

# **Layered Optical Networks -Implications to switching and transmission**

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Cover picture: The first prototype circuit-board of an 16 port opto-electrical crossconnect developed at Telia Research AB 1998 for the Winchester project.

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## Abstract

With the aim of supporting and enhancing high-capacity communication networks, such as telephony, Internet and others, this work has investigated:

- transmission gains with time-slotted optical communication,
- performance of optical add/drop multiplexers (OADMs) and optical crossconnects (OXC),
- OXC networks serving Internet Protocol (IP)-routers,
- packet hop reductions in IP-controlled optical networks,
- a simple optical neighbour discovery method,
- economics of complementing a client network with an optical express layer.

Time-slotting was shown to enable bi-directional transmission at the same frequency and multi-wavelength transmission over dispersion-shifted fibre.

The cascadability of fixed and reconfigurable OADMs of various technologies was investigated using re-circulating loop experiments. The fixed OADMs could allow more than 20 hops of DWDM signals while the reconfigurable OADMs displayed somewhat poorer performance. A similar study where done for OXC with electrical switch matrices (OEXC) and an experimental model of an optical matrix. The OEXC in 2R mode could allow 7 cascades within 2dB power-penalty given that the signal bandwidth was substantially lower than the bandwidth of the electrical switch (in the order of  $\frac{1}{4}$  to  $\frac{1}{2}$ ).

An experimental network, “Winchester”, consisting of OEXC, IP-routers with Gigabit Ethernet ports, and DWDM links, was built and investigated in the Stockholm area. This work investigated cost-effective IP-over-optical networks and the possibilities and difficulties of wavelength configurable IP backbones from an operator’s perspective. A management systems based on IP, Java and CORBA was also developed and evaluated. It was concluded that a cost-effective IP/Gigabit Ethernet network is well enhanced by OEXCs to achieve a well-operated network. Computer simulations showed the possibility to reduce IP-traffic hop-count by adjusting the reconfigurable network to the traffic characteristics. Up to 25% reduction is achievable.

A simple method for automatic neighbour discovery was proposed and evaluated. Eliminating the need for costly electronics to read/write channel overhead information, the method make use of functions already supported by common optical ports.

Finally, the cost-benefit of complementing a client network with an optical (reconfigurable) express layer was analytically investigated. With appropriate port and common equipment cost of the optical elements, the total network cost can be substantially reduced: around 30% for medium size networks (30 nodes) and up to 60% for large networks (100 nodes).



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At my first employer, Telia Research AB, I was lucky to be surrounded by lots of skilled and experienced persons: first Leif Östlund for pushing me to start the studies and helping with useful guidance, Carl Wickman for his continuous support and system knowledge and 9 years of proof-reading most of the material I've written, Hans Carlén for his rare insight into experimental work and Björn Hermansson for his knowledge in non-linear fibre optics.

As this work crosses many boundaries, my knowledgebase has much benefited from many discussions with experts in IP, Video and SDH networking: colleagues at Telia, KTH, and especially Wavium.

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## List of papers

This thesis is based on the following papers, listed in chronological order, which will be referred to by their letters in bold face:

- A.** S. N. Larsson, "**Improving Rayleigh-limited bidirectional optical transmission systems by using time-slotting and frequency detuning**", European Conference on Optical Communication, pp. 485-486, Madrid, 1998.
- B.** E. Almström, S. N. Larsson and H. Carldén, "**Cascadability of optical add/drop multiplexers**", European Conference on Optical Communication, pp. 589-590, Madrid, 1998.
- C.** C. P. Larsen, S. Larsson, E. Almström, H. Carldén, B. Stoltz, O. Öberg, and J. E. Falk, "**Experimental evaluation of novel, tunable MMI-MZI demultiplexer in InP**", European Conference on Optical Communication, pp. 121-122, Madrid, 1998.
- D.** S. N. Larsson, "**Improving four-wave mixing-limited optical transmission systems by using time-slotted packet transmission**", European Conference on Optical Communication, pp. 418-419, Nice, 1999.
- E.** E. Almström and S. N. Larsson, "**Experimental comparison between optical and electrical switches for transparent networks**", European Conference on Optical Communication, pp. 60-61, Nice, 1999.
- F.** S. N. Larsson, S. Hubendick, H. Carldén, C. Wickman, E. Almström, "**Wavelength Label Switched IP Backbone: Architecture and Field Trial**", Optical Fiber Conference, ThE4-1 / 71, Baltimore, 2000.
- G.** S. N. Larsson and S. Hubendick, "**Reduction of Hop-Count in Packet-Switched Networks using Wavelength Reconfiguration**", Optical Network Design and Modelling, pp. 104-124, Athens, 2000.
- H.** E. Almström, P. Evaldsson, S. Hubendick, C. P. Larsen, S. Larsson, C. Wickman, "**Requirements and solutions for reconfigurable metro WDM systems**", National Fiber Optic Engineers Conference, session B2, Denver, 2000.
- I.** S. N. Larsson, S. Hubendick, R. Nedelchef, "**Simple optical neighbor discovery (SOND): architecture, applications and experimental verification**", Journal of Optical Networking, Vol. 2, No. 10, pp. 350-360, October 2003.
- J.** S. N. Larsson, "**Analytic investigations of cost benefits of complementing a client network with an optical express layer**", Journal of Optical Networking, Vol. 3, No. 2, pp., February 2004.

The following papers are related to the work in this thesis but not included:

- a. S. Larsson, "10Gbit/s experiments on Midspan Spectral Inversion (MSSI)", 5.2p, RVK'1996, Lulea, Sweden.
- b. S. N. Larsson and B. Hermansson, "Simple expression of the conjugate power generated by four-wave mixing of signal and a single pump", SAD4-1, pp. 79-81, Non-linear Guided Waves (NLGW), Cambridge, April 1996.
- c. S. Larsson et al., ACTS Meton "Node and network demonstrator performance", 1998.
- d. S. Larsson et al., ACTS Demon "D1 Definitions and interim results", AC354/Telia/DS/L/002/b1, December 1998.
- e. S. Larsson et al., ACTS Demon "D3 Qos monitoring and performance modeling", AC354/DTAG/DS/L/004/b1, August 1999.
- f. S. Larsson et al., Eurescom Project P918-GI, "Integration of IP over Optical Networks: Networking and Management", Deliverable 1, IP over WDM, Transport and Routing, October 1999.
- g. S. Larsson et al., Eurescom Project P918-GI, "Integration of IP over Optical Networks: Networking and Management", Deliverable 2, Network scenarios for IP over optical networks, Volume 1 of 2: Main Report, September 2000.
- h. S. Larsson et al., Eurescom Project P918-GI: "Integration of IP over Optical Networks: Networking and Management", Deliverable 4, Proposal for test-beds and experimental assessment, September 2000.
- i. Keyword "Wavelength Assignment", Nortons Telecom Dictionary, 19<sup>th</sup> ed.

## List of acronyms

All-optical	Network element with no o/e or e/o conversion of the high-speed data
AOLS	All Optical Label Switching
ASIC	Application Specific Integrated Circuit
ASON	Automatically Switched Optical Network
ASTN	Automatically Switched Transport Network
ATM	Asynchronous Transfer Mode
BGP	Border Gateway Protocol
CAPEX	CAPital eXpenditures
CDR	Clock and Data Recovery
CoS	Class of Service
CRC	Cyclic Redundancy Check
CR-LDP	Constraint-based Routed Label Distribution Protocol
CWDM	Coarse Wavelength Division Multiplexing
DCN	(Management) Data Communications Network
DSF	Dispersion shifted fiber
DWDM	Dense Wavelength Division Multiplexing
DXC	Digital Crossconnect (often of SONET/SDH type)
EDFA	Erbium Doped Fiber Amplifier
EMS	Element Management System
E-NNI	External Network-to-Network Interface
e/o	electrical to optical
EoS	Ethernet over SONET
FEC	Forward Error Correction
FPGA	Field Programmable Gate Array
FSC	Fiber Switch Capable
FWM	Four-Wave Mixing
HDLC	High-level data Link Control
G.xxx	ITU-T recommendation xxx from the G-series.
GbE	Gigabit Ethernet
GFP	Generic Framing Procedure
GMPLS	Generalized Multi-Protocol Label Switching
IETF	Internet Engineering Task Force
I-NNI	Internal Network-to-Network Interface
IP	Internet Protocol
IS-IS	Intermediate System – Intermediate System
ITU-T	International Telecommunications Union – Telecommunication Standardizations Sector
LAN	Local Area Network
LCAS	Link Capacity Adjustment Scheme
LSC	Lambda Switch Capable
LSP	Label Switch Path
LSR	Label Switch Router
MAN	Metropolitan Area Network
MEMS	Micro-Electrical Machine System
MPLS	Multi-Protocol Label Switching
NMS	Network Management System
NOC	Network Operations Center
OADM	Optical Add/Drop Multiplexer
OAM(P)	Operation, Administration, Maintenance (Protection)
OC-n	SONET Optical Channel of order n, n=1, 3, 12, 24, 48, 192, 768
OCh	Optical Channel
ODSI	Optical Domain Service Interconnect
ODUk	Optical Data Unit of order k

o/e	optical to electrical
OEXC	Optical Cross-Connect with electrical switch-core
OH	(Frame/Packet) Overhead
OIF	Optical Internetworking Forum
OMS <sub>n</sub>	Optical Multiplex Section of order n
OPEX	OPerating eXpenditures
OPU <sub>k</sub>	Optical Payload Unit of order k
OSI	Open Systems Interconnection
OSPF	Open Shortest Path First
OSS	Operations Support System
OTN	Optical Transport Network
OTS <sub>n</sub>	Optical Transmission Section of order n
OTU-n	Optical Transport Unit of order n, n=1, 2, 3
OXC	Optical Cross-Connect
PDH	Plesiochronous Digital Hierarchy
PNNI	Private Network-to-Network Interface
POS	Packet over SONET, often IP/PPP/HDLC/SONET
POTS	Plain Old Telephone Service
PPP	Point-to-Point Protocol
PSC	Packet Swicth Capable
PXC	Potonic Crossconnect
QoS	Quality of Service
RFC	Request For Comment, IETF standardization
RPR	Resilient Packet Ring
RSVP	Resource ReserVation Protocol
Rx	Receiver
SAN	Storage Area Network
SCSI	Small Computer Systems Interface
SDH	Synchronous Digital Hierarchy
SDM	Space Division Multiplexing
SONET	Synchronous Optical NETwork
STM-n	Synchronous Transfer Module of order n, n=1, 4, 16, 64
TCP	Transmission Control Protocol
TDM	Time Division Multiplexing
TE	Traffic Engineering
TMN	Telecommunications Management Network
Tx	Transmitter
UNI	User-Network Interface
VC-n	SDH Virtual Container of order n, n=11, 12, 3, 4,
VoIP	Voice over Internet Protocol
VPN	Virtual Private Network
WDM	Wavelength Division Multiplexing
WAN	Wide Area Network
XPS	Cross-point switch

# 1. Introduction

In the early 1970's two (at that time) separate inventions lay the foundations of what we today witness as the information technology society. The first was optical communications with the inventions of practical low-loss optical fibres [1] and semiconductor lasers [2]. The second was the invention of packet-based communication that could run over multiple networks: the Transmission Control Protocol/Internet Protocol (TCP/IP) model [3].

Which of the two is more important can be argued: without optical communication the development of the long-distance high-capacity networks needed for the information technology society would be too costly and difficult, without the TCP/IP model and its relative simplicity the whole event of the Internet may not have happened in such an explosive way.

In the middle of the 1990's the success of both inventions was evident and ways of bridging the "optical Internet gap" started to be discussed. The concept of a "gap" was introduced since the available ways to run IP-traffic over fibres and especially Dense Wavelength-Division Multiplexing (DWDM) were not considered efficient and did not offer Gb/s capacity (e.g. IP/Asynchronous transfer Mode (ATM)/SONET with channels of only a few Mb/s). This fact has in some sense changed since then, with massive deployment of high-capacity IP-routers and DWDM systems. For optical communications the progress has, since the first systems, been focused on increasing the capacity over the fibre. When viewed as a network<sup>1</sup> of its own with optical network elements, the goal is also to increase the flexibility and scalability.

For TCP/IP, represented by IP-routers in the network, the goal was to interface with the optical fibre in the most efficient way. Also, as we now see with emerging standards such as Automatically Switched Optical Network (ASON) and Generalized Multi-Protocol Label Switching (GMPLS), interworking control planes allow IP-networks to make use of reconfigurable optical networks. By having integrated (separated but inter-working) control planes or one unified control plane, systems of different types can work together in a standardized way and services can be requested from system to system without the need for manual requests to each separate system type (layer network). The ASON/GMPLS standardisation effort is currently perhaps the most important driving force for optical networks. Thus, understanding these standards is crucial to understand the evolution of reconfigurable optical networks.

The idea of reconfigurable networks is not new. The connection set-up in the early telephony systems was almost completely manual, figure 1. But as these networks grew, manual set-up became impractical and costly. Automated cross-connection was a more efficient solution in terms of time, resources and thus overall cost. This example shows that reconfigurable networks are justified if they can show clear cost-effectiveness. Historically, the automation of higher and higher bandwidth circuits has continuously been done.

The introduction of networks built on the ASON/GMPLS standards and concepts form the final acceptance and proof of concept from over 20 years of research within optical switching.

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<sup>1</sup> The term network is general for something that ties things together, as a railroad network, electrical power network etc. An optical network ties optical network elements together using optical communication.

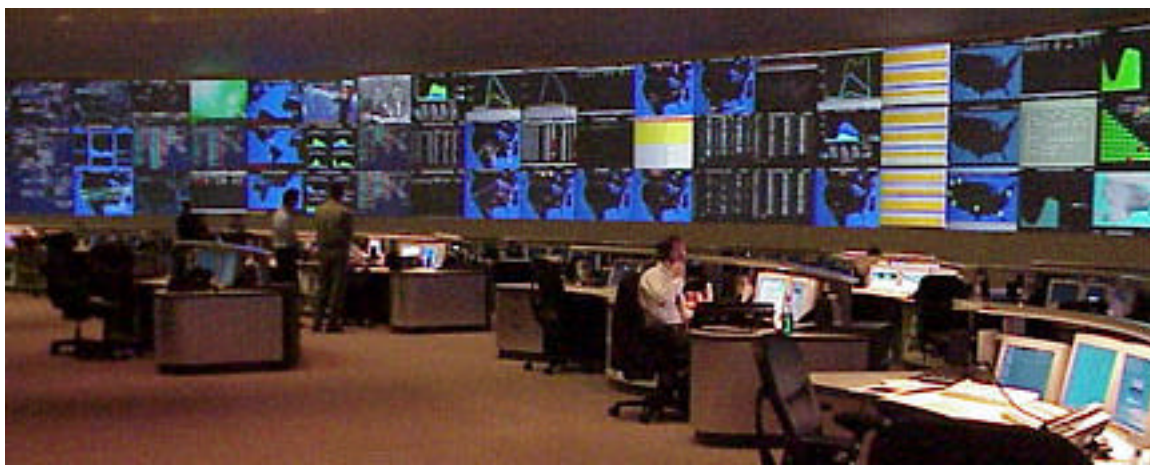


Figure 1. Picture of old telephony switchboard (top left) and central office in middle of Stockholm (top right). Ericsson finalized the perhaps largest and last manual central office in Moscow 1915. The full capacity of 60 000 lines was never fully utilized. This would have required extremely long arms of the (female) operators!  
An example of a modern central office (or more correctly Network Operations Center, NOC) is the AT&T NOC in Bedminster, New Jersey, USA (bottom).

## 1.1 Scope of this thesis

The main goal of this work was to bridge the gap between optical networks and voice and data bearing protocols, such as IP. This involves questions like: how can an optical network best be designed to enhance an IP-network in the areas of switching and transmission? This is the top-down aspect. Also, do special characteristics of such an optical network mean that changes have to be made to the IP-network for full utilisation of the enhancements? This is the bottom-up approach. As IP networks may use different kinds of underlying transport network, this work also involves understanding the behaviour and requirements of Synchronous Optical Network/Synchronous Digital Hierarchy (SONET/SDH) networks, Ethernet networks, etc. Another important aspect is to find ways of enhancing the functionality, or reducing cost, of such networks by using optical layer functionality, such as optical channel switching and protection.

In conclusion; the ultimate goal has been to decrease the cost of layered optical networks by simplifying existing solutions. This could, for example, be moving functionality from one layer to the other; up or down.

In this thesis, mainly the top-down approach has been used:

- The time-slotted transmission of papers [A, D] is influenced by, and applicable to packet-based network, such as IP. Since special characteristics of time-slotting to remedy optical

transmission impairments exists, for example with the scheme of paper [D], this also includes bottom-up issues like re-design of media access behaviour of the clients.

- Experimental investigation of optical add/drop multiplexers (OADM) and optical crossconnect (OXC) cascading for different technologies in papers [B, C, E, F, H] suitable for Gb/s clients such as SDH elements and IP-routers.
- Simulations on benefits for IP networks in using a reconfigurable optical network in paper [G], and
- Proposal of a new optical neighbour discovery method according to ASON/GMPLS standards in [I], which impose additional features of the optical equipment.
- Analytic investigations in paper [J] of port and common equipment prices for client and optical equipment necessary to achieve an overall cost-reduction when adding an optical crossconnection layer to a client network

The bottom-up approach has otherwise been restricted to discussions in the papers, for example on inter-working between an optical and IP layer regarding IP-routing and traffic statistics in paper [G].

It is my belief that a good scientific approach for research in this field is to first do a top-down investigation of the functionality needed, then do a bottom-up investigations on the impacts of the functionality possible. If needed, several such iterations should be done.

Chronologically, this work has mainly been from the physical layer up to, and including, the network layer, i.e. from optical transmission and network elements to IP-networks. Thus, the scientific approach described above, has not been strictly followed.

As both top-down and bottom-up issues are covered by the ongoing ASON/GMPLS standardisation, they form an important source in this regard. Since the evolution of networks is much dependent on current and evolving standards, knowledge of these standards are quite important for network research. This is somewhat different from transmission and, perhaps more so, for components research.

