

Khurram Kazi
Editor

Optical Networking Standards

A Comprehensive Guide for Professionals

 Springer

Nokia of America Corporation

IPR2023-00960, Ex. 1015

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OPTICAL NETWORKING STANDARDS: A COMPREHENSIVE GUIDE

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IPR2023-00960, Ex. 1015

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Edited by

Khurram Kazi

 Springer

Nokia of America Corporation

IPR2023-00960, Ex. 1015

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Ex. 1015.003

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Optical Networking Standards: A Comprehensive Guide

Library of Congress Control Number: 2006921777

ISBN 0-387-24062-4 e-ISBN 0-387-24063-2
ISBN 978-0-387-24062-6

Printed on acid-free paper.

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Dedication

*This book is dedicated to my wife
Sameema, my family and friends
and all the folks who have spent
countless hours developing
networking standards*

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FOREWORD

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SMSC

“O mankind! We have created you from a single (pair) of a male and female, and have made you into nations and tribes, so that you may know each other...” [Quran 49.13]. When one ponders over how we get to know each other; certain thoughts come to mind. As we venture outside our own region or domain, we tend to follow certain protocols that allow us to communicate with each other. Those protocols have diverse flavors; for example, the first thing we try is to communicate in a common language that both parties understand. If that fails, we use gestures or sign language or even resort to drawing pictures to get our message across. In short we find a common ground or similar footing which to build our communication platform on even though we may come from such diverse cultures and background.

Just as we have diversity in mankind, we have disparate, ever-evolving communications networks. These networks are evolving towards providing seamless connectivity between different platforms and applications so that they cater to our insatiable need to communicate with each other in many different ways. Evolutionary technologies, including Dense Wavelength Division Multiplexing (DWDM), advances in optics/optoelectronics, highly versatile electronic integrated circuits, and control and management software have provided an excellent foundation for present-day networks to emerge into robust and scalable networks with ever-increasing intrinsic intelligence.

These advances have been enabled by the relentless activities taking place within scores of technical standards committees, industry fora and consortia across the globe. In this comprehensive volume, we seek to give an overview of the converged multiservice optical transport networking development activities occurring within standards development

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organizations and industry fora including the International Telecommunication Union, ITU-T, Internet Engineering Task Force (IETF), Institute of Electrical and Electronics Engineers (IEEE), Metro Ethernet Forum (MEF) and Optical Internetworking Forum (OIF). Some of the issues these bodies are addressing are:

- Multiservice and data-optimized SONET/SDH and OTN transport infrastructure
- Ethernet and MPLS in converged transport networks spanning the enterprise, access, and core network realms
- Flexible and efficient support for a diverse set of services over existing and emerging next-generation transport network architectures
- Enhanced service provisioning, enabling more dynamic and responsive connection services, via automatically switched transport networks
- Equipment functional block specifications that enable multivendor interoperability without constraining equipment implementation
- Physical-layer specifications that enable multi-carrier network deployments and interconnection of equipments among multiple vendors
- Network and equipment management specifications encompassing FCAPS (fault, connection, administration, performance, security management) that assure common behavior and minimize the need for human intervention, reducing operational and management expenses
- Timing and synchronization in global transport networks
- Backplane and component specifications encompassing optical, electrical, and mechanical characteristics that impact, e.g., opto-electronic modules, Very Large Scale Integrated devices, and backplanes utilized in existing and next-generation equipment

PREFACE

In the late 1980s and 1990s I was exposed to ANSI, ITU-T, IEEE and ATM forum standards and implementation agreements while developing ASICs and systems for T1, SONET/SDH, ATM, and Ethernet applications. During the architecture, design, and verification, I had to go through the standards documents to ensure that my designs were standards compliant. While designing I was always on the lookout for a comprehensive source that could give me a broad prospective on all the relevant standards dealing with optical networking. Suffice it to say I did not find a single book that comprehensively covered the work being done at the major standards bodies and I ended up going through quite a few books, standards documents and technical papers. The development of the bigger picture proved to be quite useful in my design process as I started to understand which components my ASICs would be interfacing with, what systems and services features these ASICs were going to be providing etc. In short, I started to understand the design partitioning and hierarchical abstractions; from ASICs, standard VLSI products, and optoelectronic components to systems and networks architecture. With the desire to share these thoughts with the rest of the networking community, I embarked upon this project.

With the help of Eve Varma, I was able to assemble a world-renowned team of over twentyfive leading contributors and editors of the standards from networking powerhouses such as Tellabs, PMC-Sierra, Nortel, Marconi, Lucent Technologies, Cisco, Ciena, British Telecom, Atrica, AMCC, and Agere Systems, as well as independent consultants, who have come together to make this work a reality. From our collective efforts we have put together *Optical Networking Standards: A Comprehensive Guide*, which provides a single-source reference work for the specifications of networks at all levels: from components (optics, optoelectronics, and VLSI

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devices) through systems to global transport networks infrastructure, their management, and the services they offer.

While going through the standards documents, especially the designers and implementers who ensure standards-compliant products should keep in mind that generally standards documents are not easy to read. There are several reasons behind the statement. Typically, the process of defining the requirements for specific sets of functionalities kickstarts the development of a particular standard or suite of standards. During the early phases of the development of standards technologies or services, the norm is to define a generic architecture. Details are subsequently added either to the same document or to different ones to get into specifics. Generally speaking, every effort is made to ensure that the standards are written in such a way that they are technology and implementation independent. This approach results in careful usage of the language that at times makes it difficult to read. From my personal experiences as a designer, I felt anguish while going through these documents. However, persistent reading made things clearer. One lesson that I learned is that one needs to spend the time going through the documents with patience and full concentration, along with having discussion with the colleagues, to fully appreciate the subtleties of the recommendations. It is always helpful if one develops some background information base prior to going through standards documents.

Every effort is made in this book to give a reader some background information so that going through the respective recommendations is not as painful as when one starts to read them cold. The chapters are written such that they can be read as standalone chapters or can be combined to get a better understanding of the different aspects of optical networking standards. It should be kept in mind that the reader should always use the actual standards documents, implementation agreements, or RFCs as the definitive source of information.

Acknowledgements

I would like to thank ITU-T, Metro Ethernet Forum and Optical Internetworking Forum for allowing us to use appropriate information from their respective standards and the implementation agreements.

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(NYCT) for the future Second Avenue Subway line communications network.

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Steven Scott Gorshe is a Principal Engineer with PMC-Sierra's Product Research Group. He received his B.S.E.E. (University of Idaho) and M.S.E.E. and Ph.D. (Oregon State University) in 1979, 1982, and 2002, respectively. He has been involved in applied research and the development

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Stephen Shew is an Architect in the Optical Networks group at Nortel Networks. In his career at Nortel, Stephen has participated in the development and specification of distributed routing protocols, traffic engineering optimization tools, ATM PNNI, and MPLS signaling. His standards involvement has included the ATM Forum and IETF. He is currently participating in ITU-T Study Group 15 and OIF, and contributes to the architecture and protocols for the Automatic Switched Optical Network (ASON). Stephen received his Bachelor of Computer Science from Carleton University and M.Sc. from the University of Toronto.

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Eve L. Varma is a Technical Manager, Lucent Technologies, part of Lucent's Optical Networking Group. Ms. Varma has 26 years of research experience within the telecommunications industry. Her primary research areas are currently focused upon the automatically switched transport network (ASON/GMPLS) and converged multiservice transport networks. She is actively engaged in supporting the development of the associated specifications within global standards and industry fora spanning ITU-T, ATIS, and OIF. From 1995 to 1997, she led the team responsible for designing and prototyping a distributed optical network management system as part of the Multiwavelength Optical NETWORKing (MONET) Consortium (partially supported by DARPA). Previous research experience includes characterization, analysis, and development of transmission jitter requirements; systems engineering and standards for SDH/SONET and OTN transport and network management applications; as well as associated enabling technology and methodology development/assessment. Ms. Varma has been an active contributor to global standards since 1984 and has co-authored two books, *Achieving Global Information Networking*, Artech House (1999), and *Jitter in Digital Transmission Systems*, Artech House (1989). She holds an M.A. degree in Physics from the City University of New York. Ms. Varma is a 2004 Bell Labs fellow.

Tim Walker received his BS EE from Rensselaer Polytechnic Institute and his MS EE from University of Illinois at Urbana-Champaign. He is a member of IEEE, Tau Beta Pi, and Eta Kappa Nu. Mr. Walker is currently a Systems Engineer at Applied Micro Circuits Corporation (AMCC) in Andover, Massachusetts. Prior to AMCC he spent 16 years at Bell Labs/Lucent in various Hardware and Software design positions. Before that, he was an RF Engineer for four years at Teradyne. His main areas of expertise are OTN (G.709), SONET/SDH, and PON. He has presented numerous proposals to Standards bodies (ITU SG15 and T1X1).

Chapter 1

OVERVIEW

Khurram Kazi
SMSC

The late 1990s heralded the need for optical transport networks to make a transition from catering to mostly voice traffic to converged voice and multi-service data-centric traffic. This transition led to several innovative standardized solutions, developed primarily within the International Telecommunication Union, (ITU-T) to develop and more efficiently leverage new and existing transport infrastructures to support the delivery of conventional and emerging services. Associated with this trend has been the cross-fertilization of concepts and technologies between traditionally data-oriented standards organizations, such as the Institute of Electrical and Electronics Engineers (IEEE) and Internet Engineering Task Force (IETF), and the ITU-T. Further coupled with this cross-fertilization has been an industry focus upon defining the multitude of services that such networks can offer, as evidenced by diligent work efforts in industry forums such as the Metro Ethernet Forum (MEF). Industry forums, including the MEF, Optical Internetworking Forum (OIF), and TeleManagement Forum (TMF), currently play important roles related to the realization and deployment of new technologies. Last but not least, due to the large number of component vendors whose standard products are used in the design of the network elements that provide these diverse set of services, the need for standardized backplane and component interfaces has never been greater. For example, the OIF and IEEE facilitate development and deployment of optical and electrical component/backplane technologies.

The book is organized into five categories:

1. Optical Transport Network infrastructure
2. Services offered over Transport Networks

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3. Control and management of Transport Networks
4. Intra-Network Elements and component-centric standards
5. Standards development process

The chapter distribution is illustrated in Figure 1-1.

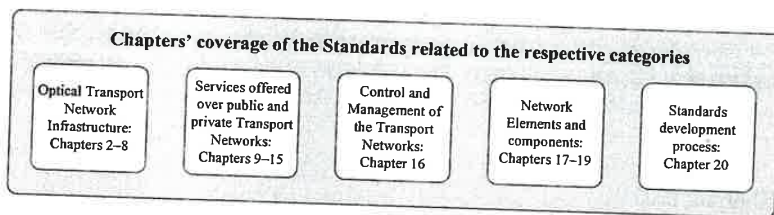


Figure 1-1. Categorical distribution of chapters

1.1. OPTICAL TRANSPORT NETWORK INFRASTRUCTURE

1.1.1 Functional Modeling Specification Technique

Optical transport networks have evolved into intelligent and complex networks that provide global connectivity and increasingly diversified services. Such networks need to interoperate between numerous carriers and service providers to ensure seamless connectivity across the globe. This requirement leads to the daunting task of representing and specifying equipment and network functionality and behavior for transport networks in a coherent and implementation-independent manner. ITU-T took the lead in defining a functional modeling specification technique that can be used as the requirements' capture and analysis tool.

Chapter 2 describes the fundamental concepts of the functional modeling approach used in multiservice optical transport networks. In reviewing the basics, it describes how the complexity of the network functions can be reduced by a "divide and conquer" approach using the concepts of layers and partitions. The simplicity and versatility of the functional modeling scheme is illustrated by demonstrating how a handful of symbols can be used to represent various networking functions, be they for the network level or for detailed descriptions of functions within the networking gear (even down to the ASIC level). To illustrate its usage, several examples are provided. For

example, functions like the mapping of a Plesiochronous Digital Hierarchy (PDH) client signal onto a Synchronous Optical Networks (SONET)/Synchronous Digital Hierarchy (SDH) server signal or Add Drop Multiplexing (ADM) equipment characteristics are shown in simple diagrams. Numerous other examples are given in illustrating the usage of the functional modeling techniques. The fundamental concepts developed in this chapter are also used in subsequent chapters where services, management, and control of the multiservice transport networks are described.

For the digital design engineer, this platform can be compared to the US Department of Defense's Very High Speed Integrated Circuit (VHSIC) project that resulted in the development of VHSIC Hardware Description Language (VHDL). The intent in creating VHDL was to use it for writing the specifications of electronic devices and systems in a standard format. However, since then the scope of VHDL has expanded significantly, it is now used for designing, simulating and synthesis of Application Specific Integrated Circuits (ASICs). Similarly, the functional modeling techniques developed by ITU-T may be utilized in the design and development process of hardware and software for multiservice transport networks.

1.1.2 Multiservice Optical Transport Network Infrastructure

Since the wide deployment of the Internet, the transport networks that once catered to low bandwidth Time Division Multiplexing (TDM) centric services required evolutionary features to simultaneously support TDM and multiservice data-centric traffic (variable length packets or frames) that had "best effort delivery" or "time and jitter sensitive" characteristics. In the late 1990s, based upon the tremendous growth in data traffic, ITU-T experts determined that there was a need to come up with a new set of standards that was optimized for this ultra-high-growth and data-driven capacity demand. Based upon a set of requirements predicated upon carrier globalization, support for gigabit-level bandwidth granularity for scaling and managing multiterabit networks, and leverage of dense wavelength-division multiple (DWDM) technology, work started on a next-generation optical transport network. This infrastructure was intended to complement the SONET/SDH infrastructure, which was designed around a mux structure starting from VT1.5/VC12 that filled the payload with voice-centric 64 Kb/s traffic. Leveraging lessons learned in the establishment of SONET/SDH standards were also developed.

1.1.2.1 Optical Transport Hierarchy

Chapter 3 describes in detail two key ITU-T standards, G.709 and G.798, that describe the implementation of Optical Transport Hierarchy (OTH). It goes through the rationales and requirements behind the development of a suite of standards. For example, it covers topics including its role as an efficient transport networking layer that supports very high rate services at 2.5, 10, and 40 Gb/s; strong Forward Error Correction (FEC); support of multiple nested and overlapping Tandem Connection Monitoring (TCM) layers; the management of frequency slots Optical Channels, (OChs); single or multiple λ s instead of time slots (STS-1s, etc.). Furthermore, it extensively covers the details of the G.709 frame structure, how various client signals can be mapped onto it, and the maintenance and management of networked DWDM signals. Prior to the bursting of the telecom bubble, it was widely anticipated that the SONET/SDH signals would become clients of the OTN. However, in the time frame during which the OTN standardization effort came to fruition, the market need for support of Gbit-level networking did not materialize, and OTN deployment has been slower than anticipated. Currently, one of the major driving factors in its deployment is the availability of strong Forward Error Correction (FEC) functionality at high speeds. This factor will become even more pervasive as we see the deployment of 40 Gb/s line rates due to the power savings and lower Bit Error Rate (BER) features of the strong FEC.

