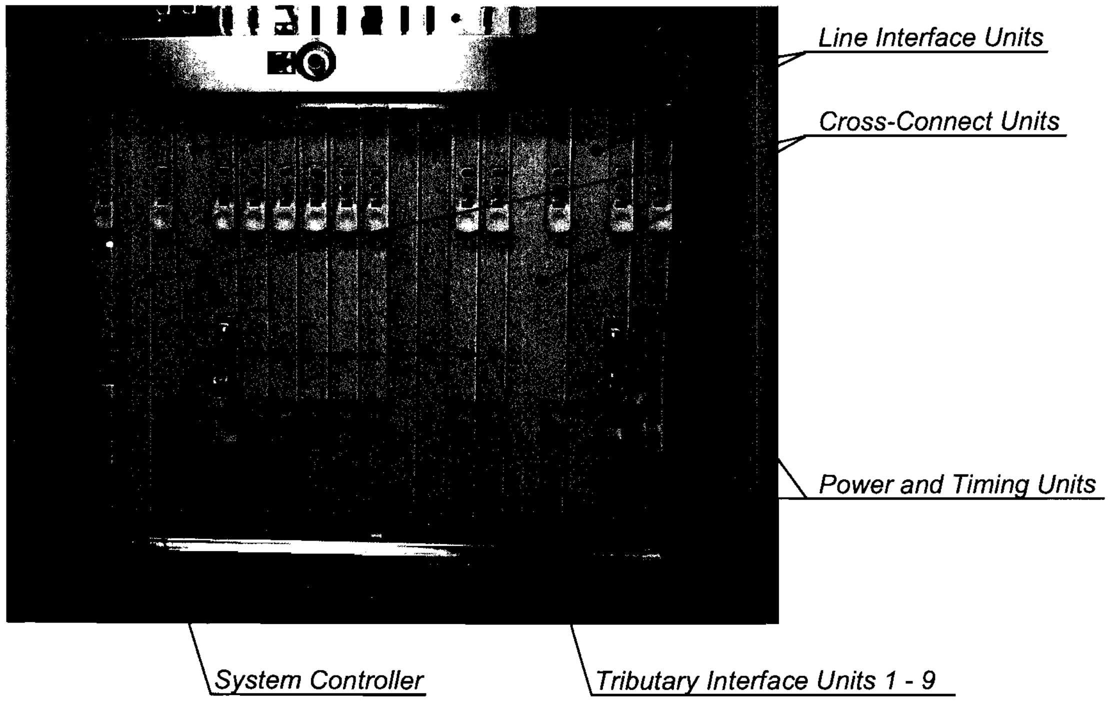

Figure 2-3: Frontview of a *WaveStar*™ ADM 16/1 subrack

1. **Line Interface Units:** The *WaveStar*™ ADM 16/1 can be equipped with STM-16, STM-4, STM-1 and STM-0 optical interface circuit packs, which are available in several types [3]. COMSAT uses two types: STM-16 SI-L 16.2 and STM-16 SI-L 16.3. These circuit packs are equipped with a universal build-out optical connector type, and transmit the multiplexed SDH signal over the fiber. Table 2-4 lists some specifications of these two line interface units.

Specifications	STM-16 SI-L 16.2	STM-16 SI-L 16.3
Optical Output [Gb/s]	2,488	2,488
Optical Line Code	NRZ	NRZ
Laser Type	DFB (SLM)	DFB (SLM)
Optical Detector	APD	APD
Wavelength Range [nm]	1535-1565	1535-1565
Maximum -20 dB width [nm]	<1	<1
Minimum Launched Power [dBm]	-2	+1
Maximum Launched Power [dBm]	+2	+4
Minimum Receiver Sensitivity [dBm] for a BER $\leq 10^{-10}$	-28	-29
Minimum Extinction-Ratio [dB]	8,2	8,2
Maximum Dispersion [ps/nm]	1800	1800

Table 2-4: Specifications of STM-16 SI-L 16.2 and STM-16 SI-L 16.3

2. **Power and Timing Units:** The *WaveStar*™ ADM 16/1 can be equipped with one or two *Power and Timing Units* (PTUs). The PTUs provide power and timing to the system. One PTU is sufficient but a second one installed as a back-up will contribute to the overall system reliability and availability. A basic function of the PTU is to filter and stabilize the incoming station power to meet the necessary ETSI requirements. Another basic function of the PTU is system timing. The local oscillator, also called the *SDH Equipment Clock* (SEC), can be synchronized to one of the user-selectable timing references.
3. **Cross-Connect Units:** The *WaveStar*™ ADM 16/1 can be equipped with one or two *Cross-Connect* (CC) circuit packs. The CC is the core of the *WaveStar*™ ADM 16/1 system and multiplexes the tributary signals to the SDH format that is then transmitted by the Line Interface Units. A second CC circuit pack installed serves as a back-up and will contribute to the overall system reliability and availability.
4. **System Controller:** The *System Controller* (SC) controls and provisions all circuit packs via a local LAN bus. The SC also provides the external operations interface for office alarms, miscellaneous discretes and connection to the overhead channels. The SC also facilitates first line maintenance by several LEDs and buttons on the front panel. The SC communicates with the centralized management system (ITM-SC and ITM-NM) located at the NOC. A part of SC, routing management information between SDH equipment and the element management system, is called *Data Packet Switch* (DPS). Communication is established via so-called data communication channels (= D1-3/D4-12 bytes), within the STM-N section overhead signals or via one of the Q-interfaces of the system. Information destined for the local system is routed to the SC, while other information is routed from the node via the appropriate embedded channels of the STM-N line or tributary signals. The ITM-SC manages the *WaveStar*™ ADM 16/1 at the element level and the ITM-NM manages the system at the Network Level.
5. **Tributary Units:** The *WaveStar*™ ADM 16/1 Multiplexer and Transport System supports a mix of 1.5, 2, 34, 45, 10/100 Base-T Ethernet, STM-0, 140, STM-1 and STM-4 tributary speed interface inputs and outputs. These speeds are provided through circuit boards that go into the tributary slots. Nine slots are available for tributary interfaces. It is possible to mix these interfaces in the same subrack for all platforms. Also, a link can be set up connecting two clients with different tributary rates. Mixing is supported not only within a Terminal, but also between Terminals. The

PDH interface (140 Mb/s) at one end of a circuit within a *WaveStar*™ ADM 16/1 network can be upgraded to SDH interfaces (STM-1) without any changes at the other end.

Figure 2-4 shows a more schematically view of the *WaveStar*™ ADM 16/1 with its possible circuit boards. As can be observed from the figure the CC serves as the heart of the *WaveStar*™ ADM 16/1 system.

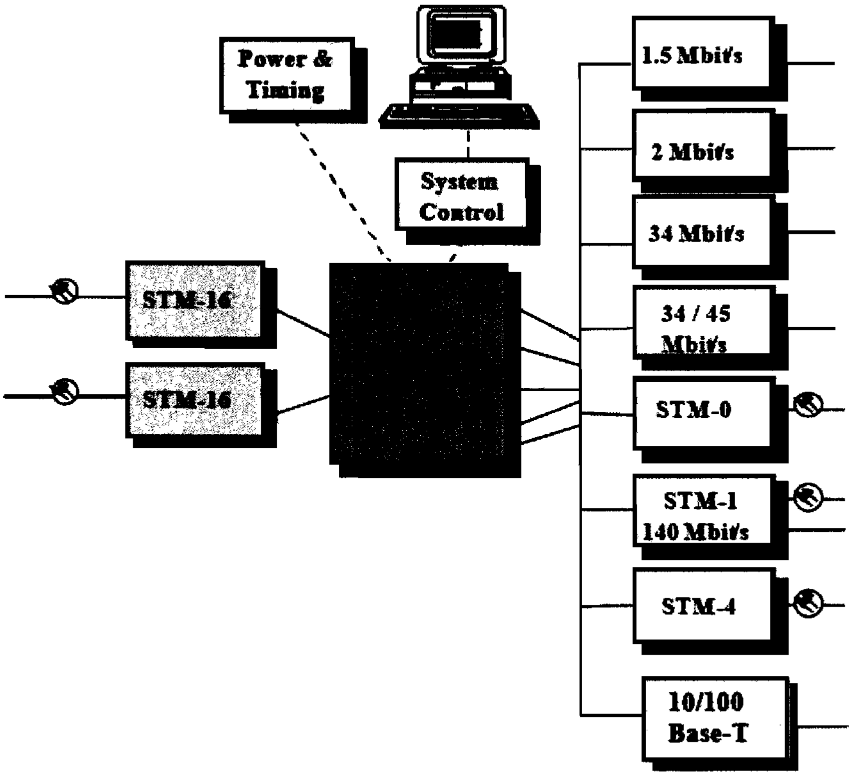

Figure 2-4: A schematical view of the *WaveStar*™ ADM 16/1

2.5 Tributary Interfaces – Clients

A SDH STM-16 frame can be divided in *Virtual Containers* (VC) with each VC having its own bit-rate. Figure 2-5 shows a schematically view of how the STM-16 can be split up in VCs. Table 2-5 lists the proportion of each VC to a smaller VC and the bit-rate associated with that. COMSAT uses three different tributary interfaces:

• LJB439 STM-1e/o Interface:	Consists of 4 x STM-1s
• LJB427 34/45 Mb/s PDH Interface:	Consists of 6 x E3 and 6 x T3
• LJB411 2 Mb/s PDH Interface:	Consists of 63 x E1

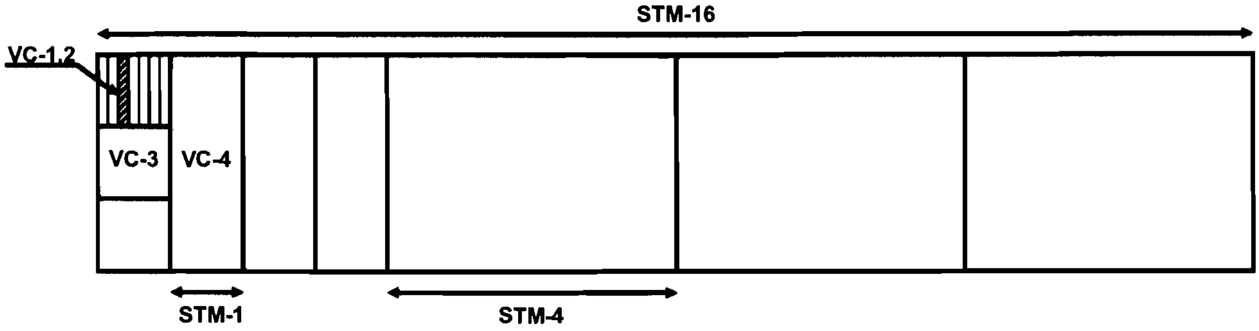

Figure 2-5: A schematical view of a STM-16 frame split up in several VCs

Virtual Container(s)		Virtual Container	Bit-rate	Remark
		VC-1.2	2,47 Mb/s	
21 x VC-1.2	=	VC-3	51,84 Mb/s	
3 x VC-3	=	VC-4	155,52 Mb/s	
VC-4	=	STM-1	155,52 Mb/s	
4 x STM-1	=	STM-4	622,08 Mb/s	
4 x STM-4	=	STM-16	2488,32 Mb/s	= 2,5 Gb/s

Table 2-5: Proportion between various VCs

The exact line speed of E1 is 2,048 Mb/s, that of E3 is 34,368 Mb/s and T3 is 44,736 Mb/s. All signals (STM-1, E3, T3, and E1) can be located in a VC. Bit-slots not occupied within the VC should be considered lost because they cannot be used for other traffic. Table 2-6 lists which VC is used for which signal and the efficiency.

Signal	Virtual Container	Used/Capacity	Efficiency
STM-1	VC-4	2488,32 / 2488,32	100%
T3	VC-3	44,736 / 51,84	86,3%
E3	VC-3	34,368 / 51,84	66,3%
E1	VC-1.2	2,048 / 2,47	82,9%

Table 2-6: Assignment of a VC to the various signals

To get an idea of what percentage of the capacity of the national SDH network is used, the bit-rates of all the tributary interfaces should be summed up. Every tributary interface adds to the capacity used over the whole ring network. This is valid because traffic is send from POP X to POP Z in two directions, for protection purposes, and the signal therefore propagates over the whole ring network. There are a couple of difficulties involved in calculating what part of the capacity is used:

- Clients can be connected to the national SDH network with several bit-rates as listed in Table 2-6. The bit-rates of the VCs (see Table 2-6) should be added instead of the client bit-rates.
- A couple of ADMs contain STM-1 tributary interfaces. These interfaces are used to set up a small ring with the ADM at that POP and another POP located outside the main ring network (this smaller ring network then handles a bit-rate of 155,52 Mb/s). Two STM-1 tributary interfaces are used to create that small ring network and are located in the tributary slots of the ADM that handles STM-16. Just one of these STM-1 tributary

interfaces should be taken into account as to calculate its part in the total capacity of the national SDH network used.

- The STM-1 tributary interfaces just mentioned consist of VC-3s and VC-1.2s. VCs that don't carry traffic remain available for use. For every STM-1 tributary interface used to create a smaller ring network the bit-rate of all used VCs should be counted instead of the total STM-1 tributary interface bit-rate of 155,52 Mb/s.

No clients are connected to the Global Crossing part of the ring network and therefore no signals are added or dropped at these POPs. Regarding the Silica Networks part of the ring network just the following POPs are used to add/drop signals: Mendoza, San Luis, Villa Mercedes, Cordoba, Rosario, El Socorro and Buenos Aires. Table 2-7 on the next page summarizes the VCs used by each of these ADMs.

As can be seen from this table the total bit-rate used is 1347,84 Mb/s. This number however, should be divided by two since each pair of VC produced by a tributary slot accounts for one VC traveling over the ring network. This results in 673,92 Mb/s used of a total capacity of 2488,32 Mb/s, which stands for a network occupation of over 27 %.[1]

---

[1] Based on the configuration of the national SDH ring network for October 2005.

Mendoza	**Virt.Cont.**	**Quantity**	**Σ Bit-rate [Mb/s]**
	VC-1.2	29	71,59
	VC-3	2	103,68
	VC-4	0	0,00

175,27

San Luis	**Virt.Cont.**	**Quantity**	**Σ Bit-rate [Mb/s]**
	VC-1.2	1	2,47
	VC-3	1	51,84
	VC-4	0	0,00

54,31

Villa Mercedes	**Virt.Cont.**	**Quantity**	**Σ Bit-rate [Mb/s]**
	VC-1.2	0	0,00
	VC-3	1	51,84
	VC-4	0	0,00

51,84

Cordoba	**Virt.Cont.**	**Quantity**	**Σ Bit-rate [Mb/s]**
	VC-1.2	15	37,03
	VC-3	3	155,52
	VC-4	0	0,00

192,55

Rosario	**Virt.Cont.**	**Quantity**	**Σ Bit-rate [Mb/s]**
	VC-1.2	10	24,69
	VC-3	1	51,84
	VC-4	0	0,00

76,53

El Socorro	**Virt.Cont.**	**Quantity**	**Σ Bit-rate [Mb/s]**
	VC-1.2	3	7,41
	VC-3	1	51,84
	VC-4	0	0,00

59,25

Buenos Aires	**Virt.Cont.**	**Quantity**	**Σ Bit-rate [Mb/s]**
	VC-1.2	110	271,54
	VC-3	9	466,56
	VC-4	0	0,00

738,10

1347,84

Table 2-7: Total number of VCs used in the national SDH ring network

3 Attenuation and Dispersion Calculations

The average length between two POPs is approximately 90 km (see Chapter 2). If an ADM is removed at a POP, as is schematically shown in Figure 3-1, the distance between two ADMs will double to 180 km. The worst-case calculations in this chapter are carried out based on the fact that a distance of at most 180 km needs to be covered. At the POP where the ADM is removed the ODFs will be connected as shown in Figure 3-1.

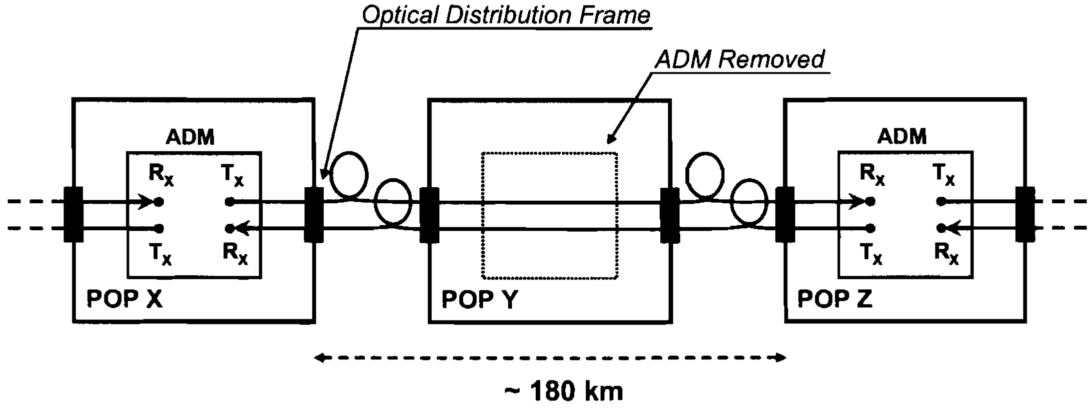

Figure 3-1: ODFs connected at the POP where the ADM is removed

3.1 Distances

Tables 3-1 and 3-2 list the distance between two ADMs if an ADM at a certain POP is removed from the Silica Networks and Global Crossing part of the ring network respectively. Distances less than 180 km are colored green whereas distances over 180 km are colored red. Furthermore the tables indicate whether or not (a) signal(s) is (are) added or dropped at that certain POP. For the POPs where this is the case the ADM cannot be removed.

3.2 Attenuation

Attenuation of a light signal as it propagates along a fiber is an important consideration in the design of an optical communication system, since it plays a major role in determining the maximum transmission distance between a transmitter and a receiver or an in-line amplifier. The basic attenuation mechanisms in a fiber are scattering and absorption. Absorption is related to the fiber material, whereas scattering is associated both with the fiber material and with structural imperfections in the optical waveguide. Attenuation owing to radiative effects originates from perturbations (both microscopic and macroscopic) of the fiber geometry [1]. As mentioned before, the worst case scenario corresponds to a signal that propagates over 180 km. Three types of losses were mentioned in section 2.2. First, there is the fiber attenuation which is 0,25 dB/km for the Silica Networks (SN) fiber and 0,22 dB/km for the Global Crossing (GC) fiber. Second, there is additional signal absorption due to splices in the fiber.