## ***1.2 Outline of this thesis***

The basic viewpoints and theoretical tools helpful for networking studies are presented in chapter 2 and serves as the foundations for later chapters and the papers. Concepts such as network partitioning (access, metro, core networks etc.), network layering (application, network, physical layers etc.) and network planes (management, control and data planes) are covered.

Chapter 3 deals with current high-capacity networks such as IP and SDH networks, which may benefit from being served by optical networks, and thus can be viewed as client in this sense. Also the evolving OTN (Optical Transport Network) is covered.

The next chapter, Optical networks, starts with a list of services offered by optical networks to clients, such as those clients described in chapter 3. The optical elements and systems used to realise these services are treated in the following section: point-to-point systems with or without WDM, ring systems with OADMs, and mesh network systems with OXCs. This section briefly covers the basic features of the different systems and the related work done in the papers.

Section 4.3, Optical networking for IP-based networks, puts many of the items of previous sections together and exemplifies this topic with an experimental network (Winchester). The future of optical networking, as defined in current standardisation in International Telecommunications Union – Telecommunication Standardizations Sector (ITU-T) and Internet Engineering Task Force (IETF), is covered in section 4.4.

Discussions and conclusions are done in chapter 5, followed by Summary of original work and References in chapters 6 and 7, respectively.

Finally, reprints of papers [A-J] end this thesis.

## 2. Structuring of networks

Modern communications networks are among the most complicated technological achievements of man. In order to divide the networks into less complicated parts, several concepts are commonly used: network partitioning, layering and division into functional planes. The concept of partitioning and layering for general transport networks is defined by the ITU-T in recommendation G.805 [4].

### 2.1 Network partitioning

A very simple network would be a point-to-point telephony line with one telephone at each end transforming the speech sound waves to electrical signals over a copper wire<sup>2</sup>.

If each telephone site needs to communicate with more than one other site, additional telephones and connection copper wires would be needed at each site. This is of course, a waste of telephones (unless simultaneous phone calls are desired) and wires, i.e. transmission equipment, and can be made more (cost) efficient by introducing switching. Now, hundreds or more sites can be connected to a central switch in a star network to gain connectivity to all other sites. The drawback is that each site would need an address to communicate with other sites. The address is the switching information needed by the central switch. This network can however be more efficient by breaking up the large central switch into several smaller switches that in turn are connected to each other. This solution provides better opportunities for scaling, as adding new sites only requires altering a minor part of the network equipment. The network described can be connected to other similar networks by introducing switches (not connected to telephones) for inter-network traffic. By introducing such network hierarchies, very large networks can be built. Dividing the network into hierarchies is sometimes called *network partitioning*. In the telephony world networks are often partitioned into access (or local loop), distribution, and transport network. (Different terms may be used by different operators.) In the datacom world it's called Local Area Network (LAN), Metropolitan Area Network (MAN), and Wide-Area Network (WAN). As telecom and datacom traffic are being mixed in equipment and networks, the terms are used loosely and are interchangeable. For example is the terms *core network/metro network* widely used today for both telephony transport/distribution networks and datacom WANs/LANs, respectively. Metro networks are often further divided into metro edge and metro core.

The difference in characteristics and thereby requirements for optical metro network compared to optical core and access networks, are discussed in paper [H]: typically the optical metro network need greater flexibility to traffic patterns (reconfigurability) and higher degree of transparency to different protocols.

Traditional telephony networks are circuit switched so that a fixed bandwidth (the circuit) is switched through the network before the traffic starts to flow. For non-human intervention, this requires signalling between equipment to set up such a circuit. The destination address is thus used only once.

In datagram networks, such as IP, the traffic consists of small pieces of data, datagrams, each with its own source and destination address. As the traffic includes its own address information, no "permanent" circuit needs to be set up. (Opposite to a telephony network, the destination address is thus used for each datagram.) On the other hand, network equipment on which a datagram enters must understand the destination address and know where to forward the datagram. I.e. routing information must be exchanged in the network.

Also packet-based communication can be circuit switched, as for example in ATM. In this context circuit switched and datagram network are referred to a connection-oriented and connection-less, respectively.

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<sup>2</sup> Note that this simple network is very application centric. Dealing with today's hierarchical and high-capacity transport networks, the end-services sometimes risk getting out of focus.



## 2.2 Network layering

In the early days of networking, i.e. the telephony systems up to the 1950's, the functions that the network performed were not strictly divided into separable functional blocks. This meant that a change in, for example, the application typically would require modifications in the switching hardware. When the networking systems grew in complexity due to size and functionality, dividing the functions into well-defined separable blocks, or layers, became advantageous.

In both circuit-switched and datagram networks, many different functions must be performed in order for the network to do its job. This is most evident for datagram networks, which include the following functions:

1. Conversion and coding of analogue information such as voice and images etc. to ordered sets of digital bits (often octets).
2. Grouping of octets into messages.
3. Dividing messages into proper sized parts, packets, for transmission.
4. Putting sequence numbers on packets to assure ordering and detect packet losses.
5. Adding error-correction/detection to remedy/detect transmission errors.
6. Find destination address and append to packet.
7. Apply signalling format and scramble or apply line-code to assure DC-levels and frequency content. Optical communication protocols use, almost without exception (datacom, telecom, video), binary two-level (digital) non-return to zero (NRZ).
8. Modulation on selected carrier frequency (commonly denoted wavelength in case of optical communication) for transmission over the physical medium.

Function 1 generates the actual data being transported while functions 2-7 provide additions needed to aid the transport. The former is usually called payload and the latter overhead (OH). Together they form integral parts of the signal being transmitted over the physical medium, both parts being equally important.

The above functions are fairly well separated and it is natural to group them into layers, implemented by protocols. Formally, a protocol is often said to be a set of rules on how to treat data within and between layers. A popular reference model, described in reference [5], combines both the TCP/IP and Open Systems Interconnection (OSI) reference models:

- Application layer -function 1 and 2
- Transport layer -functions 3-5 (end-to-end)
- Network layer -functions 3, 5, 6
- Data link layer -functions 4, 5, 6 (on each link)
- Physical layer -functions 7, 8

Introducing the concept of layers and defining their functions makes it possible to mix and match different protocols for many different user applications to achieve desired system functionality. Figure 2 shows an example of these layers and protocols, implementing them for MPEG (Moving Pictures Expert Group) video over fibre.

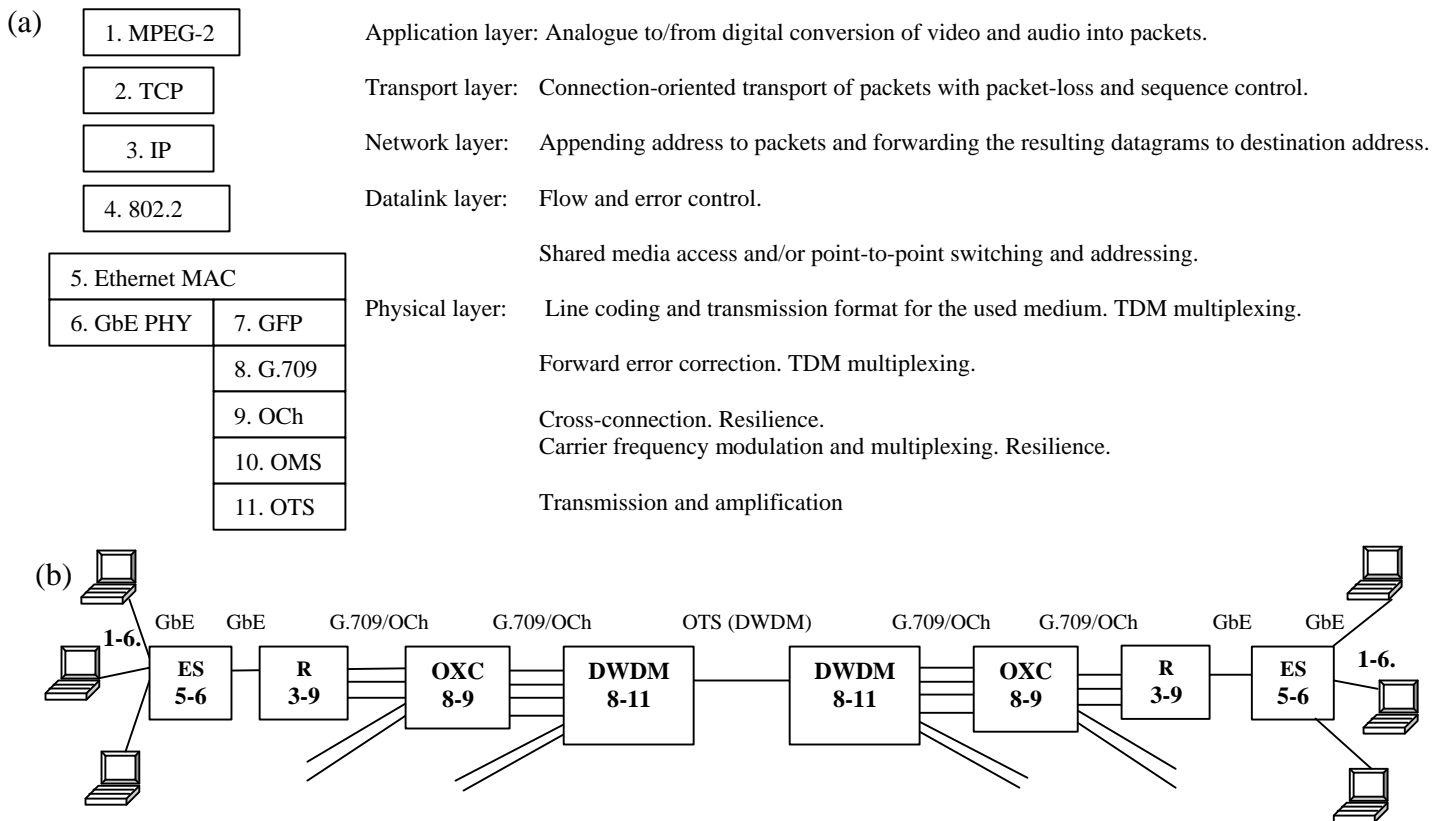


Figure 2. Example of protocols and layers for transmission of MPEG video over fibre. (a) shows the protocols and some functions they provide with the corresponding layers. (b) is a simplified view of network elements involved in such transmission including numbers referring to the protocols in (a). ES: Ethernet switch with GbE interfaces, R: IP-router with GbE and G.709 interfaces, OXC: Optical channel (OCh) crossconnect, DWDM: DWDM equipment with G.709 interfaces. The end-systems (laptop PCs) addresses each other on the network level (with IP-addresses), the ES performs switching on the datalink level (MAC-addresses), the router performs forwarding on the network level (IP-addresses) and the OXC performs crossconnection on the optical channel physical level (physical port number).

Naturally, many different cases like the example in figure 2 exist with numerous applications and protocols: Figure 3 shows some of the protocols used over fibre optical networks and some corresponding bitrates.

The term *bitrate* is used in this thesis instead of the term *baudrate* since only binary modulation is assumed. Also, when dealing with optical transmission, the physical layer bitrate is the important measure. Conversely, for a Gigabit Ethernet user, the capacity is 1 Gb/s since the line coding (each 8-bit block is coded as a 10-bit block), which results in 1.25 Gb/s on the optical fibre, is of minor interest.

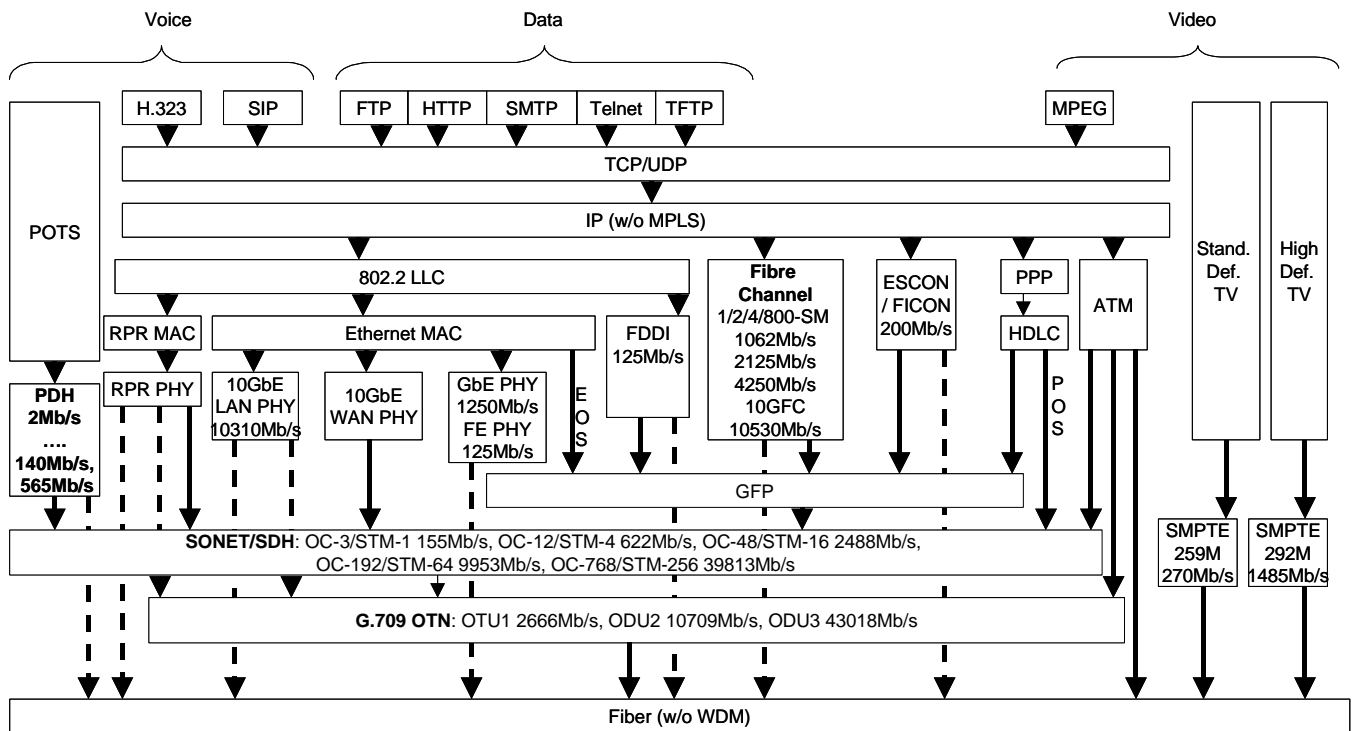


Figure 3. Example of protocols used over fibre-optic networks (several more protocols and combinations exist but are not shown due to space limitations). The OSI layers are not strictly followed horizontally. Protocols running over fibre are indicated with their transmission bitrates. Clients to the lowest optical layers can use either Optical Transport Network, OTN, (OCh/OMS/OTS), single fibre (OPS) or non-OTN WDM. In part taken from [6] and [7]. Abbreviations are according to the list of acronyms.

### 2.3 Network functional planes

In addition to networks being partitioned and layered it can also be noted that networks perform tasks of mainly three different types, which can be divided into three separate planes:

1. *Transport plane.* Data transport is the most obvious task and the main purpose of a network. It provides uni- or bi-directional information transport (transmission and switching) between users, detects faults and monitors signal quality. The dataplane makes use of the layered architecture discussed in section 2.2.

2. *Management plane.* In order for a human operator of a network to alter the data transport, e.g. reconfigure optical channels, or monitor the network performance (loss, delay, bit-error rate etc) some sort of management is needed. There are several approaches to divide network management into separate parts, see [8] for an overview. The OSI management model FCAPS (Fault, Configuration, Accounting, Performance and Security) is often used, especially in the telecommunications area.

ITU-T has produced a reference model, TMN (Telecommunications Management Network, recommendations M.3xxx), with four layers: business, service, network and network element management, see [8]. Added to the element management system (EMS) and network management system (NMS) is often an operations support system (OSS). The OSS acts as an umbrella system for management (often alarm collection) of layer transport networks. For a typical operator these layer networks are (among others) the IP network, the SDH network, and the DWDM network.

3. *Control plane.* For automatically switched networks, where network nodes may initiate switching in the network, control functions are needed. The control plane supports connection set-up and teardown by clients or the management system and also provides protection and restoration services.

This is the functional model of e.g. Automatic Switched Transport Network, ASTN [9], and consequently also ASON [10], see figure 4. With a common, or at least inter-working, control plane(s) for different network technologies, such as IP, Ethernet, SDH and optical networks, automation is much simplified.

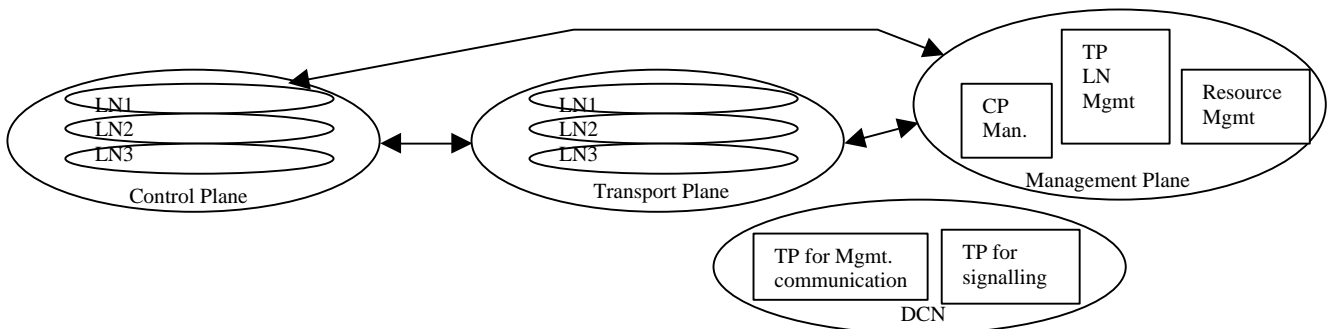


Figure 4. Relationships between transport (TP), management (Mgmt) and control planes. From G.8080 (ASON, [10]). LN: Layer Network, CP: Connection Point. In this figure three LNs are shown that could represent an IP network on a SDH network on an optical network. The arrows indicate that the management plane can either directly control the equipment of the transport plane one-by-one or leave this up to the control plane. In the latter case, the control plane could for example be given the end equipment address for a connection set-up and make a calculation on what other intermediate equipment also needing to be controlled. The control plane uses signalling for this connection set-up. The Data Communication Network (DCN) is used for communication between equipment such as network elements and management stations.