1.1.2.2 Data and TDM-Friendly Next-Generation SONET/SDH

Leveraging the worldwide investment in SONET/SDH network infrastructure and equipment to support the delivery of new services continues to be an important consideration for carriers. The advantages of this leveraging include incurring only incremental investments for deploying new services and enabling generation of revenues from delivery of new services via standardized mappings into SONET/SDH (e.g., transport of non-SONET/SDH bit-rate payloads). As the saying goes, "Necessity is the mother of all inventions" and this truth led to simple and elegant solutions that changed the status of "legacy SONET/SDH" to "the next big thing." Recent ITU-T standards added the efficient multiservice data-centric transport capabilities to the Time Division Multiplexed voice-centric SONET/SDH networks without requiring a "forklift" upgrade. There were two main issues that needed to be addressed in achieving the desired features: 1) efficient utilization of bandwidth in transporting data traffic and 2) seamless encapsulation of any data centric traffic into SONET/SDH pipes.

Chapters 4 and 5 provide extensive details of the underlying technologies that breathed new life into SONET/SDH.

From the networking point of view, a majority of the data-centric traffic across the globe originates in the form of Ethernet frames. Almost everyone who uses a networked computer knows something about Ethernet and feels comfortable with it. This situation led to the huge momentum behind the evolution of the Ethernet that resulted in its emerging from the enclosing scope of local area networks along with high-speed Internet, IP Virtual Path Networks, IP VPN, video distribution, and varied other services. This emergence created a requirement for the efficient transport of Ethernet services over the SONET/SDH and OTN transport network infrastructures. Chapter 4 describes the details of the ITU-T's work on Virtual Concatenation (VCAT) and the Link Capacity Adjustment Scheme (LCAS) to ensure that future networking needs are met by adding data-centric capabilities into the existing Time Division Multiplexed, TDM, transport structures.

The concept behind VCAT is that the primitive payload containers that carry the client data can be virtually "glued" or concatenated to build the desired bandwidth pipe. This outcome is achieved by using pointers in the overhead field of the containers. Theoretically speaking, bandwidth can be added or deleted when desired with the lowest granularity of approximately 1.5 Mb/s (VT 1.5 or VC-11). However, there are no restrictions on changing the desired bandwidth by any container size (e.g., VT-x, VC-n, STS-n, or STM-n). The Link Capacity Adjustment Scheme defines the protocol of how bandwidth can dynamically be changed. In essence, one can say that VCAT in conjunction with LCAS allows networks operators to provide bandwidth on demand without disrupting service while effectively utilizing the SONET/SDH pipes.

A nimble and efficient encapsulation protocol known as Generic Framing Procedure (GFP) that supports fixed and variable-length frames/packets over transport networks was also recently standardized within the ITU-T (post-2000). Chapter 5 describes how diverse set of protocols can be efficiently mapped into a single transport protocol (GFP) without having to go through multiple layers of encapsulation before being transported over TDM-based core networks. As an example, native IP traffic, Ethernet, Fibre Channel, and Storage Area Networking (SAN) protocols, along with others, can be mapped into GFP with minimal overhead. In GFP there are three main modes of the client frames/packets adaptation: Frame Mapped, Transparent Mapped, and Asynchronous Transparent Mapped. The Frame Mapped adaptation mode is mostly utilized in encapsulating data traffic like Ethernet, IP, MPLS etc. In this mode, the entire client data frame/packet has to be buffered locally first, prior to the encapsulation. This process causes delay

and may not be suitable for time-sensitive traffic. Transparent Mapped modes of the GFP provide low jitter and delay by encapsulating the client signal in fixed-length encoded GFP frames without having to wait for the entire client frame/packet to be buffered.

1.1.3 Global Optical Transport Network Timing

As the saying goes, "Timing is everything." This phrase is an exact fit for transport networking, since we know that timing and synchronization, among the network elements that make up the global transport network infrastructure play a very critical role in ensuring the proper operation and performance of these networks. Chapter 6 gives a comprehensive overview of the timing and synchronization techniques utilized within optical transport network infrastructures. It covers the fundamental concepts of jitter and wander and their relationship with network synchronization. These basic topics lead into the jitter, wander, and synchronization requirements for SONET/SDH networks and the differences between these requirements and those for OTN infrastructures. Moreover, topics including client signal mapping into SONET/SDH or OTN signals, and the accommodation of timing variation to ensure seamless operation, are extensively covered. The architectural solutions to accommodate effects due to jitter and wander within the components/blocks, may these be Clock and Data Recovery (CDR) or SONET/SDH or OTN framers, are provided.

The fundamental concepts covered in Chapter 6 have to some extent a high degree of abstraction, since they are described in mathematical terms. To illustrate those points explicitly, it is prudent to follow the discussion with some technology specific concepts and examples. Chapter 7 complements the content of Chapter 6 by addressing the issues within the SONET/SDH systems and networks. It starts out by reviewing why synchronization is needed, how it is administered, and why tracing the timing source is important. Numerous methods of timing extraction mechanisms utilized by the network elements are shown. Chapter 6 also reviews the hierarchical timing distribution across the network. Several architectural examples of timing distribution within the various types of network elements are also presented.

1.1.3.1 Transport Network Survivability

A very important aspect of providing uninterrupted networking services is to ensure connectivity, while maintaining an acceptable level of service quality, under conditions of natural or man-made disasters. This topic is extensively addressed in Chapter 8 under the category of network

survivability. There are two predominant techniques utilized for achieving survivable networks: (1) network protection and (2) network restoration. Network protection implies that there are dedicated resources that have already been deployed as backups and that "take over" when the primary resources have failed. Network restoration refers to the use of backup resources from a pool of resources, as opposed to dedicated backup resources. Chapter 8 starts by providing the objectives of the protection schemes and covers the details of the major five protection architectures namely, (1) 1+1, (2) 1:n, (3) m:n, (4) (1:1)ⁿ, and (5) rings. Protection switching parameters, protection switching classes, protection switching trigger criteria, automatic protection switching protocol, and examples are discussed. Topics in survivability through restoration implemented by either preplanned or on-the-fly routing with centralized route-calculation techniques and distributed techniques are also covered.

1.2. CARRIAGE OF SERVICES OVER TRANSPORT NETWORKS

The MEF, ITU-T, and IETF have taken the lead in defining technical specifications, standards and RFCs for extending the reach of Ethernet from its traditional LAN environment to metro- and wide-area networks. The intent of the effort by these standards and industry forums is to ensure that enhanced Ethernet-based services can be deployed reliably and are scalable at lower capital and operating expenses.

1.2.1 Ethernet Services Architecture and Definitions

In describing Ethernet services, it is prudent to describe reference models that can be used in defining terms and services. Chapter 9 lays the foundation for describing the reference models used in defining Ethernet services over metro area networks. These services are defined in such a way that they can be carried over any of the prevailing transport technologies like IEEE 802.3 PHY, IEEE 802.1 bridged networks, SDH VC-n/VC-n-Xc, SONET STS-n/STS-4n-Xc, ATM VC, OTN ODUk, PDH DS1/E1, MPLS, dark fiber, etc., or possibly different future networks.

1.2.1.1 Ethernet Services over Metro Networks

Traditionally, services are defined in observable terms, with clear demarcation points between the subscriber and the service provider's

equipment. The subscriber equipment is referred to as the *Customer Edge (CE)* at which observable service-level parameters are defined that become the basis for a Service Level Agreement (SLA) between the subscriber and the service provider. The physical demarcation point between the Service Provider and a single subscriber is termed a *User to Network Interface (UNI)* across which such SLAs are made. Beyond the UNI, the types of technology and the architecture inside the metro and wide-area networks are invisible to the subscriber. This transparency allows the services to be defined and observed from UNI to UNI. Moreover, the definition of the services allows the service providers to offer metro- and wide-area Ethernet services to over 100 million existing devices capable of using the services.

Chapter 10 describes the service definitions and characteristics of Ethernet Virtual Connection (EVC) as defined by MEF. Details of point-to-point, point-to-multipoint, and multipoint-to-multipoint EVCs enabled by VLAN tags are provided, along with details of how these can be used in offering E-Line and E-LAN services. Traffic and performance management is an integral part of ensuring that the SLAs are met for such services. Traffic policing becomes essential in monitoring compliance with the SLAs and is based on parameters like Committed Information Rate (CIR), Committed Burst Rate Size (CBS), Excess Information Rate (EIR), and Coupling Flag (CF). The performance-monitoring parameters such as frame delay, frame delay variation, frame loss can be used in defining different classes of service. The means whereby these parameters are used in service delivery and performance monitoring/assurance are also covered.

1.2.1.2 Ethernet Services over Public Wide-Area Networks

In Chapter 11, we see that ITU-T has taken its lead from the work done by the MEF and extended the scope by defining the Ethernet services over public wide-area transport networks. ITU-T uses traffic management and performance parameters consistent and complementary with MEF in defining its services standards. In addition to the services description, it covers the transport network models that support the Ethernet connectivity. These include Ethernet private line services that leverage the existing connection-oriented, circuit-switched TDM networks. Several service scenarios that provide diverse sets of applications are provided. Chapter 11 goes on to describe the Ethernet-based user-to-network interfaces (UNIs) and Network-to-Network interfaces (NNIs). To facilitate reliable Ethernet services, Ethernet operations, administration and management, and survivability are also discussed. It should be noted that the ITU-T's data-centric transport technologies like Virtual Concatenation (VCAT), Generic Framing Procedure (GFP), and Link Capacity Adjustment Scheme, (LCAS)

have become the enablers of Ethernet services over SONET/SDH and OTN networks.

1.2.1.3 Ethernet Services over MPLS Networks

Leveraging the extensive work done on Multiprotocol Label Switching (MPLS) networks, along with its expertise on packet-based networks, IETF has developed RFCs that are the enablers for providing Ethernet services by using MPLS networks. Chapter 12 details Ethernet services over MPLS networks. It starts by describing the fundamental concepts and architectures of layer 2 virtual private networks (VPN) over an MPLS backbone as it sets the stage for the Ethernet services over MPLS. E-Line and E-LAN functions are subsequently discussed, as well as how virtual private wire and virtual private LAN services can be offered. A walk-through example of E-Line emulation over MPLS is given to clarify the concepts and outline the steps needed to provide the service.

1.2.1.4 Circuit Emulation over Metro Ethernet

Traditional voice and other TDM services have been the core of our communication needs and over time have been offered on different technology platforms as these evolve. Ethernet as a service platform has gained significant momentum over the past couple of years. Carriers worldwide are deploying metro Ethernet networks to cater to the ever-demanding business customers' requirements for faster and cheaper data and voice transport. Moreover, these carriers are finding increased demand for their existing lucrative TDM traffic, may it be PBX trunks or private line services.

Chapter 13 describes the details of MEF's recommendations regarding Ethernet circuit emulation services, such as $N \times 64$ kbit/s, T1, E1, T3, E3, OC-3, and OC-12, across a Metropolitan Ethernet Network. It provides numerous service reference models that can be used in implementing TDM services.

1.2.1.5 Metro Ethernet Network Resiliency

We are seeing tremendous momentum behind Ethernet services that are being offered by carriers to businesses. The availability of the network services to the business is very critical, as is the Quality of Service (QoS). The combination of service availability and QoS has become a crucial aspect of the Service Level Agreement (SLA) between the user and the service provider. Service availability is tightly coupled with network resiliency.

Chapter 14 covers the metro Ethernet network resiliency as recommended by the MEF. Topics like protection types, failure types, resource selection, and event timings are covered. Chapter 14 also discusses timing issues along with service-level specification commitments. Protection reference models are described such that consistent descriptions of protection capabilities are applied on these services across various transmission technologies, network topologies, and policies. This approach enables the description of protection of services in the ETH layer (Ethernet Line Service, Ethernet LAN service, etc.). The models lend themselves nicely to a definition of requirements for the Ethernet services protection mechanism. This definition subsequently provides the framework for the protection in the metro Ethernet and the implementation of the protection schemes.

1.2.2 Storage Area Services over SONET

The data-centric upgrades to SONET/SDH networks and key developments in the Fibre Channel, the widely used protocol for storage-area networks, have provided a strong platform for connecting storage-area networks across town or across the globe. Chapter 15 provides an overview of the trends for tremendous data growth across the globe and the need to access stored data at remote sites. It briefly covers the basics of the storage-area networks and the different technologies that are used therein. It reviews the stringent requirements that storage networks place on wide-area networks when they are connected over wider distances, as well as the need for network resiliency, scalability, and performance. It gives various options for how storage data can be moved across various sites using WDM, storage over IP, Fibre Channel over IP, and SONET/SDH. It makes a strong case for why SONET/SDH (using VCAT and GFP), along with the work being done at the ANSI Technical Committee on Fibre Channel Back Bone (FC-BB-3), provides a good, strong platform for extending the storage-area networks across long distances.

1.3. CONTROL AND MANAGEMENT OF OPTICAL TRANSPORT NETWORKS

Chapter 16 provides a treatise on the activities of the ITU-T in specifying the architecture and requirements for automatic switched optical networks (ASON), concentrating on defining the critical functions and the required components for the optical control plane. Since the 2000 time frame, the ITU-T has been engaged in developing a suite of Recommendations

encompassing control plane architecture, auto-discovery, signaling, routing, and control plane management requirements and specifications related to optical transport networks. The optical control plane enables rapid establishment of connection services across heterogeneous networks by supporting intelligence that enables transport networks to be dynamically managed for traffic engineering and bandwidth-on-demand applications, particularly in the areas of QoS, connection management, and traffic restoration after network failures. To achieve this goal, it was considered essential to first establish the general networking requirements related to the service control and management functions that are essential elements of the solution. These requirements included the fundamental concepts of separation of call and connection control; relationships among the management, control, and transport planes; and establishment of a flexible control-plane component architecture. One of the goals of this work is to assure that the optical control plane may be gracefully deployed into existing and new transport network infrastructures, and varied network management environments, in an evolutionary manner. This process would allow networks operators to harness the advances in optical transport networking technologies while ensuring that the existing deployed infrastructure is not rendered obsolete. The ultimate goal of the ASON suite of Recommendations is to enable automated cross-domain connection management supporting multivendor and multicarrier interoperability on a global scale. The methodology for the development of the ASON suite of Recommendations involves a foundation of protocol-neutral specifications that facilitate common requirements and behaviors for various technology and implementation options, hence lending themselves nicely to future growth. Chapter 16 also describes the relationships among the various standards and industry forums involved in the development of control plane specifications (IETF, ITU-T, OIF, ATM Forum), including utilization of associated protocol specifications (GMPLS, PNNI).

1.4. INTRA-NETWORK ELEMENT COMMUNICATION AND COMPONENT- CENTRIC STANDARDS

1.4.1 Intra-Network Element Communication

As we have seen in the earlier chapters, we review diverse sets of networking functions and multinetworking services that are presently being

offered or will be offered in the near future. In building the networks and offering such services, numerous different types of network elements are used. Functions within network elements are primarily implemented on optoelectronic modules and ASICs. Chapter 17 starts with architectural examples of packet- and TDM-based network elements that can be used in providing multiservices. Architectural blocks described in the network element architectures can be mapped to ASICs or standard VLSI offered by semiconductor firms or developed in-house by the system vendor. OIF developed a number of implementation agreements that allowed the ASICs or standard VLSI products from different firms to communicate and interoperate with each other. Agreements such as serializer/deserializer (SERDES) to Frammer interface or system packet interface operating at different rates are covered.