SILICA NETWORKS				
From	**To**	***ADM removal at POP***	**Add/Drop of Signal(s) at Removal Site?**	**Distance [km]**
Buenos Aires	Exaltación de la Cruz	*Marcos Paz*	no	183,2
Marcos Paz	Arrecifes	*Exaltación de la Cruz*	no	180,4
Exaltación de la Cruz	El Socorro	*Arrecifes*	no	178,9
Arrecifes	Rosario	*El Socorro*	yes	188,7
El Socorro	Cañada de Gomez	*Rosario*	yes	198,6
Rosario	San Marcos Sud	*Cañada de Gomez*	no	190,6
Cañada de Gomez	Villa Nueva	*San Marcos Sud*	no	183,2
San Marcos Sud	Manfredi	*Villa Nueva*	no	181,4
Villa Nueva	Cordoba	*Manfredi*	no	192,8
Manfredi	Corralito	*Cordoba*	yes	197,2
Cordoba	Hernando	*Corralito*	no	189,6
Corralito	Rio Cuarto	*Hernando*	no	184,0
Hernando	Sampacho	*Rio Cuarto*	yes	179,7
Rio Cuarto	Villa Mercedes	*Sampacho*	no	179,0
Sampacho	San Luis	*Villa Mercedes*	yes	177,1
Villa Mercedes	La Paz	*San Luis*	yes	172,7
San Luis	Santa Rosa	*La Paz*	no	176,6
La Paz	**Mendoza**	*Santa Rosa*	no	180,1

Table 3-1: Distances and add/drop of signal(s) for the Silica Networks POPs

GLOBAL CROSSING				
From	**To**	***ADM removal at POP***	**Add/Drop of Signal(s) at Removal Site?**	**Distance [km]**
Mendoza	Desaguadero	*Lencinas*	no	179,3
Lencinas	San Luis	*Desaguadero*	no	183,9
Desaguadero	Villa Mercedes	*San Luis*	no	190,8
San Luis	Sampacho	*Villa Mercedes*	no	179,3
Villa Mercedes	Rio Cuarto	*Sampacho*	no	130,3
Sampacho	Berrotarán	*Rio Cuarto*	no	132,9
Rio Cuarto	San Agustín	*Berrotarán*	no	153,8
Berrotarán	Cordoba	*San Agustín*	no	149,7
San Agustín	Rio Primero	*Cordoba*	no	158,7
Cordoba	Arroyito	*Rio Primero*	no	138,4
Rio Primero	San Francisco	*Arroyito*	no	157,1
Arroyito	Rafaela	*San Francisco*	no	193,0
San Francisco	Santo Tomé	*Rafaela*	no	191,7
Rafaela	Barrancas	*Santo Tomé*	no	167,8
Santo Tomé	Rosario	*Barrancas*	no	158,0
Barrancas	San Nicolás	*Rosario*	no	161,4
Rosario	Rio Tala	*San Nicolás*	no	158,2
San Nicolás	Escalada	*Rio Tala*	no	164,3
Rio Tala	**Buenos Aires**	*Escalada*	no	178,8

Table 3-2: Distances and add/drop of signal(s) for the Global Crossing POPs

On average there is one splice every 4 km of fiber with a 0,10 dB loss per splice. Finally, there are also POP connector losses. The configuration shown in Figure 3-1 has eight POP connections along the 180 km link. The total attenuation can be calculated as shown in Table 3-3 for Silica Networks (SN) and Global Crossing (GC):

		SN	GC
Fiber Attenuation:	180 km x 0,25 dB/km (SN), x 0,22 dB/km (GC)	45 dB	39,6 dB
Splices:	180 km x 1 splice/4 km x 0,10 dB/splice	4,5 dB	4,5 dB
POP Connecters:	8 Connectors x 0,25 dB/Connector	2 dB	2 dB
	Total Attenuation over 160 km	**~ 52 dB**	**~ 46 dB**

Table 3-3: Worst-case (180 km) attenuation calculations for the SN and GC fiber trace

Attenuation of the signal can be calculated as well by using the measured power levels (Table 2-3) at the transmitter and receiver side of an ADM. Two examples for the Global Crossing fiber trace are given below:

Example 1: Removing the ADM located at Escalada

The signal propagates from Buenos Aires to Rio Tala and viceversa. This distance to be covered is 178,8 km which is almost the same as in the worst case scenario mentioned above.

Buenos Aires → Rio Tala:

(Buenos Aires (2) T_x – Escalada (1) R_x) + (Escalada (2) T_x – Rio Tala (1) R_x)

= (1 – (-26)) + (1 – (-17)) = **45 dB attenuation**

Rio Tala → Buenos Aires:

(Rio Tala (1) T_x – Escalada (2) R_x) + (Escalada (1) T_x – Buenos Aires (2) R_x)

= (1 – (-17)) + (3 – (-22)) = **43 dB attenuation**

Example 2: Removing the ADM located at Rio Cuarto

The signal propagates from Sampacho to Berrotarán and vice versa. This distance to cover is 132,9 km.

Sampacho → Berrotarán:

(Sampacho (2) T_x – Rio Cuarto (1) R_x) + (Rio Cuarto (2) T_x – Berrotarán (1) R_x)

= (1 – (-10)) + (1 – (-19)) = **31 dB attenuation**

Berrotarán → Sampacho:

(Berrotarán (1) T_x – Rio Cuarto (2) R_x) + (Rio Cuarto (1) T_x – Sampacho (2) R_x)

= (1 – (-19)) + (1 – (-10)) = **31 dB attenuation**

3.3 BER versus OSNR

A measure of the signal degradation after transmission can be obtained by calculating the BER, given by the following equation [4]:

$$BER = \frac{1}{2} erfc\left(\frac{Q}{\sqrt{2}}\right), \qquad (3.1)$$

where *erfc* stands for the complementary error function and Q is given by

$$Q \equiv (I_1 - I_{th})/\sigma_1 = (I_{th} - I_0)/\sigma_0, \qquad (3.2)$$

The OSNR is a measure of the signal degradation due to optical noise accumulation and can be calculated by using the following equation:

$$\mathrm{OSNR} = 10\,{}^{10}\log(P_S / P_N), \qquad (3.3)$$

where P_S and P_N are the average received optical signal and noise powers respectively.

Every transmitter suffers from the phenomenon of non-extinction for 'zero' bits. This means a non-zero average optical signal power level of a 'zero' bit. The *extinction-ratio* ε_r of a transmitter can be defined with

$$\varepsilon_r = 10\,{}^{10}\log(P_{S,1} / P_{S,0}), \qquad (3.4)$$

where $P_{S,1}$ and $P_{S,0}$ are the average transmitted optical signal power values of a 'one' bit and 'zero' bit respectively. Figure 3-2 (Script: Appendix A.1) shows the BER versus the OSNR for different transmitter extinction-ratios. The green trace (ε_r = 8,2 dB) is chosen explicitly because this corresponds to the extinction-ratio of the line interface units used in COMSAT's SDH network as can be observed from Table 2-4.

3.4 Dispersion

Single mode fibers suffer from *Group-Velocity Dispersion* (GVD), or simply referred to as *fiber dispersion*, originating from the frequency dependence of the fiber's core refractive index. In the presence of dispersion different spectral components of a transmitted pulse travel at different speeds, leading to pulse broadening and limiting system performance. Upon propagation pulses within a pulse sequence will lose peak power and flatten out. At a certain distance these pulses will start to spread across their allocated bit-slot. These pulses then interfere in adjacent bit-slots which is known as *Inter-Symbol-Interference* (ISI). A graphical view of a pulse shape broadening upon propagation in an optical fiber is shown in Figure 3-3.

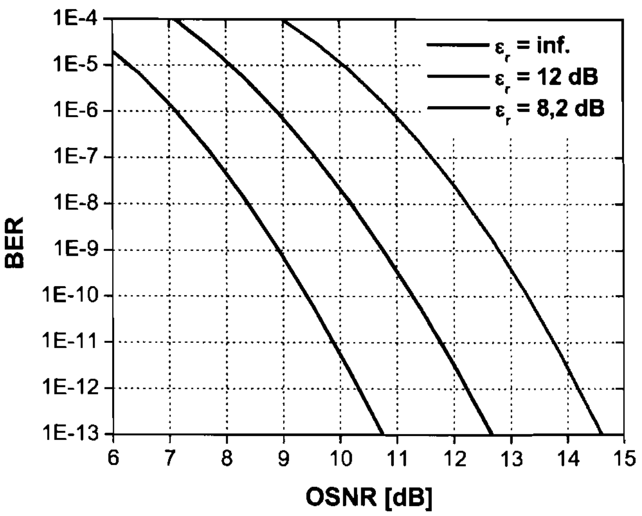

Figure 3-2: BER vs OSNR for varying ε_r. B = 2,5 Gb/s

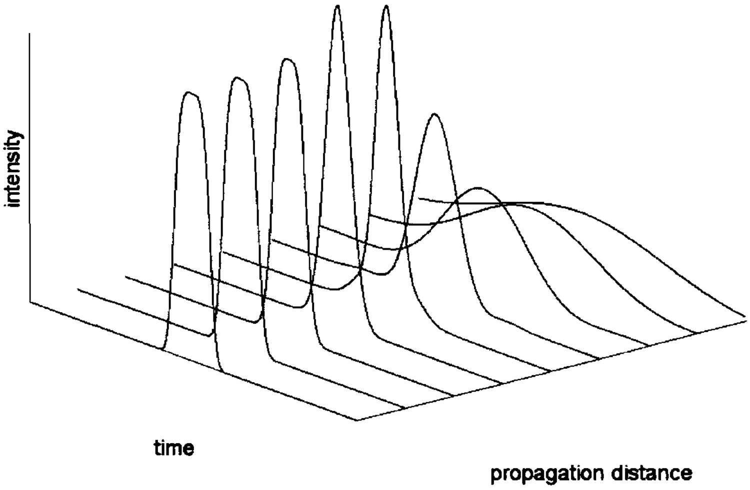

Figure 3-3: Broadening of a pulse upon dispersive propagation in an optical fiber

The dispersion length, L_D, provides a good estimation of the propagated distance at which to expect dispersion-induced impairments, and is given by [4]:

$$L_D = \frac{T_0^2}{|\beta_2|}, \tag{3.5}$$

where T_0 is the half-width of the 1/e-intensity point of the initial pulse shape contained in the pulse sequence and β_2 represents the GVD-parameter which equates to the dispersion parameter D with:

$$D = -\frac{2\pi c}{\lambda^2}\beta_2 . \qquad (3.6)$$

The assumption of initially unchirped pulses is made [4]. However, Lucent's *WaveStar*^{TM} ADM 16/1 transmitters are directly modulated producing initially chirped pulses. In this case applying straightforward Eq. (3.5) will overestimate the propagation length at which to expect dispersive problems.

The receiver part of the Lucent's *WaveStar*^{TM} ADM 16/1 line interface units allows a maximum dispersion of 1800 ps/nm (see Table 2-4). Combined with a D of at maximum 5 and 18 ps/nm·km for G.655 (NZDSF) and G.652 (SSMF) compliant fiber respectively (see Table 2-2) this results in a maximum propagation distance (dispersion-wise) of 360 and 100 km respectively. This means that for propagation upon 180 km no dispersion compensation measures have to be taken in the case of G.655 compliant fiber, but *Dispersion Compensation Modules* (DCM) are needed for the G.652 compliant fiber.

These conclusions are supported with the results of a simulation that takes into account the initially chirped pulses. Figure 3-4 shows the BER vs OSNR graphs for both the NZDSF and SSMF upon 180 km propagation. (Script: Appendix A.2)

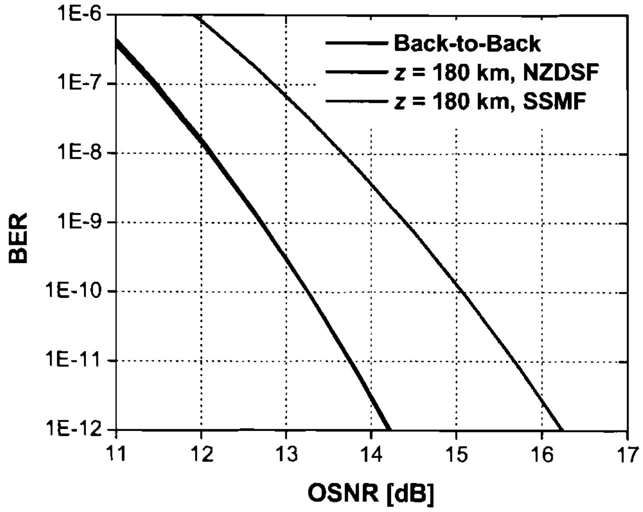

Figure 3-4: BER vs OSNR. B = 2,5 Gb/s, C = -6 and ε_r = 8,2 dB.

4 General Solutions

This chapter deals with the general solutions for removing an ADM at a POP. As discussed before, due to attenuation effects, it is not possible to remove an ADM and connect the 'loose' fiber ends. The signal needs to be amplified along the increased fiber length. Sections 4.1 – 4.3 discuss the technical aspects of three different general solutions. Aspects to be taken into account are:

- Increased attenuation due to increased propagation distance
- OSNR level to reach satisfactory BER at the receiver side
- Monitoring the performance of the new equipment to be installed

Section 4.4 then introduces some financial aspects that have to be taken into account.

4.1 In-line EDFA Amplification

Figure 4-1 shows the solution of in-line EDFA amplification at the POP where the ADM is removed. As can be seen from the figure an EDFA is inserted where the ADM is removed. Two EDFAs are needed, since there are two fibers (bi-directional traffic).

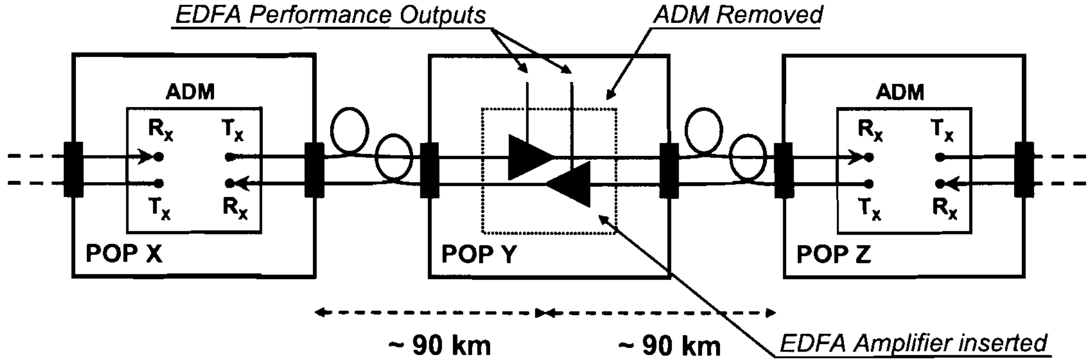

Figure 4-1: In-line EDFA amplification at POP where the ADM is removed

Optical amplification generates *Amplified Spontaneous Emission* (ASE) noise. This ASE gives rise to signal-ASE beat noise at the receiver, which limits the reach attainable in an optically-amplified transmission system. Each EDFA in a link contributes to an amount of ASE power given by [4]:

$$P_{\mathrm{ASE}} = 2h\nu \cdot \Delta\nu \cdot n_{\mathrm{sp}}(G-1), \tag{4.1}$$

where P_{ASE} is the ASE power in an optical bandwidth $\Delta\nu$, h is Planck's constant, ν is the optical frequency, n_{sp} is the spontaneous emission factor, and G is the optical amplifier gain.

The spontaneous emission factor, n_{sp}, is determined by the inversion of the amplifier's Erbium ions.

The signal-spontaneous noise impairment can be characterized in terms of the OSNR. This OSNR target must be sufficient to achieve the required system performance. The BER corresponding to a certain OSNR can be observed from Figure 3-2. For a system consisting of N_{amp} fiber spans, each of loss L_{span} (in dB) followed by an optical amplifier with output P_{out} (in dBm) per channel launched into the span and *noise figure (NF)* (in dB), the OSNR (in dB) of a signal channel at the end of the system is approximately [5]:

$$OSNR(\mathrm{dB}) = 58 + P_{out} - L_{span} - NF - 10^{10}\log(N_{amp})\,. \tag{4.2}$$

The receiver part of the Lucent line interface units used requires either -28 or -29 dBm input power to reach a BER $\leq 10^{-10}$ (see Table 2-4). As mentioned before, the extinction-ratio of these line interface units is 8,2 dB, combining both leads to an OSNR requirement of at least 13,5 dB (see Figure 3-2). The solution given in Figure 4-1 with L_{span} = 90 km x 0,25 dB/km = 22,5 dB and N_{amp} = 1 results in the following requirement for the EDFA noise performance:

$$NF - P_{out} \leq 22\mathrm{dB}\,. \tag{4.3}$$

According to Eq. (4.3) and assuming an EDFA output power P_{out} as low as 0 dBm, NF can be as high as 22 dB and still achieve the required BER. This result is expected since the link uses a single EDFA. When the whole ADM is removed, monitoring of the installed EDFAs from the NOC requires either routing the monitor signal to one of the neighboring POPs or establishing separate connections from the EDFAs to the NOC (i.e. through TCP/IP). This requires extra infrastructure adding to complexity and cost.

4.2 Booster EDFA Amplification

Figure 4-2 shows the solution of Booster EDFA amplification at the POPs neighboring to the POP where the ADM is removed. Two Boosters are needed, since traffic is sent in two opposite directions. The 'loose' fiber ends at the POP where the ADM is removed are connected as can be seen from the figure.