## 2.4 Theoretical tools for networks

The art of practical communications networking involves to a large degree non-theoretical, or non-scientific, work. This is, however, not the case for performance evaluation, improvement and other in-depth analysis and design.

Great simplification is achieved if transmission and switching can be separated, i.e. if the choice of switched path does not rely strongly on the transmission properties of the links the switched path traverses. It is then clearly possible to gain useful knowledge of the system without reverting to scientific methods, which nearly always must be used for transmission knowledge. However, to obtain certain basic network characteristics or network design inputs, theoretical models must be used.

Networks can be viewed as graphs and can thereby be examined by graph theory. See reference [11] for an introduction. Properties such as edge/node-disjoint, node-adjacent, node-degree, connected network, connectivity, planar network etc are defined by graph theory. Regular topologies, figure 5, are quite helpful in node degree dependent studies on networks. Many studies however, used irregular topologies taken from real networks such as, for example, the work in [G]. The average node degree is then the sum of node degrees divided by the number of nodes. The sum of node degrees can be found by multiplying the number of links by two.

The term *meshed networks* is typically used for networks having average node degree larger than 2 (although cases exist otherwise, for example a tree network).

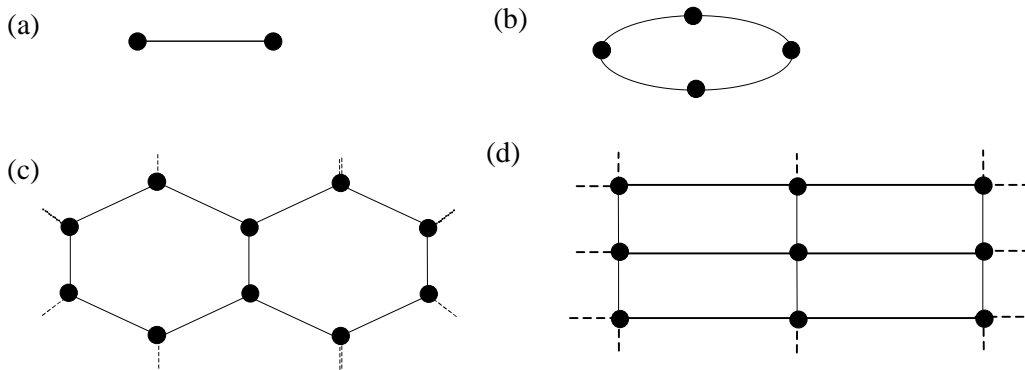


Figure 5. Regular topologies, i.e. networks where all nodes have the same node degree. (a) 1-connected (point-to-point), (b) 2-connected (ring), (c) 3-connected and (d) 4-connected. Dashed arcs symbolize the continuing topology.

Graph theory also provides algorithms for calculating, among other things, shortest paths and maximum flows. Especially useful for optical networks, and used in the present work, is shortest path algorithms, i.e. finding the shortest path between nodes in a network. “Shortest” is generally the path with the least cost when summing the cost associated with the links of possible paths. For optical networks, “shortest” could simply mean the paths with least number of links used as in [G]. More advanced costs can, for example, be based on transmission length or the number of channels already used on a link. The former can be used to minimize the propagation times while the latter can be used for load sharing of channels among available links. Amongst shortest path algorithm the Dijkstra algorithm can be shown to be the most efficient for non-negative cost links with a complexity of  $N^2$  for a network of  $N$  nodes [11]. Being central to path, protection path and restoration path calculations in optical networks this algorithm is presented in detail below. The shortest path from a start node  $s$  to all other nodes using Dijkstra is found using the following tree steps [11]:

For a network, let each node  $i$  be assigned a nonnegative real number  $l(i)$ , called the label of node  $i$ .  $l(i,j)$  is the cost of the link from  $i$  to  $j$ . Initially all labels are temporary. At each iteration, one of the temporary labels are made permanent indicated by \*, e.g.  $l(j)^*$ . After the algorithm is completed, each node label is the lowest cost from the start-node. The start-node is node  $s$ .

- Step 1: Set  $l(s)^* = 0$  and  $l(i) = l(s,i)$  for  $i \neq s$ , if  $i$  connected to  $s$ , else  $l(s,i) = \infty$ .
- Step 2: Among all temporary labels  $l(i)$ , pick  $l(k) = \min_i l(i)$ . Change  $l(k)$  to  $l(k)^*$ . Stop if no temporary labels left.
- Step 3: Update all temporary labels of the nodes  $i$  with  $(k,i)$  for all  $i$  by  $l(i) = \min [l(i), l^*(k) + l(k,i)]$ . Return to step 2.

Figure 6 shows an example of the Dijkstra algorithm.

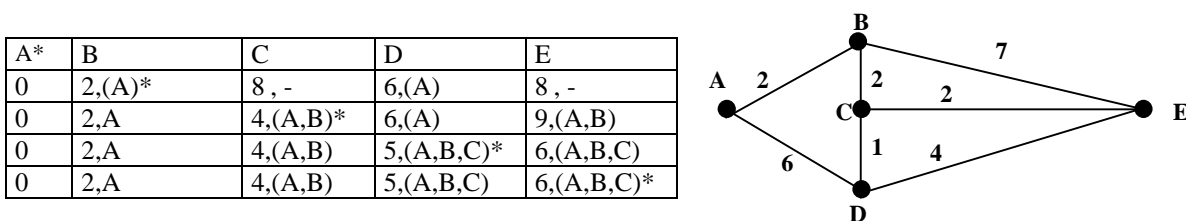


Figure 6. The Dijkstra shortest path algorithm. The network consists of nodes A-E. The link-cost is shown at each link. The lowest cost, and thereby shortest path, from node A to all other nodes B-E results from the algorithm. “\*” in the table indicate the least cost node (which haven’t earlier been the least cost node) in the present step. The next step starts from this node. The intermediate nodes in the recorded shortest paths are included within parenthesis in the table.

Shortest path algorithms are used in all types of circuit switched networks such as SONET/SDH, Asynchronous Transfer Mode (ATM) and ASON but also in IP routing protocols, such as Open Shortest Path First (OSPF).

For purposes of protection and restoration, two link (and optionally also node) disjoint paths must be formed for each connection.

In opaque optical networks, e.g. consisting of OEXCs as discussed in section 4.2.3, shortest path algorithms are a powerful tool and can be used directly for routing. In transparent WDM networks (see reference [13] for a discussion on transparency) without wavelength conversion, the wavelength allocation, or assignment, dimension must also be taken into account. This introduces the possibility that wavelength blocking might occur even when free resources (channels), of the wrong wavelength, are available. Wavelength blocking can be reduced to a great extent by using selective wavelength conversion, as discussed in both [14] and [15]. Routing and wavelength assignment algorithms have been extensively studied for optical networks, see [15] for an overview.

For both circuit switched and packet switched networks, queuing theory is used to estimate traffic blocking probability and delay characteristics, respectively. Queuing theory can also be used for estimating management and control traffic, network element CPU and memory usage etc.

Other theoretical tools for networks include abstract functional modelling, finite state machine analysis and object-oriented modelling/programming. These tools are partly used in papers [G,I] but not central to this thesis.

### 3. Clients to optical networks

All communications networks with Gb/s transmission needs have adopted optical versions for transmission. This section aims to describe some common clients<sup>3</sup> to optical networks.

Clients of different kind may co-exist and be served in parallel by a single optical network<sup>4</sup>. An example would be an IP network and an SDH network being served by the same DWDM and OXC network.

#### 3.1 IP networks

The Internet Protocol (IP) was originally ([3]) intended for transport of data between computers. This data was at first mainly for processing by supercomputers but has since expanded to encompass email, http, and pictures (JPEG, MPEG etc) among many others. Voice over IP (VoIP), functionally replacing traditional telephony, is becoming another important service over IP. Details on this can be found in [16]. Speculations that all services in the future will be carried by IP, “all-IP” are not uncommon. A reason for IP’s possible multi-service success is the fact that IP enables easier separation of services and transport. Earlier multi-service attempts, Integrated Services Digital network (ISDN) and Broadband-ISDN (B-ISDN)/ATM, had in this context a much more difficult task since it lacks programmability at the end-points and added multi-service capabilities required new terminals. With today’s personal computers (PCs) serving as end-points for IP, new (multi-) services can rapidly be introduced, independent of the transport network, since new application protocol software easily can be installed in the PCs. With increasing number of services, the traffic has a potential to increase more rapidly.

IP performs network layer functions such as framing of data units into datagrams, each with a source and destination address<sup>5</sup>. See reference [5] for an overview on data communications and layers and reference [17] for TCP/IP in particular. The datagram also includes information on version, length, fragmentation, number of router hops, among others.

The IP-addresses are global in the sense that they uniquely define a network attachment of a host (end-system). IP-addresses are grouped into networks so that an IP-address consists of network part and a host part. An analogy can be done with phone numbers or postal codes. An IP-packet is forwarded at each intermediate node, IP-router, according to its destination network address. Thus, each IP-router must have knowledge of all IP network addresses. As the number of IP-networks is very large, addresses can be summarized and grouped to form large chunks of the address space. This speeds up the forwarding decision since fewer bits of the addresses need to be examined. To determine the (best) route for each datagram each router requires information about the topology of networks (i.e. on which ports certain networks can be reached) so it can calculate shortest paths to destination networks<sup>6</sup>. This is done by routing protocols, such as OSPF and Intermediate System – Intermediate System (IS-IS).

Basic IP networks give no guarantee that a datagram will arrive at the intended destination or that the sequential order of several datagrams of an email, for example, will be kept. TCP remedies these best-effort characteristics by keeping track of packet sequences at each host and using retransmission if necessary. Understanding TCP’s behaviour is very important when dealing with TCP/IP transport: An application opens a TCP connection end-to-end and TCP typically retransmits packets if the transmission time exceeds 2-3 round trip delays. Thus, congestion or packet loss due to bit-errors increases the total traffic and affects real-time applications. With the retransmission capability, TCP does however provide some resistance against network failures (e.g. cable breaks)

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<sup>3</sup> From related paper [i]; a *client* can be said to be an object requesting or using the resources of another object, called *server*.

<sup>4</sup> A useful definition of a single optical network may be similar to the concept of an IP autonomous system [17], i.e. handled by a single administrative domain.

<sup>5</sup> For a background into the beginnings and drives for packet-based networks, see [18].

<sup>6</sup> This description is for link-state routing protocols, such as OSPF and IS-IS as opposed to distance vector protocols such as Routing Information Protocol (RIP) and Border gateway Protocol (BGP).

if they are quickly (ms) restored. Longer failures (10s of seconds) may cause the application to close the TCP connection, leading to service disrupts for the users.

IP version 4 (IPv4) is the current version used in the Internet. With Internets rapid growth the number of IPv4's 32-bit addresses will eventually run out. The Internet Engineering Task Force (IETF), serving as the Internet standardisations organisation, has therefore developed a new version, IPv6, with 128-bit addresses and improved security and multimedia support. IPv6 has been standardized and commercially available for a few years. In the literature, several ways of making the transition from v4 to v6 are proposed, for example as in reference [19]. More efficient use of v4 addresses and the amount of v4-installed equipment will stretch the life of v4 probably several years into the future but the general belief is that major transitions to v6 will happen during this decade. Presently, IPv6 transport is steadily increasing in carriers networks.

It is important to notice that IP does not include data link or physical layer functions and thus physical media, such as optical fibre, can not directly transmit IP, as seen in section 2.2. However, due to the popularity of IP, adaptations to virtually any physical medium has been made using a wide variety of protocols, see figure 3. IP-routers can be equipped with such interfaces as Ethernet ports, Asynchronous Transfer Mode (ATM) /SDH ports or Packet over SONET (POS) ports. Figure 7 show an IP-network with LAN, MAN and WAN (Core) routers and the intermediate networks and their corresponding router port types.

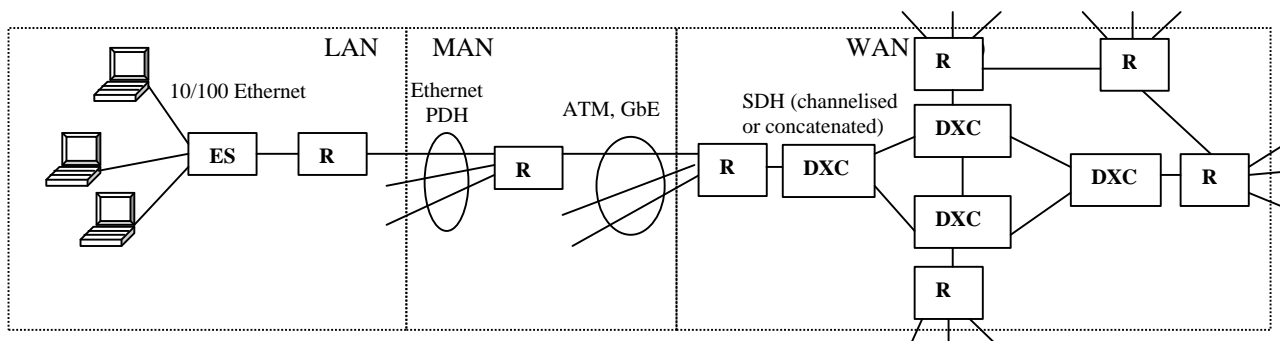


Figure 7. Simplified figure of an operator's IP-network consisting of LAN, MAN and WAN. Depending on the network part, the IP-routers (R) are connected by different networks (Ethernet, ATM, SDH) and use corresponding port types. The rings in the MAN indicate collector networks. If the core routers are equipped with high-speed interfaces, e.g. GbE or POS, they may be either directly connected (not using an SDH network) or connected over a reconfigurable optical (OXC) network. The router in the top right corner represents the directly connected case. The common practise of having dual redundant WAN (core) routers at each site is not included in the figure.

An IP-router makes use of ports with different transmission speeds by packet multiplexing; i.e. the output buffer of a port is filled with packets from different input ports in the order they are serviced and the buffer is emptied according to the specific output transmission speed.

The ability of IP to be transported on different underlying networks displays its flexible nature and consequently IP puts no special demands on optical transmission. As mentioned above, IP networks use IP-routers to find a datagrams path to its destination host. Each router-passage, or hop, has however the disadvantage of introducing unwanted effects such as packet loss and delays, collectively called Quality of Service (QoS)<sup>7</sup>. Therefore, as few router hops as possible should be used. This can be done by bypassing router using underlying networks such as ATM, SDH or optical. Optical layer bypassing was the foundation for paper [F] and [G] and is further discussed in section 4.3.

Even for the router hops that must be made (at least at the input, or ingress, and output, egress, of the network), dividing the traffic into classes with different priority can substantially improve the performance of high priority traffic [21]. This gives the possibility to assign different priorities for different types of traffic, such as delay sensitive voice, delay variation sensitive video or loss sensitive data.

IP can be enhanced with Class of Service (CoS) features using IntServ with ReSource Reservation Protocol (RSVP) signalling or DiffServ [22]. IntServ/RSVP establishes per-flow QoS with a flow defined by a 5-tuple (source address, destination address, transport protocol, source port and

<sup>7</sup> See [20] for an insight into the QoS, CoS, GoS terminology.



destination port). As the number of such flows can be very large in an IP core, IntServ is not recommended there. DiffServ on the other hand uses aggregation of traffic into different classes (using the same 5-tuple defined above) at network edges. The classes are distinguished by a Type of Service (ToS) field, which is used by the core routers instead of several fields as in IntServ. A different approach to achieve QoS in IP networks is IETF's Multi-Protocol Label Switching (MPLS), standardized in [23,24]. MPLS forms a circuit-switched layer below IP using the concept "route at the edge and switch at the core". Part of the advantages of MPLS at the outset was the fact that IP-forwarding done in software based on possibly several fields in the header is slower (i.e. lower packet throughput) than switching done in hardware based on a short label. Modern routers, however, use efficient network processors for forwarding so the switching advantage may not be substantial.

IP-packets with common characteristics (e.g. source/destination IP address, Type of Service) are labelled into a Forward Equivalence Class<sup>8</sup> by an ingress (edge) label switched router (LSR). The IP-packets are then switched based on that label at intermediate LSRs (which may change labels since they only have local meaning). The label is a 20-bit identifier, which can be encapsulated in ATM (using the virtual path/channel identifier, VPI/VCI), Frame Relay or PPP/LAN for IP transport over these protocols. MPLS thereby forms a method for efficient IP to ATM mapping. The labels give freedom in how Forward Equivalence Classes are routed for traffic engineering purposes: load balancing, Virtual Private Networks (VPNs), resilience (failure recovery) and constraint based routing in general. MPLS may use different signalling protocols to set up (signal) label switched paths (LSPs) between LSRs: CR-LDP and RSVP and BGP with traffic engineering extensions. Creation of LSPs can be *topology-driven* by pre-assigning labels based on the normal routing tables, *request-driven* using the signalling protocols or *data-traffic-driven* by identifying "large" flows and assigning them a label.

MPLS gives an operator extensive tools for traffic engineering but also introduces complexity and cost and it is debated whether MPLS will be the preferred choice for core networks.