1.4.2 Optical Interfaces

Chapter 18 covers the diverse sets of topics on the optical interface standards developed by ITU-T. It starts by giving a history and rationale behind the evolution of optical interface standards relating to PDH, SONET/SDH, DWDM, OTN, CWDM, and all optical networks (AON). This chapter covers the general concepts and reference models, along with illustrative examples, so that the reader can subsequently get further details from the relevant standards documents. This approach was deemed necessary due to the large number of standards and the intricate details each respective standard provides. Chapter 18 gives an overview of optical fiber types and optical interface recommendations. It reviews the power budget design considerations and the limitations to overcome worst-case scenarios. Uses of certain coding schemes to achieve the required bit error rates are also covered. Subsequently, examples of discrete and integrated optoelectronic solutions related to operating speeds of 140 Mb/s – 10 Gb/s are highlighted. Finally, the chapter covers the illusive topic (from the standardization point of view) of faults and degradation detection in the optical transmitters, detectors, and amplifiers.

1.4.3 High-speed serial interconnects

In highly integrated network elements with ever-increasing port speeds and port card densities, the pressure is on to reduce printed circuit board (PCB) traces, layer count, and routing complexity. This situation has lead to the usage of serial interconnects using serializer/deserializer devices commonly know as SERDES. The high-speed interconnects operating at

Gb/s rates pose some interesting challenges. Chapter 19 discusses the high-speed serial interconnects that are used in the communication between devices within the same card along with card-to-card communication using the backplane architecture. It reviews the architectural considerations and signal-integrity design challenges. The discussion on topologies and the effects of material loss, layer connection, and the environment lead into the topic of de-emphasis and equalization—a powerful method in achieving highly reliable and robust chip-to-chip interconnects solution. The chapter subsequently gives an overview of the work of OIF, IEEE, and PCI Industrial Computer Manufacturers Group (PICMG) on interconnect standards. Finally, it considers some challenges and possible solutions for 6 Gb/s and 10 Gb/s applications that are anticipated in the near term.

1.5. STANDARDS DEVELOPMENT PROCESS

The standards development process within the networking field has a long progressive history where innovative technologies are shaped in providing value-added products and services. Over the course of many decades, numerous standards organizations and fora have been working diligently to provide innovative standards and recommendations that have shaped the ever-evolving networking field. To appreciate this work, one needs to understand the behind-the-scene dynamics of what makes these standards bodies and fora “tick.” Chapter 20 provides a snapshot of the practices and procedures that are used within ITU-T in developing global networking standards. In this chapter, practices in ITU-T and fora such as MEF and OIF are discussed. It is interesting to note that how the cultures in these organizations develop based on the policies and practices. For example, in the ITU-T, the approval of Recommendations requires unanimous agreements. This very fundamental premise developed a culture at ITU-T where civility and a spirit of cooperation prevail even against a background of fierce competition in the marketplace. However, within industry fora, the culture is quite different, since majority vote (of a certain percentage) governs who “wins.” This chapter highlights some interesting insights into the whole recommendations/standards development process that are useful in understanding the “systems.” It also highlights the “behind the scenes” hard work of personnel who make such venues possible so that we can appreciate their efforts in making such meetings and gatherings successful.

Chapter 18

ITU OPTICAL INTERFACE STANDARDS

Evolution and its Impact on Implementations

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18.1. INTRODUCTION

Over the past 20 years, optical transmission systems have evolved from fairly simple, single span, point-to-point configurations, operated at a single wavelength, to rather complex multiwavelength, multispans, point-to-multi-point architectures.

Within the context of this evolution, the International Telecommunication Union (ITU) has developed a wide range of optical interface recommendations, beginning with PDH applications and later addressing SDH/SONET, DWDM, and OTN applications. An historical perspective of the various ITU recommendations is provided in this chapter, addressing not only the maturation of the industry but also the intent to use standards to modify the application space from low-volume and high cost conditions to cost-efficient and high-volume conditions. Towards that end, a description of the migration from proprietary optical solutions with custom and discrete components towards standardized integrated solutions supported by Multi-Source-Agreements (MSAs) is discussed.

The intent of this chapter is to provide the reader with a basic understanding of ITU's objectives, terminology, and typical content found within the various optical interface recommendations. Moreover, the impact that the recommendations have on practical applications and designs is also

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addressed. In this chapter, detailed specifications are not discussed, as a complete treatment of optical parameters, mechanisms, and designs is beyond the scope of this text. References to various standards documents are cited as appropriate. Finally, some information is provided on the use and implementation of optical alarms and degradation monitors. Despite the fact that the latter topic is not directly related to optical interface implementations, it is a thoroughly studied item within ITU, and as such its treatment in this chapter will prove very useful to gain a better understanding of the challenges and sensitivities surrounding the optical standards process.

18.2. ITU OPTICAL INTERFACE STANDARDS

18.2.1 Historical perspective

18.2.1.1 PDH

Between 1980 and 1988, the ITU developed two recommendations for specifying Plesiochronous Digital Hierarchy (PDH) optical line systems. Recommendation G.955 [1] contained specifications for PDH line systems for the 1.544 kbit/s hierarchy (24-channel market, mainly deployed in the USA and Canada), and Recommendation G.956 addressed PDH line systems for the 2048 kbit/s hierarchy (32-channel market). In the 1990s, both recommendations were "collapsed" into a single recommendation, namely G.955, and G.956 was subsequently withdrawn.

These recommendations are no longer relevant for today's market; however, they laid the foundation for how optical interfaces are specified within the ITU, a process that has been followed in subsequent ITU recommendations. In this approach to specifying optical interfaces, only the characteristics of the fiber optic plant,¹ principally the attenuation and the dispersion, are specified. This approach to specifying optical interfaces, where the performance properties of the transmitter and receiver are not addressed, is called *longitudinal compatibility*. Longitudinal compatibility implies that on a certain link, with standardized characteristics, the equipment on both sides of the link must be from the same vendor. In this case, the transmitter and receiver performance properties and characteristics were proprietary. In the case of PDH applications, it was also not uncommon to use proprietary balanced coding techniques, e.g., 5B/6B, to provide stable link performance. In this way, 140 Mbit/s or 4*140 Mbit/s equipment,

employing 5B/6B coding, actually operated with a line rate of 168 and 672 Mbit/s, respectively.

In the 1980s, optical components were a significant contributor to the cost of an optical transmission system. As such, Recommendation G.955 focussed only on long-haul systems, where the cost of the optical devices could be balanced by maximizing the transmission distances. The principle of longitudinal compatibility is discussed further in Section 18.2.2.

18.2.1.2 SDH/SONET

In 1988, the revolutionary concept of developing optical links with interoperable equipment from different manufacturers was introduced to ITU by Bellcore (currently called Telcordia). For a truly interoperable link, more parameters beyond just the fiber plant had to be specified. This new set of specifications was titled *SDH/SONET* for the global/North American markets, respectively. Initially, this interworking concept was called *mid-span-meet*, implying that at a certain point on the fiber link between two pieces of optical equipment, the interoperability had to be guaranteed through a specified set of parameters and associated values. Because this point was not at a fixed location, but rather at an unknown "floating" location, it was not considered appropriate for a specification principle. A floating approach lends itself to specifying formulas instead of values and is, as such, cumbersome to implement. Instead the complete optical configuration was split into three parts: transmitter equipment, the actual outside plant, and receiver equipment. These three parts were separated by two fixed reference points, namely, Point S, located between the transmitter and the outside plant; and Point R, located between the outside plant and the receiver. At these reference points, a complete and detailed set of transmitter and receiver parameters and associated values were specified. This principle of specification was called *transverse compatibility*, where the intent was to achieve interoperability between different manufacturers' equipment so long as the specifications were met at Points S and R. Note that the previous term, *mid-span-meet*, is commonly used as an alternative expression to *transverse compatibility*, although that usage of the term is not strictly correct.

Within *transverse compatibility*, it is important to note that the optical path or outside fiber plant is *not* specified by distance but rather by parameters like attenuation range, maximum (and sometimes minimum) chromatic dispersion, Differential Group Delay (DGD), etc. Distance is not a specification and is only used for the purpose of classification. A specific transmission distance can never be guaranteed, since it fully depends on local conditions associated with the fiber link, e.g., number of splices, loss/splice, presence of patching panel connectors, etc. Transverse

compatibility has become the standardization method of choice for all modern ITU recommendations for optical interfaces. The details of transverse compatibility are further discussed in Section 18.2.2, where a reference diagram is shown.

The first relevant ITU recommendation for SDH optical interfaces was G.957 [2], in which optical parameter values for STM-1 (OC-3), STM-4 (OC-12), and STM-16 (OC-48) applications were specified for distances up to 80 km. Note, that the transmission distance of 80 km is a point of classification, not a guarantee of transmission reach. Recommendation G.957 has become a template for all subsequent ITU optical interface recommendations.

During the development of G.957, the extensive experience with PDH implementations for 140 Mbit/s and 4*140 Mbit/s was reused to define the STM-1 and STM-4 parameter values. Because of the maturity of the technology for these applications, the associated parameter values have hardly been modified since the first agreements in 1990. This is, however, not true for the STM-16 parameter values. The first set of values, agreed upon in 1990, was based on the limited availability of initial test results from prototype systems. Nevertheless, the availability of an early version of an STM-16 optical interface specification appeared to be a major market driver for next generation optical applications. The wide-scale deployment of STM-16 optical interfaces resulted in a strong enough knowledge base that ITU was able to readdress the initial STM-16 specification with an update based on a "mature" set of parameter values several years later.

Around 1990, a market need for a higher transmission capacity of 10 Gbit/s in SDH/SONET transmission systems was foreseen, and the ITU started to work on a new set of optical interface recommendations to accommodate that need. At the same time the new Erbium Doped Fiber Amplifier (EDFA) technology became available, enabling longer transmission distances and multiwavelength operation on a single fiber. Optical amplifiers were being used to increase transmitter output powers (booster configuration) and to improve receiver sensitivities (optical preamplifier configuration). They were also deployed as line amplifiers by positioning them at intermediate positions on very long fiber links (multispan configuration). In this way, the physical distance between transmitting and receiving equipment could be substantially increased to multiples of the original distances specified in G.957. Because optical amplifiers were also operating over a wide optical bandwidth, well over 30 nm, they were capable of simultaneously amplifying the power levels of multiple, narrowly spaced signals (also called *channels*) over a single transmission fiber. The latter application, also called *Dense Wavelength*

Division Multiplexing (DWDM), will be further discussed in Section 18.2.1.3.

Because of the availability of this new optical amplifier technology, ITU decided to specify the new SDH/SONET rate of STM-64/OC-192 (~10 Gbit/s) along with multiwavelength (multichannel) configurations operating at 2.5 Gbit/s/channel, each with its own characteristic wavelength, as an alternative to the single-wavelength (single-channel) application at the STM-64/OC-192 rate. The multichannel application is further discussed under Section 18.2.1.3.

In order to maintain the stability of Recommendation G.957, the ITU decided to put the new sets of parameter values for STM-4 and STM-16 applications with extended distances (longer than 80 km) via OA (Optical Amplifier) technology, and the new STM-64 (OC-192) applications, into a new recommendation called G.691. Initially, it was the intent to define transversely compatible parameter value sets for both single and multiple spans. Due to a variety of reasons, the ITU discontinued the attempt to include specifications for multiple spans. It appeared to be a too significant challenge to define an unambiguous set of optical parameter values for multispan configurations incorporating line optical amplifiers. Furthermore, the ITU was unable to agree on the specification for a standard Optical Supervisory Channel (OSC), necessary for maintenance of the inline optical amplifiers.

The relevant optical parameter values for SONET applications OC-3 to OC-192 can be found in Telcordia's GR-253-CORE [3], which in most cases are consistent with the ITU specifications. Originally, the OC-192 specifications were put into a separate Telcordia specification, GR-1377, but these were incorporated into GR-253-CORE at a later stage.

18.2.1.3 DWDM

As discussed in Section 18.2.1.2, the early 1990s presented a market need for SDH/SONET transmission systems that could operate at per-channel data rates greater than 2.5 Gbit/s. Because of initial concerns about the cost of 10 Gbit/s optics (including the necessity to use optical amplifiers) and possible limitations due to Polarization Mode Dispersion (PMD) on the installed fiber base, it was decided to prepare a second recommendation, namely G.692 [4], for multichannel SDH STM-4 and STM-16 applications. In general, these applications with closely spaced channels are referred to as *Dense Wavelength Division Multiplexing (DWDM)* applications.

Initially, it was the ITU's objective to define a transversely compatible specification for these multichannel DWDM applications, but ultimately it was unable to agree on a channel plan (unique set of wavelengths) for these

applications. Naturally, to guarantee interoperability, it is essential that different manufacturer's equipment transmit on exactly the same set of wavelengths and follow the same sequence for "lighting up" new wavelengths. However, some network operators felt that the channel plan would restrict their ability to optimize the usage of their installed outside plant. Additionally, the market pressure on equipment vendors to increase performance by adding channels to the fiber (requiring that the channel-to-channel spacing becomes narrower) and increasing transmission distances necessitated that optical technology advance at a rampant pace. This pace gave the impression that there was little stability in the solution and that any attempt to standardize this solution within G.692 would be promptly outdated. The market conditions mandated that equipment vendors constantly design their equipment at the edge of available technology. Furthermore, because of the usage of optical amplifiers, the fibers operated in a nonlinear regime, making the matter even more complex from a standardization perspective. Therefore, the published version of G.692 contains the statement that it was aimed towards a future realization of transverse compatible multichannel systems. It contains listings of parameters that would be required in the case that a transversely compatible specification was ever developed for a multichannel system. Specific values were not included in this specification. The resulting Recommendation G.692 is actually a longitudinally compatible specification. One of the main achievements of Recommendation G.692 was agreement on a frequency grid for DWDM applications, a grid that is followed even today.

Because G.692 was an SDH-related recommendation, the ITU ultimately decided to put the grid definition and specification in a separate Recommendation G.694.1 [5] for generic DWDM applications. In G.694.1, the actual channel frequencies are not specified. Instead, G.694.1 provides a ruler or formula, anchored to 193.1 THz, with which to calculate the channel frequencies for a variety of channel spacings, ranging from 12.5 GHz to 100 GHz.

Within the context of grid definitions, it is important to note that the ITU decided to maintain a wavelength-based signal spectral specification for *widely* spaced signals and a frequency specification for *narrowly* spaced signals. At first pass, this appears to be a confusing way to specify wavelengths. The reason for this choice is the fact that a frequency specification is exact and unambiguous, whereas a wavelength specification depends on the medium in which the wavelength is measured (air, vacuum and glass all have different values for the speed of light, which is used to calculate wavelength from frequency²). As an indication for the demarcation point between the two specification methods, it can be noted that in G.692, the frequency-based specification is used up to a channel spacing of 1000

GHz (equivalent to approximately 8 nm), above which a wavelength-based specification is used.

Very recently the ITU established two new recommendations for DWDM applications intended for use within the Optical Transport Network, described in Section 18.2.1.4.

In Recommendation G.696.1 [26] physical layer specifications are given for point-to-point multispan DWDM applications within a single administrative domain with bitrates up to 40 Gbit/s. Because of the technical complexity of these systems, the specifications given in G.696.1 are longitudinally compatible, thus with equipment from a single vendor. As in the case of Recommendation G.692, this means that specifications are provided only for the outside plant. G.696.1 further contains some extensive information on theoretical limits and design considerations for DWDM systems.

