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Reconfigurable and Transparent Wavelength Division Multiplexed Optical Transport Networks

Experiments, Evaluations, and Designs

Thesis by

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Abstract

This thesis is about reconfigurable and transparent wavelength division multiplexed (WDM) networks. Reconfigurability is used to achieve higher surveillance and throughput in the network. This is done by wavelength selective and independent network elements. These network elements can accomplish bypass and protection switching of the traffic. Transparency in the optical layer enables the transport network to accept new bit rates, codes and formats of the clients. The enabling technologies to achieve a reconfigurable and transparent network are integrated tuneable devices and switches. In this thesis some of these devices have been experimentally evaluated according to theirs cascadability and crosstalk performance.

A unidirectional self-healing wavelength division multiplexed ring was designed, assembled and evaluated. By utilising WDM, logical networks could be constructed with optical add drop multiplexers (OADM) to support communicative and distributive services. The main transmission limitation of the ring was homogenous broadening of the optical amplifiers.

The second network element investigated, was the optical crossconnect (OXC). The OXC was comprised of optical InP and $LiNbO_3$ switches and tuneable filters, which were experimentally evaluated. Two OXCs and an OADM were installed in the Stockholm gigabit network (SGN) with fault and configuration management.

The cascadability of OXCs with reshaping repeaters and optical or electrical switches was investigated. The jitter of the OXC with electrical switches limited its performance, while the OXC with optical switch was limited by its crosstalk. Crosstalk especially intra-band crosstalk, which beats with the signal, is a severe limitation of optical networks. Experiments and simulations were performed on the time dependence of the intra-band crosstalk. It was shown and experimentally confirmed that the quasi-correlated intra-band crosstalk could be the worst case.

In the next phase of the network five OADMs and one OXC, which interconnected a unidirectional and a bidirectional protected ring, were integrated into SGN with a web based management system.

The OADMs were evaluated in a recirculating loop to investigate the cascadability of the nodes. The nodes could be divided into optical channel or fibre protection and notch or demultiplex filtering. An optimum of loss of the cascaded optical amplifiers were found, which maximised the gain flatness and the signal to noise ratio. The OXC utilising fixed WDMs and polymer switches was designed and evaluated taking into account the configuration, fault handling and performance monitoring of the optical layer. Data services were evaluated as clients to the optical layer, especially to provide optical protection without interfering with its client.

Descriptors: Optical Network, Wavelength Division Multiplexing, Reconfigurable Network, Optical Cross Connect, Optical Add Drop Multiplexer, Transparency, Crosstalk, Cascading, Protection, Optical Switch, Electrical Switch, Tuneable Filter, Self-Healing Ring, Logical Network, Stockholm Gigabit Network, Internetworking

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Acronyms

1+1/1:1/m:n	Dedicated and reserved/ Dedicated / Shared
1R/2R/3R	Reamplification /1R+Reshaping /2R+Retiming
ACTS	Advanced Communications Technologies and Services
ADM	Add Drop Multiplexer (an SDH/SONET network element)
ADSL	Asymetric Digital Subscriber Line
AOTF	Acousto-Optical Tuneable Filter (usually made in $LiNbO_3$)
ATM	Asynchronous Transfer Mode (connection oriented 53 bytes cell format)
AWG	Arrayed Waveguide Grating (Phased array usually made in SiO_2/Si)
B&S	Broadcast & Select
BER	Bit Error Rate
CDR	Clock and Data Recovery
DBR	Distributed Bragg Reflector
DMUX	Demultiplexer
DST	Dispersion Supported Transmission
DXC	Digital Cross Connect (an SDH/SONET network element)
DWDM	Dense Wavelength Division Multiplexing (channel spacing < 1THz)
ECL	Emitter Couple Logic, (voltage levels V_+=xV and V_-=yV)
EDFA	Erbium Doped Fibre Amplifier
F-P	Fabry-Perot
FDDI	Fibre Distributed Data Interface
FEC	Forward Error Correction
IP	Internet Protocol
ISDN	Integrated Service Data Network
ITU	International Telecommunication Union
IX	Inter Exchange
LE	Local Exchange
LMDS	Local Multicast Distributed Services
MAC	Media Access Control
METON	Metropolitan Optical Network
MGF	Multi Grating Filter
MIB	Management Information Base
MMI	Multi Mode Interferometer
MONET	Multiwavelength Optical Network
MPLS	Multi Protocol Label Switching
MUX	Multiplexer
MWTN	Multi Wavelength Transport Network
MZI	Mach-Zehnder Interferometer
NE	Network Element (Is a manageable node)
NRZ	Non Return to Zero
NRZI	Non Return to Zero Inverted
OADM	Optical channel Add Drop Multiplexer (also called WADM)