The most common carrier of IP is Ethernet<sup>9</sup>. 90% or so of the worlds LANs run on Ethernet making the technology cost effective and well known. Ethernet use 6-byte hardware addresses pre-assigned by the vendor (unlike IP-addresses or phone numbers) so that every network interface is globally unique. The Ethernet frame accepts payloads of 0-1500 bytes, allowing, for example, variable sized IP-packets. Error-detection comes via a 32-bit Cyclic Redundancy Check (CRC) at the end of the frame. Ethernet comes with several versions in speeds and media (see reference [25] for an extensive overview):

10BaseT uses twisted pair cables connected in a star between end-systems and a hub (where the cables are physically jointed) or a switch. For a hubbed network, 10 Mb/s half-duplex shared media communication takes place, i.e. one transmitter (Tx) at the time can transmit at 10Mb/s. Before transmitting, a Tx listens to the media to make sure nobody else is transmitting (i.e. *carrier sense*). A switched network allows for simultaneous full-duplex communication between systems and also allows a network of both 10BaseT and 100BaseT systems (with a corresponding switch interface). Today typical LANs are switched with auto-sensing 10/100BaseT ports where the host port and switch port negotiate to find the highest common speed.

Fiber-optic Ethernet versions exist for 10 Mb/s (10BaseF), 100 Mb/s (100BaseF), 1 Gb/s (GbE, 1000Base-LX or SX for single-mode or multimode fibre) and recently also 10Gb/s for LANs and WANs (STM-64 framed). Fibre-optic Ethernet is normally full duplex.

Ethernets asynchronous nature enabling it to use shared media where each transmitter must obey silent periods to avoid collisions, lead to the idea to also use for example Ethernet to improve fibre-optic transmission impairments: in paper [A] silent periods of Ethernet communication would be advantageous for bi-directional fibre-optic systems while in paper [D] the silent periods could be used to avoid four-wave mixing.

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<sup>8</sup> Abbreviated by *FEC* in the MPLS community but this abbreviation is not used here to avoid confusion with Forward Error Correction used in section 3.3.

<sup>9</sup> The standard, IEEE 802.3, is called "Carrier sense multiple access, collision detect (CSMA/CD)". Ethernet is a product prior than the standard but the name hangs on. When "Ethernet" is used, "802.3" is intended.

With the introduction of Gb/s interfaces, Ethernet can provide an alternative to SONET/SDH for high-capacity core links. The lower price per transported bit of IP/GbE compared with POS has led to introduction of “Ethernet-based” operators, which also has forced the prices of SONET/SDH ports down.

Enhancements to Ethernet with priority classes and virtual LAN (VLAN) provide means for service differentiation and secure networking in, for example, an operator’s access network as discussed in [H].

Besides being used in the transport (data) plane, IP is widely used for management communication. In this case the hosts (end users) are the network elements and management stations communicating with IP over a DCN. Prioritisation of this traffic is typically desirable and done via e.g. MPLS.

### **3.2 SONET/SDH networks**

When telephony networks started to go digital with Pulse Code Modulation (PCM), a multiplexing TDM hierarchy, Plesiochronous Digital Hierarchy (PDH), was formed. See [26] for an insight into digital telephony systems. The higher levels of PDH, 140 Mb/s and 565 Mb/s, started to use fibre for transmission in the 1980’s but PDH’s weak points became clear as the traffic volume and network sizes increased. To accommodate for variations in bit-rates of different channels buffers had to be used, which were quite expensive at the time. Also, lack of good support for Operations, Administration and Maintenance (OAM) made the networks difficult to manage and thereby costly for operators. The introduction of SONET (initially in North America and then standardized as SDH<sup>10</sup> in the rest of the world) by ITU-T, promised remedies for all of PDH shortcomings. Details on SONET can be found in [27]. SONET and SDH are more similar than one might expect; most modern ASICs can be run in either SONET or SDH mode. The overhead octets are in general identical but the interpretation of the content may vary<sup>11</sup>.

SDH is synchronous meaning that a distributed reference clock<sup>12</sup> determines the basic bit frequency in the whole (operator’s) network. This gives that multiplexing, grooming, crossconnecting etc can be done without buffers. Multiplexing forms higher bit-rate channels out of lower bitrate channels typically in order to achieve more cost-effective transmission. Grooming is done to fill up (in order to reduce the number of) higher bitrate channels in the network. Crossconnecting is needed for connection setup, protection, restoration and grooming, among other functions.

SDH networks are optimised for 2 Mb/s and 140 Mb/s tributary channels but can also be used for 1.5, 34 and 45 Mb/s channels.

These channels are then synchronized to the network and put in virtual containers (VC-11, 12, 3, 4) Channels below VC-4 are called lower-order paths while VC-4 is called higher-order path.

SDH add/drop multiplexers (ADMs) and crossconnects (DXC) exist for different path levels: DXCs are labelled with m/n with m the highest access level and n the lowest crossconnection level.

Typical DXC are 4/1 or 4/4.

For transport, one or more VC-ns are put into transmission frames called Synchronous Transfer Modules (STM). These frames or transport modules come with bitrates in multiples of 4: STM-1/4/16/64/256 at 155/622/2488/9953/39813 Mb/s, according to the current standard ([28]).

Electrical versions exist for STM-1 while the rest are only defined for optical transmission. In reference to the DXC labelling above, an OXC with port-speeds and crossconnection at STM-16 would be called a 6/6 DXC (with the difference that the OXC does not alter the overhead as discussed in section 4.2). Thus, there’s no fundamental difference in moving from a 4/1 DXC to a 4/4 DXC compared with moving from a 4/4 DXC to an OXC handling STM-16 channels.

The OAM features of SDH are extensive (too extensive to some) including QoS parameters, in-band management and identifiers for all channels.

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<sup>10</sup> Since all the features of SONET and SDH is the same in the context of this text, the term “SDH” is collectively used for both SONET and SDH to avoid writing SONET/SDH whenever used.

<sup>11</sup> An example of the dissimilarities (as discussed in [27]) is the pointer handling. But if SONET equipment ignores some bits of the SDH pointer and vice versa, SONET and SDH equipment is in principle interoperable.

<sup>12</sup> The main clock is normally (dual) redundant.

Figure 8 shows a simple SDH network and summarizes some features.

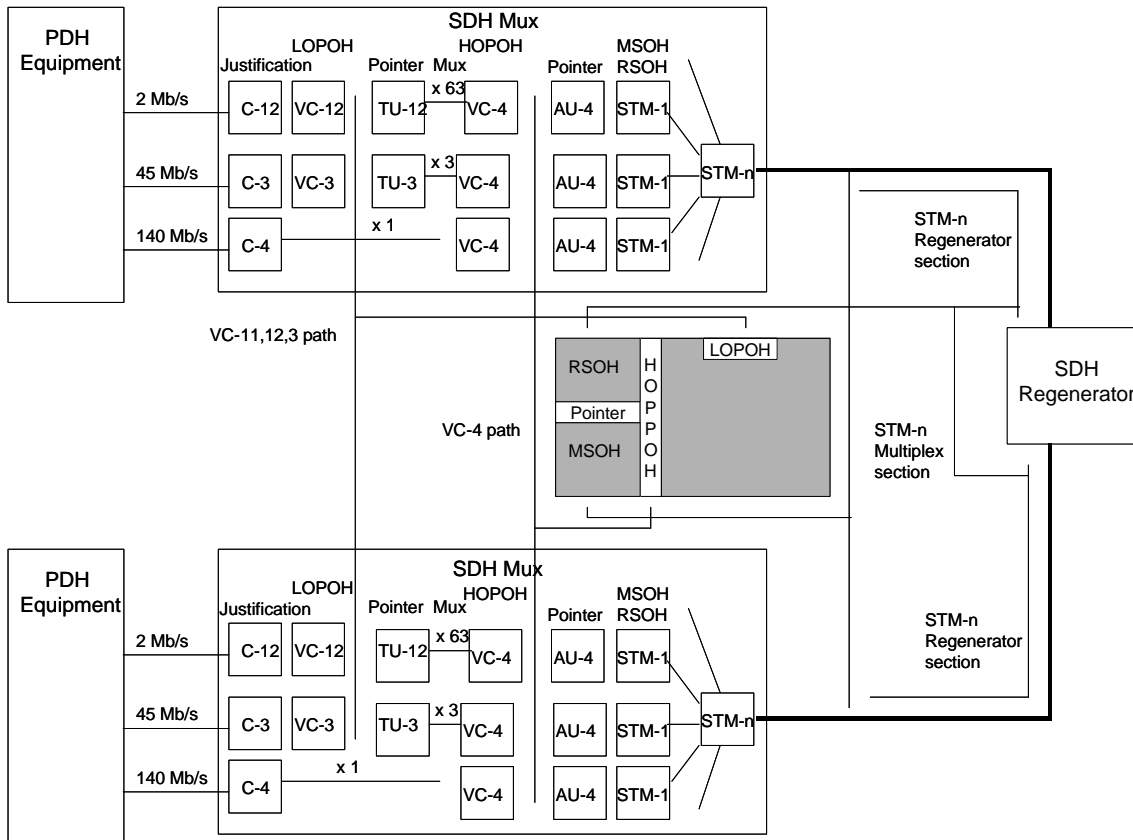


Figure 8. Channel mapping and multiplexing in SDH. PDH equipment with various interfaces (2, 45 and 140 Mb/s in this example) may use SDH muxes and regenerators for transport. The PDH signals are adapted to the synchronous frequency by justification and forms a C-n. Adding lower- or higher-order path overhead (LO/HOPOH) forms a VC-n. Pointers are used to indicate the start of the signal in the VC-ns. Lower order VC-ns are multiplexed to form a VC-4, which finally forms an STM-n (n=1, 4, 16, 64, 256) signal. The SDH regenerator terminates a regenerator section and the multiplex section is formed between the endpoint SDH muxes. The location of the overhead of the different paths and sections are indicated in the SDH frame in the middle.

One of the weak points of SDH is its inflexibility and coarse divisions of bandwidth channels: for a 5 Mb/s service a 2 Mb/s (VC-12) channel is not enough while a 34 Mb/s channel (VC-3) means low utilization. Virtual concatenation, see [28], makes it possible to allocate several VC-n's into a group (VCG) of bundled channels giving 2 Mb/s granularity. The term "virtual" comes from the fact that the transport network (ADMs/DXC) need not know about or identify the different channels in the VCG, which only is defined at the end-nodes. Dynamic channel re-sizing end-to-end can be done using Link Capacity Adjustment Scheme (LCAS) signalling [29].

Despite predictions of SDH reduction in favour of lower cost transmission, such as Gigabit Ethernet, still the vast majority of traffic in the operators transport networks runs of SDH. Therefore, the major client to optical networks of today is SDH. Apart from the need for well-defined protection switching strategies, treated in [30], SDH on reconfigurable optical networks is quite straightforward. When the cost for an OXC port is lower than for a DXC port an optical bypass layer can be formed reducing the total network cost, especially if protection is done in the optical layer, as investigated in [J].

### 3.3 OTN networks

What will come after SONET/SDH as the architecture of transport networks? The answer by ITU-T is the Optical Transport Network (OTN) defined in G.872 [31]. OTN deals with the transport and management planes of optical network (complemented by ASON for the control plane). OTN is intended to be more general than SDH when handling different client signals and be better adapted

to WDM networking by introducing management functions such as supervision, performance assessment and resilience. Three layers are introduced:

- Optical Channel (OCh) layer. Provides end-to-end networking of different clients (SDH, ATM, PDH etc.) with optical channel crossconnection and optical channel OAMP.
- Optical Multiplex Section (OMS<sub>n</sub>, n: number of channels) layer. Adds OAMP for WDM signals.
- Optical Transmission Section (OTS<sub>n</sub>) layer. Adds OAMP for transmission of WDM signals.

An additional layer of “Physical media layer network”, defined by the fibre type (specified by ITU-T recommendations G.652/653/655 etc.) is identified but not covered by OTN.

OTN also classifies processes to mitigate accumulation of transmission impairments (dispersion, non-linearities, noise etc.) with 1R, 2R and 3R regeneration. 1R deals with (linear) processes such as WDM amplification, channel equalisation and dispersion compensation. 2R adds digital reshaping (converting amplitude to phase noise) and noise suppression. With 3R, the signal is re-timed and re-shaped. It should be noted, however, than even with 3R, jitter and wander accumulates and limits the maximum network size for synchronous networks. For regenerator type elements, recovering the clock and data out of the signal itself using a clock and data recovery circuit (CDR), the minimum number of hops is 20 according to ITU-T G. 958.

The only specification of the OCh covering all requirements of OTN so far is the Optical Transport Unit (OTU) described by G.709 [32]. Adding overhead and Forward-Error Correction (FEC) to a client signal forms the OTU, see figure 9. The FEC adds 16 error-correction bits to every 239 bits. Stronger FEC codes are possible and intended for the future.

The main reason for deploying G.709 today is the improved transmission performance due to FEC, typically for upgraded DWDM systems (number of channels or channel bit-rates) or ultra-long haul systems such as submarine systems.

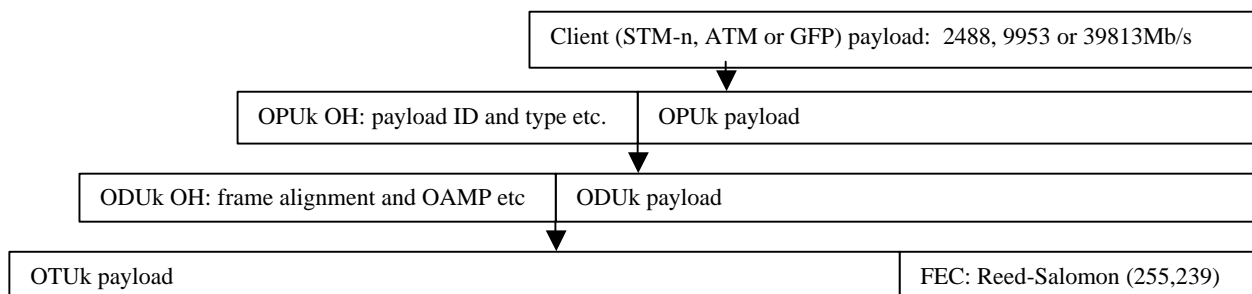


Figure 9. G.709 frame structure and relationships between Optical Payload Unit of order  $k$  (OPU $k$ ), Optical Data Unit of order  $k$  (ODU $k$ ) and Optical Transport Unit of order  $k$  (OTU $k$ ).  $k=1,2,3$ .

Closely related to OTN, and the foundation for its flexible payload mapping, is Generic Framing Procedure (GFP) [33]:

The need for flexible mapping into SDH or OTN was evident due to the rapid evolution of LAN and Storage Area Network (SAN) technologies such as Gigabit Ethernet and Fibre Channel. Instead of making special mapping standards for every protocol needing SDH or OTN transport, ITU-T and ANSI jointly formed GFP specified in G.7041 [34]. The GFP frame comes with a 0-65535 octets payload area and a 4-64 octets core header. The header includes payload length and header error correction. The payload further includes a payload header with a type field indication. Currently Ethernet, Point-to-Point Protocol (PPP), Fibre Channel, FICON, ESCON, and GbE types are defined; with more types to be added in the future. Client data can be mapped into the payload using frame-mapped or transparent-mapped modes. “Frame-mapped” encapsulates whole packets, producing variable length GFP frames while “transparent-mapped” fixed-length frames applies to 8B/10B linecode signals with the linecode stripped of before the data is put into the GFP payload. For transport over SDH networks, GFP can use virtual concatenation with a minimum number of VC-3/4 required for each client type.

### **3.4 Other common clients**

Video applications have long been anticipated as the main driver for bandwidth in optical networks. Most applications today are based on compressed video over IP, typically using MPEG-2 or MPEG-4. However, uncompressed video would demand even more bandwidth and naturally provides better quality. The benefit of digital transmission, storage, editing and processing was evident in the 1980's as TV studios began to replace the old analogue equipment. The standardizations organization, Society of Motion Picture and Television Engineers (SMPTE), then developed a serial digital interface for standard definition TV called SMPTE 259M, which could also be used over fibre. The data rate over fibre is 143 Mb/s up to 360 Mb/s depending on TV standard (NTSC with 525 horizontal TV lines at 30 frames/s, or PAL with 625 lines at 25 Frames/s) and the aspect ratio (standard 4:3 or wide-screen 16:9). A two TV channel interface at 540 Mb/s also exist. A standard for High-definition TV (HDTV) Serial interfaces, SMPTE 292M (1485 Mb/s) was developed in 1996. See reference [35] for a rare overview.

Ideas to not only use the uncompressed serial digital video within studios but also for transport over optical (WDM) network began with experimental networks in the mid 1990's, and forms an interesting client for optical network.

Storage area networks (SANs) are a major player in fibre optic communications, largely contributing to the number of optical interfaces deployed worldwide. SANs deal with the transport of data between servers and data storage devices such as disk arrays and tape libraries. The main protocol for this transport is Fibre Channel (see reference [36] for an in-depth coverage), which provides a more cost-effective solution than previous 50 or 100 parallel twisted copper pairs. Although Fibre Channel supports TCP/IP and others, the main protocol is Small Computer Systems Interface (SCSI), which provides a simple protocol stack with less overhead load on the host processor. Fibre channel includes 5 layers from upper layer protocol mapping (e.g. IP or SCSI) to physical interfaces and media. The basic data rate is 100 MBytes/s (1062.5 Mb/s with 8B/10B line code) with double-speed (2125 Mb/s) and quadruple-speed (4250 Mb/s) defined. Alternatives to Fibre Channel for SANs is Gigabit Ethernet and Infiniband. While Ethernet typically is less efficient for SAN applications is has a volume-, and thereby cost-advantage over Fibre channel. Infiniband is the new contender providing a more efficient connection to server processors [36]. Infiniband provide up to 12 parallel optical links for a total of 24 Gb/s on a basic 2 Gb/s serial bit-rate (2.5 Gb/s after line code). See [37] for a short overview.

## 4. Optical networks

The term *optical network* is quite general. It can mean, as in SONET, “just” optical point-to-point transmission over a single wavelength between network elements, i.e. a laser, fibre and a detector. The term is however often used to point out that more functionality than transmission is involved. The terminology for optical networks will probably not be fully set until the emerging standards for automatically switched optical networks, see section 4.4, are mature. Figure 10 show some terms used in the industry, but others exist.