In Recommendation G.698.1 [27] optical interface specifications are given for transversely compatible point-to-point DWDM systems in a metro environment. By using the black-link specification method, as described for CWDM applications in Section 18.2.1.5, interworking is enabled at the single-channel points, i.e. at the inputs of the multiplexer and at the outputs of the demultiplexer. The realization of this transversely compatible DWDM recommendation has been a ground-breaking achievement, enabling operators to mix and match equipment from different vendors at the single-channel level. G.698.1 contains specifications for applications with a channel spacing of 100 GHz, bitrates up to 10 Gbit/s, covering transmission distances in the range of 30 to 80 km. For further details, see Recommendation G.698.1. In a similar way as for CWDM applications, G.698.1 is relevant to the new hot-pluggable SFP and XFP packaging technologies described in Sections 18.3.2.2 and 18.3.3.2.

Future versions of G.698.1 are intended to address the inclusion of optical amplifiers in order to achieve transmission distances longer than 80 km, further widening the application space for network operators to deploy multi-vendor DWDM systems.

18.2.1.4 OTN

In 1996, the potential use of DWDM technologies was recognized as having the opportunity to extend beyond relatively straightforward point-to-point applications. ITU embarked on a new generation of recommendations intended to support the Optical Transport Network (OTN), which would include formats beyond SDH/SONET. As an example, the new OTN would address Forward Error Correcting (FEC) codes (which were once proprietary to the equipment vendor) and enhanced optical network architectures, which

included new optical network elements like Optical Add Drop Multiplexers (OADMs) and Optical Cross Connects (OXC's).

Details on OTN architecture and the associated rates and formats specifications are contained in a variety of ITU recommendations, including G.872 [6] and G.709 [7].

The ITU decided to make a distinction in optical interfaces for Intra-Domain Interfaces (IaDI) and Inter-Domain Interfaces (IrDI). As is clarified in Recommendation G.872, the IaDI refers to a physical interface that lies within an administrative domain and the IrDI to a physical interface representing the boundary between two administrative domains. In general an IrDI will be bound by 3R regeneration at both sides of the interface. 3R regeneration requires that the signal is re-amplified, reshaped and retimed. Currently, transversely compatible optical interface specifications are only required for the IrDI. The IrDI configurations are relatively simple in that they are limited to a single span and are either single-channel (single-wavelength) or 16-channel configurations. The required technology for these IrDI applications was considered sufficiently mature to create a basis for agreement on complete sets of transversely compatible parameter values. Because the IaDI involved more complex optical architectures, like very long distance multi-span configurations with high numbers of closely spaced channels, possibly including OADM configurations, it was decided to specify the IaDI optical interfaces in a longitudinally compatible form. This kind of specification provides the highest level of freedom and flexibility for designing systems for the IaDI. To illustrate, it is quite common to use proprietary Forward Error Correction (FEC) techniques within the IaDI to further optimize the optical performance. Refer to Section 18.2.2 for a more detailed description on transverse versus longitudinal compatibility.

The ITU established two new optical interface recommendations, namely, G.959.1 [8] and G.693 [9], originally intended to address the new OTN applications having rates as specified in Recommendation G.709. Before being completed, these two recommendations were transformed into a more generic form, permitting usage across a variety of applications, including the originally intended OTN applications in G.709, along with SDH/SONET and even Gigabit Ethernet. The introduction of optical tributary signal classes, which addressed a range of data rates rather than a specific data rate, made this possible. As a consequence of this choice for generic specifications over a range of data rates, the previous optical interface Recommendation G.691 [10], which previously addressed only SDH/SONET applications, was updated with appropriate references to either G.693 or G.959.1.

Recommendation G.959.1 was intended to be a general specification for single-span, unidirectional, point-to-point optical links, which addressed

single and multichannel line systems. This recommendation was generated in conformation with the approach in the earlier G.957 and G.691 recommendations, but was generalized to apply over ranges of data rates rather than specific data rates. G.693, however, introduced new optical links beyond what was previously addressed in Recommendation G.691. Recommendation G.693 targeted Very Short Reach (VSR) applications, with link distances up to 2 km and potentially higher-than-“normal” losses, at nominal 10 Gbit/s and 40 Gbit/s aggregate bit rates. G.693 specifically included the possibility of inserting optical cross-connects in the optical link (which at the time had very high insertion losses). As a result, a wide range of link-loss categories is included, ranging from 4 dB to 16 dB. Even higher link losses are foreseen as next-generation network elements are added to the optical link.

18.2.1.5 CWDM

Because of a market need for relatively low-cost point-to-point multichannel systems, the ITU decided to work on a new set of recommendations supporting Coarse WDM (CWDM) applications with channel spacing of 20 nm. Note that a wavelength specification is used instead of a frequency specification. The requirements for coarsely spaced channels permitted the use of low-cost uncooled lasers and low-cost WDM filter technologies.

In Recommendation G.694.2 [1], the 20 nm grid has been specified with 1551 nm as one of the grid wavelengths. Recommendation G.695 [12] provides optical interface parameter values for CWDM applications with up to 16 channels and up to 2.5 Gbit/s.

Recommendation G.695 contains two general specification methods: the *black-box* method and the *black-link* method.

In the case of the black-box method, sets of parameter values for the aggregate multichannel reference points (after the optical multiplexer and prior to the optical demultiplexer) are given, implying that the parameters for the individual channels, which lie within the black box, are not specified.

Alternatively, in the black-link approach, optical interface parameter values are only specified at the individual tributary single-channel interfaces. In this approach, interworking is enabled only at the single-channel points and not at the aggregate multichannel points. In this case, the combination of optical multiplexer and demultiplexer is treated as a single set of devices. This means that in the specified per-channel losses, the partitioning between on one hand the actual fiber losses and on the other hand the losses of the optical multiplexer and demultiplexer is not specified. The same is valid for other per-channel link parameters like chromatic dispersion and polarization

mode dispersion. In particular, this black-link approach is relevant to the new hot-pluggable SFP packaging technologies described in Section 18.3.2.2. For further details, see Recommendation G.695.

In the most recent version of G.695 OADM network elements have been included in the treated CWDM architectures.

18.2.1.6 All Optical Networks (AON)

Recently the ITU began studying the physical characteristics of Optical Network Elements (ONE) and optical interfaces for All Optical Networks (AON). One of the major challenges the ITU faces is whether it is possible to generate transversely compatible interface specifications for these networks or whether a new method of specification is required. One of the key considerations is to *not* drive the optical performance specifications to their physical or state-of-the-art limits, and as such be able to specify mutually compatible network elements and to more easily build and configure interoperable AONs. A similar challenge was addressed when ITU evolved from specifying proprietary PDH equipment to specifying interoperable SDH/SONET equipment.

18.2.2 Transverse versus longitudinal compatibility

18.2.2.1 Introduction

In the previous section, a brief explanation for the differences between longitudinally and transversely compatible specifications was given. In this section, a more detailed explanation is given. An excellent overview of the two principles is provided in ITU G.Sup39 [13], "Optical System Design and Engineering Considerations", which is a very important reference document for many of the design considerations used in defining the various ITU optical interface recommendations.

18.2.2.2 Physical layer longitudinal compatibility

The first definition for longitudinally compatible optical interfaces was developed for PDH applications and can be found in Recommendation G.955. In this case, only the optical path (optical fiber or outside plant) characteristics are specified. Other optical interface parameters, like transmitter output power, source spectral characteristics, receiver sensitivity and overload, are not specified. Furthermore, the actual line rate and data transmission format are also not specified. This principle simply implies that

operators can use "standardized" outside-plant characteristics for tendering purposes, permitting almost total implementation freedom to equipment manufacturers. For obvious reasons, the transmitting and receiving equipment must be from the same manufacturer.

Initially, only the outside-plant maximum attenuation and chromatic dispersion were specified. Later, when bit rates of 2.5 Gbit/s and higher were introduced, the maximum Differential Group Delay (DGD) and optical line reflection characteristics were added.

It should be noted that the maximum path characteristics are based upon End of Life (EOL) specifications, indicating that they should include appropriate margins for temperature and aging variations and for repair splicing.

For further details on longitudinal compatibility, see G.sup39.

18.2.2.3 Physical layer transverse compatibility

To achieve complete interworking between equipment from different manufacturers on a single optical section, additional requirements beyond just the optical physical layer must be specified. In other words, the pieces of equipment at both sides of the optical link should be able to "talk to" and "understand" each other.

Essential to a transversely compatible specification is the definition of appropriate reference points in the fiber path at which optical parameters can be both specified and measured. Two reference points were chosen to reflect where the transmit signal enters the outside plant (S-type reference point) and where the signal leaves the outside plant and is received by an optical receiver (R-type reference point). At these reference points, a full set of optical parameters and associated (verifiable) values is necessary to enable interoperability at the optical level. The first definition of this partitioning and associated parameter definition and specification is found in Recommendation G.957. Examples of parameters at Point S are transmitter output power (min and max) and the spectral characteristics of the transmitter, and at Point R the minimum receiver sensitivity, receiver overload, and maximum optical path penalty. The optical path penalty describes the apparent reduction of receiver sensitivity due to distortion of the signal waveform (generated by the transmitter) during its transmission over the optical path. A complete overview of the relevant parameters can be found in the various ITU optical interface recommendations. Some further details on optical power budget design considerations and limitations are given in Section 18.2.6.

G.Sup39 gives a complete overview of levels of transverse compatibility, with the single-span configuration being the most straightforward.

See Figure 18-1 for a generic single-span transversely compatible configuration.

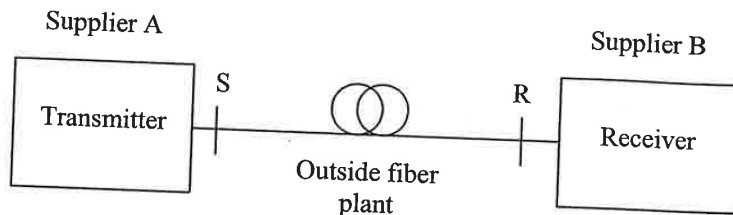


Figure 18-1. Generic single-span transversely compatible configuration

When adding line optical amplifiers into the middle of an optical link configuration, a transversely compatible specification reaches an increased level of complexity, because some parameters apply to a single section (e.g., attenuation), whereas others apply to the complete end-to-end section (e.g., chromatic dispersion and differential group delay). In such a multispan configuration, additional reference points are required to differentiate between end-to-end and per-section parameter specifications. One example configuration is shown in Figure 18-2, where a single-line Optical Amplifier (OA) has been inserted. In this case, slightly different reference points are used—MPI-S and MPI-R—to indicate Main Path Interfaces, relevant for end-to-end performance. Also OA reference points R' and S' are used to indicate the parameters at the input and output of the Optical Amplifier. In general, different reference point nomenclatures are used across the various optical interface Recommendations.

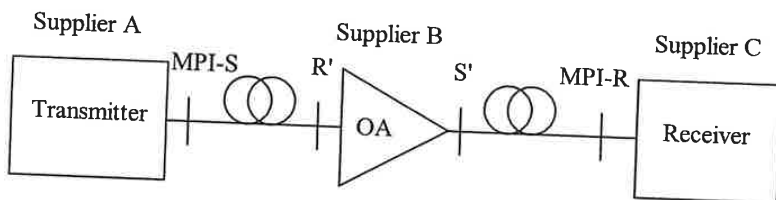


Figure 18-2. Example of multispan configuration

It should be obvious that when adding Optical Network Elements (ONEs) like optical add-drop multiplexers or optical cross-connects, the complexity

of defining transversely compatible specification reaches an even higher level.

18.2.3 Overview of optical fiber types and associated recommendations

In parallel with the development of a range of optical interface recommendations, the ITU has also developed a variety of recommendations for optical fiber cables. The evolution of the various fiber types had a significant impact on the development of optical interface recommendations, described later in Section 18.2.4.

In the early 1980s, most optical fiber systems were deployed on multimode fiber. Many fiber types were developed, all with different characteristics and dimensions. In Europe the so-called 50/125 μm graded-index type (with a 50 μm fiber core diameter and a 125 μm cladding diameter) was mostly used, whereas in the USA 62.5/125 μm fibers were mostly deployed. ITU has only specified the properties of 50/125 μm graded-index multimode fiber types, found in Recommendation G.651 [14]. In general, multimode fibers are used in the 850 nm and 1310 nm wavelength windows.

Because of a variety of technical issues with multimode fibers, e.g., limitations on transmission distance in relation to system speed, single-mode fibers became available and were generally deployed. Single-mode fiber was and is still used today for laser-based telecom applications. In the late 1990s, there was an interest in transmitting 10 Gbit/s Ethernet-based data rates over multimode fibers. A significant amount of work was done to improve the properties of the multimode fiber, resulting in the ability to transmit multimoded lasers over a distance of 300 m at 10 Gbit/s. Because applications using multimode fibers are not specified in a majority of the ITU optical interface recommendations, they are not further discussed in this chapter.

The first single-mode fiber type is commonly referred to as Standard Single-Mode Fiber (SMF or SSMF). The ITU has developed Recommendation G.652 [15] in order to specify the properties of cables that utilize this fiber type. Initially, this fiber was only used in the 1310 nm wavelength window, where the chromatic dispersion is near-zero, theoretically providing unlimited transmission bandwidth. Around 1990, the SSMF fiber was additionally used in the 1550 nm window, due to the combination of a market drive for longer distances (at 1550 nm, the fiber loss is about half the value in the 1310 nm window) and the availability of 1550 nm laser sources. Because of the subsequent need to transmit at higher data rates (10 Gbit/s) and the need to utilize more of the wavelength range

between 1360 nm and 1530 nm, additional specification details were necessary for Recommendation G.652. For this purpose, three subcategories have been defined within G.652:

- Subcategory A, for the base G.652;
- Subcategory B, having additional requirements on Polarization Mode Dispersion (PMD) for 10 Gbit/s applications; and
- Subcategory C, having additional requirements for operation in the wavelength range between 1360 nm and 1530 nm, relevant to wideband CWDM applications.

PMD occurs when the cross-section of the fiber core is not perfectly circular and tends to be more elliptical in shape. This results in the fiber effectively transmitting in a dual-mode instead of a single-mode condition. Because both modes have different group delays, additional pulse broadening beyond the traditional broadening, caused by chromatic dispersion, will occur. PMD is typically significant for transmission speeds of 10 Gbit/s or higher. In certain cases, however, it is known to affect the performance of 2.5 Gbit/s systems. Further information on PMD can be found in G.Sup39 or Recommendation G.650 [16].

Despite the huge advantage of a low fiber loss in the 1550 nm region, G.652 fiber exhibits a fairly high chromatic dispersion of around 17 ps/nm*km at 1550 nm, severely limiting the transmission distance of systems operating at 2.5 Gbit/s or higher. Therefore a new fiber, called Dispersion Shifted Fiber (DSF) was developed, which is specified by ITU Recommendation G.653 [17]. This fiber was specifically designed to give low losses around 1550 nm and to provide near-zero chromatic dispersion in the 1550 nm wavelength window.

At the same time, the ITU developed Recommendation G.654 [18] to address fiber types for submarine applications operating in the 1550 nm window. Because this fiber type is not used in terrestrial applications, further details are not provided here. An overview of ITU's single-mode fiber recommendations is provided in Table 18-1.