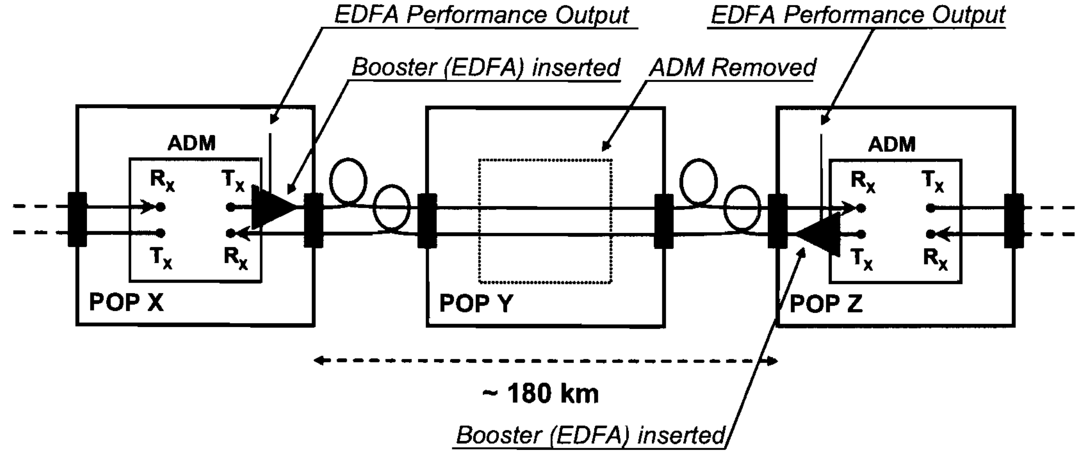

Figure 4-2: Booster EDFA amplification at neighboring POPs

The same conclusions from the preceding section regarding the OSNR level at the receiver side still apply. The amount of ASE added to the signal due to the Booster EDFA remains low and yields an acceptable OSNR level.

Management of the Boosters at the NOC is done by connecting their management channel to the Lucent *WaveStar*™ ADM 16/1 present at the POP. (Both pieces of equipment, ADM and Booster, are located at the same POP.) This solution requires no extra infrastructure to manage the Boosters.

4.3 Raman Amplification

Figure 4-3 shows the solution of Raman amplification at the POPs neighboring to the POP where the ADM is removed. Two Raman amplifiers are needed, since traffic is sent in two opposite directions. The 'loose' fiber ends at the POP where the ADM is removed are connected as can be seen from the figure.

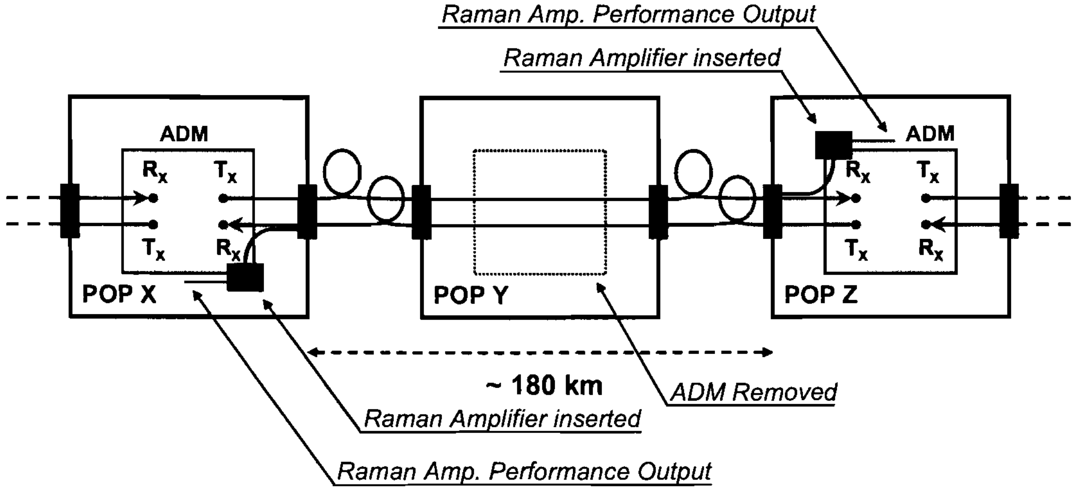

Figure 4-3: Raman amplification at neighboring POPs

Stimulated Raman scattering (SRS) is an interaction between light waves and the vibrational modes of silica molecules. If a photon with energy $h\nu_1$ is incident on a molecule having a vibrational frequency ν_m, the molecule can absorb some energy from the photon. In this interaction, the photon is absorbed and a new photon is emitted with a lower frequency ν_2 that corresponds to a lower energy $h\nu_2$ (see Figure 4-4).

This principle of SRS is used in Raman amplifiers. A pump wave with a smaller wavelength than the signal wave counterpropagates in the backward-pumping configuration used in this solution. Raman pumping requires relatively high pump power; approximately a few hundred milliwatts are needed to provide gains of 10-15 dB.

The distributed Raman gain induced in the fiber can dramatically improve the OSNR. This is because the distributed Raman amplification overcomes the attenuation in the latter part of the span and the minimum signal power is increased roughly by the loss of the fiber over that portion of the span where the Raman amplification exceeds the fiber attenuation. This improvement in performance is typically represented by an "equivalent" noise figure, which is the noise figure of a hypothetical lumped amplifier located at the end of the span that would

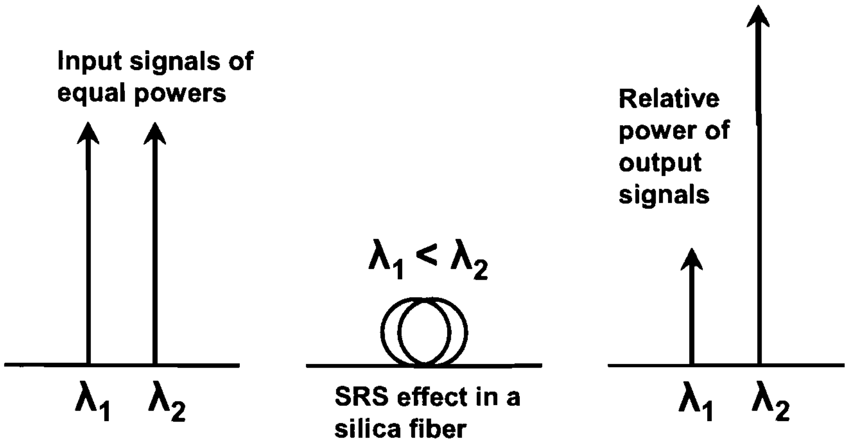

Figure 4-4: SRS transfers optical power from a shorter to a longer wavelength

produce the same gain and the same contribution to the accumulated ASE. The equivalent noise figure for a counter-pumped distributed Raman pump is [6]:

$$NF_{\mathrm{eq}} = 2(\ln G_{\mathrm{R}})^{-\alpha_s/\alpha_p}\left(\frac{G_{\mathrm{R}}}{G_{\mathrm{R}}-1}\right) - \frac{1}{G_{\mathrm{R}}} \approx \frac{2}{\ln G_{\mathrm{R}}} \tag{4.4}$$

where NF_{eq} is the equivalent noise figure in linear units, G_{R} is the Raman gain in linear units at the signal wavelength, α_s is the fiber attenuation at the signal wavelength and α_p is the attenuation at the Raman pump wavelength. The approximation for NF_{eq} holds for large gain $G >> 1$ and in the approximation that $\alpha_s \approx \alpha_p$. In general, the noise figure of a Raman amplifier is better than that of an EDFA and therefore the expected OSNR at the receiver will produce a satisfactory BER.

Management of the Raman amplifiers can be implemented in the way described in section 4.2. This solution requires no extra infrastructure to monitor the Raman amplifiers.

4.4 Financial Aspects

Among financial aspects to be taken into account are:

- Economical value of the equipment removed
- Cost of the new equipment
- Leasing costs of the POPs
- One-time installment/testing cost
- Maintenance expenses of the equipment at the POPs

The cost of the new equipment to be installed depends on the solution and vendor chosen. Chapter 5 discusses the solutions given by a couple of vendors.

A solution with no equipment installed at the POP where the ADM is removed eliminates the necessity of leasing that particular POP. (Solutions in sections 4.2 and 4.3)

Installment and test costs are a result of changing the network configuration. Removing an ADM and applying one of the solutions given in sections 4.1 – 4.3 results in as many as four employees working on this task for a day. Three of these employees would go to the POPs and the fourth would stay at the NOC to apply software configuration changes. Transportation and wage costs should be taken into account. These costs however, are small compared to the value of the equipment.

A solution with no equipment installed at the POP (Figures 4.2 and 4.3) where the ADM is removed results in lower maintenance expenses. The engineer performing the maintenance has now less POPs to visit. The time saved, however, is negligible since it falls within the standard deviation of the total maintenance-time needed for the whole network. Maintenance savings are therefore ignored.

5 Vendor Solutions

This chapter deals with the specific solutions offered by several equipment vendors. COMSAT can decide which solution to implement based on the technical solutions offered by these vendors. The following vendors were considered in the search for a solution:

- Lucent Technologies (USA)
- Padtec (Brazil)
- Meriton Networks (Canada)

Lucent has a standard technical solution, discussed in section 5.1, which could be derived from the *WaveStar*$^{\text{TM}}$ ADM 16/1 technical documentation. Padtec and Meriton Networks proposed various technical solutions which are discussed in sections 5.2 and 5.3 respectively. As COMSAT did not have a Non-Disclosure Agreement with most of the vendors mentioned above, a high-level document, found in Appendix B, was generated to initiate interactions.

5.1 Lucent Technologies

Lucent Technologies has a standard solution for bridging "very-long distances" (up to 120 km) and "ultra-long distances" (up to 160 km). 120 km is not sufficient to eliminate an ADM at any given POP and bridge the neighboring POPs (see Tables 3-1 and 3-2). This solution is not considered for this reason. A distance of 160 km is long enough to remove at least 6 ADMs. The solution Lucent Technologies offers is schematically shown in Figure 5-1. A Booster / Pre-Amplifier is inserted in the ADMs at the neighboring POPs. This Booster / Pre-Amplifier is a circuit pack that can be placed in any of the tributary slots. Furthermore the line interface units need to be changed to the type SI-EML-U 16.2/1 because the ones currently used are not interoperable with the Booster / Pre-Amplifier unit. There is no need to discuss or perform calculations concerning technical aspects such as attenuation, dispersion and non-linearities since this is a proven solution by Lucent Technologies. Management of the Booster / Pre-Amplifier and line interface units is obtained automatically by integrating these circuit packs in the system. This solution is not financially feasible, although it is quite favorable concerning technical aspects, since the cost of it is much higher than the price of a new ADM.

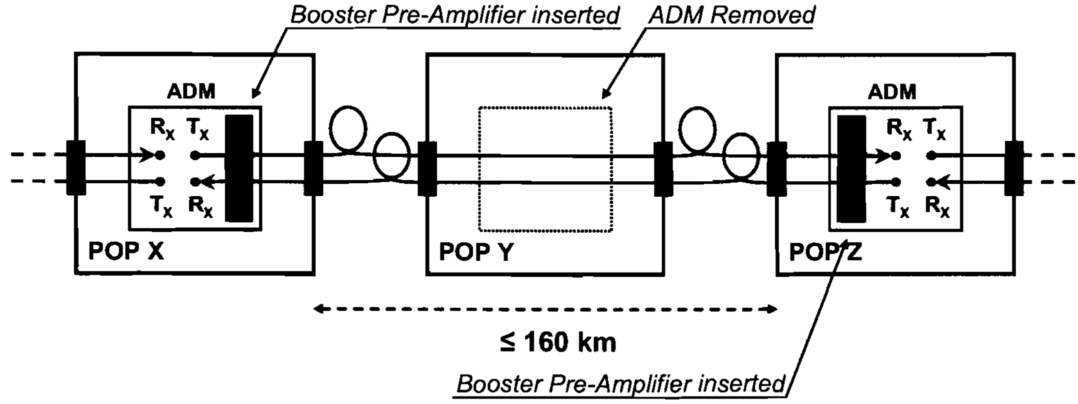

Figure 5-1: Lucent Technologies solution for removing the ADM at the intermediate POP

5.2 Padtec

Padtec proposed three solutions for removing the ADM at the intermediate POP shown in Figures 5-2 through 5-4. Technical and financial aspects of these solutions are discussed below. All solutions are based on removing the ADM at the POP Escalada within the Global Crossing part of the network.

As mentioned before there is no need to compensate for dispersion since NZDSF is used. The solutions given below are not suited for the Silica Networks part of the network since no DCMs are integrated.

Solution 1a

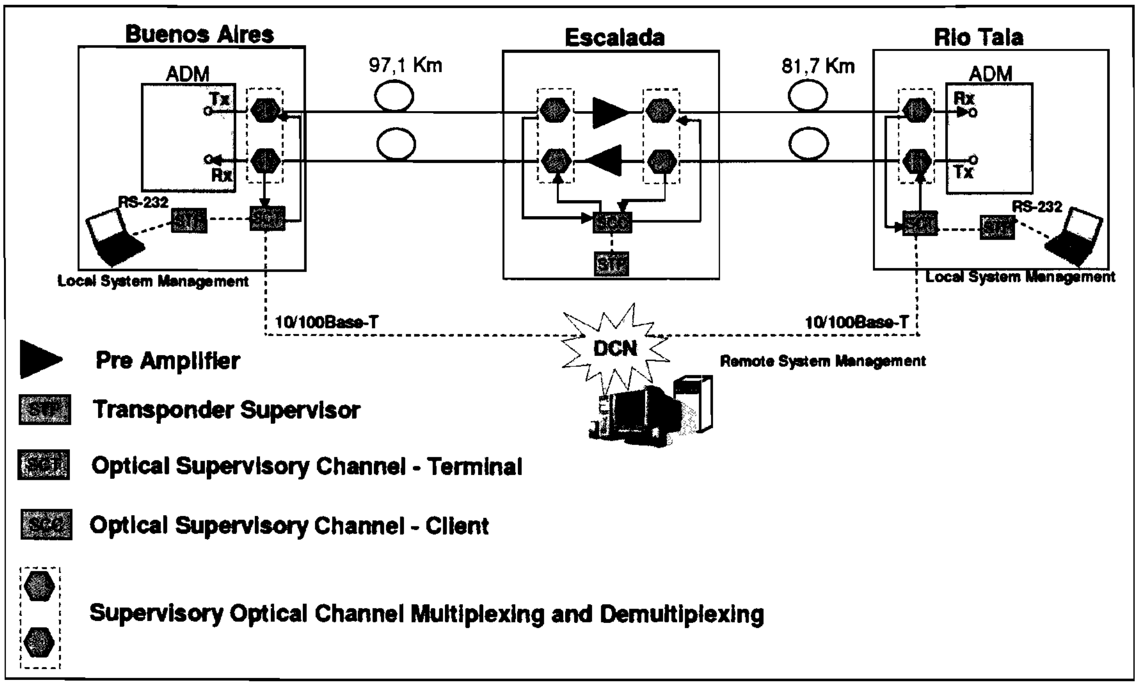

Figure 5-2: Padtec's solution 1a for removing the ADM at the intermediate POP

This solution uses an Optical Supervisory Channel at 1510 nm (out-of-band) and Ethernet Interface that allows communication with the *Data Communication Network* (DCN) through POP Buenos Aires and Rio Tala and uses the Padtec Management System in order to manage the amplifiers at the intermediate POP Escalada. Both local and remote management possibilities are provided.

The *WaveStar*™ ADM 16/1 has two ways of transmitting external signals, in this case used to manage and monitor the amplifiers through POP Buenos Aires and/or Rio Tala, to COMSAT's NOC located in Buenos Aires. The first one is an 'on/off' dry contact relays. No detailed information about the amplifier performance can be sent with this feature.
Another way to connect the amplifier's performance output is available on the *WaveStar*™ ADM 16/1 through to the Q-LAN.[1] This Q-LAN makes use of a *Network Service Access Point*

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[1] Q-LAN is a communication protocol.

(NSAP) address. With this feature it is possible to both manage and monitor the amplifiers in detail from the NOC. The Padtec Management System, however, uses a fast Ethernet connection with a TCP/IP protocol. Conversion between these two protocols is required, thus adding to cost and complexity. Padtec proposed to manage and monitor the amplifiers by using an E1 connection at the ending POPs (Buenos Aires and Rio Tala). This implies using part of the SDH network payload for management of the amplifiers. Unfortunately there are no E1 connections available within the Global Crossing part of the network since no tributary units are installed.

The power budget of this solution is shown in Table 5-1. Attenuation losses are based on the information given in Table 2-3.

	Buenos Aires - Escalada	Escalada - Rio Tala	Rio Tala - Escalada	Escalada - Buenos Aires
Distance [km]	97,1	81,7	81,7	97,1
Transmission Power [dBm]	+1	+1	+1	+5
Attenuation on Fiber [dB]	27	18	18	25
Mux/Demux Losses [dB]	1,5	1,5	1,5	1,5
Power on reception [dBm]	-27,5	-14,5	-18,5	-21,5
Sensitivity [dBm]	-35	-28	-35	-28
Margin [dB]	7,5	13,5	16,5	6,5

Table 5-1: Power budget calculations for Padtec's solution 1a

Solution 1b

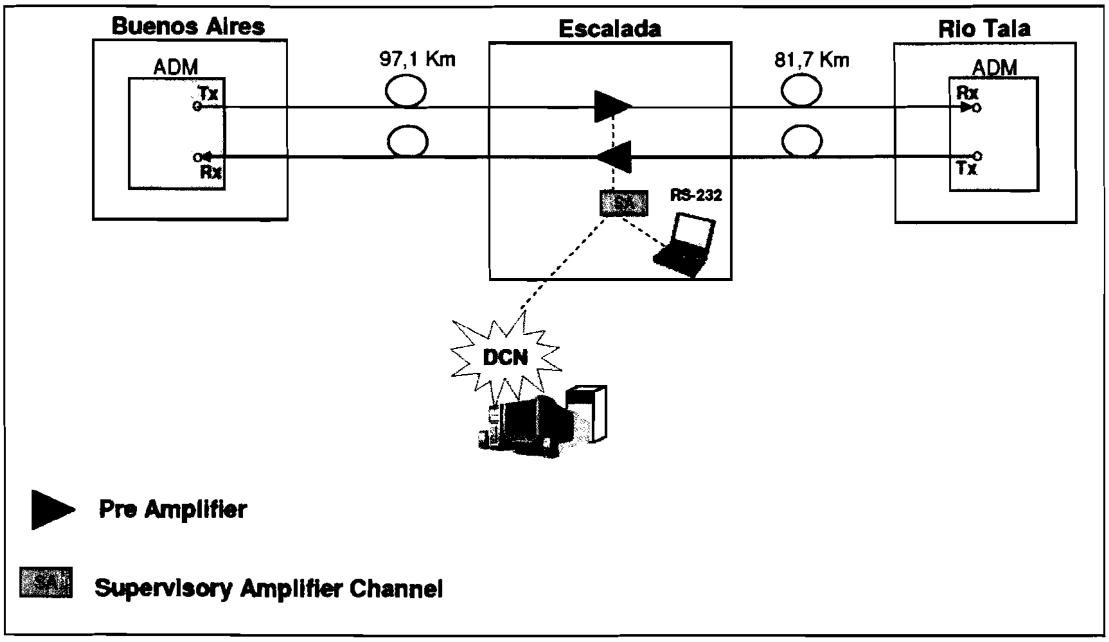

Figure 5-3: Padtec's solution 1b for removing the ADM at the intermediate POP

Solution 1b shown in Figure 5-3 is derived from solution 1a. Management of the amplifiers is not done through the ending POPs Buenos Aires and Rio Tala since no out-of-band Optical Supervisory Channel is implemented. A management link to the NOC is only possible through the intermediate site Escalada but there are no means left to do this from within the existing SDH network since the ADM is removed. Local management is still possible.