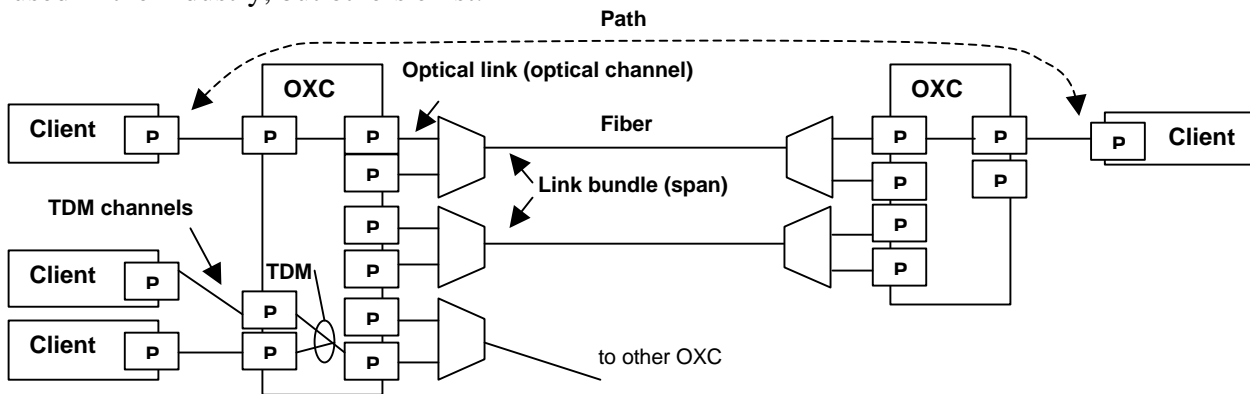


Figure 10. Subset of terms used for optical networks. *P*: Optical port consisting of a transmitter and a receiver, typically integrated into an optical transceiver. A path is formed between clients, which use one or more optical links, typically wavelengths, over one or more fibres. Several fibres between the same elements form link bundles. Fibres or link bundles subject to a failure from a single cable break form shared risk link groups (SLRG), see [67].

### 4.1 Services offered by optical networks

To understand the evolution of optical network elements one can look at the functions that are required for certain services desirable from an operator’s perspective. The success and deployment of the services offered is dependent on the relative cost of the optical solution compared to other solutions. The following is a non-exhaustive list of generic optical network services. Possible public relations (PR) advantages for an operator introducing optical services may exist, to an extent depending on the market climate, but are difficult to estimate and not further treated.

**1. Multi-wavelength transmission** reduces the number of fibres needed, which is cost effective (reducing the capital expenditures, CAPEX) and easily quantified for long distance networks. WDM can also be cost-effective short distance networks in special cases such as extreme cost of build-out (embedding), high rental cost for fibres etc.

**2. Network element bypassing.** By allowing traffic not terminated at a site to be bypassed by optical networks elements, the port count of client network elements can be reduced. This bypassing is referred to as creating an *optical express layer*. Given that the port cost of the optical element is lower than the client element, a quantifiable cost reduction, i.e. CAPEX, is obtained. This has been investigated in several papers, with SONET/SDH elements and IP-routers as clients in [38] and [94,95], respectively.

Paper [J] performs an analytical investigation, in contrast to the computer simulations done in the papers above, on how large the optical port and common equipment cost can be compared to the client ports and common equipment cost. Using the fact that a particular path in a network is “blind” to the rest of the networks topology, (i.e. regardless if the network is a ring or a mesh, a path only sees an ingress node, one or more intermediate nodes and an egress node) a simple model not dependent on network topology was formed. This paper provides simple expressions for the port costs alone and also makes investigations on the more complex combined port/common equipment cost. The analysis also incorporates the fact that introducing optical bypass (an optical express layer) enables the use of smaller client equipment, and thus lower client common equipment cost. The analysis shows that an overall cost reduction (both ports and common equipment) typically can

be in around 30% for medium size networks (30 nodes) and up to 60% for large networks (100 nodes).

An even larger cost-reduction can be obtained if letting bypassing traffic be directly connected using an optical patch-cord. This results, however, in static networks where manual labor cost, i.e. OPEX, may significantly increase and eliminates cost-effective optical failure recovery.

Beside a port-cost reduction, bypassing of intermediate nodes also improves the QoS for packet-based traffic. The reduction of such intermediate hops was quantified in paper [G] and is discussed in section 4.3.

**3. Provisioning.** This is the basic service of setting up a connection from an optical network ingress point to an optical network egress point for a client demand. This could for example, be of virtual private network (VPN) type, as discussed in paper [F], where a customer to the optical network operator leases the optical channel. This is currently subject to increasing interest in the form of *Wavelength services*. Such services offer more transparency and flexibility compared to framed connections such as an SDH VC-n connection and compared to leasing dark fibres; service demarcation with several management options.

The shorter provisioning times made possible with reconfigurable optical elements increases the revenue and reduces manual labour cost, i.e. OPEX, which may be larger than the equipment cost as pointed out in [39].

Fast provisioning also facilitates dynamic time-sharing of resources, such as content (e.g. video) servers.

**4. Network reconfiguration** (not based on provisioning of new connections) needs to be done more or less frequently when network elements are being installed, removed, replaced or serviced. This could be due to network optimisation, such as re-routing of existing circuits to links where capacity exist instead of upgrading congested links [40]. Using optical network elements such as OXC reduces time and manual labour, i.e. OPEX reductions.

**5. Loop-back testing** is a useful tool for a network operator to, for example, isolate performance degradations.

**6. Failure recovery**<sup>13</sup> protects or restores channels from cable breaks or failing network elements, which can be costly for a capacity provider guaranteeing a certain quality. The recovery can either be non-signalling-based (except for failure propagation), called protection switching, often done in hardware, or signalling-based, called restoration, often done on software<sup>14</sup>.

The recovery can be done on OCh or OMS/OTS level and on span or path (end-to-end) level.

Protection can be of 1+1 or n:m type. For the 1+1 type, switching to the protection resource is performed at the receiving (or transmitting) side only in case of failure of the working resource<sup>15</sup>.

Thus at the transmitting (or receiving) side only a splitter is needed. For the n:m type, a failure on any of the m working resources is switched on both sides to the n dedicated protection resources.

This gives that the n protection resources can be used for low-priority traffic.

In the case of mesh network path protection, finding two link or node disjoint paths with total minimum transmission cost is not trivial. Surballe's algorithm solves this problem by using the basic Dijkstra algorithm and dividing each node into an input and output part [12].

The main advantage of protection is the fast recovery (<10ms for an OXC<sup>16</sup>) that can be achieved since switching does not need to be performed in, and signalled to, the intermediate network. The

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<sup>13</sup> Instead of *failure recovery*, the terms *resilience*, *survivability*, among others, are often used.

<sup>14</sup> ITU-T G.805 defines protection as replacement of a failed resource with a pre-assigned standby, and restoration as replacement of a failed resource by re-routing using spare capacity.

<sup>15</sup> Working and protection resources are in the literature also sometimes called primary or ordinary and secondary, backup, or spare, respectively.

<sup>16</sup> The total recovery time (the time from the service interrupt to when the service is recovered on the physical level) depend on several things such as on the element(s) switching time, and the failure detection and propagation time (dependent on the network size).

drawback is the relative high additional cost for dedicated protection capacity, which in the 1+1 mesh network path protection case means an increase of more than 100% since the protection path normally is longer than the (shortest) working path.

To achieve lower cost for recovery in mesh networks, restoration can be used which utilizes shared back-up<sup>17</sup> capacity. For an overview on restoration in mesh networks, see [87]. The sharing can be done between working paths that are not affected by the same link or node failure(s) but whose back-up paths can be made to overlap at some links. Now, at the overlap links, one of the back-up resources is not needed since the working paths are not affected by the same link/node failures. The main advantage is that the back-up capacity now can be as low as 50% [81]. The possibility of achieving such low numbers is however strongly dependent on the network topology and the demand set. The main drawback is the signalling and switching needed at intermediate nodes, which severely can delay the recovery. Also, if the restoration path for each working path has not been computed prior to the failure (pre-planned) this may increase the recovery time.

Finding solutions for working and protection routing using minimum number of links is very complex. Computational methods using linear programming have been presented and used by several groups [88-90].

Figure 11 exemplifies the difference between dedicated protection and shared restoration in a mesh network.

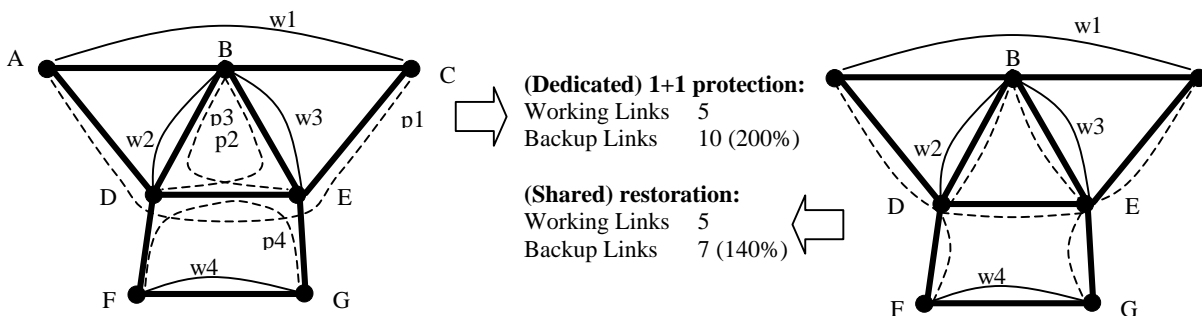


Figure 11. Example of protection (left) and restoration (right) for single link failures. Four demands (A-C, B-D, B-E, F-G) with working paths in a 7 node network. In the 1+1 protection case, 200% backup links are needed while for restoration this reduces to 140%. For the restoration case also a new demand D-E could be deployed without adding backup capacity.

Other services can be listed based on more special cases, such as optical peering instead of IP-peering at operators IP inter-connecting points, as discussed in [41].

When it comes to whether the services above require reconfigurability in the optical layer or not, four groups can be formed: Service 1 does not require reconfigurability, services 2-4 does not require it but benefits thereof, service 5 requires reconfigurability in reality while service 6 requires it for meaningful function.

Based on these groups, the failure recovery service is the most obvious, and thereby the most natural, reason for deploying reconfigurable optical elements today.

It can be noted that the services 2-6 are all variations of the basic space switch function in OXCs or dynamic OADMs.

## 4.2 Optical systems and network elements

The term *optical network elements* is used for network elements that do not alter either the overhead or payload of the frames or packets traversing them, or when such alteration is done totally in the optical domain. Conversely, electrical network elements, such as SDH elements, alter overhead content of channels in the electrical domain. These are fairly well accepted definitions although others may exist.<sup>18</sup>

<sup>17</sup> When dealing with restoration, the term *back-up* is used for the recovery capacity instead of *protection* to avoid confusion with dedicated protection.

<sup>18</sup> One of the reasons for excluding overhead write possibility for OXCs is the view that they should be protocol (and bitrate) independent. However, with the new generation of programmable logic devices capable of up to 10 Gb/s



Since the middle of the 70's when fibre optic transmission became practical, the evolution has followed traditional networking. First, the research and development of point-to-point links has taken off with major advancements in materials and components: single channel transmission of up to several 100 Gb/s and multi-channel transmission with several Tb/s. Then, simple network topologies such as busses and rings using OADM can be achieved. Finally general mesh topologies with OXC were developed. Figure 12 show examples of optical point-to-point, bus and mesh networks. This thesis focuses most on OXCs, which lay the foundation for papers [E-I].

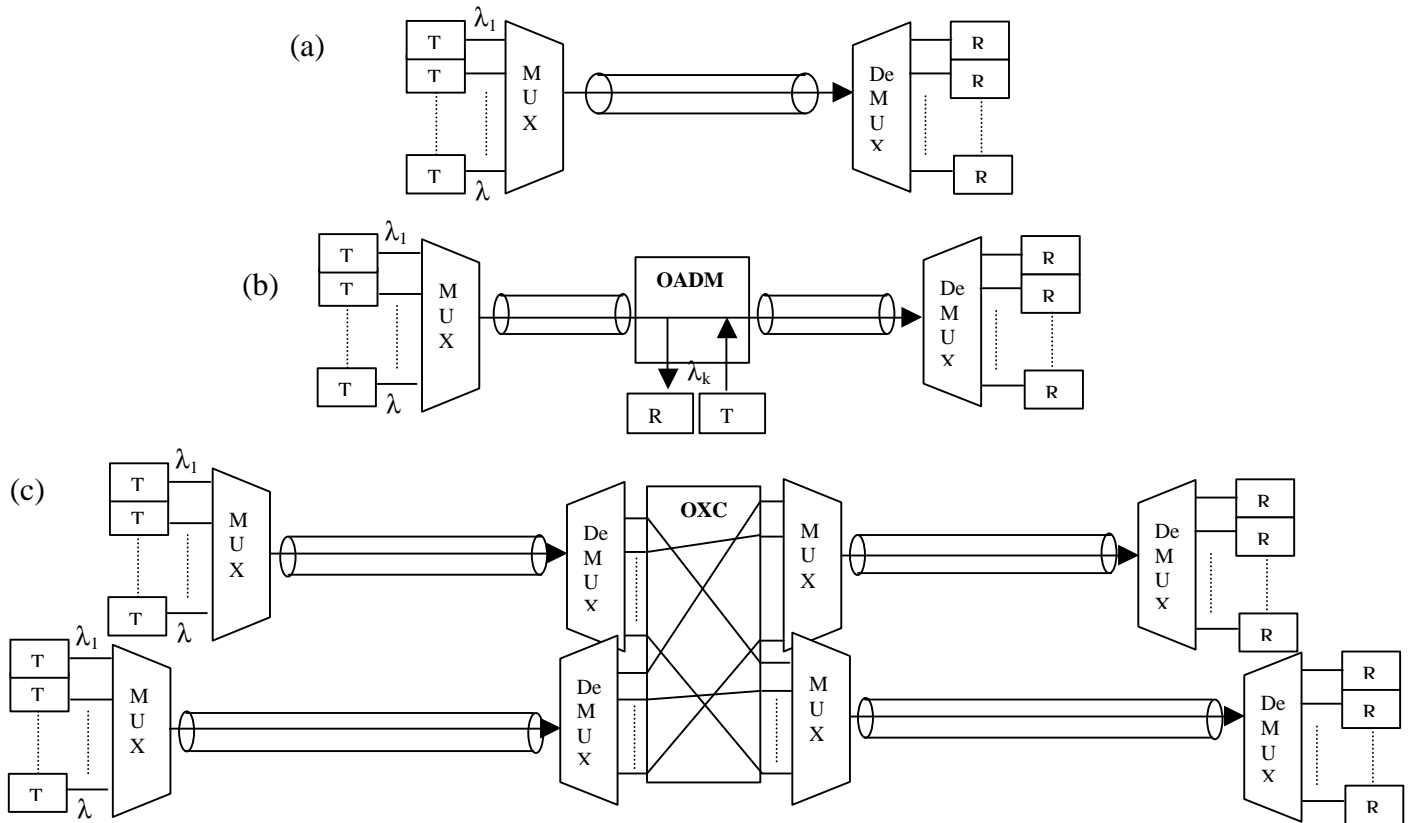


Figure 12. Different optical network elements needed for different topologies: (a) point-to-point WDM with transmitters (lasers), wavelength mux, demux and receivers (photo-diodes), (b) bus (open ring) with OADM and (c) mesh with OXC. (a) and (b) are in correspondence with figure 5 while (c) are used for higher node degrees such as (c-d) in figure 5. For all networks, WDM or space-division multiplexing (SDM) may be used. Only unidirectional elements are shown but in practice bi-directional elements are almost always used.

#### 4.2.1 Point-to-point systems

The proven advantage and success of fibre-optic communications is due to the fibres low loss and small phase distortion. The loss is minimum at 1550 nm where it may be slightly below 0.2 dB/km. Reference [49] give further details on mechanisms contributing to the loss.

Linear and non-linear effects, defined by their independence or dependence on the optical signal power respectively, may distort fibre optic signals for high signal levels and/or long transmission lengths.

Linear impairments include chromatic and polarization dependent dispersion from the material/waveguide refractive index frequency dependence and the residual non-cylindrical shape of the fibre, respectively. Chromatic dispersion can be fully compensated in the optical domain by, for example, compensating fibres and also to some extent in the (analogue) electrical domain. Chipsets for electrical compensation of several dB is commercially available today. Polarization dependent dispersion (PMD) is more difficult to compensate for since it may change on different timescales as the signal polarization and/or the fibre changes.

Non-linear impairments come from the real and imaginary parts of the non-linear susceptibility as described in reference [93]. It manifests through several phenomena such as self-phase modulation (SPM), cross-phase modulation (XPM) and four-wave mixing (FWM) for the real part and stimulated Raman scattering (SRS) and stimulated Brillouin scattering (SBS) for the imaginary part. The real part contributes to the refractive index so that a high-power signal may affect the refractive index (leading to signal distortion) for itself (SPM), or in case of multi-channel systems also for other channels (XPM and FWM). Paper [b] presents a simple expression for the FWM effect in the case of a signal and a single pump wavelength.

The imaginary part of the susceptibility leads to molecule and/or atomic vibrations, which scatter portions of the light (and thereby distort the signal) mainly in the forward direction (SRS) and backward direction (SBS) respectively. The distortion due to SRS increases with the frequency spacing (due to e.g. high channel-count) while the distortion due to SBS is self-dependent on the channel's signal power.

ITU-T has specified<sup>19</sup> six transmission bands: the O-band (1260-1360 nm), E-band (1360-1460 nm), S-band (1460-1530 nm), C-band (1530-1565 nm), L-band (1565-1625 nm) and the U-band (1625-1675 nm). The O-band and C-band has also been known as the second and third transmission window. Not specified by ITU-T as a band is the first window around 850 nm in multimode fibres, today mainly used for short distance LANs or optical interconnects. A dramatic improvement of fibre-optic systems was the introduction of fibre optic amplifiers in the late 1980's, which could compensate for the loss. First, and still the most widely commercially used was the erbium-doped fibre amplifier (EDFA), which operates in the C-band. An overview of fibre amplifier types for the other bands is given in [91].