When DWDM systems with closely spaced optical signals were being introduced, it appeared that the near-zero chromatic dispersion in G.653 fibers was the cause for the occurrence of the nonlinear Four-Wave-Mixing (FWM) effect. FWM, also called *four-photon mixing*, occurs when additional optical signals are generated by the interaction of two or three adjacent channel optical signals operating at closely spaced wavelengths at equivalent speeds. These additional signals, which transmit at wavelengths other than their parent wavelengths, are called *mixing products*.

Table 18-1. Overview of ITU single-mode fiber recommendations

ITU Recommendation	Recommendation title
G.652	Characteristics of a (standard) single-mode optical fibre cable
G.653	Characteristics of a dispersion-shifted single-mode optical fibre cable
G.654	Characteristics of a cut-off shifted single-mode optical fibre and cable
G.655	Characteristics of a nonzero dispersion-shifted single-mode optical fibre cable
G.656	Characteristics of a fibre and cable with nonzero dispersion for wideband optical transport

Because of FWM, a new fiber generation was developed that had nonzero dispersion and would generally prevent FWM from occurring in the optical line. These new fibers are specified in Recommendation G.655 [19]. A complete variety of these fibers has since become available, all with very different characteristics for actual zero-dispersion wavelength and chromatic dispersion slope. No further details are given here, because that would entail a detailed theoretical treatment of DWDM systems and is beyond the scope of this chapter. More details on nonlinear effects can be found in Recommendation G.663 [20].

The first DWDM systems were operated with wavelengths around 1550 nm, coinciding with the transmission bandwidth of the first generation of optical fiber amplifiers. Subsequent deployments of DWDM equipment utilized wavelengths above and below the 1550 nm region. To simplify discussion of these wavelengths, the ITU defined a range of wavelength bands in G.Sup39, reproduced in Table 18-2.

Most recently, the usage of DWDM and CWDM systems have extended a large range of bands, including S-, C-, and L-bands. ITU has created a new fiber Recommendation G.656 [21], which addresses the optimal performance of the fiber in wide-band applications.

Full details of key parameters and associated values can be found in the relevant ITU Fiber recommendations.

Table 18-2. Overview of wavelength bands

Band	Description	Range (nm)
O-band	Original	1260 to 1360
E-band	Extended	1360 to 1460
S-band	Short wavelength	1460 to 1530
C-band	Conventional	1530 to 1565
L-band	Long wavelength	1565 to 1625
U-band	Ultralong wavelength	1625 to 1675

18.2.4 Overview of optical interface recommendations

It has been clarified in the previous sections that over time the ITU has developed a whole range of recommendations related to optical interface specifications. In retrospect, it might not seem logical how the ITU recommendations are organized and where to look for a certain specification. In this chapter, an attempt is made to guide the user/designer of optical interface technologies.

Table 18-3 provides an overview of ITU's various optical interface recommendations existing to date.

As stated previously, the ITU decided to use its latest Recommendations G.693 and G.959.1, to serve as generic documents for most optical interface specifications. The basis for this generic specification was the definition of signal classes in Recommendation G.959.1, covering a range of data rates for which sets of optical parameter values are specified. Presently, the following signal classes are addressed: NRZ 1.25G, NRZ 2.5G, NRZ 10G, NRZ 40G, and RZ 40G (see the Table 18-4 for details).

The parameter values for the older STM-1 and STM-4 interfaces remain within G.957 along with most of the STM-16 interfaces. For the NRZ 10G data rate class, ITU put almost all the sets of parameter values into either G.693 or G.959.1, except some of the applications that use optical amplifiers for 80 km or 120 km distances, which remain in G.691.

One of the blocking issues that prevented the generic recommendations (G.959.1 and G.693) from covering the STM-1, STM-4, and STM-16 data rates was the fact that the reference BER applicable to G.957 differed from that of G.959.1 or G.693. At the time that G.957 was originally drafted, the parameter values were specified relative to an optical section design objective of a Bit Error Ratio (BER) not worse than 1×10^{-10} , whereas for all of the more recent Recommendations (G.691, G.692, G.693, and G.959.1), the BER design objective is 1×10^{-12} . The more stringent BER objective was derived from error performance requirements specified in Recommendation G.826 [22]. At the time of drafting and agreement of the first version of G.957, G.826 was not in existence yet, and as such, a BER design objective of 10^{-10} was considered appropriate. Because of the wide deployment of SDH interfaces based upon this early version of G.957, the ITU decided to maintain the parameter value sets within G.957. Had ITU decided to adopt the more stringent BER requirement for STM-1 to STM-16 interfaces, substantial changes to some of the parameter values like maximum optical path attenuation and/or minimum receiver sensitivity would have been necessary. This could have resulted in inoperability issues between new and installed systems. Further discussion is provided in Section 18.2.6.

Table 18-3. Overview of relevant ITU optical interface recommendations

Recommendation	Application area	Description
G.691	SDH (SONET)	Transversely compatible specification for single-channel SDH STM-64 in general and STM-4 and STM-16 interfaces with optical amplifiers for distances longer than 80 km; design objective BER $\leq 10^{-12}$
G.692	SDH-DWDM	"Limited" transverse compatible specification for multichannel SDH systems; actual parameter values "for further study"; design objective BER $\leq 10^{-12}$
G.693	Generic VSR	Transversely compatible specification for single-channel signal classes NRZ 10G and NRZ 40G for link distances up to 2 km with potentially high losses up to 16 dB; design objective BER $\leq 10^{-12}$
G.694.1	Grid for DWDM	DWDM grid specification with spacing ranging from 12.5 GHz to 100 GHz
G.694.2	Grid for CWDM	CWDM grid specification with 20 nm grid spacing
G.695	CWDM	Transversely compatible specification for up to 16 channels, up to 2.5 Gbit/s per channel; design objective BER $\leq 10^{-12}$
G.696.1	OTN-DWDM	Longitudinally compatible specification for multispan, multichannel OTN systems; design objective BER $\leq 10^{-12}$
G.698.1	OTN-DWDM	Transversely compatible specification for 100 GHz spaced channels, up to 10 Gbit/s per channel; design objective BER $\leq 10^{-12}$
G.955	PDH	Longitudinal compatible specification single-channel, single-span up to 4*140 Mbit/s; design objective BER $\leq 10^{-10}$
G.957	SDH (SONET)	Transversely compatible specification for STM-1, STM-4, and STM-16 interfaces for link distances up to 80 km; design objective BER $\leq 10^{-10}$
G.959.1	Generic IrDI	Transversely compatible specifications for single-channel signal classes, NRZ 1.25G, NRZ 2.5G, NRZ 10G, NRZ 40G, and RZ 40G, and 16-channel signal classes NRZ 2.5G and NRZ 10G; design objective BER $\leq 10^{-12}$

Table 18-4. Overview of signal classes

Signal class	Range of nominal bitrate [Gbit/s]
NRZ 1.25G	0.622 – 1.25
NRZ 2.5 G	0.622 – 2.67
NRZ 10G	2.4 – 10.71
NRZ 40G	9.9 – 43.02
RZ 40G	9.9 – 43.02

Table 18-5. Overview of optical interfaces and the related optical interface recommendations

Bit rate	Distance	BER Objective	Relevant Recommendation
STM-1 (OC-3)	≤ 80 km	10^{-10}	G.957
STM-4 (OC-12)	≤ 80 km	10^{-10}	G.957
STM-4 (OC-12) + optical amplifiers	≤ 60 km @ 1310 nm ≤ 160 km @ 1550 nm	10^{-12}	G.691
STM-16 (OC-48)	≤ 80 km	10^{-10}	G.957
STM-16 (OC-48) + optical amplifiers	≤ 160 km	10^{-12}	G.691
Signal Class NRZ 2.5G	≤ 80 km	10^{-12}	G.959.1
STM-64 (OC-192) + optical amplifiers	40 – 120 km	10^{-12}	G.691
Signal Class NRZ 10G (incl. STM-64 / OC-192)	≤ 2 km	10^{-12}	G.693
Signal Class NRZ 10G (incl. STM-64 / OC-192)	2 – 80 km	10^{-12}	G.959.1
Signal Class NRZ 40G (incl. STM-256 / OC-768)	≤ 2 km	10^{-12}	G.693
Signal Class NRZ 40G (incl. STM-256 / OC-768)	2 – 80 km	10^{-12}	G.959.1
Signal Class RZ 40G (incl. STM-256 / OC-768)	40 – 80 km	10^{-12}	G.959.1
NRZ OTU3 with FEC	40 – 80 km	10^{-12}	G.959.1

In Table 18-5, an overview provides a map between various optical interface types and their associated ITU recommendations.

As a consequence of the standards evolving with the available technology and market needs, it is possible to find multiple standards covering the same nominal data rate (e.g., 2.5 Gbit/s). For this example, one can find STM-16 parameter value sets in G.957 or G.691 and NRZ 2.5G parameter value sets in G.959.1. A detailed comparison between G.957, G.691, and G.959.1 demonstrates that some parameters have different values. These differences are actually a consequence of having different target BERs, but nevertheless they are intended to be mutually consistent. As an example, the STM-16 40 km long-haul specification in G.957 contains a worst-case receiver sensitivity of -27 dBm at a reference BER of 10^{-10} , whereas the equivalent application in G.959.1 shows a worst-case receiver sensitivity of -25 dBm at a reference BER of 10^{-12} .

Finally, it should be noted that the maximum data rate for the NRZ signal classes in Recommendations G.959.1 and G.693 is slightly higher than the equivalent SDH-rate in Recommendations G.957 and G.691. Because in both cases the same optical path penalty applies for equivalent application

codes, the requirements for receivers and transmitters parameters are potentially more stringent in the case of the higher data rate.

18.2.5 Application code terminology related to distance

Historically, ITU and Telcordia (Bellcore) have used different naming conventions to indicate the various application codes and associated transmission distances. Also, within the ITU, some confusion might arise from the naming conventions, which exist primarily for historical reasons. In this section, an attempt is made to clarify the naming conventions and correlate them with Telcordia.

At the time the first version of G.957 was drafted, 1310 nm technology was used as a preferred technology for all distances up to 40 km and bit rates up to 2.5 Gbit/s. While 1550 nm parameter values are also included in G.957 for distances up to 40 km, 1550 nm technology was typically used in practice for longer distances up to 80 km. Therefore the name *long-haul* or *long-reach* was used to indicate possible transmission distances of 40 km when operated in the 1310 nm window and of 80 km when operated in the 1550 nm window. Later, when 10 Gbit/s technology was introduced, 1550 nm technology became the preferred technology for 40 km distances due to the lower attenuation of the outside plant in the 1550 nm window. This 40 km application, operated in the 1550 nm window, is referred to as a *short-haul* or *intermediate-reach* application in order to distinguish it from the 80 km 1550 nm long-haul applications. As a consequence, a 40 km distance is referred to as *long-haul/long-reach*, when operated at 1310 nm, and as *short-haul/intermediate-reach* when operated at 1550 nm.

In Table 18-6, an overview is given of the various target distances, including a correlation between ITU and Telcordia (Bellcore) nomenclature. In some cases, different target distances apply. As already mentioned in Section 18.2.1.2, these target distances are only used for classification and *not* for guaranteed specifications.

In Recommendation G.693, a totally different nomenclature has been introduced and is defined by the following attenuation categories: R(estricted), L(ow), M(edium), H(igh), and V(ery high). In G.693, three target distances are defined: 0.6 km, 1 km and 2 km. The reader can refer to Recommendation G.693 for further details.

It should be noted that G.695 and G.959.1 also contain some application codes for transversely compatible multichannel/multiwavelength interfaces, which are not described here.

Table 18-6. Overview of application code naming conventions in relation to target distances

ITU naming	Equivalent Telcordia naming	Target distance
I-codes: Intra-office	SR-codes: Short-reach	2 km in G.957 2 km @ 1310 nm in G.691, G.959.1 25 km @ 1550 nm in G.691, G.959.1
I-r-codes: Intra-office-r (reduced target distance)		0.6 km @ 1310 nm in G.691, G.959.1 2 km @ 1550 nm in G.691, G.959.1
VSR codes		0.6, 1 and 2 km in G.693
S-codes: Short-haul	IR-codes: Intermediate-reach	15 km in G.957 and for NRZ 2.5G in G.959.1 20 km @ 1310 nm in G.691, G.959.1 40 km @ 1550 nm in G.691, G.959.1
L-codes: Long-haul	LR-codes: Long-reach	40 km @ 1310 nm 80 km @ 1550 nm
V-codes Very-long-haul	VR-codes Very-long-reach	60 km @ 1310 nm 120 km @ 1550 nm
U-codes Ultra-long-haul		160 km @ 1550 nm

18.2.6 Power budget design considerations and limitations

18.2.6.1 Worst-case design approach

The optical parameter values contained in the various optical interface recommendations have been chosen according to a worst-case design approach. Details of this principle are provided in Recommendation G.sup39.

This worst-case design approach means that in an optical link, where all of the specified optical parameters simultaneously are at their worst-case End-Of-Life (EOL) value, the system BER shall not be worse than the value specified for the application, e.g., 10^{-12} . Within this context, End Of Life refers to a condition where the characteristics of a piece of equipment (e.g., the optical transmitter or receiver) or the outside plant have degraded such, that they are outside the intended specifications and consequently imply a failed condition.

Thus, when the transmitter optical output power level is at its End Of Life (EOL) minimum value, the receiver sensitivity is at its EOL maximum value,³ the outside plant loss is at its EOL maximum value, and the source spectral characteristics are such that the optical path penalty is at its maximum value, the resulting system BER should not be worse than the

value specified for the application, e.g., 10^{-12} . This conclusion does not imply that it is generally accepted that an optical link operates at this reference BER. Instead, it is commonly expected by system users that an optical link operates virtually error free under nominal operations conditions, leveraging the fact that the probability that all optical parameters are simultaneously at their worst-case limits is very low.

For the manufacturers of optical interface technologies (transmitters and receivers) this method of specification implies that their designs should have sufficient margins between Beginning-Of-Life (BOL) and EOL parameter values. Within this context, BOL refers to the performance of the equipment at the initial condition at the time of installation. The actual choice of defining appropriate margins (for temperature and aging effects and design variations) is fully dependent on the actual implementation and has therefore always been considered outside the scope of the various optical interface recommendations. In many cases, component manufacturers have used these ITU specifications directly as reference specifications for their solutions, whereas they are specifically intended to be systems specifications. This approach is acceptable as long as the ITU EOL specifications are not used as component BOL specifications. As an example, a receiver device with a BOL receiver sensitivity of -14.1 dBm is very likely to fail in a system application that has an EOL receiver sensitivity requirement of -14 dBm. It has, however, become more and more common practice that manufacturers of optical interface devices, like transmitters, receivers, and transceivers, use a one-to-one copy of the optical interface parameter values from the various ITU recommendations for their device interface specifications. In many cases margins to the EOL values are not indicated, making it very challenging for the user to judge whether appropriate design margins have been used.