Margins within the power budget calculations improve with 1,5 dB compared to solution 1a (Table 5-1) since there are no mux/demux losses.

Solution 2

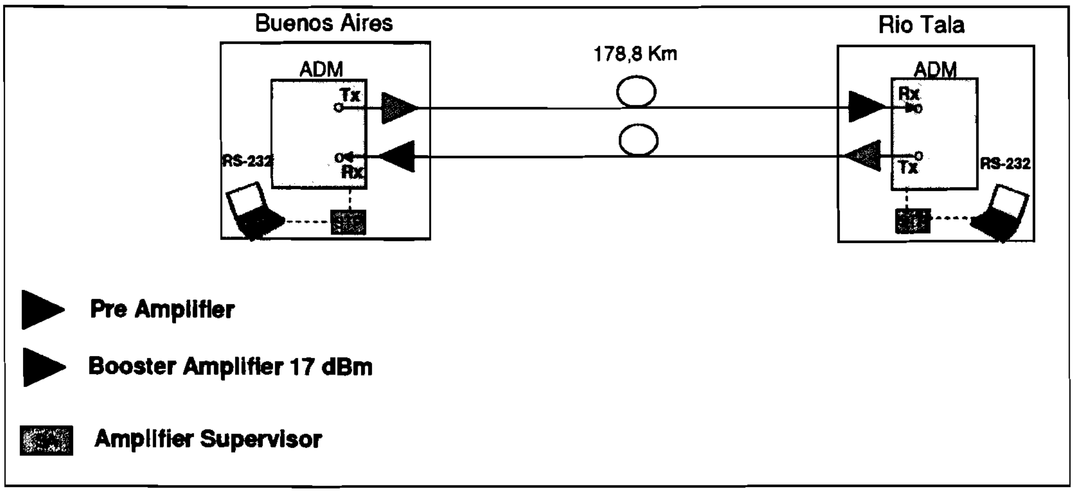

Figure 5-4: Padtec's solution 2 for removing the ADM at the intermediate POP

Solution 2 (Figure 5-4) features a set-up were no equipment is installed at the intermediate POP Escalada. The amplifiers are managed through the dry contact relays available on both the amplifiers and the *WaveStar*™ ADM 16/1. No remote management is possible with this configuration.

The power budget of this solution is shown in Table 5-2. Attenuation losses are based on the information given in Table 2-3.

	Buenos Aires - Rio Tala	Rio Tala - Buenos Aires
Distance [km]	178,8	178,8
Transmission Power [dBm]	+17	+17
Attenuation on Fiber [dB]	45	43
Connection losses Escalada [dB]	2	2
Power on reception [dBm]	-30	-28
Sensitivity [dBm]	-35	-35
Margin [dB]	5	7

Table 5-2: Power budget calculation for Padtec's solution 2.

Launching +17 dBm into the fiber as can be seen from the power budget in Table 5-2 raises the question whether non-linear effects will impair transmission. A possible upgrade to WDM in the future makes this question even more relevant. Non-linearities have a small negative effect on the eye-pattern as can be seen from the graphs in Figure 5-5. WDM adds to the total power launched into the fiber and transmission impairment due to non-linearities will increase rapidly.

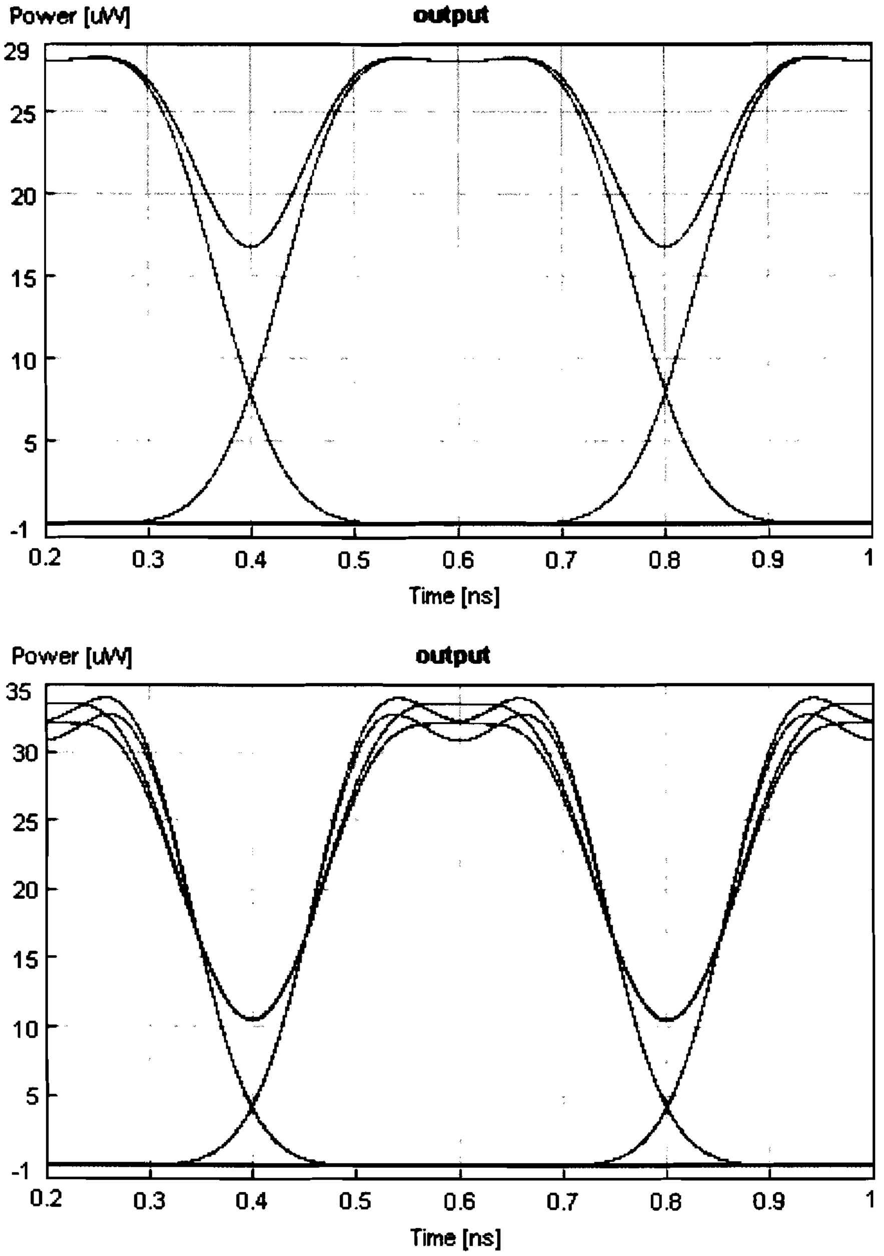

Figure 5-5: Eye-patterns; Top: without Non-linearities, Bottom: with Non-linearities

The following parameters were used to generate the eye-patterns in Figure 5-5:

- T_x: $P_{out} = 0$ dBm, 2,5 Gb/s NRZ directly modulated, extinction-ratio = 8,2 dB
- Booster: $P_{out} = 17$ dBm, noise figure = 6 dB
- Fiber: NZDSF, $D = 5$ ps/nm·km, $S = 0{,}045$ ps/nm^2·km, $A_{eff} = 55$ µm^2, $n2 = 2{,}6 \cdot 10^{-20}$ m^2/W, length = 178,8 km, attenuation loss = 39,3 dB
- Pre-Amplifier: gain = 15 dB, noise figure = 6 dB
- No dispersion compensation
- R_x: An 80 GHz optical band-pass filter and a 2,5 GHz electrical low-pass filter

5.3 Meriton Networks

Meriton Networks proposed a solution based on the use of NZDSF and SSMF shown in Figures 5-6 and 5-7 respectively.

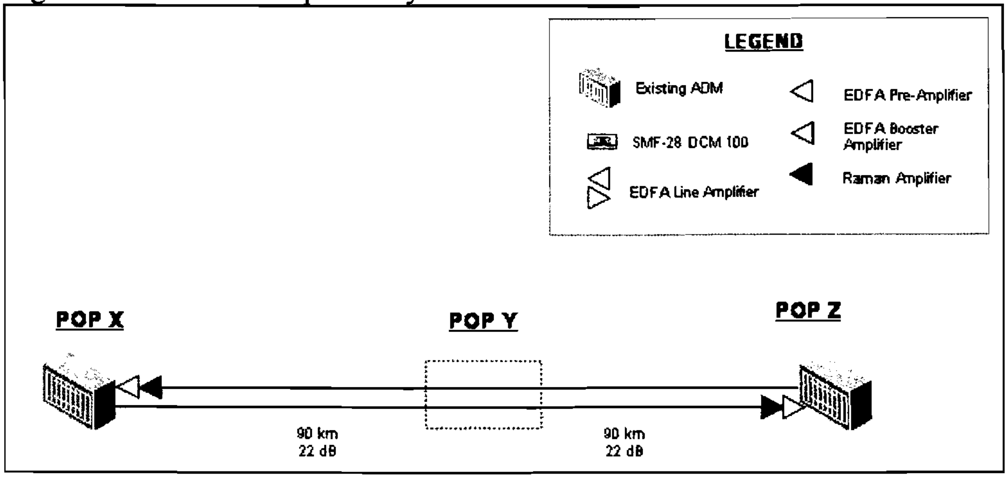

Figure 5-6: Meriton Networks' solution based on NZDSF

The solution for NZDSF uses both a Raman and an EDFA Pre-Amplifier at the ending POPs X and Z. No power budget is provided but employing two amplifiers suffices to reach the required amplification of 20 dBs (see calculations Appendix B). No equipment is installed at POP Y and the 'loose' fiber ends at this POP are connected. No specific information on how to manage and monitor the amplifiers is provided by Meriton Networks but the same conclusions hold as for Padtec's solution 2 in section 5.2.

The solution for SSMF shown in Figure 5-7 is identical to the NZDSF solution with the addition of DCMs. This is in accordance with the conclusion drawn in section 3.4 that DCMs are needed when applying a solution for SSMF. Furthermore the same conclusions for this solution hold as for the NZDSF solution in Figure 5-6.

Costs of both solutions are way over the allocated budget to make the project financially feasible. In the end Meriton Networks was not able to propose a less costly alternative.

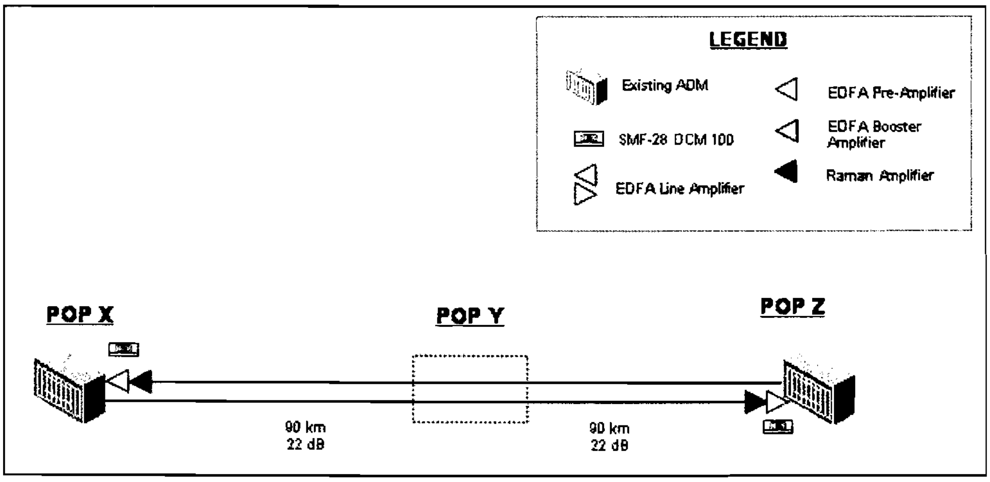

Figure 5-7: Meriton Networks' solution based on SSMF

6 Implementation

This chapter deals with the implementation of a solution for removing an ADM from COMSAT's SDH network. The chapter is divided in three sections. First, the chosen solution is discussed. Then, the schematic measurement setup is shown and preparations for the actual measurement are discussed. The last section presents measurement results.

6.1 Implemented Solution

After evaluating the possible solutions for the removal of an ADM from the SDH network (Chapter 5) COMSAT chose to implement Padtec's solution 1b (see Figure 5-3). At this moment, the cost of this solution is less than the price of a new ADM so this makes the replacement of an ADM with these amplifiers financially feasible.

As explained before, this solution is only valid for NZDSF due to dispersion effects. The EDFA supplied by Padtec is a single-stage amplifier but is also available in a dual-stage configuration capable of carrying a DCM, making the solution suitable for SSMF. The use of a dual-stage amplifier equipped with a DCM makes it possible to remove two or more consecutive ADMs. Note that all ADMs between Buenos Aires and Mendoza could be removed as long as dispersion is properly compensated for and the required OSNR is delivered.

For the rest of this chapter we will only consider the case of a single-stage amplifier and NZDSF.

As seen before, no remote management of the amplifiers is implemented. It is however highly recommended to be able to distinguish between a cable cut and an amplifier failure. Figure 6-1 and 6-2 show the case of a cable cut and EDFA failure respectively.

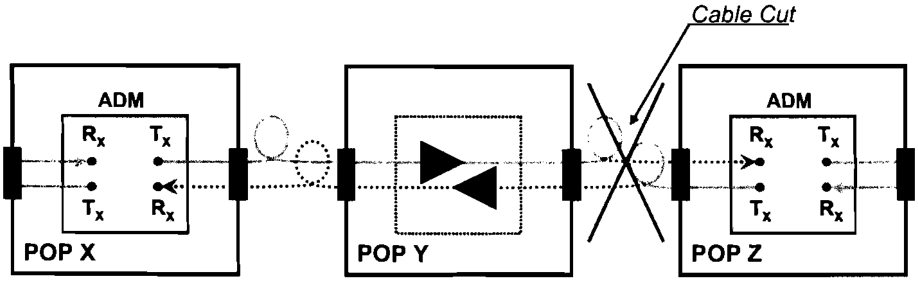

Figure 6-1: Errors reported by the ADMs in case of a cable cut

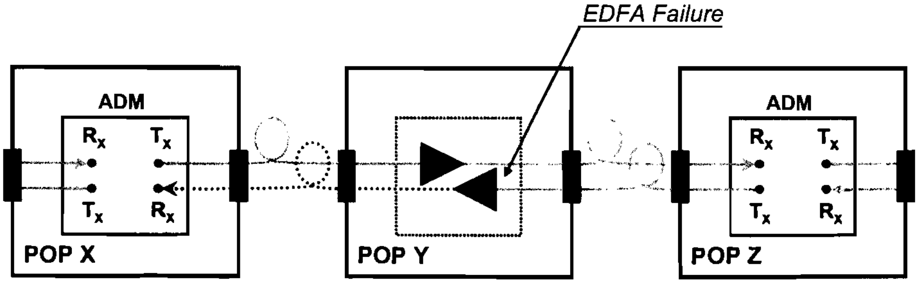

Figure 6-2: Errors reported by the ADMs in case of an EDFA failure

Note that a cable cut affects (breaks or damages) all fibers within a cable and not just a single fiber. Observe the difference between a cable cut and an EDFA failure. In case of an EDFA failure the receiving ADM (in this case at POP X) reports errors, while in the case of a cable cut, the receivers on *both* ADMs (POP X and POP Z) report errors.

6.2 Schematic Measurement Setup – Preparations

Figure 6-3 shows the schematic measurement setup. Both ADMs are installed at COMSAT's Buenos Aires POP. (It speaks for itself that, from a logistic viewpoint, this setup is preferable over a setup in which both ADMs are located far apart.) The length of the fiber between the ADMs and the Padtec amplifiers will have to be approximately 90 km to simulate the real COMSAT network configuration. The amplifiers are managed by means of a notebook computer. Both ADMs are equipped with a STM-1 tributary interface which has a 155,52 Mb/s signal bit-rate. The Cross Connect multiplexes this STM-1 signal to the STM-16 signal with a bit-rate of 2,5 Gb/s. Both STM-1 tributaries are connected to a STM-1 *Bit-Error-Rate Tester* (BERT). Note that two redundancies can be observed. The first one involves the use of two ADMs instead of one in order to rule out any advantages that could be obtained concerning clock recovery. With the setup shown in Figure 6-3 clock recovery is done by two separate ADMs which is the case in the real SDH network as well.
The second redundancy involves the use of two loops where both ADMs transmit and receive signals at the same time, thus closely simulating conditions encountered in the real network.