Fibre-optic transmission can be done with one or several carrier frequencies or wavelengths, referred to as single-channel or multi-channel systems respectively. Single-channel systems are sometimes called electrical time-division multiplex (ETDM) systems, as the fibre-optic signal often, as with SDH, consists of several channels within the serial stream of bits. ETDM systems, contrary to multi-channel (WDM) systems, do not need optical components for multiplexing and demultiplexing the wavelength and are therefore more cost-effective up to a certain bit-rate. This bitrate is today typically 10 Gb/s (i.e. a single-channel 10 Gb/s system is less expensive than a 4-channel 2.5 Gb/s system). There is presently much debate whether this also will be true for 40 Gb/s systems (compared with 4x10 Gb/s or 16x2.5 Gb/s systems) and if so, when? One of the reasons for questioning a near-term large-scale introduction of 40 Gb/s is the much increased accuracy requirement of compensations for chromatic and polarisation-dependent dispersion.

When not willing to risk running out of capacity, multi-channel systems provide smooth capacity upgrade supported by fibre amplifiers. The term WDM often means two channels at 1310 and 1550 nm, more channels with a channel spacing of up to 400 GHz around 1550 nm is called Dense-WDM (DWDM) while Coarse-WDM (CWDM) is for 20 nm spacing around 1310 nm and/or 1550 nm. ITU-T has specified the DWDM grid and recently also the CWDM grid. See [42] and [43] for the corresponding standards.

The ultimate capacity of a fibre optic system can be estimated using Shannon's information theory [44]. By assuming Poisson statistics, see [45], the capacity is in the order of a few hundred Tb/s. Recent ultra-high capacity systems do not quite reach this capacity but still show that impressive 10 Tb/s systems are possible [46]. It should be noted, however, that this is around 10 times the total core traffic of a mid-sized European operator of today<sup>20</sup>.

Optical communication, almost without exception, consists of a continuous flow of binary amplitude-modulated signalling, i.e. bits. The physical layer protocols designed for fibre-optic links often use contiguous frames (e.g. Gigabit Ethernet, STM-16). Communication using IP, on the other hand, consist of asynchronous flow of packets. This is well suited for e.g. Ethernet over shared media, which utilizes transmission time-sharing using asynchronous frames.

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<sup>19</sup> In the literature, ITU-T is often cited for the specification of these bands, but the author of the presents thesis have not been able to find the recommendation of this specification.

<sup>20</sup> Based on information from several European operators.

When sending IP-packets over fibre-optic links, asynchronous, or time-slotted, transmission could also be used. The research field of optical packet switching considers both switching and transmission in the optical domain [82]. Such approaches, e.g. all-optical label switching (AOLS), use the argument that electronic processing and o/e conversion consumes high power, space and cannot handle Tb/s traffic. But, given historic development with decreasing low-voltage electronics and small form-factor optical transceivers<sup>21</sup>, the possible gain of optical processing is still pushed into the future. Thus, while following the paradigm of *electronic processing and optical transmission* proven effective in the last decade, time-slotted transmission was investigated. Papers [A,D] was shown to improve certain transmission impairments:

Rayleigh scattering, leading to back-scattering, limits bi-directional transmission using the same wavelength in both directions over a signal fibre [83]. This is a particular drawback in using bi-directional DWDM systems where bi-directional transmission at the same wavelengths is not possible over a single fibre. Today, almost all bi-directional transmission takes place over fibre pairs, with one fibre for each transmission direction. If bi-directional transmission of the same wavelength was possible, not only would the number of fibres be cut in half but also the number of OXC and OADM ports, given that they are optically (bidirectionally) transparent. However, since current WDM systems typically are using o/e/o transponder and uni-directional EDFA, new systems would have to be installed to utilize the reduction in fibres and OXC/OADM ports. Rayleigh scattering is the effect of accumulated small back-reflections in the amorphous fibre core. The net sum of optical power due to back-scattering is a function of the time-average power emitted into the fibre. If the emission consists of time-slotted packets the net sum of back-scattering power reduces and so does the power penalty compared to uni-directional transmission. Paper [A] show this experimentally and the result is approximately that the power penalty decreases with the ratio of transmission period over total period, i.e. duty-cycle. A duty-cycle of 1/2 gives a power penalty of around 3dB, 1/4 around 2 dB, and 1/10 around 0.5 dB. Also frequency detuning (of A-to-B's carrier frequency compared to B-to-A's) was evaluated. As the frequency detuning exceeds the signal's electrical bandwidth, the power penalty compared to uni-directional communication becomes negligible.

See figure 13 for a schematic on time-slotting and frequency-detuning in bi-directional fibre-optic transmission:

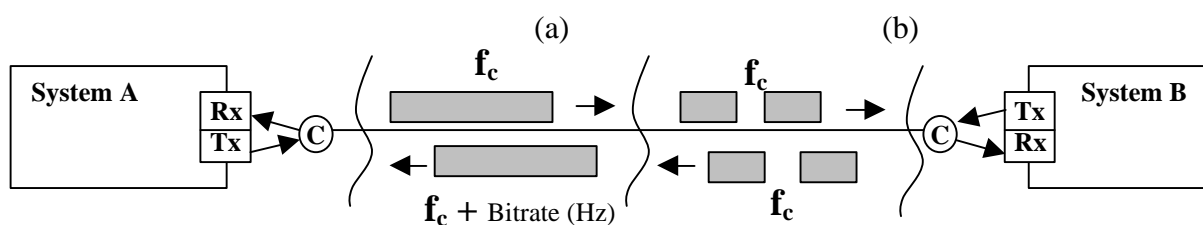


Figure 13. Bi-directional transmission using frequency-detuning (a) and time-slotted transmission (b). The frequency-detuning method uses continuous transmission at different carrier frequencies ( $f_c$ ) in the two directions: one of the carries are detuned by (at least) the electrical bandwidth of the opposite direction signal. Time-slotting may use identical carrier frequencies but introduces silent periods in between transmitted data. Note that the single-fibre transmission comes at the expense of one optical circulator (denote C) at each end.

Also non-linear effects in uni-directional transmission can be improved by time-slotting. Four-wave mixing, FWM, is a severe transmission impairment when using DWDM over low-dispersion fibre (Dispersion Shifted Fibre, DSF) if signal powers are in the order of  $-10$  dBm or higher. Since DSF is not unusual in older installations in some countries, notable Japan and Italy, FWM prevents the use of DWDM as a capacity upgrade option. Due to the widespread rollout of DWDM systems, the use of DSF fibres will probably be reduced over time.

<sup>21</sup> Witch shifts from 5V->3.3V->2.5V->1.8V supply voltage and small line width processes ( $<0.25 \mu\text{m}$ ) the power consumption and chip space allows for 40Gb/s processing, however deployed in small volume due to weak market demand. Further, with small form-factor 10 Gb/s transceivers, such as XFP, 800 Gb/s 19''/9U (483 x 400 mm) systems are possible today. On the other hand, new results within the field of optical nano-structures (see for example [84]) may lead to size and power efficient optical functions in the future.

Figure 14 show that the FWM product of two neighbour channels can distort a DWDM channel. Now, as presented in paper [D], time-slotting is used with the condition that a channel is allowed to transmit only when one of the two shorter (or higher) wavelength channels are transmitting. This rule guarantees that distortion due to FWM of close wavelength channels (which is more effective due to lower phase-mismatch compared to far off wavelength channels) is eliminated. This gives that 2/3 of the channels are allowed to transmit simultaneously, which could be a good solution for packet based systems such as IP.

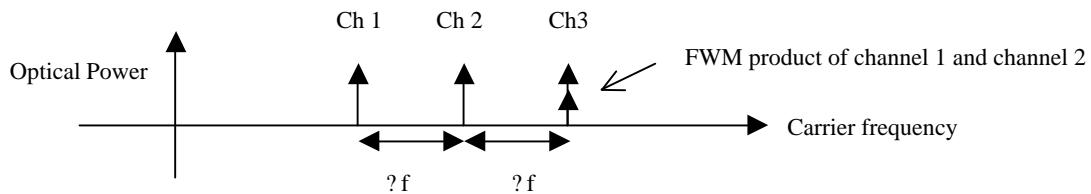


Figure 14. DWDM system of equidistant spaced channels (channel 1, 2, 3). Channel 1 and 2 produces a FWM product that distorts channel 3. Only one FWM product is shown. If one of the channels 1 and 2 is not transmitting, channel 3 will not be distorted.

Time-slotted transmission could also possibly be used to remedy other types of transmission impairments. One could be optical cross-talk in all-optical devices, such as OADM or OXC. See reference [47] for details on cross-talk. Another could be optical amplifiers, such as EDFAs. In the saturated region, the gain of an EDFA is inversely proportional to the average total input power. If this power is reduced due to time-slotting a higher output power can be realized and thereby longer amplifier spans.

#### 4.2.2 Ring (OADM) systems

Ring networks have traditionally offered more simple management and planning than meshed networks and is thus often the first choice for a new operator. Furthermore, ring networks have the advantage of requiring the least amount of fibre for a protected against link failures but the nodes must in general handle more bypass traffic than higher degree networks. Cost-effective OADMs should then not have too high cost per bypassed channel. Rings have traditionally utilized wavelength re-use. However, when the number of usable wavelengths exceeds the number of connections desired, this is no longer necessary.

The relative simplicity of ring based DWDM systems and the availability of several wavelength-selective technologies useful for OADMs has lead to substantial effort and research being applied this area [15]. OADMs can be either static (fixed wavelength channels added and dropped) or dynamic (added or dropped channels can be selected). The latter type is sometimes called *reconfigurable* OADM (ROADM). Presently, commercial static or dynamic OADMs for DWDM systems can handle up to 160 10Gb/s channels, typically with 80 channels in each of the C- and L-bands.

Only OADM without o/e conversion, as shown in figure 12(b), is treated here.

As rings experience large number of average hops for the connections (thereby large amount of bypass traffic), the *cascadability* of the OADMs, i.e. the number of hops possible from a transmission point of view, is an important characteristic. The performance measures relates to the following effects:

- Insertion loss (attenuation or gain): wavelength-dependent, polarization dependent.
- Dispersion: Chromatic, Polarization-Mode.
- Optical band-pass filtering.
- Crosstalk: optical in/out-band, electrical in/out-band, phase-matched/not phase-matched. (See reference [47]).
- Noise, if gain is involved

OADM architectures can be divided into three base types: broadcast and select (BS) [48], (de)multiplexer, and notch. For bypassed channels, effects other than wavelength-independent attenuation should in principle not be present for BS and notch types. Conversely, the (de)multiplexer type has the disadvantage of filtering effects at each node. Paper [B] used a re-circulating loop to experimentally evaluate 6 different OADMs: multi-layer thin-film filter and bulk grating as (de)multiplexers and bulk Fabry-Perot, fibre grating, silica-on-silicon and LiNbO<sub>3</sub> acousto-optic Bragg grating as notch filters. A tuneable Indium Phosphide (InP) de-multiplexer, forming one-half of a (de)multiplexer type OADM, was also similarly evaluated in [C]. The experiments was performed at 2.5 Gb/s with four 400 GHz (3.2 nm) spaced DWDM channels. In summary, the experiments showed that:

1. Low insertion loss improved the cascability due to reduced ASE in the EDFAs (ASE ~ gain ~ 1/Pin) [49]
2. Channel power equalization becomes an important factor in cascade.
3. Polarization-dependent loss is an issue for bulk or planar devices which severely degrade the performance
4. Filtering effects degrade the performance depending on how the filter characteristics evolve in cascade.
5. Crosstalk values were low in these experiments and no significant power penalty due to crosstalk could be found.

Consequently, building large networks, and in particular up-grading with additional nodes, based on OADMs can be quite difficult due to combination of the above effects. This fact lead to the investigation of OEXCs treated in the next section.

#### 4.2.3 *Mesh (OXC) systems*

Compared with ring networks, meshed networks offers easier capacity upgrade since fewer elements typically needs upgrading. Also, meshed networks offers a larger variety of resilience mechanisms, such as low spare-capacity restoration, as discussed in section 4.1 item 6. On the downside are the more complex management and planning procedure and the necessity of crossconnects, often seen as very complicated to introduce.

While the OADM handles one input fibre from which channels may be switched to the output fibre or dropped (“terminated”), the OXC, figure 12(c), can handle multiple line interfaces, switch channels between them, or drop channels. This more general functionality imposes more complex technology on all-optical OXCs compared with the OADM. In fact, while OADM is somewhat common in carrier’s networks of today, almost no all-optical OXCs are commercially deployed. As with OADMs, OXCs can be static or dynamic [13]. Only dynamic, matrix-based OXCs are treated here.

The matrix part, or switch, of the OXC can be realised optically or electrically [53,54]. Optical matrices can be realized using small switching elements, such as 2x2, or using larger cross-point switches. Small devices can be electro-optical (LiNbO<sub>3</sub>, InP etc), acousto-optical, thermo-electric (polymer, liquid etc) or mechanical. Larger cross-points can be of micro-mechanical (MEMS) [55,56] or liquid “bubbles” type. The performance measures of all-optical OXCs are the same as for the OADM (in section 4.2.2) but the performance difficulties are more pronounced due to the more complex architecture. In spite of over 20 years of research in to optical switches there’s so far been either lack of prize/performance or substantial interest leading to commercial break-through<sup>22</sup>. Also, all-optical OXCs without wavelength conversion are blocking since the same wavelength from two input fibres cannot be connected to the same output fibre. Thus, a non-blocking OXC requires wavelength converters. The wavelength conversion can be optical or opto-electrical. The

<sup>22</sup> The optical technology believed to have the highest chances of realizing all-optical crossconnects; MEMS, took a severe down-fall when the largest vendor, OMM Inc., shut down in early 2003.

optical one has potentially the advantage of being bit-rate limit-less while the opto-electrical typically experience both a lower and higher bitrate limit.

Although several all-optical technologies exist, see [50], opto-electric converters based on receivers (detector, trans-impedance amplifier and limiting amplifier) and/or transmitters (laser, driver w/o external modulator) are commercially dominant today: i.e. transponders in WDM systems. OXCs with o/e conversion are sometimes called “opaque” [51,52]. It should be noted that opaque elements does not prevent bitrate and protocol transparent networks if they operate in 2R or multi-rate 3R mode. However, due to the electric nature<sup>23</sup> of o/e conversion and electrical switches only binary amplitude modulation is supported.

With the different technologies mentioned above, OXCs of different types can be formed, see figure 15:

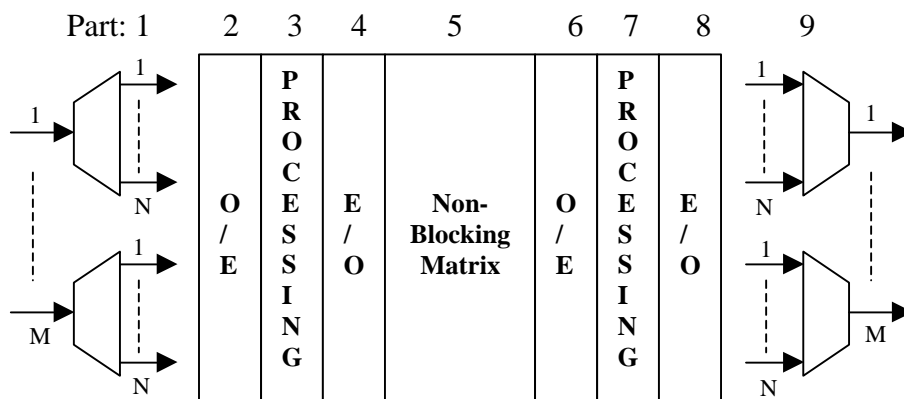


Figure 15. Generic building blocks of optical crossconnects. *M*: number of fibres, *N*: number of wavelengths. Combining different building block, indicated by a number on the top, forms different OXC types. Parts 1 and 9 (WDM MUX, DeMUX) may not be a part of the OXC.

- Type 1: Optical matrix. No o/e/o, omitting parts 2-4, 6-8. Sometimes referred to as Photonic crossconnect, PXC.
- Type 2: Optical matrix. Uses o/e/o at the output only, omitting parts 2-4. (Note that o/e/o at the input only case is not included since it does not resolve wavelength blocking.)
- Type 3: Optical matrix. O/e/o at both input and output.
- Type 4: Electrical matrix: O/e at input and e/o at output, omitting parts 4, 6. Sometimes referred to as OEXC or *optically interfaced electrical crossconnect*.

For all types, the processing part (7 and/or 3) may be 1, 2 or 3R and may also include overhead read/write capability. It should be noted that if parts 1, 9 are parts of an external DWDM system with (o/e/o) transponders, type 1 form a type 3 non-blocking architecture.

Paper [E] made an experimental comparison, using a re-circulating loop, of optical- and electrical-matrix based opaque OXCs. (The paper does not use the term *OEXC* used elsewhere in this thesis). In the first case the o/e/o converters were placed after the matrix while in the latter the electrical matrix was placed in between the o/e and e/o part.

The main limiting effect when cascading optical switches is coherent crosstalk and the number of crosstalk terms is equal to the number of input ports. In the experiments, this was represented by two 3 dB interconnected 1x2 splitters with a variable attenuator in one arm allowing to vary the amount of total coherent crosstalk. For electrical switches both crosstalk and timing jitter are

<sup>23</sup> Digital logic: typically Positive Emitter Coupled Logic (PECL) or versions hereof, such as Low Voltage PECL or Current Mode Logic (CML).

limiting effects. The electrical crosstalk comes from inductive coupling<sup>24</sup> between neighbour channels and the jitter comes from both bandwidth limits, called deterministic jitter, and noise, stochastic (or random) jitter. The crosstalk was found not to have a major impact while the total jitter effect was investigated by using two switches with 1.25 Gb/s and 2.5 Gb/s bandwidths, respectively.