18.2.6.2 Optical path penalty modeling and verification

When the first version of G.957 was drafted, it was the intent to define a unique set of optical spectral characteristics for each transmitter type, which would be unambiguously related to a specified value of optical path penalty through a mathematical model. In this way, a system BER test could be avoided since such a test would require a reference receiver. At the time of this writing, ITU has only succeeded in defining a sufficiently reliable model for predicting the optical path penalty for Multi-Longitudinal-Mode (MLM) or Fabry Perot laser devices. The details of this relationship, called the *epsilon model*, can be found in G.957 as well as in G.Sup39. G.Sup39 states that the epsilon model can, in principle, be extended to other types of laser sources, e.g., Single-Longitudinal-Mode (SLM) or Distributed Feedback

(DFB) lasers. However, for these laser types, chirp¹ plays a dominant role in determining the path penalty, and as such, the epsilon model most likely is not reliable enough to predict optical system performance. Furthermore, G.957 states that a reliable method for estimating the dispersion penalties arising from laser chirp and finite side-mode suppression ratio for SLM lasers has not been agreed upon, indicating that only the use of a true BER test can provide sufficient verification of proper transmitter functioning with respect to path dispersion performance. Since the time that G.957 was written, this issue has yet to be resolved, and therefore in most optical interface specifications a complete set of transmitter spectral characteristics is missing, denoted by *ffs* to indicate "for future study". As an example, ITU once considered defining a very narrow SLM laser linewidth for the 1550 nm 80 km 2.5 Gbit/s application in Recommendation G.957, with the intent to reliably predict a limitation of the dispersion penalty to 2 dB. After an extensive investigation, it was demonstrated that a number of laser sources, which failed a BER test, could pass the linewidth test, while other sources that failed the linewidth test would pass the BER test. Clearly, in practice, a situation where "good" devices are rejected and "bad" devices are accepted is unacceptable and should be avoided, as it would have a huge impact on the manufacturing yield and device cost.

18.3. OPTICAL INTERFACE IMPLEMENTATIONS

18.3.1 General

Over the past 20 years, the technology and approach for designing and manufacturing optical interfaces has migrated from proprietary and/or company-specific designs with discrete components towards fully integrated transceiver devices that follow Multi-Source-Agreements (MSAs) for standardized packages, conforming to ITU and Telcordia specifications for standardized optical parameters. For the initial discrete designs, standards were not yet available to serve as a reference for specifying optical performance. The current SDH/SONET/OTN applications offer a full range of optical interface specifications enabling interoperability between devices and systems from different manufacturers. The early optics designs, manufactured in low volumes, were relatively high in cost. Today's optics, in particular for the lower rates between 155 Mbit/s and 2.5 Gbit/s, which at present are identified as commodity products, are typically manufactured at

high volumes, have the very competitive prices that are typical with commodity products, and are available from a large range of vendors. The interoperability provided by the optical interface standards paved the way for optical devices to evolve from proprietary devices to commodity products.

In this section, an overview is given of the various designs used for transmitting data for various SDH/SONET/OTN applications, along with their associated migration paths.

18.3.2 140 Mbit/s – 2.5 Gbit/s technology

18.3.2.1 Discrete solutions

18.3.2.1.1 140 Mbit/s – 622 Mbit/s

Approximately 20 years ago, optical transmitters and receivers were designed and built using “discrete” devices. These initial laser devices and pin-FET receiver modules were typically packaged in their own housing. The complete optical transmitter or receiver function, requiring more than just the laser or receiver, was realized by using a Printed Circuit Board (PCB), upon which the laser driver, receiver amplifier, and decision circuitry were placed using non-integrated parts.

The laser package typically contained a laser chip, an integrated backface monitor photodiode to control the laser output power, in some cases (depending on the package style) a Thermo-Electric Cooler (TEC) and a fiber pigtail with a coupling lens. Initially, two package styles were available: bulky coaxial packages and the 14-pin Dual-In-Line (DIL) style. The coaxial packages were uncooled and there were many (non-standardized) versions, each requiring a vendor-specific bracket and electrical interface, and therefore vendor-specific PCB mountings and wiring. In general, these early packages were difficult to handle in a manufacturing environment. The DIL package became a *de facto* packaging standard for optics, as it was easier to implement in a general manufacturing environment. Both cooled and uncooled DIL versions existed. In early implementations TECs were used to control the laser temperature⁵ (mostly at room temperature), thus improving the reliability of the laser. Unfortunately, the TEC devices were also the most unreliable component in a laser package. Initially lasers were used in 850 nm and 1310 nm applications for bit rates up to around 1 Gbit/s. The first laser chips were Multi-Longitudinal-Mode (MLM) or Fabry Perot types. Later, 1550 nm Distributed Feedback (DFB) laser chips became available, exhibiting narrow spectral width and being useful for distances up to 80 km. The 1550 nm lasers were initially packaged

in DIL housings in order to get improved laser stability and high-power operation through the use of the TEC for laser chip cooling.

Early lasers for optical transmission operated at fiber-coupled optical output powers of approximately 1 mW or above. Newer low-power lasers, operating in the 1310 nm window around 0.1 mW, were later introduced, allowing the coupling between the laser chip and the fiber pigtail to be less critical. In this case, one could work with mechanical tolerances much higher than those for laser devices with high fiber-coupled powers. It was recognized that, when lasers are manufactured at high volume, the majority of the cost of a laser is in the optical coupling between the laser and the fiber as well as the package and not in the laser chip itself. As such, anything that could be done to increase the yield of optical coupling or simplify the manufacturing resulted in significant cost savings. The trend towards using lower-power lasers to save cost is reflected in the definition of intra-office/short-reach and short-haul/intermediate-reach interface specifications in ITU Recommendation G.957.

At the beginning of the 1990s a *de facto* standard for smaller-sized coaxial pigtailed packages arose. This new package, together with an improved performance of uncooled laser devices, allowed a migration towards using uncooled transmitters for almost all applications with distances up to 80 km for bit rates up to 622 Mbit/s.

For discrete receiver modules, the packaging evolution has proceeded at a slower pace. In most cases the receiver devices required additional semiconductor parts, like GaAs FETs or preamplifier ICs, in order to obtain the standardized receiver sensitivity performance. For receivers, both DIL and coaxial housings have been used. Initially only pin receivers were available to the market. However, due to the need to achieve improved receiver sensitivities, APD (Avalanche Photo-Diode) receiver devices were introduced to the market and the standards. The APD receivers were initially used for 622 Mbit/s 120 km applications. The lower cost PIN receiver technology has been appropriate for all applications at bit rates up to 622 Mbit/s for distances up to 80 km.

18.3.2.1.2 2.5 Gbit/s

Approximately 15 years ago, the first 2.5 Gbit/s optical interfaces were designed, and with that, several new challenges related to High Frequency (HF) performance and signal integrity through the package were introduced.

At this speed, optical isolators were necessary inside the laser packages to minimize the influence of back-reflection from the outside plant towards the laser chip, since this could cause transmission errors with the laser. The traditionally used DIL packages were not suitable at 2.5 Gbit/s because of their limited HF performance. As such, "butterfly" packages were

introduced, incorporating impedance-matching circuitry for optimized HF performance. For all 2.5 Gbit/s applications, SLM or DFB laser chip technology was required to meet the dispersion requirements of the various applications. Moreover, TECs were initially also used to obtain stable laser performance.

At the end of the 1990s, DFB laser performance had improved such that uncooled operation was becoming possible and a miniature version of the butterfly package was introduced, since the space for a TEC was no longer needed. The mini-butterfly packages initially served 1310 nm applications and later were used also for 1550 nm applications.

When the first 2.5 Gbit/s DWDM applications were being introduced at the beginning of the 1990s, direct laser modulation was no longer suitable for transmission over distances beyond 80 km. Instead, external modulation was required to minimize the effect of laser chirp, permitting transmission distances well above 80 km. The laser and external modulator were ultimately integrated into a single package, known as an Externally Modulated Laser (EML), and later the device was integrated onto a single chip. The single-chip EML device consists of a laser section, operating in Continuous Wave (CW) mode, and an electro-absorption modulator section, in which the light emitted by the laser section is modulated. A new range of EML driver ICs had to be developed, because EMLs work in "reverse" mode: no light is emitted when current is applied, which contrasts with conventional laser chips, where light emits when current is applied to the laser. For the first 2.5 Gbit/s DWDM applications, with channel spacings of 100 GHz (0.8 nm) or more, the drift of the EML frequency was not significant enough to result in optical link problems. However, for narrower channel spacing, wavelength lockers were necessary to achieve the required frequency stability and minimize the drift of the laser's wavelength.

2.5 Gbit/s were initially deployed in 40 – 80 km long-haul/long-reach spans. The link budget of these spans required the use of a very sensitive receiver; hence APD receivers were initially deployed. In order to maintain high-frequency signal integrity, the electrical leads coming out of the receiver package needed to have a minimum number of discontinuities. Because of this, the electrical leads were typically oriented parallel to the axis of the cylindrically shaped package. At 2.5 Gbit/s, integration of (pre)amplifier electronics within the receiver package was required in order to achieve the required performance. Later, once 2.5 Gbit/s systems were deployed in short-haul/intermediate-reach and intra-office/short-reach applications, the lower-cost pin-type receiver devices were introduced, employing the same packaging concepts as for APD-type receivers.

18.3.2.2 Integrated solutions

18.3.2.2.1 Initial versions

The availability of ITU's SDH/SONET optical interface Recommendation G.957 served as a reference for manufacturers of optical interface technology to design full functionality transmitter and receiver devices with standardized performance characteristics. In most cases, these devices were housed in the DIL packages. The supporting electronics for the transmit and the receive functions, e.g., laser driver circuitry and receiver amplification stages, were the first elements to be integrated into the packages. For certain applications, clock extraction circuitry was needed, and that also was integrated into the package. Initially, and to some extent even today, an industry agreed-upon packaging standard (*de facto* or real) didn't exist, and many vendors offered proprietary, vendor-specific solutions for transmitters and receivers for bit rates up to 2.5 Gbit/s. These initial versions were equipped with fiber pigtails.

18.3.2.2.2 1 x 9 device

Towards the end of 1990s, the emerging market of Gigabit Ethernet applications served as a driver to introduce the first integrated transceiver devices without fiber pigtails. These initial integrated transceivers (since they contained both a transmitter and a receiver in one module) were called the *1 x 9 transceivers*. These modules were approximately 25 mm (1 inch) wide, 10 mm high, and 40 mm long, with two integrated SC-style optical "receptacle-type" connectors. The electrical interface consisted of nine pins, positioned in one line at the side of the package opposite to where the optical connectors were located. This interface was of a "serial" type, implying that the electrical data rate given/received to/from the device is exactly the same as the data rate that is transmitted/received from the optics. These devices were mounted directly on the edge of a system's Printed Circuit Board (PCB), and mounted with the faceplate of the circuit. Previous implementations allowed the laser/receiver devices to be mounted anywhere on a PCB, and the adjoining fiber pigtail was used to bring the light up to PCB faceplate. A *de facto* reference design was available for designers to properly manage the mechanical and electrical interfaces of the 1 x 9 transceiver with their PCBs.

The 1 x 9 transceiver ultimately served 1310 nm short-haul/intermediate-reach distances for Gigabit Ethernet, Fibre Channel, SDH/SONET STM-1/OC-3, and STM-4/OC-12 applications.

18.3.2.2.3 Small Form Factor (SFF) devices

The market requirement to grow the capacity of network equipment also required that the density of the network equipment improve. This requirement manifested itself in a need to improve the density of optical interfaces at a faceplate. This was addressed by putting multiple channels (e.g., multiple 1 x 9 transceivers) on a single PCB, but ultimately required that the package be redesigned. Leveraging the newly available *LC* fiber optic connector, which was much smaller than previous connectors, a new transceiver package was introduced by multiple vendors, that was only half the size of a 1 x 9 transceiver. This new type of transceiver is most commonly referred to as a *Small Form Factor (SFF)* device. Its width is only 0.5 inch (12.7 mm), and the optical interface consists of two LC optical connectors. The electrical interface consists of two parallel rows of pins, either in a 2*5 or 2*10 configuration, depending on the features included in the transceiver. This package was developed through a voluntary industry cooperative effort, a practice which is now commonly referred to as a *Multi-Source Agreement* or *MSA*. The official specifications for the SFF MSA can be found at: www.sffcommittee.org/ie/. An example of an SFF device is shown in Figure 18-3.

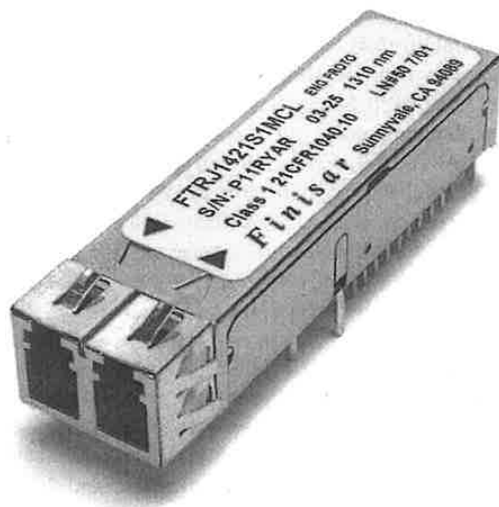


Figure 18-3. Example of SFF device (courtesy of Finisar Corporation)

SFF devices are not only available for the same application space as the 1 x 9 device but also now address 2 Gbit/s Fibre Channel and 2.5 Gbit/s SDH/SONET applications. Initially only devices for 1310 nm short-haul/intermediate-reach were available. However, due to subsequent improved performance with uncooled 1310 nm and 1550 nm SLM or DFB lasers and APD receivers, devices for 2.5 Gbit/s 40 km and 80 km long-haul/long-reach applications have become available.

This package achieved very competitive market pricing, because the module-level package was utilized in so many applications, which allowed the volumes to be converged on the manufacturing line.

18.3.2.2.4 SFP devices

The availability of SFF devices enabled very high port densities in optical transmission systems. Examples are circuit packs with 16 SFF devices next to each other for STM-4/OC-12 and 1 GbE applications. While solving the density problem, the SFF package had to be soldered down to the board, meaning that the end customer was required to buy all 16 channels, even if only a couple of channels were initially needed. The physical layout of so many devices on the faceplate of the PCBs proved to be an incredible challenge. Additionally, it was generally not feasible to support multiple applications (e.g. different transmission reach) on the same circuit pack, despite the fact that the package lent itself to this opportunity. Finally, there is an increased reliability risk when so many optical devices are mounted on a single circuit pack. In the case of a single transceiver failure, either the complete circuit pack must be replaced and repaired or the relevant optical port had to be permanently taken out of service.

In order to resolve the aforementioned drawbacks, a completely new generation of electrically pluggable transceivers was developed. The most prominent transceiver today is called the *Small Form-factor Pluggable (SFP)* module. The SFP modules are similar in size to the SFF devices; however, they are hot-pluggable, implying that they can be inserted into and removed from a live circuit pack without disrupting service or impacting the performance of any of the other ports already in service. This new concept offers full flexibility, permitting a mix of various transceiver types on a single circuit pack under a "pay as you grow" scenario. Also, in case of a transceiver failure, only the impacted device will require replacement. An example of an SFP device is shown in Figure 18-4.

In order to facilitate simple pluggable insertion and removal from the board, along with minimized EMC interferences, a protective cage is mounted at the front of the host PCB. The width of the cage is slightly larger than that of an SFF device, implying a slightly lower port density than for SFF devices, but the gain in flexibility more than compensates for this

reduced density. The electrical interface is realized through a 20-pin electrical connector, providing all necessary input and output signals. In order to manage the device, a two-wire serial bus is incorporated into the electrical pin field. Access to the device's performance and alarm monitors is provided through this bus.