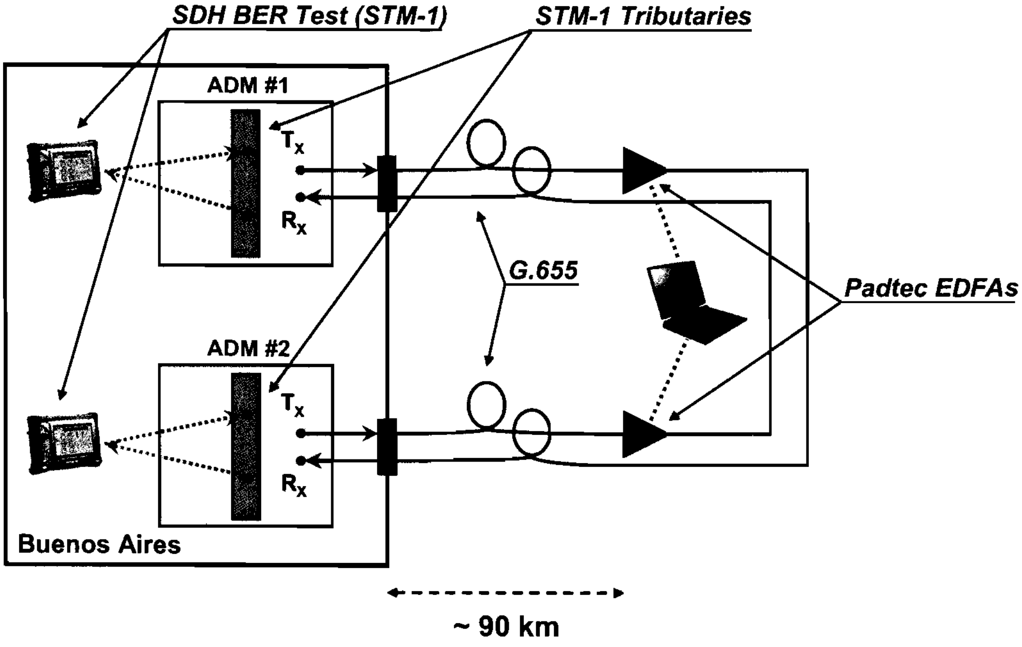

Figure 6-3: Schematic Measurement Setup with the Padtec EDFAs

6.3 Measurements

It is not possible to use the existing network (which is in operation 24/7) to do the measurements. Although the network is protected from link failures (by means of a ring configuration) COMSAT cannot risk a link failure in the main network link while the protection path is out of service due to measurements.[1] A stand-alone measurement setup, that resembles (part) of the real network, needs to be built.

Configuration 1

COMSAT borrowed four dark fibers running from Buenos Aires to Escalada from Global Crossing. The corresponding measurement setup is shown in Figure 6-4. The distance between Buenos Aires and Escalada is approximately 123 km. Note that this value differs from the value given in Table 2-1. This is due to the fact that Global Crossing's node in Buenos Aires, named Chacarita, is not the same node as COMSAT's Buenos Aires POP, named Wilde. The distance to cover between these two nodes is approximately 26 km so that two loops can be set up going from ADM #1 to ADM #2 via Escalada and viceversa.

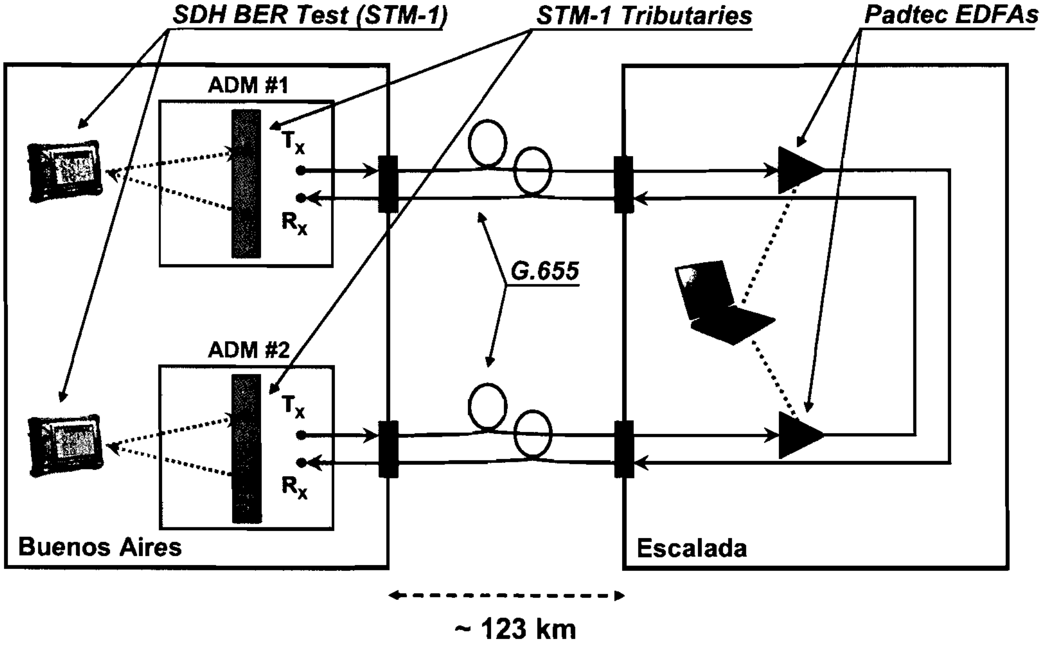

Figure 6-4: Measurement setup with the Wilde – Chacarita – Escalada link

The longest distance between two POPs for the Global Crossing part of the network is shorter than 100 km. (see Table 2-1). The 123-km link between the ADMs and the amplifiers, with its corresponding high attenuation, may lead to an unacceptable BER performance.

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[1] Service Level Agreements require COMSAT to have their clients up and running > 99,98% of the time.

Figure 6-5 shows the *Optical Time-Domain Reflectometer* (OTDR) trace measurement for one of the four fibers running from Buenos Aires to Escalada. The first peak occurring at 0 km is due to connector reflections. At approximately 9 km a small drop can be observed and is due to a bad fusion splice. At a distance of 26 km a small peak is also observed on account of ODF connections made at the POP Chacarita. The high peak at 123 km indicates the end of the trace. The small ripple before this peak is due to insufficient OTDR power.

Attenuation losses account for a 32 dB drop in signal power, way over the 27 dB loss assumed in the power budget of Table 5-1. However, since Lucent ADMs launch +1 dBm signal power, the amplifier input power is approximately -31 dBm, which is within the sensitivity of -35 dBm specified by the vendor.

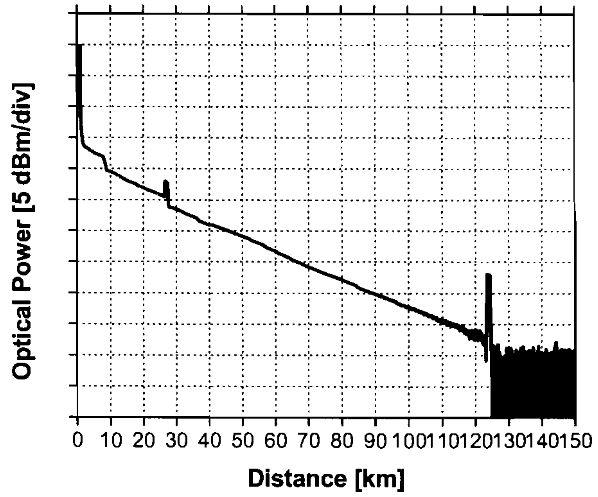


Figure 6-5: OTDR trace for the Wilde – Chacarita – Escalada link

Implementing this setup resulted in a frame loss reported by the STM-1 BERTs. Even boosting the amplifiers to a +8 dBm power output, and with that a power input to the receiving ADMs of -24 dBm, did not result in an acceptable BER performance. Since both the amplifier input power (-31 dBm) and the ADM receiver power (-24 dBm) were well above the specified minimum input value of -35 dBm and -28 dBm respectively, attenuation losses are not the cause of the link failure. Figure 6-6 shows the measured spectrum of the optical signal at the ADM receiver input. An OSNR of over 20 dB is measured. We observed that by increasing the OSNR to 22 dB the link operated successfully. This measurement was performed by connecting the ADMs to the amplifiers with patchcords and variable optical attenuators. This 22 dB OSNR limit can only be reached with an input power to the amplifiers of at least -28 dBm. Below this power level the noise performance of these amplifiers deteriorates rapidly. Solving Eq. 4.2 for the noise figure *NF* gives

$$NF = 58 + P_{\mathrm{out}} - OSNR - L_{\mathrm{span}} - 10\,{}^{10}\log(N_{\mathrm{amp}})\,. \tag{6-1}$$

Using P_{out} = 6 dBm, OSNR = 22 dB, L_{span} = 32 dB and N_{amp} = 1 results in a noise figure *NF* = 10 dB for the Padtec amplifiers at -28 dBm input power. Note that this 22 dB OSNR limit lies well above the value found in literature and calculated in section 3.3 (Figure 3-2). The reason for this is that the Lucent line interface units are not equipped with an optical filter at the receiver input.

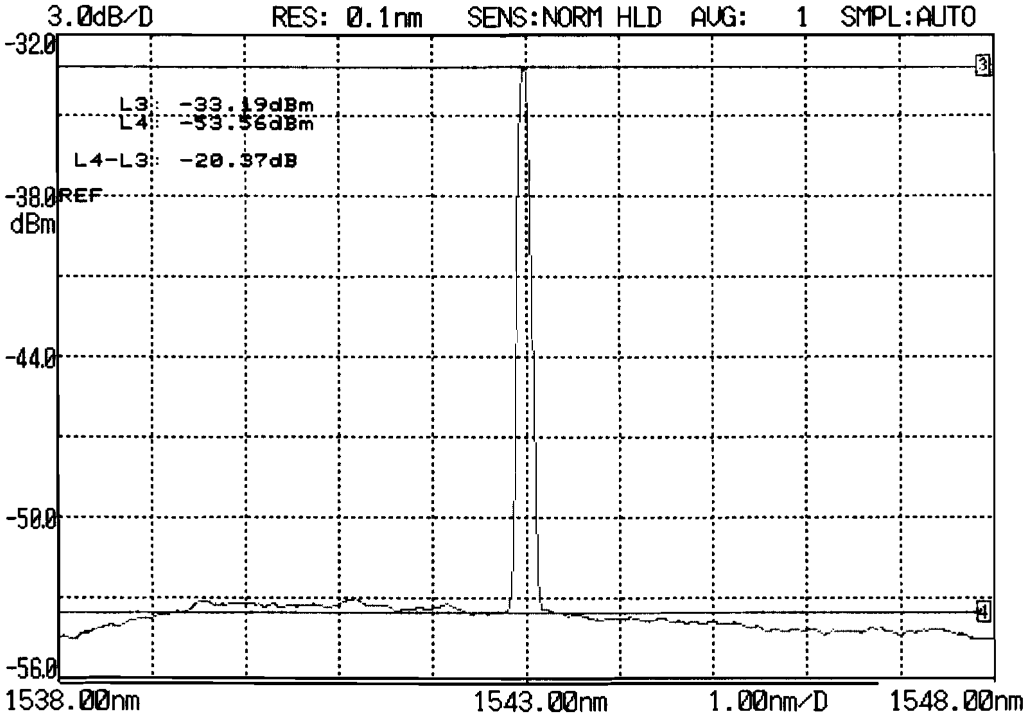


Figure 6-6: Spectrum of the ADM receiver input power for the failing link

Configuration 2

To obtain a shorter link, with a corresponding lower attenuation, the measurement setup shown in Figure 6-7 was implemented. Loops were set up between the Global Crossing POP Chacarita and COMSAT's Buenos Aires POP Wilde. The total transmission distance is 4 x 26,5 = 106 km. (Note that this time only one complete loop is employed due to fiber availability.) An attenuation of at most 29 dB, corresponding to an ADM receiver input power of -28 dBm, was expected along this link. However, because of many extra fusion splices along the fiber, the attenuation of this 106-km link resulted in approximately 31 dB. The amplifier input power (~ -30 dBm) was then not sufficient to obtain an acceptable OSNR at the ADM receiver input. For this reason, the system exhibited a very poor BER. In order to solve this problem the fiber link going from the ADM to the amplifier was shortened as discussed in the next configuration.

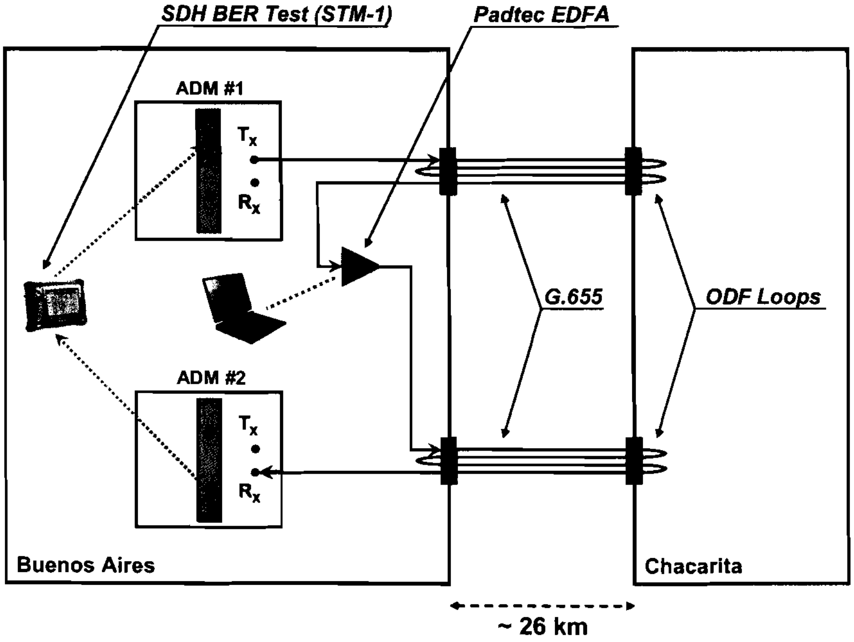


Figure 6-7: Measurement setup with the Wilde – Chacarita 4 x ~26 km loops

Configuration 3

Figure 6-8 shows the measurement setup used in configuration 3. One of the fibers running from COMSAT's Buenos Aires POP Wilde to Global Crossing's POP Chacarita is looped back before reaching the POP Chacarita. This way a transmission distance of 2 x 20,5 + 2 x 26,5 = 94 km is achieved. Fiber loops going from the amplifier to the ADM are not changed.

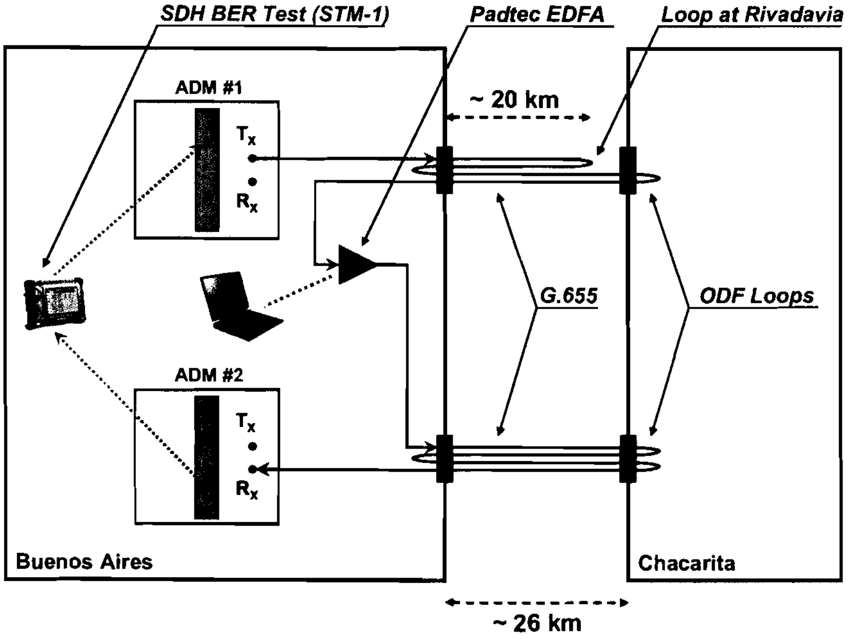


Figure 6-8: Measurement setup with the 2 x 20 + 2 x 26 and the 4 x 26 km loops

Figure 6-9 shows the OTDR traces for both the 94- and 106-km fiber links. Attenuation losses along these fiber links are 28,5 and 31 dB respectively. This corresponds to an amplifier input power of -27,5 dBm, which is within the acceptable input range to the amplifier. With an 7,5 dBm amplifier output power, the ADM receiver power was -24 dBm. Figure 6-10 shows the measured spectrum of the optical signal at the ADM receiver input. An OSNR of over 24 dB, 2 dB above the required limit, is measured.