OADU	Optical Add Drop Unit
OC	Optical Channel
OCH	Optical Channel
OEO	Opto-Electrical Optical
OFA	Optical Fibre Amplifier (also called WAMP)
OFC	Optical Fibre Coupler
OFXC	Optical Fibre Cross Connect (also called FXC)
OMS	Optical Multiplex Section
OTM	Optical channel Terminal Multiplexer (also called WTM)
OTS	Optical Transmission Section
OXC	Optical channel Cross Connect (static OXC also called WR, dynamic wavelength path OXC also called WSXC, dynamic virtual wavelength path OXC also called WIXC)
PDH	Plesio Digital Hierarchy
PDL	Polarisation Depedent Loss
PDF	Probability Distribution Function
POTS	Plain Old Telephone Service
PP	Power Penalty (the power deviation from the reference system)
PMD	Polarisation Mode Dispersion
PMF	Polarisation Maintaining Fibre
PSTN	Public Switched Telecommunication Network
RACE	Research and development in Advanced Communications technologies in Europe
RET	Receive End Transponder
RX	Receiver
RZ	Return to Zero
SCM	Sub-Carrier Multiplexing
SDH	Synchronous Digital Hierarchy
SGN	Stockholm Gigabit Network
SHR	Self-Healing Ring
SNR	Signal to Noise Ratio
SONET	Synchronous Optical Network
STM	Synchronous Transfer Mode
TCP	Transmission Control Protocol
TET	Transmit End Transponder
TX	Transmitter
UDP	User Datagram Protocol
VC	Virtual Container (SDH), Virtual Circuit (ATM)
VP	Virtual Path
VWP	Virtual Wavelength Path
WDM	Wavelength Division Multiplexing
WP	Wavelength Path
WR	Wavelength Reuse
WWW	World Wide Web

1. Introduction

At the end of the 1960s, fibre based communication system started to be investigated due to the dramatic reduction in fibre loss, Figure 1.1a. Independently, the Internet was launched into the telecommunication network. The available and required bandwidth was rather modest, especially over long distances. After a while, processor capacity started to follow Moores law (doubling the capacity every 18 months) and transmission techniques evolved to higher bit rates and longer distances, independently. However, the required transmission bandwidth grew linearly, due to the capacity demands of the telephone traffic had become saturated as no user friendly Internet services were available. Not until 1994, when the World Wide Web became publicly available, did the capacity started to increase exponentially, Figure 1.1b.

The concept of using wavelength division multiplexing (WDM) for taking advantage of the enormous fibre bandwidth (200THz with less than 2dB/km loss [1]), is nothing new [2] [3]. At the end of the 1980s, the WDM systems capacity length performances began to increase exponentially, Figure 1.1c, partly due to the invention of the erbium doped fibre amplifier (EDFA) in 1987. However, it was in response to the increased Internet demands, WDM systems became commercially available in 1995.

Because of multiplexing and transmission technologies development, the cost of transmitting one bit over one km has decreased significantly, Figure 1.1d. This and the distance independent services of the Internet today, has changed the traffic demands from being mainly local to more long distance. However, the switching cost per bit has more or less remained the same, even though high-speed router and switch ports, which can interface the optical layer directly, have become available.