Figure 18-4. Example of SFP device (courtesy of Finisar Corporation)

The SFP was developed through a voluntary cooperative industry agreement. Additional information on the MSA specification, detailing the mechanics, pinning, and electrical interface can be found at www.schelto.com/SFP.

The application space for the SFP devices covers all speeds up to 2.5 Gbit/s, and most recently, 4 Gbit/s for quadruple Fibre Channel applications. The SFP is used in single-channel applications as well as in CWDM applications as specified under ITU Recommendation G.695. The operation of DFB lasers in uncooled conditions matches very well with the 20 nm channel spacing requirements for CWDM systems in G.695. Recent advances in packaging and micro-cooling of substrates has enabled the introduction of SFP devices also for 2.5 Gbit/s DWDM applications.

Prior to the formation of the SFP hot-pluggable device, a package called the GBIC (GigaBit Interface Converter) module had been developed, primarily covering 1–2 Gbit/s Fibre Channel and Gigabit Ethernet applications. Its dimensions, including alignment guides and the electrical

connector, are approximately $13.7 \times 38 \times 76 \text{ mm}^3$ ($h \times w \times d$) and it contains either one or two optical ports. The GBIC part used the SC-style optical connectors. Because this device has not been applied to the broad range of SDH/SONET interfaces, no further attention is given to it here. There is one exception: couple of companies developed 2.5 Gbit/s and GbE DWDM applications and packaged them in a GBIC. The long-term opportunity for this part is unclear, given that the same capability is available in SFPs. An example of a GBIC device is shown in Figure 18-5. Additional information about the GBIC can be found at www.schelto.com.



Figure 18-5: Example of GBIC device (courtesy of Finisar Corporation)

18.3.2.2.5 2.5 Gbit/s transponders

Before the aforementioned SFF and SFP transceivers were available for 2.5 Gbit/s applications, transponder devices were introduced to aid in the implementation of 2.5 Gbit/s optical interfaces onto circuit boards. In contrast to the transceiver devices, which have serial electrical interfaces, exhibiting the same speed on the electrical interface as on the optical interface, a transponder contains electrical (de)multiplexing functions in order to equip the device with electrical signals that can be fairly easily handled at circuit pack level. The transponders contained an electrical interface that operated with sixteen channels operating at 155 Mbit/s/channel. An industry-wide MSA has not been developed for the 16-

channel 2.5 Gbit/s transponder. Instead, several smaller-scale MSAs were agreed upon by some manufacturers of optical interface technology. Initially, transponders were developed for single-channel SDH/SONET interfaces and later as well for DWDM optical interfaces. In most cases, the latter were proprietary. Today, the 2.5 Gbit/s transponders are mostly used for the latter DWDM applications, while the (serial) transceivers are used for the single-channel applications.

18.3.3 10 Gbit/s technology

18.3.3.1 Discrete solutions

When the first 10 Gbit/s optical interfaces were being designed, the available technical choices were fairly limited. APD receivers were not yet available and transmitter output powers were limited. The first 10 Gbit/s transmitters were based upon a combination of 1550 nm CW-lasers and Mach Zehnder (MZ) modulators. Only when using optical amplifiers, either in a booster or in an optical preamplifier configuration, could distances of 80 km and beyond be achieved. Furthermore, dispersion compensation was necessary to achieve transmission distances above 50 – 60 km. For the first draft of ITU Recommendation G.691, it appeared almost impossible to define an appropriate set of parameter values for 40 km distances because of the performance limitations of the first generation of 10 Gbit/s optical technology.

For a long period, the design of 10 Gbit/s optical interfaces was quite challenging, not only due to the limited availability of appropriate optical devices, but also due to signal integrity issues related to the transmission of High Frequency (HF) data between lasers, detectors, and board-level interconnections. As such, proprietary 10 Gbit/s optical interfaces dominated the designs of equipment manufacturers. This is true in particular, even today for DWDM applications, where stringent requirements surrounding high-channel count and multispan configurations are needed to guarantee system performance. For channel spacing of 100 GHz or less, wavelength locking devices were added to the optical train to meet stringent transmitter frequency stability requirements.

Due to advances in laser technology and the upcoming availability of Electro-absorption Modulated Lasers (EMLs), it was possible to develop smaller solutions than what was possible with the existing MZ-based technology. Moreover, these new integrated devices were significantly easier to manufacture and were much more cost-effective than MZ devices. As such, it was possible to define a new set of parameters for 40 km

applications in Recommendation G.691 without the need for an optical amplifier. However, despite these advances, the first SDH/SONET 80 km application codes in G.691 were specified with the assumption that an optical amplifier would be required. Subsequent advances in the use and packaging of 10 Gbit/s APDs made it possible to extend the reach beyond 40 km, without the need for an optical amplifier.

18.3.3.2 Integrated solutions

18.3.3.2.1 300-pin transponder

At the end of the 1990s and towards the turn of the century, 10 Gbit/s optical component technology had matured to the point where proprietary optical interfaces could be standardized with an integrated package that could be supported by multiple vendors. One example of this was developed through a multivendor consortium, resulting in the 300-pin transponder MSA.

Like the 2.5 Gbit/s transponders described above, the 10 Gbit/s transponder contains electrical (de)multiplexing functions to aid designers in managing the signal integrity at the circuit pack level. In the case of the 300-pin transponder, a 16-channel multiplexing function was used, so the lower-speed electrical interface was 622 Mbit/s. The Optical Internetworking Forum (OIF) developed a standard around the electrical interface and signal management, called OIF-SFI4-01.0: "Common electrical interface between framers and serializer/deserializer parts for OC-192/STM-64 interfaces" [23]. This standard defines the interoperability between the transponder electrical signals and the framer, which resides on the host printed circuit board. The OIF specification is commonly referred to as the *SFI4 specification* and, with the 300-pin MSA specification, provided the industry a complete specification around the mechanical housing, the electrical interface, and the optical interface. The 300-pin MSA contains a full description of the mechanical aspects of the module package (module outline, dimensions, mounting holes, location of electrical interface connector, etc.), as well as optical and electrical characteristics. With respect to the optical interface, reference is made to the relevant ITU and Telcordia SDH/SONET requirements. The transponder contains SERDES (serializer/deserializer) ICs, and for this transponder, the SERDES refers to a 16:1 multiplexer and 1:16 demultiplexer functionality. In addition to the laser and laser driver, the transmitter section contains circuitry intended to minimize jitter. In the receiver section, clock and data recovery circuitry is included. The electrical interface is implemented through a 300 (10*30) Pin

Grid Array connector, which allows for straight forward integration of the optical module with the host PCB. Because this connector is separable, the 300-pin transponder is also referred to as a *cold-pluggable device*. Through the electrical connector, the usual data and clock signal interconnects are provided along with a variety of digital alarm and analogue signals to report on the “health” of the various parts within the transponder. Initially, a maximum footprint of 5 x 5 inch² was defined, but in practice, the footprint was typically 3.5 x 4.5 inch². Recently, a small-form-factor version was defined with a maximum size of 2.2x3 inch², reflecting the need for higher optical channel densities on the host PCB, and was enabled by technologies focusing on improved component integration within the transponders. An example of a 300-pin transponder is shown in Figure 18-6.

A separate MSA for an I2C digital diagnostic interface, provided through a two-wire serial bus, has been defined to provide an improved means for remote transponder monitoring and provisioning. This was an improvement over the polling technique that was typically conducted to monitor the performance of the transponders through the analogue pins in the 300-pin connector as described above.

Full details of both the 300-pin transponder MSA and the I2C digital diagnostic MSA can be found at www.300pinMSA.org.

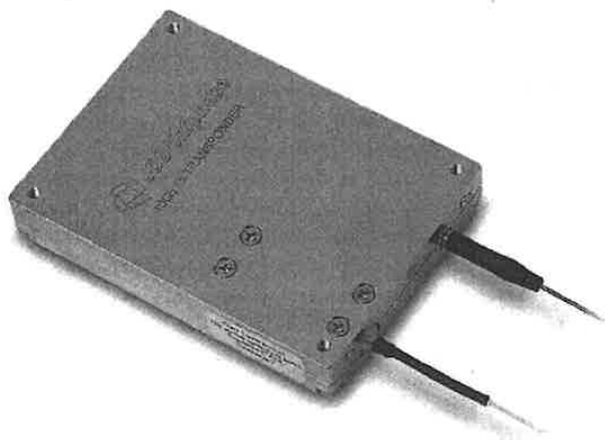


Figure 18-6. Example of 300-pin transponder (courtesy of JDS Uniphase)

The 300-pin transponders were initially available only for the 1550 nm short-haul/intermediate-reach 40 km and the 1310 nm intra-office/short-reach applications. Based on market demand, a complete variety of transponders became available to accommodate longer ranges, e.g., 80 km, SDH/SONET, and DWDM applications. In the latter case, MZ modulators and/or tunable lasers have been incorporated within the transponders. No reference optical interface specifications exist for the DWDM transponders, and therefore the corresponding designs and associated specifications are mostly proprietary.

During the transponder design phase, it was discovered that it was extremely challenging to meet Telcordia's transmitter jitter generation requirements, in particular the RMS-jitter requirements. As a result, a whole range of successive SERDES devices has been developed by various ASIC vendors to improve jitter performance.

Because of advances in EML output powers and the availability of 10 Gbit/s APD receivers with improved receiver sensitivity, it became possible to bridge 80 km distances without the use of optical amplifiers. Therefore, new application codes have been defined in the generic ITU Recommendation G.959.1 as an alternative to the SDH/SONET Recommendation G.691 80 km application codes, which previously required optical amplification.

In order to manage the total module cost, Very Short Reach (VSR) transponders became available, principally to leverage cost reductions that had occurred with 10 Gbit/s optical component technology and also the shorter-reach applications (e.g., 600 m) that had been standardized in ITU Recommendation G.693. With these transponders, it was possible to build cost-efficient interconnects over VSR distances between SDH/SONET and DWDM systems.

In addition to SDH/SONET applications, the 300-pin transponders can in principle also be used for G.709-based OTN as well as 10 GbE applications, because of provisions within the 300-pin MSA to operate at bit rates between 9.9 and 10.7 Gbit/s. Whereas in some transponder designs the relevant transmitter jitter filter frequency has to be set through the 300-pin connector, others are able to operate without the need to independently set the jitter filter frequency by employing a broadband jitter filter approach. A judgement on which version works best is considered outside the scope of this book.

18.3.3.2.2 200-pin transponder

Soon after the introduction of the 300-pin MSA, a competitor transponder MSA arose. This transponder was based on a 200-pin connector, and initially promised a smaller package and footprint, which proved to be

especially interesting for high-density intra-office/short-reach applications. Ultimately, the market favored the 300-pin MSA as the transponder of choice for 10 Gbit/s SDH/SONET applications. Consequently, no further details are provided here.

18.3.3.2.3 XENPAK

Because of continued breakthroughs in component-level integration, it became possible to package a “transponder” in increasingly smaller packages. At the same time, a market need arose for systems with more than one 10 Gbit/s optical port on a single optical interface card and an interest to leverage the same “hot pluggability” feature that was available with the SFP modules that covered lower data rates. The density and pluggability issue was in particular true for 10 Gigabit Ethernet (10 GbE) applications but also for SDH/SONET applications. A new MSA became available, called the *XENPAK-MSA*, to address the above-mentioned market needs.

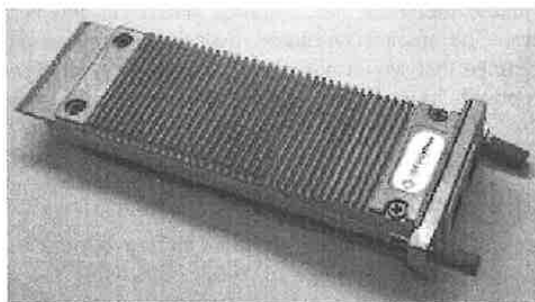


Figure 18-7. Example of XENPAK device (courtesy of JDS Uniphase)

The XENPAK housing is equipped with two SC optical connectors, and its board attachment scheme requires a cut-out in a PCB with alignment to a mating PCB connector. Unlike the SFP pluggable device, the XENPAK package was intended to be fully EMI compliant; hence a cage or guidance system is not required. Its size is approximately 2×5 inch². An example of a XENPAK device is shown in Figure 18-7. An industry standard 70-pin electrical connector provides the electrical interface. The input and output data signals are transmitted according to a new electrical interface specification, called *XAUI*, which was defined in IEEE 802.3ae. XAUI

details can be found at www.10gea.org. In short, the XAUI interface specification is based on four bidirectional lanes carrying 3.125 Gbit/s per channel. This setup simplified electrical trace management on the host PCB board relative to the 300-pin transponder, which required 16 parallel electrical channels per 10 Gbit/s optical signal. However, it also required that each trace carry a higher data rate. In order to simplify design and layout, additional overhead processing was added to the signal with which to correct for signal integrity challenges in the host PCB. The four 3.125 Gbit/s XAUI lanes give an aggregate bandwidth of 12.5 Gbit/s in order to transmit a 10.3125 Gbit/s optical signal. Full details on the XENPAK module can be found at www.xenpak.org.

While use in SDH/SONET applications was foreseen in principle, most versions are specifically aimed at 10 GbE applications, where large volumes were expected.

18.3.3.2.4 X2, XGP, and XPAK

Many transceiver users faced difficulties applying XENPAK devices, mainly due to the module's size, required board cut-out, and associated thermal issues. The market requested that an alternative smaller sized package be defined that would not require a board cut-out. Three solutions have been proposed: XGP, X2, and XPAK. The application area is the same as for XENPAK, 10 Gigabit Ethernet, and Fibre Channel, but SDH/SONET applications are also foreseen.

The XGP concept has since been abandoned due to lack of agreement on a specification.

The two remaining and competing MSAs are the X2 and XPAK. These were developed around the middle of 2002, both using the same 70-pin electrical interface connector that was required for XENPAK. However, unlike the XENPAK, both modules require a guiding/cage system. Both of the packages are of smaller size than XENPAK. The first parts available to the market were intended for 10 GbE applications, and the input and output data signals are according to the XAUI specification (as for XENPAK). Versions accommodating SDH/SONET STM-64/OC-192 applications are also foreseen, where the electrical interface would be addressed with four 2.5 Gbit/s data signals based upon the OIF SFI4 Phase 2 based electrical interface specification [24]. An example of an X2 device is shown in Figure 18-8.

For further details, please visit www.x2msa.org or www.xpak.org.

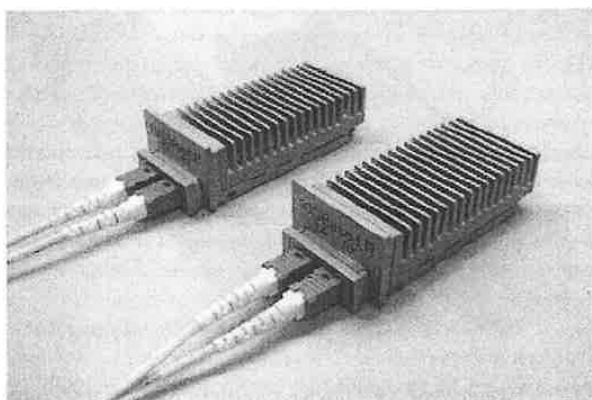


Figure 18-8. Example of X2 device (courtesy of JDS Uniphase)

18.3.3.2.5 XFP

Because of a continued market drive for further size reduction in optical modules and the need for flexibility with respect to application space, together with the foreseen availability of new IC generations that could operate directly at 10 Gbit/s interface speeds, a new hot-pluggable, small-form-factor transceiver, called *XFP*, was conceived. The XFP was defined specifically to cover all of the possible 10 Gbit/s applications, including SDH/SONET STM-64/OC-192, OTN G.709 rates, 10 Gigabit Ethernet and Fibre Channel. An example of an XFP device is shown in Figure 18-9.