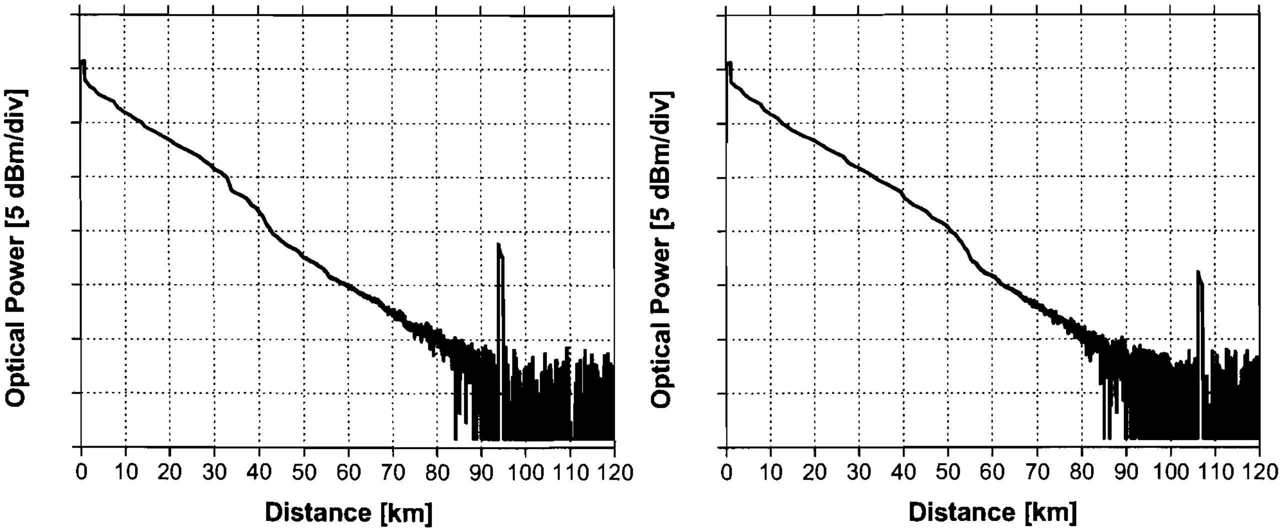


Figure 6-9: OTDR traces for the 2 x 20 + 2 x 26 and the 4 x 26 km loops

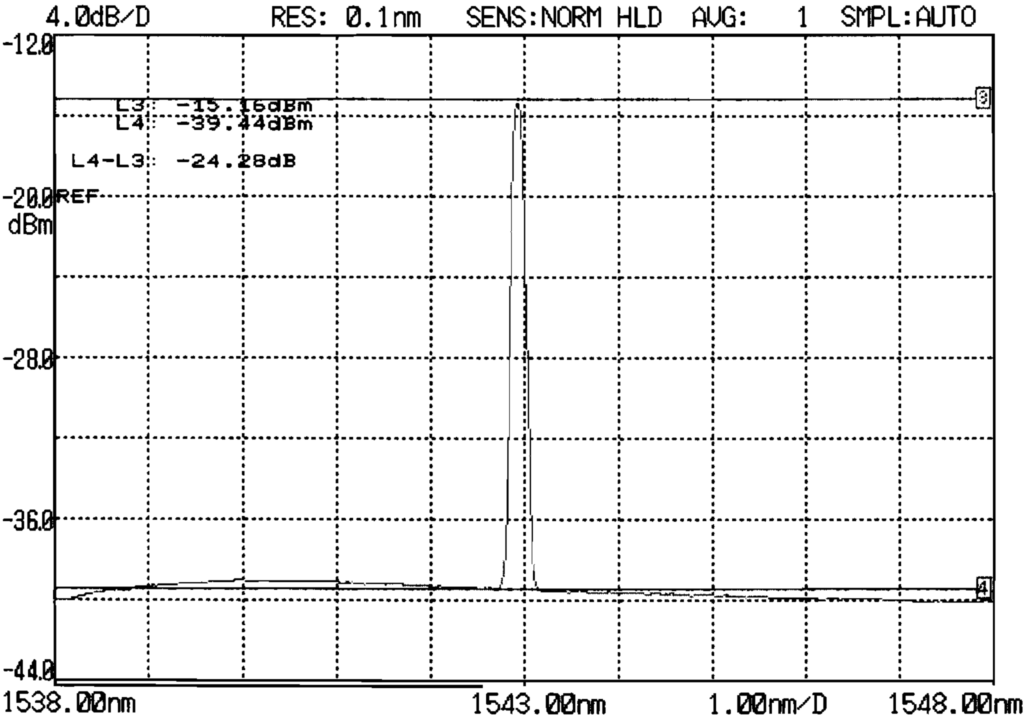


Figure 6-10: Spectrum of the ADM receiver input power for the working link

This time the setup *did* function correctly and a measurement test period of 7 days was started. Several important analyses, of which amongst the M.2110 and G.826 analyses defined by the ITU, were carried out. The complete test results are shown in Appendix C. The M.2110 analysis states a *PASS* or *FAIL* of the communication link for a 15-min., 1-hour, 2-hour, 24-hour and 7-day time interval. All test period intervals passed. One bit-error was recorded during the 7 day test period. To statistically calculate an exact BER more bit-errors need to be recorded. It is however safe to assume a BER of $\leq 1 \cdot 10^{-13}$ for the transmission link. This is well within the limit for good transmission between the ADMs.
The following values, defined by the G.826 analyses, were recorded:

- Errored Second Ratio = $1{,}650 \cdot 10^{-6}$
- Background Block Error Ratio = $2{,}063 \cdot 10^{-10}$

Both values are within the limits defined by this analysis. No errors were counted due to jitter.

The following system margins are then calculated:

- Amplifier input margin: -27,5 – (-28) = 0,5 dB
- ADM receiver input margin: -24 – (-28) = 4 dB
- OSNR at the receiver margin: 24,3 – 22 = 2,3 dB

The attenuation losses of fiber links between POPs in the real network are at least 3 dB below the attenuation losses of this measurement setup, due to fewer fusion splices and shorter distances. Implementing this solution in the real network will result in the following increased system margins:

- Amplifier input margin $\geq$ 3,5 dB
- ADM receiver input margin $\geq$ 7 dB
- OSNR at the receiver margin $\geq$ 2,3 dB

Pump laser decay in an EDFA cause the noise performance to deteriorate [7]. This might cause the OSNR level to drop below the 22 dB limit. This can be solved by inserting an optical band-pass filter at the ADM receiver input.
Two screens of the Padtec Management Tool are shown in Appendix D and Figure 6-11 shows measurement setup pictures.

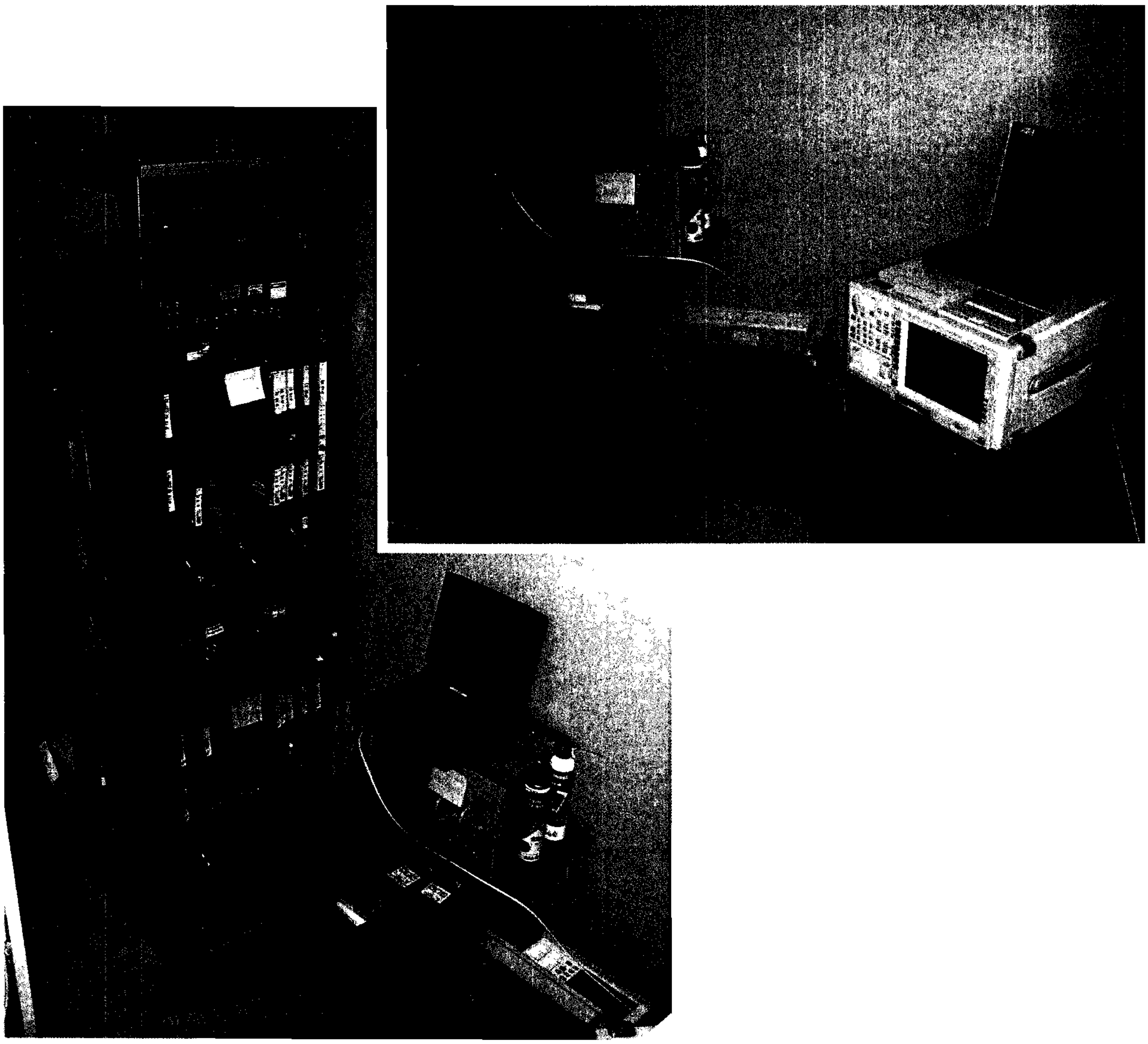


Figure 6-11: Measurement setup

7 Future Capacity Upgrades

COMSAT SDH network, after the construction in 2000, reached an occupation of approximately 27 % by the end of 2005. Lots of clients can still be added to the network before it starts to saturate. At this moment there is no need to start thinking about capacity upgrades. However, it is of importance to know to what extent the amplifiers, as being used in the measurement setup of chapter 6, are compliant with eventual future capacity upgrades. This chapter discusses two possible future capacity upgrades. The first one involves upgrading to WDM of four 2,5-Gb/s wavelength channels. The second one involves changing the network to one single 10-Gb/s wavelength channel.

7.1 WDM of four 2,5-Gb/s wavelength channels

WDM involves adding more wavelength channels to the already existing single channel network. Changing from one to four channels involves a + 6 dB power output requirement for the amplifiers. A power output of the amplifiers of at most +3 dBm for each wavelength channel is sufficient to obtain an acceptable BER since this is equal to the highest line interface power output of the network at present (see Table 2-3). For this reason the amplifier needs to be capable of a total power output of +9 dBm. This is no problem for the amplifiers but it should be noted that care has to be taken since the maximum power output of the amplifiers depends on the input power. Calculations and simulations should be done to prove functionality.

A network upgrade to a single 10-Gb/s wavelength channel is cheaper than the upgrade to a four channel 2,5-Gb/s WDM system because of lower equipment cost. Moreover, equipment for the 2,5-Gb/s WDM variant may not be available anymore in the future.

7.2 Single 10-Gb/s wavelength channel

All the calculations in this report are based on a single wavelength channel at 2,5 Gb/s. Upgrading to a 10-Gb/s single wavelength system requires new dispersion calculations since dispersion goes with the square of the bit-rate. Also, new simulations for non-linear effects have to be made. There is no need to perform new calculations for the attenuation since they are not bit-rate depended. Moreover, the amplifiers are compliant to a 10 Gb/s bit-rate. Increasing the bit-rate from 2,5 Gb/s to 10 Gb/s causes the maximum propagation distance, dispersion-wise, to drop to 1/16th of its original value. A new calculation for the maximum propagation distance length based on the maximum allowed dispersion by the 10 Gb/s line interface units can be done. It is expected that this maximum propagation distance will not be long enough for the COMSAT SDH network. The use of DCMs is then required. The amplifiers, as mentioned in section 6.1, are available in a single- and a dual-stage version. The dual-stage version can be equipped with a DCM and is recommended, although it has a higher cost, if future plans to upgrade to a 10-Gb/s single wavelength channel are within the possibilities. Calculations and simulations should be done to prove functionality.

8 Conclusions

In this report we came up with a solution for the network changes that COMSAT wanted to implement. Most ADMs in COMSAT's national-scale SDH network are not used to their full extent. They do not add and/or drop traffic and only have a 3R regeneration function while 1R regeneration would suffice. These ADMs are costly devices which could be used in COMSAT's metropolitan networks were signals *do* need to be added and/or dropped. The assignment was to find a solution for removing an ADM from the national-scale SDH network and keep the network operative. The removed ADMs can then be deployed in the metropolitan SDH networks.

We proved the functionality and financial feasibility of inserting two Padtec EDFAs at the POP where the ADM is removed. This solution was measured with a test setup using NZDSF. Note that DCMs need to be inserted in the link if the solution is used for SSMF. The solution has no infrastructure for remote management implemented to cut cost, but a first distinction between a cable cut and an amplifier failure is still possible. Cost of the solution is the most important factor. Any given solution needs to be cheaper than buying a new ADM to make it financially feasible. Cost calculations have to be made every time the implementation of the solution is considered.

While testing the measurement setup based on Padtec's solution the following limits were measured:

- Amplifier input power ≥ -28 dBm
- ADM input power ≥ -28 dBm
- OSNR at the ADM receiver ≥ 22 dB

The difference in OSNR requirement at the ADM receiver with the value of 13,5 dB calculated in Chapter four is explained by the lack of an optical filter at the ADM receiver input.

The following parameters of the operational measurement setup were recorded:

- ADM output power = +1 dBm
- ADM → Amplifier attenuation (over 94 km) = 28,5 dB
- Amplifier input power = -27,5 dBm
- Amplifier output power = +7,6 dBm
- Amplifier → ADM attenuation (over 106 km) = 31 dB
- ADM input power = -24 dBm
- OSNR at the ADM receiver = 24,3 dB

The ITU M.2110 analysis resulted in a link *PASS* for a 15-min, 1-hour, 2-hour, 24-hour and 7-day test time interval. One single bit-error was recorded during this 7-day test. It is then safe to assume a BER of $< 1\cdot10^{-13}$. The ITU G.826 analysis gave the following results:

- Errored Second Ratio = $1{,}650\cdot10^{-6}$
- Background Block Error Ratio = $2{,}063\cdot10^{-10}$

Both values are within the limits defined by this analysis. No errors were counted due to jitter. The following system margins for the test setup were calculated:

- Amplifier input margin: -27,5 – (-28) = 0,5 dB
- ADM receiver input margin: -24 – (-28) = 4 dB
- OSNR at the receiver margin: 24,3 – 22 = 2,3 dB

Due to lower attenuation levels these margins will increase when the solution is implemented in the real SDH network. The OSNR at the ADM receiver will decrease in time due to EDFA pump laser decay. If it drops below the limit of 22 dB the insertion of an optical filter right before the ADM receiver will resolve this problem.

The amplifiers used in the proposed solution are compatible to eventual future network capacity upgrades to WDM of four 2,5-Gb/s wavelength channels or a single 10-Gb/s wavelength channel. Solution adjustments however, like the insertion of DCMs, are required. Calculations for attenuation, dispersion and non-linear effects need to be done to prove functionality.

9 Conclusiones en Castellano

En este informe presentamos una solución para los cambios de red que COMSAT quiso poner en práctica. La mayoría de los ADMs de la red SDH a escala nacional de COMSAT no se usa en su totalidad. Estos ADMs no suben y/o bajan tráfico y solamente tiene una función de regeneración 3R, cuando bastaría utilizar regeneración 1R. Los ADMs son equipos caros que podrían ser usados en las redes metropolitanas de COMSAT donde la demanda de subir y bajar señales es mayor. El trabajo consistió en encontrar una solución para sacar un ADM de la red escala nacional y mantenerla operativa. Estos ADMs pueden ser luego empleados en las redes SDH metropolitanas.

Demostramos la funcionalidad y factibilidad financiera de insertar dos EDFAs Padtec en el POP donde se reemplazaba un ADM. Esta solución fue evaluada con un sistema de prueba que usa NZDSF. Nótese que hay que insertar DCMs en la red si la solución es implementada en SSMF. Para bajar el precio de la solución, la misma no ofrece la posibilidad de gestión remota. Una primera distinción entre un corte de cable y un problema del amplificador todavía es posible. El costo de la solución es el factor más importante. Cualquier solución tiene que ser más barata que la compra de un nuevo ADM para hacerlo económicamente factible. Hay que hacer cálculos de costo cada vez que se considere implementar una solución óptica. Como resultado de las medidas utilizando la solución de Padtec se encontraron las siguientes reglas de ingeniería:

- Potencia de entrada al amplificador ≥ -28 dBm
- Potencia de entrada al ADM ≥ -28 dBm
- Relación señal/ruido en la entrada del ADM ≥ 22 dB

La diferencia en el requerimiento de la relación señal/ruido a la entrada del ADM y el valor de 13,5 dB, calculado en el Capítulo Cuatro, se explica por la falta de un filtro óptico en el receptor del ADM. Se obtuvieron los siguientes parámetros del sistema de medida:

- Potencia de salida del ADM = +1 dBm
- Atenuación entre el ADM y el amplificador (> 94 Km) = 28,5 dB
- Potencia de entrada al amplificador = -27,5 dBm
- Potencia de salida del amplificador = +7,6 dBm
- Atenuación entre el amplificador y el ADM (> 106 Km) = 31 dB
- Potencia de entrada al ADM = -24 dBm
- Relación señal/ruido en el receptor del ADM = 24,3 dB

El análisis de M.2110 de la ITU resultó exitoso en un intervalo de tiempo de 15 minutos, 1 hora, 2 horas, 24 horas y de 7 días de prueba. Sólo se registró un error durante la prueba de 7 días. De esta forma, la tasa de error de bits es menor a $1 \cdot 10^{-13}$. El análisis de G.826 de la ITU produjo los siguientes resultados:

- Errored Second Ratio = $1{,}650 \cdot 10^{-6}$
- Background Block Error Ratio = $2{,}063 \cdot 10^{-10}$

Ambos valores están dentro de los límites definidos por este análisis. Ningún error fue debido al 'jitter'.
Se calcularon los siguientes márgenes para el sistema:

- El margen de potencia a la entrada del amplificador: -27,5 – (-28) = 0,5 dB
- El margen de potencia a la entrada del ADM: -24 – (-28) = 4 dB
- El margen de relación señal/ruido en el receptor: 24,3 – 22 = 2,3 dB

Se espera que estos márgenes aumenten cuando la solución sea utilizada en la red de SDH "real" debido a los niveles de atenuación más bajos. La relación señal/ruido en el receptor del ADM empeorará con el tiempo debido al decaimiento del láser de bombeo del EDFA. Si la relación señal/ruido cae debajo del límite de 22 dB hay que insertar un filtro óptico justo antes el receptor del ADM para resolver este problema.

Los amplificadores usados en la solución propuesta son compatibles con futuras expansiones de la capacidad de la red a WDM de 4 x 2,5-Gb/s canales o a 1 x 10-Gb/s canal. Sin embargo, en este último caso, la solución requiere ajustes, como la inserción de DCMs. Cálculos de atenuación, dispersión y efectos no lineales deberán ser llevados a cabo para demostrar la funcionalidad.