The experiments concluded that around 8 cascades were possible at 622 Mb/s with 2 dB power penalties for both the 1.25 Gb/s and 2.5 Gb/s electrical switches and the “optical switch” with –21 dB crosstalk. In fact, the lower bandwidth electrical switch showed less total jitter at 622 Mb/s but opposite to the higher bandwidth switch, the total jitter increased rapidly above 1 Gb/s due to deterministic jitter. With less than –21 dB crosstalk, the “optical switch” displayed the best performance with 15 cascades possible for 2 dB penalty (compared to no crosstalk inserted).

Electrical matrices have made large advances during the past few years with 10Gb/s capacity per port and up to 64 x 64 ports. For 3 Gb/s per port, 144x144 is commercially available. Comparing matrices of different sizes shows only weak dependence on performance degradation vs. port-count. With low-voltage bipolar complementary metal oxide semiconductor (Bi-CMOS) the power consumption has been reduced. Also, integrated output pre-emphasis and input equalisation is typically available to accommodate for chip-to-chip signal transmission degradation. Using single-chip matrices avoids the use of multi-staging as for example with the Clos architecture; see [5], which rapidly increases the control complexity, power consumption, and board space.

These improvements in switch technology from paper [E] has enabled up to 8-10 hops at 1.25Gb/s on 2.5 Gb/s switches. The hop count for a 2.5 Gb/s signal with a 2.5 Gb/s switch may, however, only be 1-2, which is quite insufficient for even a small network. This forces the OEXC to be in 3R mode using Clock and data Recovery circuits (CDR). Fortunately, modern CDRs are multi-bit-rate or even any-rate using self-adaptation to the bit-rate. Given this, the OEXC may be transparent to bit-rate even in 3R mode. The cost of such multirate CDR is, unlike the sometimes-stated high cost of electronics, in the order of two optical patchcords.

The neighbour discovery method of paper [I] utilizes the laser shut-down capability of OEXCs and can thus not be directly implemented on PXCs.

The OEXC builds basically on the same components found in high-capacity IP-routers, Ethernet switches or SDH crossconnects, figure 16. The manufacturing volume of these components gives that the component costs for OEXC can be kept low. The network element cost difference from IP-routers and SDH elements compared to an OEXC is typically substantial, a fact used in paper [J] and discussed in section 4.2 item 2, which cannot simply be explained by the hardware cost. This is also largely due to the large difference in software, firmware and resulting overall control/management capabilities.

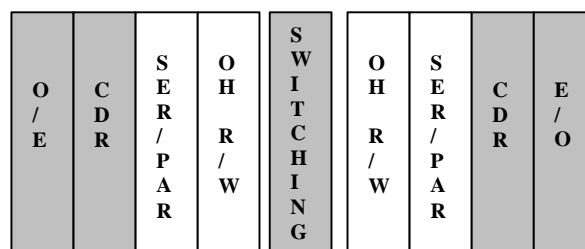


Figure 16. Generic building blocks of routers, switches and cross-connects. OH R/W: Overhead Read/Write. CDR and serial/parallel functions are sometimes integrated into one chip. For routers and switches the OH R/W gives the forwarding information. The white blocks are not used by OEXCs. For transparent (2R) OEXC, the CDR blocks are not used.

<sup>24</sup> The crosstalk from inductive coupling is proportional to the time derivative of all possible crosstalk generating signals, i.e.  $V_{\text{crosstalk}} \sim \Sigma dV/dt$ . This crosstalk thus give rise to “spikes” on the signal subject to crosstalk, which can be seen on an oscilloscope.

Given the availability of low-cost multirate 3R OXC, the benefits of transparent (1/2R) sub-networks or islands, discussed in [57,41], are arguably no longer crucial. Moreover, using the same type of (3R) OXC throughout optical networks simplifies management by using homogenous network elements and de-coupling of transmission limitations on route selection.

Table 1 summarizes the pros and cons of the OXC types:

Table 1. Comparison of OXC types according to figure 15.

OXC type	Switching speed	Bitrate limit	Cascadability	Number of ports (single stage matrix)	Cost* grading	Comment /Commercially used in volume today
Type 1	~1ms**	No	Medium	<256	3	Wavelength blocking. Good for fiber switching. / No
Type 2 with 1/2R	“	0.1-2.5/10Gb/s	Medium	“	4	Port bitrate upgradeable without reduced portcount by replacing output o/e/o. /No
Type 2 with 3R	“	“	High	“	5	“ /No
Type 3 with 1/2R	“	“	Medium	“	6	“ /No
Type 3 with 3R	“	“	High	“	7	“ /No
Type 4 with 1/2R	~1ns	“	Low	144 at 3Gb/s, 64 at 10Gb/s	1	Higher bitrates then supported by matrix can be solved by parallelism. /No
Type 4 with 3R	“	“	High	“	2	Can be upgraded with optical matrix. /Yes

\* From 1-7 with 1 lowest. Based on prices for commercially available components 2002/2003.

\*\* See reference [98] for an overview of switching speeds for different optical switching technologies.

The main advantages of OEXCs vs. PXC can be summarized as the following:

- The cost of optical matrices is still higher than the combination of optical transceivers, CDRs and electrical matrices at 2.5 Gb/s per port. At higher port speeds, e.g. 40 Gb/s, this may no longer be true.
- Electrical matrices have an intrinsic multicast capability.
- The ability to do signal monitoring in the electrical, digital domain for e.g. SDH B1 monitoring. In combination with the multicast capability, only a few such monitors per system is needed for non-intrusive monitoring.
- Manufacturing of electric systems such as an OEXC is still less advanced and costly compared to optical systems such as PXC.
- The typical high and well-proven availability of electrical switching components vs. optical ones.

The results from paper [E], and the advantages listed above lead to further work on OEXC based networks. This work gave input to papers [F-J] and is covered in the following sections.

### 4.3 Optical networking for IP-based networks

As pointed out in section 3.1, IP cannot directly be transported over fibre. Further, a weak point of IP in large networks is its best-effort nature giving no guarantee of the bandwidth available or delay variation from endpoint to endpoint. This poor QoS [20] performance can be improved using at last three different methods:

One method is introducing priority classes as with IntServ or DiffServ as discussed in section 3.1. Another method is over-provisioning. This means providing more than two times the capacity for a given traffic demand to thereby reduce the load on IP-routers. (E.g. equip the routers with 1 Gb/s ports where the maximum traffic is only 300 Mb/s or so.) For traffic following Poisson statistics it can be shown, see [21], that an average load of 50% results in only one packet in the input buffers on average. This effectively reduces packet drops, excessive delay and delay variations. The main drawback of over-provisioning is the additional cost of network equipment and the fact that over-provisioning may not always solve the problem if, for example, special priority traffic is of concern.



The third method is to form circuits below (layer-wise) the connection-less IP<sup>25</sup> to reduce the number of router-hops. This can be done using different protocols:

Having an ATM layer is the traditional way, see [58]. ATM is then used to bypass the IP-layer of intermediate routers and thus introduce more deterministic transport characteristics between IP end-points. ATM has benefits when it comes to traffic management and transporting different types of traffic but for pure IP transport it may be sub-optimal and costly due to problems with effectively mapping IP onto ATM (regarding data, performance parameters and addresses as discussed in [59]) and the, in this case, excessive functionality of ATM<sup>26</sup>.

Another possibility is MPLS: Using basically the same idea as ATM, MPLS adds to the IP-packet a label, which is dynamically allocated to a flow upon circuit creation and then used for switching decisions. Using a label to append to the IP-packet instead of fragmenting the IP-packets into fixed-size cells is the main difference between MPLS and ATM.

A third way is using SDH VC-n channels. In high-capacity IP core networks the channel bandwidths offered by SDH, typically VC-12 of 2 Mb/s or VC-4 of 140 Mb/s may however not be enough. Since VC-ns and not higher capacity links, such as STM-16/64, are intended to be crossconnected by SDH, OXC's may be used instead. In analogy with labels used in MPLS, the use of OXC wavelength switching may be called *wavelength label switching*, as done in paper [F]. This term may however be misleading when dealing with OXC with external DWDM systems. In this case, the label is actually the number of the in/egress optical port.

Figure 17 shows how IP traffic can be handled using ATM, SDH and OXC equipment. In this example three nodes are shown, each consisting of an IP router, an ATM switch, a SDH cross-connect and a wavelength channel (OCh) OXC. Case 1 is for an IP-router network only, where only layer 3 directs traffic (the other layers are of course present, such as e.g. Ethernet for layer 1 and 2, but is not used for switching). In Case 2, the IP routers are connected to ATM switches using virtual circuit/virtual path switching (the ATM switches normally use SDH for transport but in this case SDH is not used for crossconnection). In case 3, the node consists of IP-routers and SDH cross-connects where the SDH DXC connects the IP-routers. Case 4 displays the largest bypass of equipment by connecting IP-routers to each other by wavelength cross-connects (OXC). Different layer 1/2 protocols can be used for framing, such as Ethernet or POS.

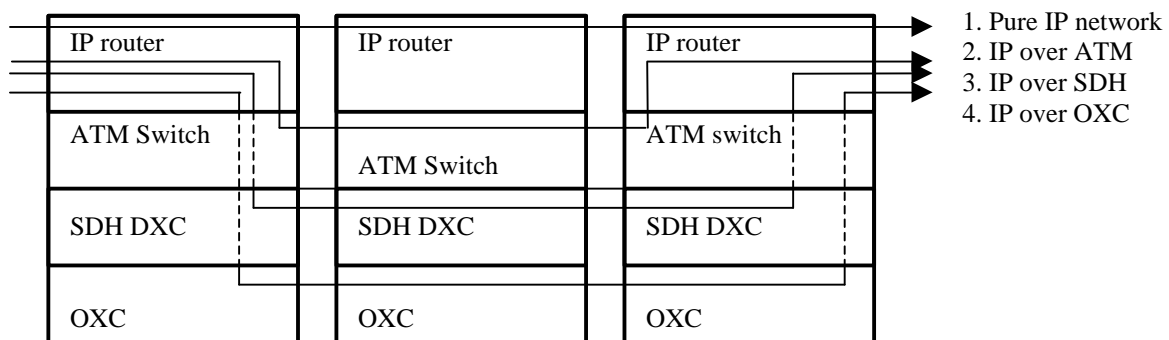


Figure 17. IP traffic handling in different layers exemplified by IP, ATM, SDH and optical channel with corresponding network elements. Dashed lines represent bypassed equipment.

A circuit-switched layer below IP can also be used for fast failure recovery. Optical channel (OCh) or optical multiplex section (OMS) protection in the order of ms usually goes unnoticed by the IP routing protocols providing high-availability networks, as reported in [60].

In order to investigate a wavelength label switched experimental network (case 4 in figure 17), the project Winchester was formed as described in papers [F,H]. Each of the four network sites contained IP-routers with GbE interfaces connected to an OEXC, which in turn was connected to a

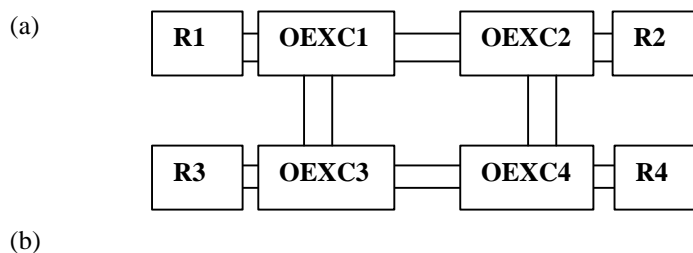
<sup>25</sup> Circuits are by definition connection oriented.

<sup>26</sup> ATM is fully capable of providing the network layer functions needed for global network but has been out competed by IP. Thus, when running IP over ATM, the ATM network layer functionality is redundant and adds only to the complexity and cost.

DWDM system. The OEXCs used was equipped with 16 transceivers connected to a 1.25 Gb/s electrical matrix of the type used in paper [E]. In 2R mode, the OEXC could do 2-3 hops error-free at GbE speed (1.25 Gb/s) but as up to 4 hops was needed in the network, it was concluded that CDRs was necessary.

Winchester included to a large extent management issues and EMS/NMS prototypes based on IP, Java and CORBA was developed. CORBA provided an abstract interface for communication between elements and the central NMS while Java enables the operator to run the graphical user interface on any operating system.

With the OEXCs the optical network could connect any routers to any other router. Enough DWDM links were available to avoid blocking. Figure 18 illustrates how blocking may or may not occur depending on the available links and the demand set.



(b)

Demand 1	Routing	Demand 2	Routing	Demand 3	Routing
1<->2	1,2	1<->2	1,2	1<->4	1,3,4
1<->3	1,3	1<->4	1,3,4	1<->4	1,3,4
2<->4	2,4	2<->3	2,4,3	2<->3	Blocking =>rearrange
3<->4	3,4	3<->4	3,1,2,4		

Figure 18. Routers (R) connected to OEXCs with two ports each and two links in between OEXCs. Part (a) shows the network while (b) shows the demands and routings table. A simple shortest path routing is used. Three demand sets (1-3) from left to right is applied to this network: the first demand set is satisfied, the other demand set experienced a long path for the last demand and the last demand set experience blocking for the third demand. The demand set can however be satisfied if rearranging of previous demand is allowed. With fewer than two links in between the OEXCs, network blocking occurs for some demand sets. Also, blocking occurs if more than two demands aim at the same router since it has only two ports. Thus, each router can only be connected to two other routers unlike if e.g. a shared media Ethernet was used to connect the routers.

The ambitious objectives of Winchester were to investigate the possibilities of IP/GbE/OXC/DWDM networks. Mainly three questions were raised:

1. Was the relatively simple management system of OXCs, compared to the (much) more complicated management of SDH networks, sufficient (for an operator) to complement the lack of transport network management of an IP/GbE network?

From GbE, connection ID is given by the source/destination address and a BER estimate can be derived from the CRC and line code violations. Usage of these parameters requires the ability to read the Ethernet header at the OXCs. The OXCs provide physical layer parameters such as optical input/output power. Operators normally provide service layer agreements (SLAs) based on ITU-T G.826 parameters (number of errored frames, errored seconds etc.) corresponding to connection IDs. G.826 parameters could in principle be derived from GbE but this is not covered by the standards. Until (if) this happens, a transition from SDH is proprietary. So, the answer is in principle yes but depends on the operator's usual way of operations.

2. What transmission performance could be achieved with potentially low-cost GbE and 2R OEXCs or would 3R OXCs be needed?

For the OEXCs used in Winchester, 2R mode was not sufficient due to the matrix' lack of sufficient excess bandwidth giving that 3R had to be used for satisfactory transmission performance. It was however shown that 3R had only to be used in every second or third OEXC. The conclusion was that the small cost reduction in partly equipping with 3R does not justify the added complexity of the management system taking in such constraints in making routing decisions. Such constraints may also lead to sub-optimal route selections. In this sense partly 3R functionality can be compared with limited wavelength conversion.

3. How could the possibility of a fast reconfigurable physical layer be used for an IP-network and what problems could arise?

A problem when using a reconfigurable optical network to connect IP-routers is that two interconnected router ports expect to be on the same IP network. One cannot simply connect any two router-ports to each other; unless the ports are on the same IP network, no traffic will be forwarded across these ports. This can be solved by using (IP-network) unnumbered ports, which reduces the number of IP-numbers needed on point-to-point links.

Also the slow convergence of IP routing protocols to changes in the physical topology means that the traffic is disturbed when reconfiguring the physical network. However, when the routers have the control over the optical layer (using ASON/GMPLS, section 4.4) they initiate the set-up of optical channels and can then adjust the forwarding (label switching) accordingly. This is addressed in the GMPLS framework with the same concept used for MPLS [61].

The advantage of being able to configure the physical topology according to the traffic pattern of packets between routers was investigated in paper [G]. Networks of different sizes (6/11/26-node) and OEXCs were utilised so that wavelength blocking was not of concern. The number of links per router was always lower than the number of neighbours and the traffic applied to the network was randomly varied so that the bulk of traffic could be forced to take multiple-hops to reach its destination. Now, the optical network was configured according to the applied traffic, assigning wavelength channels to the largest demands (flows). This corresponds to data-traffic-driven LSP creation in MPLS. It was shown that the reconfigurable optical network reduced the average number of packet hops from 5% to 25% dependent on the demand set, network size, and available resources (number of router ports and WDM channels). Allowing for the large traffic flows to take the shortest path to its destinations also reduces the load on the intermediate routers. Thus, redirected flows are not only experience better QoS (lower delay and jitter) but do also not influence the QoS of other flows. The result is lower capacity requirements on routers (ports, forwarding capacity) and thereby lower cost.

#### **4.4 Automatically switched optical networks**

Given the services offered by reconfigurable optical network elements commercially available, as discussed in section 4.1, the standardization of the management and control of these elements is clearly needed. Fully automated network are realized by introducing a control plane along side transport and management planes, as treated in section 2.3<sup>27</sup>.

Currently within this field, limited work on the fundamental issues (such as routing and signalling efficiency, centralized vs. distributed control etc as discussed below) is done outside the standardisation. Thus, the description below involves to a large degree standards and standardisations work.

The standardisation efforts within the field of automated optical networks are currently ongoing in several organizations. Such forums as Optical Domain Service Interconnect (ODSI, for an overview, see [62]) and Optical Internetworking Forum (OIF) mainly feed the standardisations organization, ITU-T and IETF, with input. ITU-T and IETF seems to converge in this field with

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<sup>27</sup> Automation can be achieved without a standardized control plane by having integrated management systems, but this type of integration is typically specific to integrating a small set of products from two vendors, i.e. proprietary solutions.

framework and architecture produced by the ITU-T and the protocols developed by IETF. This co-operation can then provide one uniform standardisation framework for future optical networks, much improving the chances of success.

The general transport network framework ASTN [9] and the optical network architecture ASON [10] are now being followed by recommendations listed below. For overviews and initial experimental networks on ASTN and ASON, see [63,64] and [65,66], respectively.