This XFP transceiver has a serial interface, implying that both the electrical and optical interface speed is operating at 10 Gbit/s. This setup is similar to the concept employed with the SFP modules. This approach is forward-looking in that it is designed around the future availability of framer ICs with 10 Gbit/s interface signals, but it can still be operated by interfaces with a serial-to-parallel converter on the host board. By taking the (de)multiplexer electronics out of the module, the device power dissipation could be substantially lowered in comparison with to earlier devices and this also makes the device less dependent on the exact application bit rate.

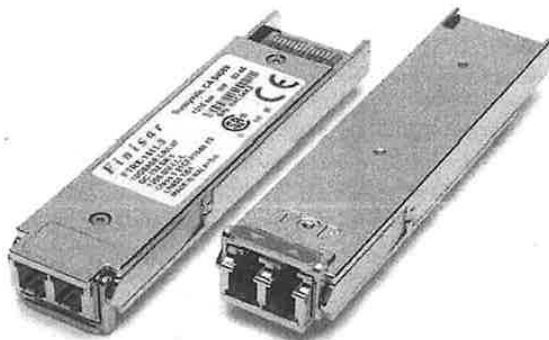


Figure 18-9. Example of XFP device (courtesy of Finisar Corporation)

An MSA has been defined, including specifications for the XFP module itself, cage hardware to fit to PCBs, digital diagnostics, and electrical interface specifications. For full details, please visit www.xfpmsa.org.

The package size is approximately $18 \times 71 \times 8.5 \text{ mm}^3$ ($w*d*h$). The electrical interface is realized through a 30-pin connector, and the optical connectors are of the LC receptacle-type, similar to those used in SFP packages for bit rates up to 2.5 Gbit/s. The XFP MSA also contains guidance on mechanical provisions to provide optimum thermal management on the host PCB. Given the reduced number of pins available relative to the 300-pin transponder (a 10x reduction), it was necessary to adopt a digital diagnostic to provide access to the alarms and performance of the 10G optical module. The digital diagnostic is accessible through a two-wire serial bus, called the *I²C*. The high-speed 10 Gbit/s electrical signals and their specifications are commonly referred to as *XFI*, pronounced “Ziffie”.

Initially, only versions for STM-64/OC-192 intra-office/short-reach (2km) and 10 GbE long reach (10 km) applications were available, based upon usage of uncooled 1310 nm DFB laser chips. Recently, the availability of semi-cooled 1550 nm EMLs has opened a road to the availability of XFP devices for longer-reach single-channel and DWDM applications with transmission distances up to 80 km.

18.3.4 40 Gbit/s technology

18.3.4.1 Discrete solutions

Currently most implementations for 40 Gbit/s optical interfaces, both for single-channel and DWDM multichannel applications, are still completely proprietary. The cost is still extremely high and the market demand is limited, and as such, it is somewhat premature to build an extensive set of industry agreed-upon MSAs.

18.3.4.2 Integrated solutions

Around 2002, it was anticipated that there would be a market need for commercially available integrated, multisourced 40 Gbit/s devices. Therefore, an MSA was defined for a 300-pin transponder in a way similar to the 300-pin transponder for 10 Gbit/s applications. Initially, only Very Short Reach (VSR) applications as defined in G.693 were foreseen.

For full details, please visit www.300pinMSA.org.

18.4. CONSIDERATIONS ON OPTICAL FAULT AND DEGRADATION DETECTION

18.4.1 General

Since the initial deployments of optical fiber systems, the philosophy on how to handle optics-related faults and degradations in optical transmission systems has substantially changed. In this section, a perspective on this evolution is provided.

18.4.2 Faults in conventional transmitters and receivers

At the time that the first optical transmission systems were being deployed in the 1980 – 1985 time frame, optical technology was not yet mature with respect to reliability.

Optical transmitters were mostly based on 850 nm laser technology, and there were still many reliability issues with respect to laser chip technology and laser-to-fiber coupling stability. In particular, the 850 nm laser threshold/bias currents were in many cases continuously degrading

(increasing) versus time, and a laser End-Of-Life condition was relatively quickly reached. Because of these reliability issues, several monitors were built into the transmitter in order to track the laser degradation to provide the user with a means to predict equipment failure. Examples of monitoring parameters are laser bias current, laser backface monitor diode current (to give an indication of the laser output power), and laser chip temperature (in the case that a Thermo-Electric Cooler was used). Furthermore, two alarm levels were defined: a degraded alarm, indicating a close-to-failure condition to provide the end-user some time to replace the degraded equipment, and a failure alarm, requiring immediate replacement of the failing parts.

At the receive side of the optical link, monitors were built into the optical receivers in order to measure the optical input power into the receiver so as to check the condition of the line and the actual receiver input signal.

Originally, the aforementioned monitor points were connected to test points at the front of the equipment. Because these points were very sensitive to ESD/EMC effects, the industry moved to fully integrated monitoring methods based upon analogue-to-digital conversion techniques.

The generated analogue information was collected by the equipment and used to raise alarms at preset levels or for network and/or equipment health monitoring.

In particular, when the first SDH/SONET recommendations were being developed, several optical degraded and fail alarms were defined with the intent to indicate when the relevant optical interface parameters had degraded to a value outside the range specified.

Since that time, many of these monitors have been implemented in most of the various transmitter, receiver, transceiver, and transponder designs. The way they are being used, however, has substantially changed. While some equipment users are still requiring the actual analogue values for their own assessment of network and/or equipment health, a completely new philosophy on the usage of optics-related alarms has been developed within the ITU. It is being recognized that putting alarms only on lasers is not very useful, in particular when a laser cannot be replaced separately. A failing solder joint on a low-cost resistor can be as dramatic to the performance of an optical system as the failing of a relatively expensive laser.

Within the relevant ITU equipment recommendations, one no longer speaks of alarms, but of defects. Defects are being defined in an unambiguous way and should be one-to-one coupled to "consequent actions"; i.e., if the failure of a piece of equipment is reported, it should be immediately clear what the follow-up action is. Therefore, measuring analogue values only makes sense if sensible thresholds can be defined. Furthermore, it is critical for the user to make a distinction between equipment defects and transmission defects. Only then can appropriate

consequent actions be defined. The equipment defects should be coupled to replaceable (e.g., hot-pluggable) units and not to individual parts integrated on these units. As a result, the definition of optical interface-specific defects (alarms) at the component level has been abandoned by the ITU.

Furthermore, optical technology has matured substantially over the past twenty years to a level where the reliability of the involved parts, in particular for the 1310 nm and 1550 nm components, has significantly improved. Today's failure mechanisms are very different as compared with the initial degradation patterns that were associated with 850 nm laser technology. With today's technology, if a laser component fails, the actual failure remains very difficult to predict by using measured laser performance parameters. This makes the reporting of analogue values even less useful as a tool to perform preventive maintenance than one would expect. Therefore the usage of the "degraded alarms" as mentioned above has been abandoned by the ITU. In practice, the laser's failure could be either within a minute, thus faster than the actual repair time, or within a year after the moment that the degraded alarm was raised.

A further complexity is the fact that while equipment vendors initially had extensive knowledge of the optical interface design details, this expertise has dispersed into the whole of the optics supply chain. As such, local experts are rarely available in a single institution to interpret analogue optical monitoring values. Today, instead of using sub-component level alarms, the use of highly-integrated modules, like transceivers or transponders can provide relevant alarm information to the board upon which they are placed. These module-level alarms can then be used to generate notification of equipment defects. The manufacturers of these technologies have the best design knowledge for defining how the appropriate defect levels predict the failure of a module.

18.4.3 Faults in optically amplified systems

When the first optical amplifiers were being designed and used in single- and multichannel transmission systems, a similar discussion on degradation and failure alarms took place within the ITU. As for the conventional optical transmitter and receiver technologies, the performance degradation alarms were regarded as implementation specific and therefore not suitable for incorporation into the applicable standards. Furthermore, the design-specific failure alarms were expected to be incorporated in the general equipment defects, in a way similar to the description in Section 18.4.2. As before, the analogue monitoring was considered to be only useful when sensible thresholds and related consequent actions could be defined. The specific technologies used in optical amplifiers, e.g., pump lasers, generally did not

exhibit the same linear degradation patterns that were observed for transmission-based lasers. Finally, there was a period when the very dangerous and unpredictable phenomenon of "sudden death" was known to occur and to dominate failures with optical amplifiers, and it could not be prevented by laser parameter monitoring.

Recently, a lengthy discussion took place within the ITU on the topic of optical monitoring in optical networks. In very long-haul DWDM networks, the distances between access points, where there is (electronic) access to the relevant network and/or equipment performance data, are so great that it is not easy to locate faulty equipment or fiber breaks in the outside fiber plant. In order to have the capability to trace these faults, some users wanted to standardize the mandatory measurement of several analogue optical parameters, like total power, individual channel power, channel wavelength, Optical Signal-to-Noise Ratio (OSNR), and Q-factor. Unfortunately, it appeared virtually impossible to unambiguously relate these optical parameters directly to network error performance, and as such, sensible thresholds and consequent actions couldn't be defined within the ITU. The fact that most of the parameters and their values are very equipment design specific was one of the complexities of this topic. It was recognized, however, that optical monitoring is a useful tool to perform network and equipment fault location, but that this tool should stay proprietary and should not be considered mandatory by the standards bodies. Naturally, not all DWDM networks would require this degree of optical monitoring, and as such, the ITU wanted to avoid the impression that it should be performed in all multi-wavelength systems. In particular, use of these monitoring methods in low-cost CWDM systems would not provide any added value and would only add unnecessary elements and cost to the system. Instead, it was decided to provide some general information on optical monitoring in DWDM systems in a new Recommendation G.697 [25], which specifically avoids the implication that optical monitoring is necessary in all multichannel systems.

18.5. NOTES

1. In this chapter, *fiber optic plant* and *outside plant* will be used interchangeably.
2. The general relationship between signal frequency f and wavelength λ (measured in vacuum) is given by $\lambda = c/f$, with c being the speed of light in vacuum, for which a value of 2.99792458×10^8 m/s should be used when carrying out this conversion.
3. Within this context, the maximum value of the receiver sensitivity refers to its worst-case value, reflecting the notion that a (mathematically) higher sensitivity value implies a less sensitive receiver.

4. Laser chirp is the phenomenon by which the laser center wavelength is varying during a binary pulse. This phenomenon is evident in particular during the rising and falling edges of a pulse.
5. This control implies that TECs are used to cool the laser under hot ambient conditions and heat the laser under cold ambient conditions.

18.6. ACKNOWLEDGMENTS

The author of this chapter would like to sincerely thank two of his ex-colleagues from Lucent Technologies for their extremely valuable suggestions for improving the contents of this chapter: George Newsome, author of another chapter in this book and currently engaged with consulting, and Michael J. Schabel, Ph.D., Member of the Technical Staff at Bell Laboratories, Lucent Technologies, Murray Hill, NJ.

18.7. REFERENCES

- [1] ITU Recommendation G.955, *Digital line systems based on the 1544 kbit/s and the 2048 kbit/s hierarchy on optical fibre cables*, November 1996.
- [2] ITU Recommendation G.957, *Optical interfaces for equipments and systems relating to the synchronous digital hierarchy*, July, 1999, plus Amendment 1, December 2003, plus Amendment 2, January 2005.
- [3] Telcordia GR-253-CORE, ISSUE 3, *Synchronous Optical Network (SONET) Transport Systems: Common Generic Criteria*, September 2000.
- [4] ITU Recommendation G.692, *Optical interfaces for multichannel systems with optical amplifiers*, October 1998, plus Corrigendum 1, January 2000, plus Corrigendum 2, June 2002, plus Amendment 1, January 2005.
- [5] ITU Recommendation G.694.1, *Spectral grids for WDM applications: DWDM frequency grid*, June 2002.
- [6] ITU Recommendation G.872, *Architecture of optical transport networks*, November, 2001, plus Amendment 1 December 2003, plus Corrigendum 1, January 2005.
- [7] ITU Recommendation G.709, *Interfaces for the Optical Transport Network (OTN)*, March 2003, plus Amendment 1, December 2003.
- [8] ITU Recommendation G.959.1, *Optical transport network physical layer interfaces*, December 2003, plus Erratum 1, April 2004.
- [9] ITU Recommendation G.693, *Optical interfaces for intra-office systems*, January 2005.
- [10] ITU Recommendation G.691, *Optical interfaces for single channel STM-64 and other SDH systems with optical amplifiers*, December 2003, plus Amendment 1, January 2005.
- [11] ITU Recommendation G.694.2, *Spectral grids for WDM applications: CWDM wavelength grid*, December 2003.
- [12] ITU Recommendation G.695, *Optical interfaces for coarse wavelength division multiplexing applications*, January 2005, plus Erratum 1, June 2005.
- [13] ITU Recommendation G.sup39, *Optical system design and engineering considerations*, October 2003.

- [14] ITU Recommendation G.651, *Characteristics of a 50/125 μm multimode graded index optical fibre cable*, February, 1998.
- [15] ITU Recommendation G.652, *Characteristics of a 50/125 μm multimode graded index optical fibre cable*,
- [16a] ITU Recommendation G.650.1, *Definitions and test methods for linear, deterministic attributes of single-mode fibre and cable*, June 2004.
- [16b] ITU Recommendation G.650.2, *Definitions and test methods for statistical and non-linear related attributes of single-mode fibre and cable*, January 2005.
- [17] ITU Recommendation G.653, *Characteristics of a dispersion-shifted single-mode optical fibre and cable*, December 2003
- [18] ITU Recommendation G.654, *Characteristics of a cut-off shifted single-mode optical fibre and cable*, June 2004.
- [19] ITU Recommendation G.655, *Characteristics of a non-zero dispersion-shifted single-mode optical fibre and cable*, March 2003.
- [20] ITU Recommendation G.663, *Application related aspects of optical amplifier devices and subsystems*, April 2000, plus Amendment 1, January 2003.
- [21] ITU Recommendation G.656, *Characteristics of a fibre and cable with non-zero dispersion for wideband transport*, June 2004.
- [22] ITU Recommendation G.697, *Optical monitoring for DWDM systems*, June 2004.
- [23] OIF implementation agreement, OIF-SFI4-01.0, *Proposal for a common electrical interface between SONET framer and serializer/deserializer parts for OC-192 interfaces*, September, 2000.
- [24] OIF implementation agreement, OIF-SFI-02.0, *SERDES Framing Interface Level 4 (SFI-4) Phase 2: Implementation Agreement for 10 Gb/s Interface for Physical Layer Devices*, September, 2002.
- [25] ITU Recommendation G.826, *End-to-end error performance parameters and objectives for international, constant bit-rate digital paths and connections*, December 2002.
- [26] ITU Recommendation G.696.1, *Longitudinally Compatible Intra-Domain DWDM Applications*, July 2005 (pre-published).
- [27] ITU Recommendation G.698.1, *Multichannel DWDM applications with single channel optical interfaces*, June 2005.