So far, the increased number of users and the duration of the established connections can explain the exponential growth of the Internet capacity. The end-user bandwidth has increased slowly, but because applications and computer-to-computer communication is starting to require more bandwidth, the threshold to installing high-speed access techniques has been reduced. One cost-effective way to respond to this next phase of the network evolution is by utilising a scalable, reconfigurable and transparent optical network layer. In this thesis, experiments, evaluations and designs of such networks have been performed.

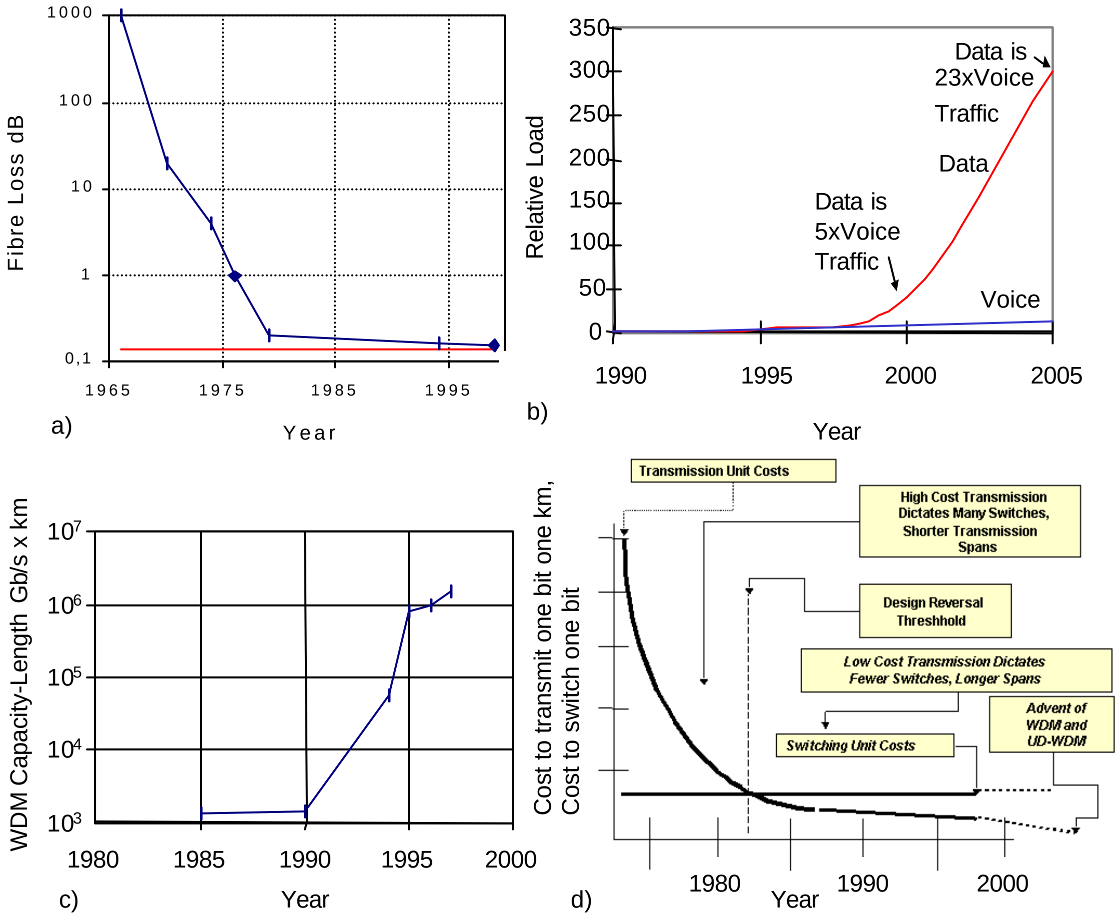


Figure 1.1: a) Fibre loss, b) Data and voice capacity, c) WDM capacity length. d) Transmission and switching cost

2. Wavelength Division Multiplexed Transport Networks

Today optical fibre bandwidth is being exploited more aggressively, by utilising wavelength division multiplexing. The consequence of this is that the previous bottleneck in point-to-point transmission systems has been widened to support more capacity. The challenge today is to transform this bandwidth into network connectivity by utilising various optical devices as a complement to already existing and coming transport technologies. Before entering the area of optical networking, some basic transport network terms are defined in this thesis for clarification purpose (with the risk of redefining some of the standardised words).