List of Figures and Tables

Appendix A: Matlab Scripts

A.1 BER vs. OSNR for various transmitter extinction-ratios

```
% This script calculates and plots the BER vs. OSNR for several transmitter
% extinction-ratios.

% First a suitable time and accompanying frequency vector are created

B = 2.5e9;                       % the bit-rate of the signal
Nsamples = 2^8;                  % number of samples taken per bit
Nbits = 512;                     % number of bits in the sequence
duty_cycle = 0.95;               % duty cycle of the signal
m = 2;                           % factor for creating a 'square' Super Gaussian pulse
C = 0;                           % chirp factor of transmitting laser

T0 = (duty_cycle/(B*2));         % characteristic time width of a single pulse
T = 1/B;                         % time duration of one bit
Ntotal = Nsamples * Nbits;       % total number of samples within bit sequence
dt = T / Nsamples;               % time stepsize between two samples
deltaT = dt * Nsamples * Nbits;  % total time duration of bit sequence

max_t_bit = (dt * Nsamples/2)-dt/2;
min_t_bit = -(dt * Nsamples/2)+dt/2;
t_bit = linspace(min_t_bit,max_t_bit,Nsamples);

t_bit_0th_half= linspace(min_t_bit - (dt * Nsamples/2),min_t_bit -dt,Nsamples/2);
t_bit_1st_half= linspace(min_t_bit,-dt/2,Nsamples/2);
t_bit_2nd_half= linspace(dt/2,max_t_bit,Nsamples/2);
t_bit_3rd_half= linspace(max_t_bit + dt,max_t_bit + (dt * Nsamples/2), Nsamples/2);
t_total = linspace(dt/2,(deltaT-dt/2),Ntotal);

dw = 2*pi / deltaT;              % frequency stepsize
deltaw = 2*pi / dt;              % total frequenct band
maxw = dw * (Ntotal/2-1);        % maximum frequency
minw = -dw * Ntotal/2;           % minimum frequency
w = linspace(minw,maxw,Ntotal);  % frequency vector

Z = randsrc(1,Nbits-4,[0,1]);    % random bit sequence(1)
E = [0 1 0 Z 0];                 % random bit sequence(2)

Bo = 6e9;                        % optical filter bandwidth
[d,c] = butter(3,(2*pi*Bo/w(length(w))));
Be = 2e9;                        % electrical filter bandwidth
[b,a] = butter(3,(2*pi*Be/w(length(w))));

% The NRZ-sequence with various extinction-ratios is created

for e = 1:5,
  if e == 1,
    er_dB = 1000
  elseif e == 2,
    er_dB = 12
  elseif e == 3,
    er_dB = 8.2
```

```
end

er_lin = 10^(er_dB/10)          % extinction-ratio transmitter linear
er_lin_h = sqrt(er_lin)         % h-field multiplication factor due to extinction-ratio

h_low = 1/er_lin_h;
h_high = 1/er_lin_h + (1-1/er_lin_h).*exp(-((1+i*C)/2).*((-dt/2./T0).^(2*m)));
h_rise = 1/er_lin_h + (1-1/er_lin_h).*exp(-((1+i*C)/2).*((t_bit_1st_half./T0).^(2*m)));
h_fall = 1/er_lin_h + (1-1/er_lin_h).*exp(-((1+i*C)/2).*((t_bit_2nd_half./T0).^(2*m)));
h_low_after_fall = 1/er_lin_h + (1-1/er_lin_h).*exp(-((1+i*C)/2).*((t_bit_3rd_half./T0).^(2*m)));
h_rise_after_low = 1/er_lin_h + (1-1/er_lin_h).*exp(-((1+i*C)/2).*((t_bit_0th_half./T0).^(2*m)));

for f=1:Nbits,
  if E(f) == 0,
    q = [(f-1)*Nsamples + 1:1:Nsamples*f];
    h(q) = h_low;
  elseif E(f) == 1,
    q_1st_half = [(f-1)*Nsamples+1:1:(f-1)*Nsamples+Nsamples/2];
    if f > 1,
      q_0th_half = q_1st_half - Nsamples/2;
      h(q_0th_half) = h_rise_after_low;
    end
    h(q_1st_half) = h_rise;
    break
  end
end

for p=f:(Nbits-1),
  q_minus_half = [p*Nsamples-(Nsamples/2-1):1:p*Nsamples];
  q_plus_half = q_minus_half + Nsamples/2;
  if E(p) == 0 && E(p+1) == 0,
    h(q_plus_half) = h_low;
    h(q_minus_half) = h_low;
  elseif E(p) == 0 && E(p+1) == 1,
    h(q_plus_half) = h_rise;
    h(q_minus_half) = h_rise_after_low;
  elseif E(p) == 1 && E(p+1) == 0,
    h(q_plus_half) = h_low_after_fall;
    h(q_minus_half) = h_fall;
  elseif E(p) == 1 && E(p+1) == 1,
    h(q_plus_half) = h_high;
    h(q_minus_half) = h_high;
  end
end

einde = [Nsamples*Nbits-(Nsamples/2 -1):1:Nsamples*Nbits];
if E(Nbits) == 0,
  h(einde) = h_low;
elseif E(Nbits) == 1,
  h(einde) = h_fall;
end

figure(e);
plot(t_total,h);
hold on;
plot(t_total,(h.^2),'r');
```

```
axis([0 10e-9 0 1.2]);

% Noise is added and the minimum BER is calculated

h_power = (abs(h)).^2;
signal_power = sum(h_power);

for k = 1:50,

  SNR =  9.0 + k*0.2;
  Signal_to_noise_ratio(k,e) = SNR-3;
  Res_bandwidth_f = 12.5e9;
  Res_bandwidth_w = 2*pi*Res_bandwidth_f;
  Pn = signal_power/(10^(SNR/10));
  delta_Pn = Pn/Res_bandwidth_w;
  Pn_total = delta_Pn * deltaw;

  SNR_new = 10 * log10(signal_power/Pn_total);

  h_noise = awgn(h,SNR_new,'measured');

  h_noise_filtered = filter(d,c,h_noise);
  h_noise_power = (abs(h_noise_filtered)).^2;

  h_noise_power_filtered = filter(b,a,h_noise_power);

  H_noise_power = fftshift(fft(h_noise_power));
  H_noise_power_filtered = fftshift(fft(h_noise_power_filtered));

  T = 1;
  while h_noise_power_filtered(T) < 0.1,
    T = T + 1;
  end
  while h_noise_power_filtered(T) < h_noise_power_filtered(T+1),
    T = T + 1;
  end

  P = h_noise_power_filtered(T);

  gemiddelde = mean(h_noise_power_filtered);
  U = 0;

  for q = 1:100,
    treshold = gemiddelde * (0.5+(q)/100);
    i_one = 0;
    i_zero = 0;

    for u = 1:(Nbits-2),
      r = T + (u-1)*Nsamples;
      if h_noise_power_filtered(r) > treshold,
        i_one = i_one + 1;
        for l = (r + ceil(-Nsamples*0.01)):(r+floor(Nsamples*0.01)),
          U = U + h_noise_power_filtered(l);
        end
        h_one(i_one) = U/((r+floor(Nsamples*0.01))-(r + ceil(-Nsamples*0.01))+1);
        U = 0;
```

```
            elseif h_noise_power_filtered(r) < treshold,
               i_zero = i_zero + 1;
               for l = (r + ceil(-Nsamples*0.01)):(r+floor(Nsamples*0.01)),
                  U = U + h_noise_power_filtered(l);
               end
               h_zero(i_zero) = U/((r+floor(Nsamples*0.01))-(r + ceil(-Nsamples*0.01))+1);
               U = 0;
            end
         end

         total_bits = i_zero + i_one;

         h1= mean(h_one);
         h0 = mean(h_zero);
         sigma1 = std(h_one)/sqrt(2);
         sigma0 = std(h_zero)/sqrt(2);

         Q(q) = (h1-h0)/((sigma1+sigma0));
         Ber(q) = (1/2)*erfc(Q(q)/sqrt(2));
         clear h_one;
         clear h_zero;
      end

      [B W] = min(Ber);

      BER(k,e) = B;
      Treshold(k,e) = gemiddelde * (0.5+(W)/100);
   end
end

Matrix = transpose([Signal_to_noise_ratio(:,1) BER]);

fid = fopen('BER_vs_OSNR_NRZ_with_extinction_ratio','w');
fprintf(fid,'%6.5e\t %6.5e\t %6.5e\t %6.5e\n',Matrix);
fclose(fid);
```

A.2 BER vs. OSNR for NZDSF and SSMF with Chirp and z = 180 km

```
% This script calculates and plots the BER vs. OSNR for NZDSF and SSMF with
% Chirp and propagation upon 180 km.

% First a suitable time and accompanying frequency vector are created

B = 2.5e9;                       % the bit-rate of the signal
Nsamples = 2^8;                  % number of samples taken per bit
Nbits = 512;                     % number of bits in the sequence
duty_cycle = 0.95;               % duty cycle of the signal
m = 2;                           % factor for creating a 'square' Super Gaussian pulse
C = -6;                          % chirp factor of transmitting laser
er_dB= 8.2;                      % extinction-ratio of the transmitting laser
er_lin = 10^(er_dB/10)           % extinction-ratio transmitter linear
er_lin_h = sqrt(er_lin)          % h-field multiplication factor due to extinction-ratio

T0 = (duty_cycle/(B*2));         % characteristic time width of a single pulse
T = 1/B;                         % time duration of one bit
Ntotal = Nsamples * Nbits;       % total number of samples within bit sequence
dt = T / Nsamples;               % time stepsize between two samples
deltaT = dt * Nsamples * Nbits;  % total time duration of bit sequence

max_t_bit = (dt * Nsamples/2)-dt/2;
min_t_bit = -(dt * Nsamples/2)+dt/2;
t_bit = linspace(min_t_bit,max_t_bit,Nsamples);

t_bit_0th_half = linspace(min_t_bit - (dt * Nsamples/2),min_t_bit -dt,Nsamples/2);
t_bit_1st_half = linspace(min_t_bit,-dt/2,Nsamples/2);
t_bit_2nd_half = linspace(dt/2,max_t_bit,Nsamples/2);
t_bit_3rd_half = linspace(max_t_bit + dt,max_t_bit + (dt * Nsamples/2), Nsamples/2);
t_total = linspace(dt/2,(deltaT-dt/2),Ntotal);

dw = 2*pi / deltaT;              % frequency stepsize
deltaw = 2*pi / dt;              % total frequenct band
maxw = dw * (Ntotal/2-1);        % maximum frequency
minw = -dw * Ntotal/2;           % minimum frequency
w = linspace(minw,maxw,Ntotal);  % frequency vector

Z = randsrc(1,Nbits-4,[0,1]);    % random bit sequence(1)
E = [0 1 0 Z 0];                 % random bit sequence(2)

Bo = 6e9;                        % optical filter bandwidth
[d,c] = butter(3,(2*pi*Bo/w(length(w))));
Be = 2e9;                        % electrical filter bandwidth
[b,a] = butter(3,(2*pi*Be/w(length(w))));

% The NRZ-sequence with various extinction-ratios is created

h_low = 1/er_lin_h;
h_high = 1/er_lin_h + (1-1/er_lin_h).*exp(-((1+i*C)/2).*((-dt/2./T0).^(2*m)));
h_rise = 1/er_lin_h + (1-1/er_lin_h).*exp(-((1+i*C)/2).*((t_bit_1st_half./T0).^(2*m)));
h_fall = 1/er_lin_h + (1-1/er_lin_h).*exp(-((1+i*C)/2).*((t_bit_2nd_half./T0).^(2*m)));
h_low_after_fall = 1/er_lin_h + (1-1/er_lin_h).*exp(-((1+i*C)/2).*((t_bit_3rd_half./T0).^(2*m)));
```

```
h_rise_after_low = 1/er_lin_h + (1-1/er_lin_h).*exp(-((1+i*C)/2).*((t_bit_0th_half./T0).^(2*m)));

for f=1:Nbits,
  if E(f) == 0,
    q = [(f-1)*Nsamples + 1:1:Nsamples*f];
    h(q) = h_low;
  elseif E(f) == 1,
    q_1st_half = [(f-1)*Nsamples+1:1:(f-1)*Nsamples+Nsamples/2];
    if f > 1,
      q_0th_half = q_1st_half - Nsamples/2;
      h(q_0th_half) = h_rise_after_low;
    end
      h(q_1st_half) = h_rise;
    break
  end
end

for p=f:(Nbits-1),
  q_minus_half = [p*Nsamples-(Nsamples/2-1):1:p*Nsamples];
  q_plus_half = q_minus_half + Nsamples/2;
  if E(p) == 0 && E(p+1) == 0,
    h(q_plus_half) = h_low;
    h(q_minus_half) = h_low;
  elseif E(p) == 0 && E(p+1) == 1,
    h(q_plus_half) = h_rise;
    h(q_minus_half) = h_rise_after_low;
  elseif E(p) == 1 && E(p+1) == 0,
    h(q_plus_half) = h_low_after_fall;
    h(q_minus_half) = h_fall;
  elseif E(p) == 1 && E(p+1) == 1,
    h(q_plus_half) = h_high;
    h(q_minus_half) = h_high;
  end
end

einde = [Nsamples*Nbits-(Nsamples/2 -1):1:Nsamples*Nbits];

if E(Nbits) == 0,
  h(einde) = h_low;
elseif E(Nbits) == 1,
  h(einde) = h_fall;
end

H = fftshift(fft(h));
H_power = (abs(H)).^2;

for e = 1:3,
  if e == 1,
    z = 0;
    D = 5;
    beta = - (((1550).^2)/(2*pi*3e5)) * D * 1e-24;
  elseif e == 2,
    z = 180;
    D = 5;
    beta = - (((1550).^2)/(2*pi*3e5)) * D * 1e-24;
  elseif e == 3,
```

```
    z = 180;
    D = 18;
    beta = - (((1550).^2)/(2*pi*3e5)) * D * 1e-24;
end

J = H .* exp((j/2) .* beta .* (w.^2) .* z);
J_power = (abs(J)).^2;
h  = abs(ifft(J));
h_power = (abs(h)).^2;
signal_power = sum(h_power);

% Noise is added and the minimum BER is calculated

for k = 1:50,

    SNR =  9.0 + k*0.2;
    Signal_to_noise_ratio(k,e) = SNR-3;
    Res_bandwidth_f = 12.5e9;
    Res_bandwidth_w = 2*pi*Res_bandwidth_f;
    Pn = signal_power/(10^(SNR/10));
    delta_Pn = Pn/Res_bandwidth_w;
    Pn_total = delta_Pn * deltaw;

    SNR_new = 10 * log10(signal_power/Pn_total);

    h_noise = awgn(h,SNR_new,'measured');

    h_noise_filtered = filter(d,c,h_noise);
    h_noise_power = (abs(h_noise_filtered)).^2;

    h_noise_power_filtered = filter(b,a,h_noise_power);

    H_noise_power = fftshift(fft(h_noise_power));
    H_noise_power_filtered = fftshift(fft(h_noise_power_filtered));

    T = 1;
    while h_noise_power_filtered(T) < 0.1,
       T = T + 1;
    end
    while h_noise_power_filtered(T) < h_noise_power_filtered(T+1),
       T = T + 1;
    end

    P = h_noise_power_filtered(T);

    gemiddelde = mean(h_noise_power_filtered);
    U = 0;

    for q = 1:100,
       treshold = gemiddelde * (0.5+(q)/100);
       i_one = 0;
       i_zero = 0;

       for u = 1:(Nbits-2),
          r = T + (u-1)*Nsamples;
          if h_noise_power_filtered(r) > treshold,
```

```
                i_one = i_one + 1;
                for l = (r + ceil(-Nsamples*0.01)):(r+floor(Nsamples*0.01)),
                    U = U + h_noise_power_filtered(l);
                end
                h_one(i_one) = U/((r+floor(Nsamples*0.01))-(r + ceil(-Nsamples*0.01))+1);
                U = 0;
            elseif h_noise_power_filtered(r) < treshold,
                i_zero = i_zero + 1;
                for l = (r + ceil(-Nsamples*0.01)):(r+floor(Nsamples*0.01)),
                    U = U + h_noise_power_filtered(l);
                end
                h_zero(i_zero) = U/((r+floor(Nsamples*0.01))-(r + ceil(-Nsamples*0.01))+1);
                U = 0;
            end
        end

        total_bits = i_zero + i_one;

        h1= mean(h_one);
        h0 = mean(h_zero);
        sigma1 = std(h_one)/sqrt(2);
        sigma0 = std(h_zero)/sqrt(2);

        Q(q) = (h1-h0)/((sigma1+sigma0));
        Ber(q) = (1/2)*erfc(Q(q)/sqrt(2));
        clear h_one;
        clear h_zero;
    end

    [B W] = min(Ber);

    BER(k,e) = B;
    Treshold(k,e) = gemiddelde * (0.5+(W)/100);
  end
end

Matrix = transpose([Signal_to_noise_ratio(:,1) BER]);

fid = fopen('BER_vs_OSNR_NRZ_er_82_C','w');
fprintf(fid,'%6.5e\t %6.5e\t %6.5e\t %6.5e\n',Matrix);
fclose(fid);
```

Appendix B: Initial Communication with Vendors

COMSAT SDH Network Changes

COMSAT operates a SDH STM-16 network (2,5 Gb/s) between Buenos Aires and Mendoza. The following specs apply:

- Single wavelength @ 1550 nm. (so no WDM)
- G.652 or G.655 ITU compliant fiber (~ 0,22 and 0,25 dB/km attenuation)
- Distance between POPs ~ 90 km.

Approximately every 90 km the signal is regenerated by means of an ADM. These ADMs are located at the so-called POPs (Point of Presence). At most POPs no signal is added or dropped and the ADM at these POPs therefore solely perform the function of regeneration. We would like to remove the ADMs at those POPs where no signals are added or dropped. Because of attenuation considerations (and possibly dispersion considerations as well) it is not possible to just remove the ADM and connect the 'loose' ends. At some place in the link regeneration of the signal needs to take place. This is made visual in Figure 1 and 2, which show a possible solution. Figure 1 shows the solution of inserting an In-line Optical Amplifier at the place where the ADM is taken out. Figure 2 shows the solution of inserting a Booster / Pre-Amplifier just after the ADM of the two neighboring POPs.