The IETF has broadened its MPLS architecture to also include TDM, e.g. SDH, and optical networks. Label switching network elements can thus be time-division multiplex capable (TDM), lambda switch capable (LSC), and fiber-switch capable (FSC) in addition to packet switching capable (PSC) and layer-2 switch capable (L2SC) already supported by MPLS. This new architecture is called *Generalized MPLS*, GMPLS, and include concepts such as wavelength label switching and multi-protocol lambda switching, MP<sup>2</sup>S. See [97] for an overview on GMPLS. The recent GMPLS framework draft [67] is now followed by drafts and Request For Comments (RFCs, the IETF term for its standards) listed below.

The ultimate goal of these standardization efforts is fully automated connection and recovery functionality [85] in heterogeneous (IP, Ethernet, SDH, OXC etc.), multi-vendor and multi-operator networks. This allow for improved time-sharing (from months or years of connection times down to days and perhaps hours) and failure recovery of resources.

Automated switching networks, for example enabling the provisioning service of section 4.1, requires certain base functions such as neighbour discovery, resource discovery, topology distribution, routing and signalling. Following the outline in paper [H], below is a brief description of the different functions and the current standardisation:

**1a. Neighbour discovery** (often called topology discovery) is the process whereby a network element detects its neighbours and which working links they have in common. Without this process, all nodes and links must be manually input into e.g. a topology database, which may not match with what is actually installed in the network. If a topology database exist, the automated the neighbour discovery process may be used to verify this.

**1b. Resource discovery** is the process of exchanging the capabilities of neighbour links. The capabilities include the supported protocols etc.

Both 1a and 1b is covered in G.7714 ([68]) by ITU-T and by the Link Management Protocol (LMP) ([69,70]) by IETF, which also includes the control channel set-up/tear-down and maintenance. With LMP, GMPLS allows for separation of the control channel and the data channel contrary to MPLS. This is beneficial for optical network elements not having of read/write access to the data channels.

**2. Topology distribution** carries the neighbour and resource information to either a central network management instance or, in case of a fully distributed intelligence network, to all other nodes concerned. The result is that the elements, or a centralized NMS, have a topological view of the network. This can now be used for routing purposes. Routing hierarchies are supported in that routing instances may present for different levels of the network, including subnetworks and routing areas. Across the different network interfaces (UNI, E-NNI, I-NNI, see below) the routing information may be more or less open as discussed below for the different integration models.

**3. Routing** takes place upon a connection requests from a client such as an IP-router to find a suitable path to the desired destination.

ITU-T deals with the requirements of 2. and 3. in G.7715 ([71]) and makes further requirements for link-state routing methods in G.7715.1 ([72]). Work in IETF to come up with protocols satisfying these requirements is ongoing with extensions to existing OSPF and IS-IS protocols ([73]). The extensions are needed to accommodate for circuit switching with the new type of switching elements (TDM, LSC, FSC) as discussed above. An analysis of the performance of such an extended OSPF protocol is done in [92].

**4. Signalling** finally takes place to assure resource allocation in order for the connection to be established.

ITU-T requirements on signalling are found in G.7713 ([74]) and the general GMPLS signalling architecture RFC is found in [86]. Further recommendations for signalling protocols are based on ATM PNNI signalling in [75], GMPLS extended RSVP-TE ([76]) signalling in [77] and GMPLS extended CR-LDP ([78]) signalling in [79]. The GMPLS extension to the signalling includes hierarchical label set-up (a PSC label can be nested in an TDM LSP, in turn nested in an LSC LSP etc.), suggested label (useful for assuring that both directions of a bidirectional path goes through the same transceiver), and bi-directional label set-up, not supported by MPLS.

Unlike functions 2-5, neighbour discovery needs to be done on the actual ports and links to be discovered in order for them to be unambiguously identified. I.e. to find out what ports are connected has to be done using communication over these ports. This has to be done in-band since out-of-band (on separate wavelength) is normally not possible on the individual ports. The traditional way of doing this is using overhead field within the physical layer frames, such as SDH, OTN etc. This excludes protocol transparent devices, such as OXC's, from the process and a large portion of the automation benefit is lost.

Paper [I] describe and evaluate a method, Simple Optical Neighbour Discovery (SOND), for neighbour discovery. The method use common properties of optical ports: laser shutdown and signal detect. Using these functions, a time-orthogonal channel to the ordinary data (transport) plane is formed that can be used for neighbour discovery since this takes place before set-up of the data channels. It cannot be used for ordinary signalling since this also takes place after connection set-up.

The neighbour discovery consists of a port sending its (local) port-number and the IP-address of its network element. Since the IP-address of the element also is the interface for signalling, various control-plane information exchanges can take place after the SOND discovery process. SOND was implemented in OEXC's and experiments were done on single-channel, CWDM and DWDM systems. The aim of SOND is to provide low-cost neighbour discovery between OEXC's, DWDM and OEXC, DXC and OEXC etc.

With the control planes of ASON and GMPLS basically three types of optical connections can be done, as discussed in [65]:

- A (hard) *permanent* connection is made typically via the management system by provisioning resources at each network element along the path.
- A *soft-permanent* connection (SPC) is initiated by the management system at the edge of the network where network generated signalling and routing takes over to make the connection end-to-end. This involved the network-node interface (NNI) inside the network. I-NNI is used within one administrative domain while E-NNI is used between domains.
- A *switched* connection is initiated by a client network using a user-network interface (UNI). The UNI is used at the edge where network generated signalling and routing takes over to make the connection end-to-end as in the soft-permanent case.

As the interest of automatically switched networks comes both from the telecom (ITU-T) and datacom (IETF) communities with different (historic) approaches to networking, several models for the control plane have been discussed. The difference is whether the IP/MPLS control plane and the ASON control plane should be separated or not, as discussed in [66]:

- The *overlay model* deals with separate control planes and the IP network acts as one client (of many) to the optical network, which provides connection set-up using the UNI. This restricts the optical network visibility. This is typically desired by telecom operators not willing to advertise their network resources.

- The *peer-to-peer model* uses a single control plane for the IP/MPLS and optical networks. This simplifies integration but makes non-IP networks difficult to support.
- The *augmented model* uses separated control planes but allows routing information to flow between the networks similar to the peer-to-peer-model.

Automatically switched networks can also be centralised more or less distributed: There are two main drawbacks of centralised network management: One is the scalability: a large network can lead to a large amount of management traffic, a large load on the NMS and long execution times for management operations. See [80] for an insight on this. The second is its vulnerability to single-point of failure. Distributed management, on the other hand, are in general more complex and may lead to sub-optimal (longer) route selection as reported in [81], and an increase in total links (working and backup) as reported in [96].

As the full suite of ASON/GMPLS standards is not yet finalized it will take another two years or so until such networks can be deployed. However, given the large interest from operators and several vendors offering part of the functionality today (notably by implementing OIF UNI 1.0) seems promising for the future of reconfigurable optical networks.

## 5. Discussions and conclusions

This work has mainly done top-down investigations of the benefits of optical layer services to client layer and what the requirements for the optical layer then should be. Also, the implications, and possible modifications, to the clients of such services should be investigated bottom-up.

The most successful optical layer service so far is multi-wavelength (WDM) transmission. WDM offers cost-effective capacity without the need for client layer modifications applicable to virtually any client communicating on optical fibres. Using DWDM, fixed OADMs, investigated in [B], offer effective n-out-of-m optical wavelength channel add and drop.

The optical layer also offers dynamic services based on reconfigurability (switching) of optical channels (or whole fibres) within an optical network. The problem of implementing reconfigurability with all-optical (1R) devices is the dependence of transmission on the route selections. Implementing large, reconfigurable all-optical networks means designing for a wide variety of transmission cases and number of network elements in cascade. Two main approaches to this problem can be attempted: 1) improve the hardware (optical elements) with cost-effective optical 3R functions or 2) improve the software (management systems) to make switching decisions based on transmission constraints. 1) is not yet realised and 2) will probably not happen (as management systems are the most costly part of communications systems today) unless no other solution exists.

Fortunately, switching and transmission can be separated using opto-electrical network elements with multi- or any-rate 3R. Today, the most cost-effective implementation of an OXC, providing the desired optical layer reconfigurability, uses an electrical switch core interfaced by o/e and e/o conversion. This type of OXC is the basis of papers [E-I]. Now, optical layer services in optical network based on reconfiguration can be investigated:

The ability of optical networks to provide direct channels between client equipment means possible bypass of intermediate client equipment. If client equipment ports are more expensive than optical equipment ports, a cost reduction is obtained, as investigated in [J]. If intermediate client equipment introduced delays or losses to the traffic, a QoS improvement is achieved, as investigated in [G]. A reconfigurable optical network provides, compared to manual work, faster provisioning of client connections over the optical network. Automation of such provisioning can be done ultimately all the way to no manual intervention where client equipment and optical network equipment cooperate with inter-working (or integrated) control planes. This is the ASON/GMPLS ultimate benefit. It can be noted that inter-working between layers (represented by optical and client equipment in this case) also makes use of the bottom-up approach since the upper layer(s) need to be enhanced with new functionality.

The optical network may need to be reconfigured also without client channel set-ups. This reconfiguration could be due to network elements being installed, removed, replaced or serviced or for optimisation purposes. Thus, more efficient operations processes are enabled by this optical network service.

The optical layer service, beside WDM, most treated in the literature is optical protection and restoration from cable breaks and equipment failure. The optical layer can protect, or restore, optical channels between client equipment ports by using dedicated or shared protection/restoration resources between optical network ports. Since optical network ports typically are less costly than client ports, a cost reduction is obtained. Also, the optical layer may have the advantage of faster protection/restoration from physical layer failures than the client layer, which lowers the client traffic loss. As failure recovery may take place in several layer networks (when several client layers reside on the optical layer), a well-defined recovery strategy is needed to avoid competing and conflicting recovery processes.

The services discussed above are summarized in table 2:

Table 2. Applications and implications for optical network services.

Service offered by reconfigurable optical network	Implication to client network	Applicable to	Client modifications required
WDM	Cost reduction	All client networks	No
Client Bypassing	Cost reduction	“	Automation requires control plane integration.
“	QoS improvement	Connection-less networks, e.g. IP	“
Provisioning of optical channels	Fast set-up time giving OPEX reduction, physical layer control	All client networks	“
Physical network reconfiguration	More efficient network operations processes giving OPEX reduction	“	No
Failure recovery	Cost reduction, Reduction of client layer traffic loss	Client networks with non-competing failure recovery	A well-defined strategy needed if recovery may take place in several layers or layer networks.

Finally, top-down investigations have also lead to the proposal of time-slotted optical transmission to reduce impact of optical transmission impact such as Rayleigh back-scattering and four-wave mixing. Time-slotted transmission is difficult to implement in common TDM networks, such as SDH, but is quite feasible for packet-based network such as IP, especially in combination with carriers designed for shared media networks, such as Ethernet. Time-slotting would then be functionally the same as avoiding collisions on a shared media. Protocol adaptation of for example Ethernet to the cases in papers [A,D] would have to be done. Details on these possible adaptations are not described in this work.

Making an outlook into the future, a few important drivers for optical networks can be mentioned:

- The introduction of ASON/GMPLS due to operators' need/wish to have standardized integration of networking equipment.
- Wavelength services will evolve as the bulk of the carriers (-carrier) connections will be optical channels (GbE/STM-16,64).

This will drive the introduction of optical crossconnects. These will, for cost-effectiveness, be based on electrical switching which will benefit from the rapid advances in high-speed electronics and, not least, programmable logic.



## 6. Summary of original work

### ***Paper A: Improving Rayleigh-limited bidirectional optical transmission systems by using time-slotting and frequency detuning***

Two methods to enable bi-directional transmission over a single fibre limited by Rayleigh scattering were investigated. The experiments were conducted at STM-16 (2488 Mb/s) over 80 km of G.652 standard single-mode fibre. Frequency detuning (i.e. using different carrier frequencies in the two directions) is the obvious choice and was shown to effectively remedy Rayleigh scattering when the detuning was larger than the electrical bandwidth of the receiver. The novel idea to let the transmission consist of time-slots, or packets, to remedy Rayleigh scattering was also verified. The 20  $\mu$ s packets were produced by an acousto-optic switch with 58 dB extinction ratio. Decreasing the ratio of packet period to silent period, duty-cycle, decreased the penalty, flattening out at around 1/10.

*Contributions by the author of the present thesis:* All.

### ***Paper B: Cascadability of optical add/drop multiplexers***

Since the scalability sets the limit on the possible size of the network, such experimental work is important to evaluate candidate technologies. A re-circulating loop experimental platform was used to investigate the cascadability of six different optical add-drop nodes representing different technologies: fibre-grating, bulk grating, multi-layer thin film, Fabry-Perot, SiO and acousto-optic. The loop made it possible to highlight and compare the transmission impairments of the different technologies: loss, un-equal channel loss, cascaded filter effects and cross-talk. The maximum number of cascades was mostly limited by gain tilt of the optical amplifiers used. This gave that one of the OADMs, which used loss equalization, achieved the highest number of cascades, 28, which corresponded to 1120 km.

*Contributions by the author of the present thesis:* Designing and setting up the re-circulating loop. Performing most of experiments and processing experimental data. Co-defining the experiments.

### ***Paper C: Experimental evaluation of novel, tunable MMI-MZI demultiplexer in InP***

This integrated 4-channel demultiplexer (e.g. one side of a OADM) was investigated in a similar way as in paper B. The device could be cascaded over 100 times but displayed too large crosstalk and losses to be used for OADM.

*Contributions by the author of the present thesis:* Designing and setting up the re-circulating loop. Performing most of experiments. Co-defining the experiments.

### ***Paper D: Improving four-wave mixing-limited optical transmission systems by using time-slotted packet transmission***

Another application of the time-slotting idea used in paper A and the same set-up was used to generate packets at four, 0.8nm spaced, wavelength channels. The experiments verified a time-slotting scheme designed to eliminate the worst contributions of FWM for DWDM in 40 km of DSF.

*Contributions by the author of the present thesis:* All.

### ***Paper E: Experimental comparison between optical and electrical switches for transparent networks***

A comparison between the transmission performances of transparent optical switches with electrical or optical switch cores was done. In order to compare the optical and electrical matrix (cross-point switch, XPS), an experimental model of an optical matrix was used to find the amount of optical cross-talk to achieve the same performance for the two types.

The comparison with the electrical switch cores was possible by the, at the time, new development of 1.2 and 2.5 Gb/s 16x16 cross-point switches. The comparison showed that, given that the electrical XPS has excess bandwidth to the signal, the performance was similar in cascade when the

optical switch had  $-21$  dB of coherent crosstalk in total. The limiting transmission impairment of the electrical XPS was timing jitter rather than crosstalk.

*Contributions by the author of the present thesis:* Designing and setting up the re-circulating loop. Performing most of experiments. Major part in designing the electrical XPS experiments. Co-defining the optical XPS experiments.

#### ***Paper F: Wavelength Label Switched IP Backbone: Architecture and Field Trial***

Based on paper E, 4 OEXC nodes (1.2Gb/s XPS) was developed and put into a Stockholm research network together with high-performance IP-routers from different vendors. The routers used Gigabit Ethernet interfaces. DWDM equipment was used for transmission. The paper described the architecture of the network and initial transmission tests on the OEXCs in 2R and 3R mode.

Also, a element and network management prototype system based on distributed objects was described. The management system was using Java, Corba and IP.

*Contributions by the author of the present thesis:* Major part in defining the network. Major part in defining and performing the experiments on 2R and 3R modes on OEXCs.

#### ***Paper G: Reduction of Hop-Count in Packet-Switched Networks using Wavelength Reconfiguration***

This paper investigated by computer simulations the gain of having a reconfigurable optical network serving a packet-switched client network. A uniform statistical distribution for the packet traffic was used when evaluating 5-node, 11-node and 26-node networks. The number of available ports per node and (WDM) channels per link was varied. By allowing for configuration of the optical layer to the client layer demand, up to 25% reduction in hop-count could be achieved.

*Contributions by the author of the present thesis:* Major part in defining and performing the work. Minor part in algorithmic implementation and abstraction.

#### ***Paper H: Requirements and solutions for reconfigurable metro WDM systems***

Functionalities and technology solutions for metro optical networks was investigated. Both transport plane, management and control plane issues was discussed. As an experimental platform the Winchester network of paper [F] was described with, compared with paper [F], more focus on the management system.

*Contributions by the author of the present thesis:* Major part in Winchester network parts. Influence on paper topics.

#### ***Paper I: Simple Optical Neighbor Discovery: Architecture, Applications and Experimental Verification***

When architecting automatically switched optical networks, as defined by ASON and GMPLS, automatic neighbour discovery is an important function. Most described solutions to this were prior to this paper based on overhead field in OTN or SONET/SDH frames. Including such OTN/SDH functionality in OXCs significantly increases their complexity and cost.

A simple solution is described and evaluated by this paper which makes use of common functionalities of optical ports: turning on/off the laser and detecting presence of optical input signal. Due to this fact, the method can be used by virtually all switching or transmission equipment with optical ports and enables a fast-track towards the vision of the automatically switched optical network currently being standardized.

Experiments were done on single-channel, 4/8-channel CWDM and 32-channel DWDM systems.

*Contributions by the author of the present thesis:* Major part in defining architecture and experiments. Major part in experimental work. Influence on programmable logic implementations.

#### ***Paper J: Analytic investigations of cost benefits of complementing a client network with an optical express layer***

A model of the cost of common equipment and ports of a client network and an optical network suitable for analytic analysis was presented. This is unlike most similar papers, which makes use of computer simulations. The model takes into account the distribution of the hop-lengths of the paths but can be used regardless of the network topology (ring, mesh, etc.). The effect of protection and restoration is also included.

Expressions for port cost analysis alone and analysis combined with common equipment are presented. Case studies with reasonable assumptions are done for all-optical and opto-electrical crossconnects for different network sizes; small (10 nodes), medium (30 nodes) and large (100 nodes).

*Contributions by the author of the present thesis: All.*



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