A *network* consists of *links* and *nodes*, Figure 2.1. Nodes, which can be monitored and controlled from a management system, are called *network elements*. A node can consist of several network elements. Between all nodes there exists a certain traffic capacity demand. All these demands combined, are described by a *traffic matrix*. Several topology options exist, which solve the capacity demands in the traffic matrix. The challenge, when designing a network, is to meet the required network capacity, taking into account the network evolution, in a most cost-effective way.

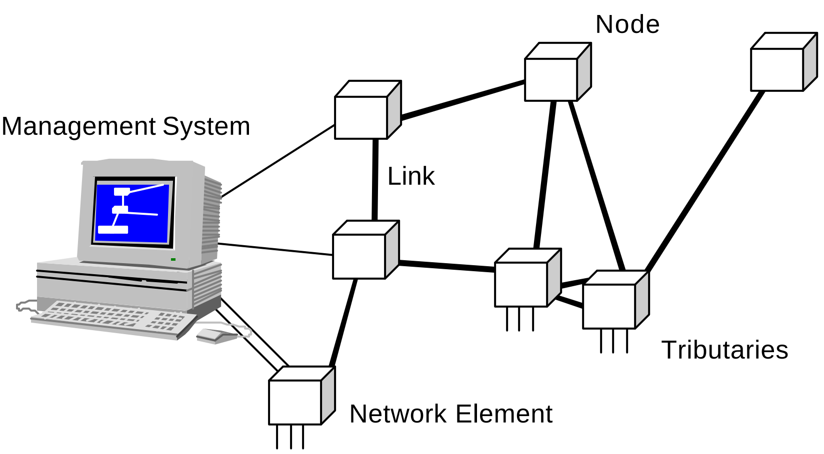


Figure 2.1 Network with its sub elements

Node-to-node demands in the traffic matrix result in node and link capacity requirements. The required *tributary* (input and output ports toward the network in each node) capacity is determined by the sum of all traffic demands for a certain node in the matrix. *Connections* are established between nodes to meet the traffic demands. A link can be shared by several connections. Each connection consists of *circuits*, or *paths*. A circuit (or call) is set up between end-nodes. A path (or channel) used in the transport network, usually consists of a number of circuits. Paths can be switched (i.e. crossconnected) within *a reconfigurable* (or *dynamic*) network. Crossconnections are controlled by the network management system.

The network can be further divided into *access networks*, which connects the user (end nodes) to the closest network node (*local exchange LE*), and *transport networks*, which connect the access networks together. A *metropolitan* network can also be defined, which connects a couple of local exchanges to the transport network via an *inter-exchange (IX)* node.

The access network is only a few kilometres and today is seldom based on fibre optics. For access rates below 1Mb/s, it is diffcult for fibre optics to be cost competitive. On the contrary, transport networks are usually based on fibre optics. To understand when different network topologies are preferred, an instructive example is shown in Figure 2.2. Though there are several ways to optimise a network, one important parameter is to minimise the number of required connections, as shown in the example.

The given network shows a number of nodes N, where all nodes are directly connected to each other, however, only M connections (*tributaries*) are active per node at the same time. The network can be represented in either a logical or physical way. In a physical network the connections between the nodes represent the actual links. In a *star* network all nodes are connected to each other via a hub, while in a *fully meshed* network all nodes are connected directly to each other. The star configuration requires NM connections while the fully meshed configuration requires N(N-1)/2 connections. The hub within the star configuration can be a switch or a broadcast medium, which is usually the case in local area networks. The broadcast medium enables connections to be frequency or time. In order to achieve the same connectivity in the star network compared to the fully meshed, the hub has to be an MNxMN strictly non-blocking switch [4]. As a matter of fact, all nodes in the meshed case have an Mx(N-1) switch for choosing the desired active connections. In the star case all these Mx(N-1) switches are just interconnected in the hub.