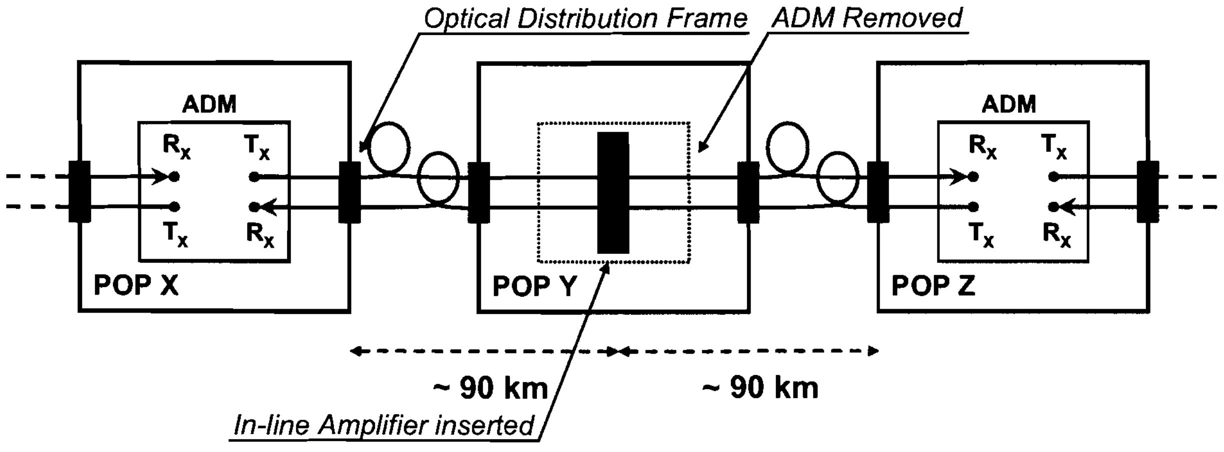


Figure 1: An In-line Optical Amplifier inserted where the ADM is taken out.

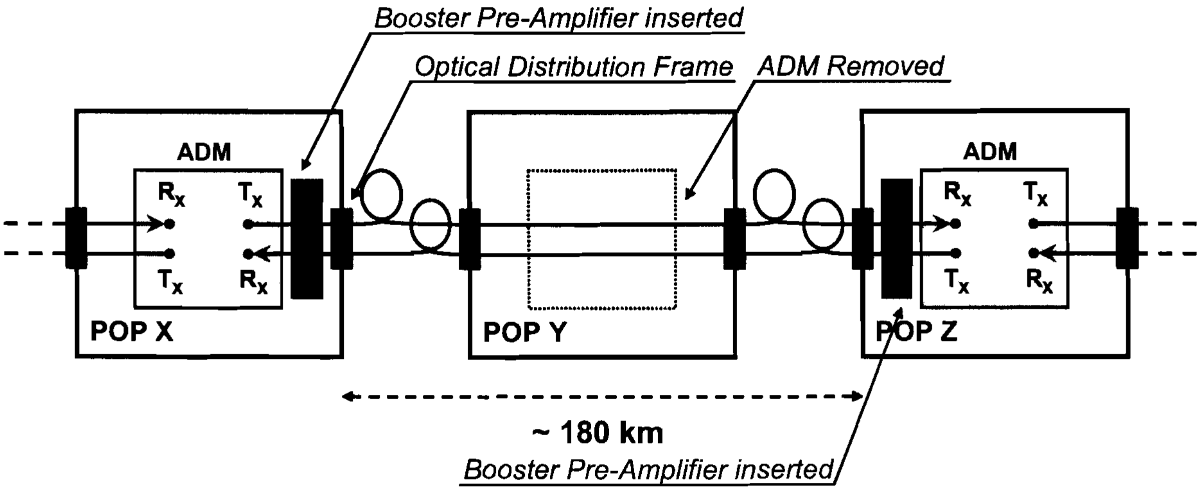


Figure 2: Booster / Pre-Amplifier inserted just before the ADMs of neighboring POPs

It is not necessary to stick with the solutions given in Figure 1 and 2. Any other suggestions are more than welcome.

For you to have a general idea what the total attenuation (fiber attenuation and connector losses) between two POPs would be I can share some averages. Over a 90 km trace there is approximately 22 dB total attenuation. The ADMs used are of the type Lucent *WaveStar*™ ADM 16/1. They operate with a transmission power of +1 dBm and the receiver side works well until -28 dBm. The amplifier(s) inserted would therefore need to have the following gain:

$$-28-1+(2\cdot 22)+7(\text{margin})=20\text{dB}$$

It would be nice to have some information on expected dispersion effects and non-linearities. (if either one of them can cause problems, etc.). Furthermore information on how to monitor and manage the amplifiers is requested as well.

I hope that you are able to give me a general solution for bridging a 180 km gap between two ADMs with the information that I have provided you with above. The idea is to implement a chosen solution for one POP first and run some tests on this. If this then is satisfactory we can start removing more ADMs.

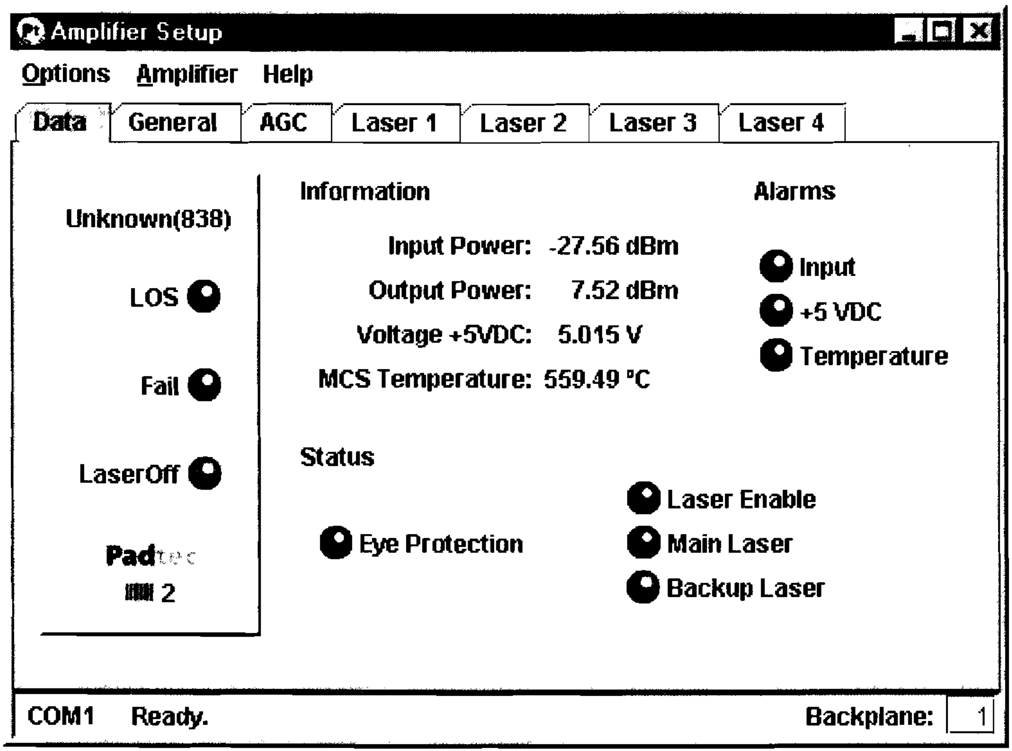
Appendix C: SDH STM-1 BERT Results

```
|==============================================================================|
| 12:23:29  PRINT DEMANDED- RESULTS SNAPSHOT     Elapsed Time   07d 00h 20m 09s|
|==============================================================================|
|                              Cumulative Results                              |
|                                                                              |
| Error Results :                                                              |
|                   A1A2 FRAME      B1 BIP      B2 BIP      MS-REI      B3 BIP |
| Error Count                0           0           0           0           1 |
| Error Ratio                0           0           0           0   1.098E-14 |
|                                                                              |
|                       HP-REI      TC-IEC      TC-ERR         OEI      TC-REI |
| Error Count                0         N/A         N/A         N/A         N/A |
| Error Ratio                0         N/A         N/A         N/A         N/A |
|                                                                              |
|                       TU BIP      LP-REI                                     |
| Error Count              N/A         N/A                                     |
| Error Ratio              N/A         N/A                                     |
|                                                                              |
|                                                                              |
|                                      BIT        CODE         CRC        REBE |
| Error Count                            1         N/A         N/A         N/A |
| Error Ratio                    1.185E-14         N/A         N/A         N/A |
|                                                                              |
|                                                                      JITTER |
| Hit Count                                                                  0 |
| Hit Seconds                                                                0 |
| Hit Free Seconds                                                      606009 |
| Positive Peak                                                          0.085 |
| Negative Peak                                                          0.055 |
| Peak-to-Peak                                                           0.140 |
| RMS                                                                    0.016 |
|                                                                              |
| Analysis Results :                                                           |
|                               G.826 ANALYSIS                                 |
|                                   B1 BIP      B2 BIP      MS-REI      B3 BIP |
| Errored Blocks                         0           0           0           1 |
| Errored Seconds                        0           0           0           1 |
| Severely Errored Seconds               0           0           0           0 |
| Unavailable Seconds                    0           0           0           0 |
| Path Unavailable Seconds             N/A           0           0           0 |
| Background Block Errors                0           0           0           1 |
| Errored Second Ratio                   0           0           0   1.650E-06 |
| Severely Errored Sec Ratio             0           0           0           0 |
| Background Block Err Ratio             0           0           0   2.063E-10 |
|                                                                              |
|                                   HP-REI      TC-IEC      TC-ERR         OEI |
| Errored Blocks                         0         N/A         N/A         N/A |
| Errored Seconds                        0         N/A         N/A         N/A |
| Severely Errored Seconds               0         N/A         N/A         N/A |
| Unavailable Seconds                    0         N/A         N/A         N/A |
| Path Unavailable Seconds               0         N/A         N/A         N/A |
| Background Block Errors                0         N/A         N/A         N/A |
| Errored Second Ratio                   0         N/A         N/A         N/A |
```

```
| Severely Errored Sec Ratio             0         N/A         N/A         N/A
| Background Block Err Ratio             0         N/A         N/A         N/A
|
|                                   TC-REI      TU-BIP      LP-REI
| Errored Blocks                       N/A         N/A         N/A
| Errored Seconds                      N/A         N/A         N/A
| Severely Errored Seconds             N/A         N/A         N/A
| Unavailable Seconds                  N/A         N/A         N/A
| Path Unavailable Seconds             N/A         N/A         N/A
| Background Block Errors              N/A         N/A         N/A
| Errored Second Ratio                 N/A         N/A         N/A
| Severely Errored Sec Ratio           N/A         N/A         N/A
| Background Block Err Ratio           N/A         N/A         N/A
|
|
|
|                               M.2101 ANALYSIS
|                                          Section          High Order Path
|                                       Rx          Tx          Rx          Tx
| Errored Seconds                        0           0           1           0
| Severely Errored Seconds               0           0           0           0
| Unavailable Seconds                    0           0           0           0
|
|                                G.821 ANALYSIS
|                          BIT    FAS 140M     FAS 34M      FAS 8M      FAS 2M
| Errored Sec                1         N/A         N/A         N/A         N/A
| %Errored Sec         0.00017         N/A         N/A         N/A         N/A
| %ES (Annex D)        0.00000         N/A         N/A         N/A         N/A
| Error Free Sec        606008         N/A         N/A         N/A         N/A
| %Error Free Sec     99.99983         N/A         N/A         N/A         N/A
| Severely Err Sec           0         N/A         N/A         N/A         N/A
| %Severely Err Sec    0.00000         N/A         N/A         N/A         N/A
| Degraded Minutes           0         N/A         N/A         N/A         N/A
| %Degraded Minutes    0.00000         N/A         N/A         N/A         N/A
| Unavailable Sec            0         N/A         N/A         N/A         N/A
| %Unavailable Sec     0.00000         N/A         N/A         N/A         N/A
|
|                                G.826 ANALYSIS
|                                     Near 140Mb/s Far        Near 34Mb/s  Far
| Errored Seconds                        0         N/A         N/A         N/A
| Severely Errored Seconds               0         N/A         N/A         N/A
| Unavailable Seconds                    0         N/A         N/A         N/A
| Errored Second Ratio                   0         N/A         N/A         N/A
| Severely Errored Sec Ratio             0         N/A         N/A         N/A
|
|                               BIT Errors
| Errored Blocks                         1
| Errored Seconds                        1
| Severely Errored Seconds               0
| Unavailable Seconds                    0
| Background Block Errors                1
| Errored Second Ratio           1.650E-06
| Severely Errored Sec Ratio             0
| Background Block Err Ratio     2.063E-10
```

```
|                                                                              |
|                               M.2100 ANALYSIS                                |
|                                       Rx 140Mb/s  Tx          Rx  34Mb/s  Tx |
| Errored Seconds                        1         N/A         N/A         N/A |
| Severely Errored Seconds               0         N/A         N/A         N/A |
| Unavailable Seconds                    0         N/A         N/A         N/A |
|                                                                              |
|                               M.2110 ANALYSIS                                |
|                         15-min       1-hr       2-hr       24-hr       7-day |
| BIS Results            PASS         PASS       PASS        PASS        PASS |
|                                                                              |
|                                                                              |
|                                                                              |
| Frequency :  155520079 Hz       Offset :     +79 Hz     Offset :     +0.5ppm |
| Power Level :    -11.4 dBm     STM-1o OPTICAL                                |
|                                                                              |
| Pointer Results :                  AU POINTER                 TU POINTER     |
|                                Count     Seconds          Count     Seconds  |
| NDF                                            0                        N/A  |
| Missing NDF                                    0                        N/A  |
| +ve Pointer Adjustments            0           0           N/A        N/A  |
| -ve Pointer Adjustments            0           0           N/A        N/A  |
| Implied VC Offset                0.0                       N/A              |
| Pointer Value                    659                       N/A              |
|==============================================================================|
```

Appendix D: Padtec Management Tool Screens



Unknown(838)

LOS ●

Fail ●

LaserOff ●

Information

Input Power: -27.56 dBm

Output Power: 7.52 dBm

Voltage +5VDC: 5.015 V

MCS Temperature: 559.49 °C

Alarms

● Input

● +5 VDC

● Temperature

Status

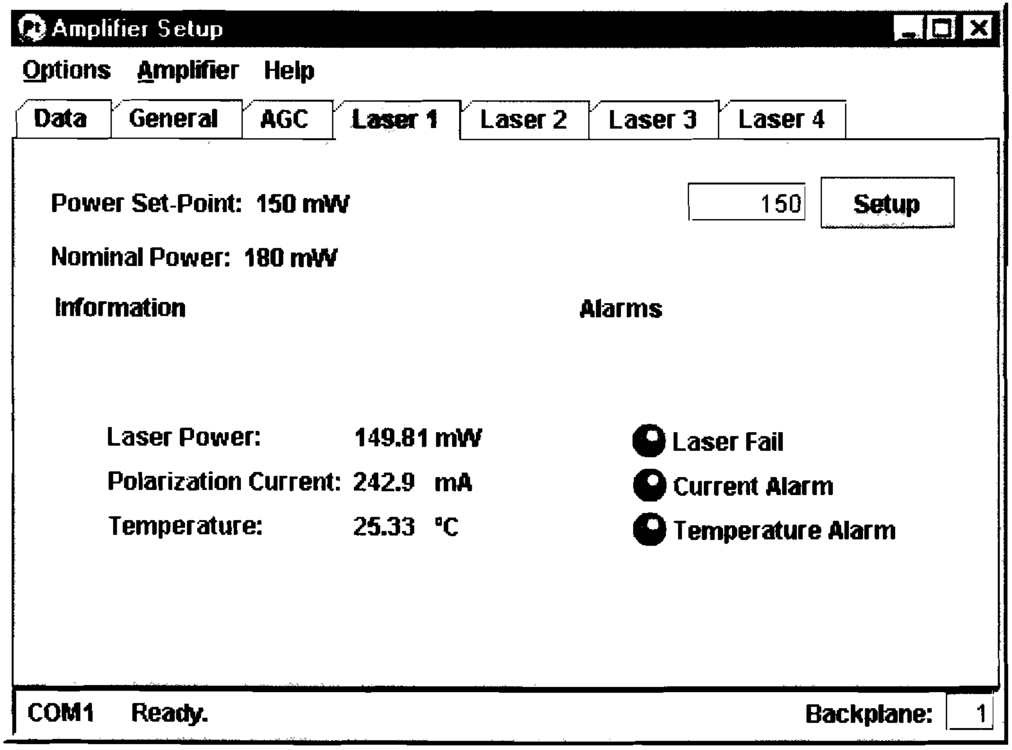
● Eye Protection

● Laser Enable

● Main Laser

● Backup Laser

COM1 Ready. Backplane: 1



Power Set-Point: 150 mW 150

Nominal Power: 180 mW

Information

Laser Power: 149.81 mW

Polarization Current: 242.9 mA

Temperature: 25.33 °C

Alarms

● Laser Fail

● Current Alarm

● Temperature Alarm

COM1 Ready. Backplane: 1

Appendix E: Software & Equipment

Software

- Adobe Photoshop
- Agilent OTDR Traceview III version 2.02
- Lucent ITM-CIT System Software 12.0
- Matlab 6.5
- Microcal Origin 6.0
- Microsoft Office Word 2002
- Microsoft Office Excel 2002
- Microsoft Office PowerPoint 2002
- Microsoft Paint 5.1
- Microsoft Windows XP
- Padtec Amplifier Setup version 2.3

Equipment

- Agilent Omniber 718
- ECE Rectificador 220AC – 48DC converter
- GENERAC Rectificador 220AC – 48DC converter
- Lucent EFA4 Subrack 9TAD (D700) B
- Lucent LJB436 STM-16 L 16.2 1.5μm ITU, Ruby
- Lucent LJB439 STM-1e/o
- Lucent LMB401 Pwr Filter&Timing str3
- Lucent LJB434 Cross-Connect 64/32, Ruby
- Lucent Rack 2200mm ETSI Assembled
- OTDR Wavetek MTS 5100
- OTDR Agilent E6000 Series
- OSA ANDO AQ6317
- WWG OLS-6 Optical Laser Source
- WWG OLP-6 Optical Power Meter

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Suggestions for Further Reading

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