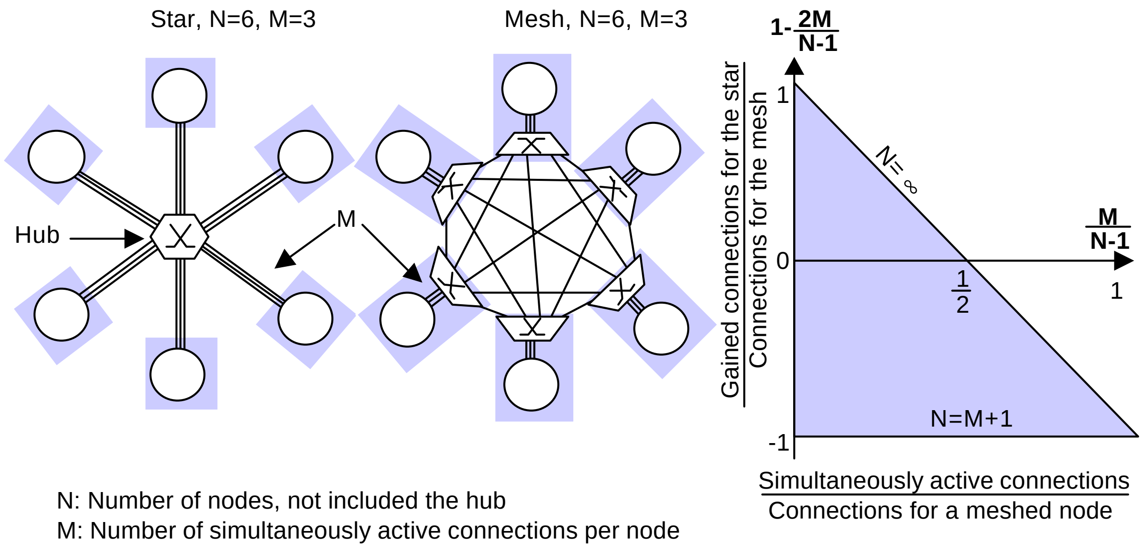


Figure 2.2 Full mesh versus star (hub network),

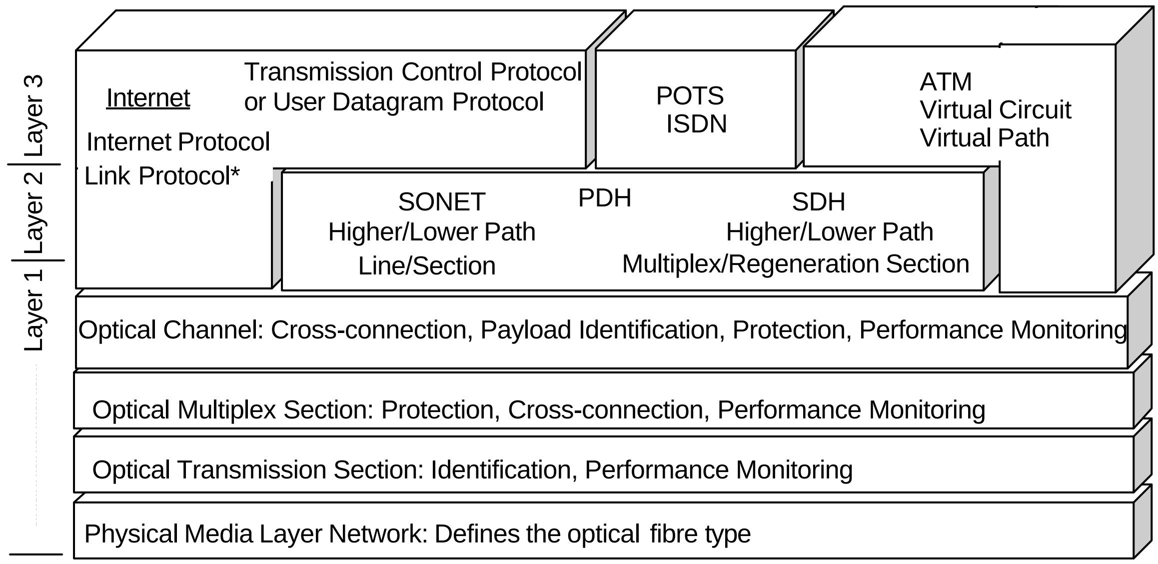
The number of connections in a mesh always scales quadratically with the number of nodes (N(N-1)/2), while the number of connections in a star scales linearly to twice as much as that in a mesh, depending on the number of tributaries (NM). In other words, the number of connections of the star will decrease by a factor of $1-\frac{2M}{N-1}$, as compared to a fully meshed network, Figure 2.2. In essence, the access network with M=1 usually is formed as a star, while the transport network with M less than N but larger than 1 results in a mixture of mesh and star.

Other topologies, which utilise multiplexing more effectively, are the *bus* and *ring*. These topologies save and share the cost of interconnecting links, however, the bypass traffic leads to excess load on the node. Every time a multiplexing layer exists, an opportunity arises to create *logical (or virtual) networks*, consisting of paths released from the physical infrastructure within the transport network. In this thesis, wavelengths are utilised to achieve the logical networks, but it is also possible to achieve the same functionality by using other types of optical techniques such as time, polarisation and code division multiplexing.

In *tree* (interconnected stars) and bus topologies, it is guaranteed to have only one possible path between two nodes, which simplifies the control and saves links, but is inherently non-redundant. On the contrary, a ring topology guarantees to have two and only two possible paths between any two nodes, which minimise the number of links for a protected network. The above discussion has focused mainly on minimising the number of connections. *Dense networks*, such as, de Brujin, Kautz, and Hyper cube, maximising the number of nodes for a fixed number of switch ports and a fixed number of maximum hops. However, it is usually difficult to map these regular networks to existing infrastructures and traffic demands.

To simplify the design and management of networks, it is common to divide them into *layers*, Figure 2.3. Each layer is associated with a *protocol* (a set of rules) used for communcation with other elements within the same layer. An interface between each layer that specifies what services the lower layer (*service* layer) offers to the upper layer (*client* layer). An advantage with the optical network layer is the potential of providing an open interface towards several clients (client transparency) [***K***].

To simplify the management of the optical layer, it is subdivided into an optical channel (OCH), an optical multiplex section (OMS) and an optical transmission section (OTS) [5]. Each layer has its own overhead information and adaptation functions. The overhead is processed to ensure integrity of the client adapted information. The supervisory functions are used to enable network level operations and management functions, such as crossconnection, identification, protection, and performance monitoring.



*) To be able to carry IP packets over the WDM networks a link protocol has to be added, which guarantees at least "0" to "1" transitions of the bits, start and stop identification of the IP packets and packet error detection [K].

Figure 2.3 Layering of the network into physical, optical, link and network layers. The optical layer is divided into an optical channel, an optical multiplex section and an optical transmission section. Sometimes the optical and the physical media layer is referred to as layer 0. (The acronyms are listed at page XI)

In section 2.1-2.3, the physical and optical layer is described from the simplest, i.e. the point-to-point link to the most complex, i.e. the mesh network. Network elements are also introduced which are necessary parts of the optical network.

2.1 Link and star

Wavelength division multiplexed systems have so far been deployed to boost the point-to-point capacity of already installed fibres and existing transport systems such as PDH (Plesio Digital Hierarchy), SDH (Synchronous Digital Hierarchy) and SONET (Synchronous Optical Network). Two optical network elements are used to establish a point-to-point link. The first one is the optical channel terminal multiplexer (OTM), which extends the dispersion limit for the same fibre capacity, compared to time multiplexed systems. The second one is the optical fibre amplifier (OFA), which extends the optical loss limit and can amplify all wavelength-multiplexed channels simultaneously.

A simple extension of the point-to-point network is point-to-multipoint. WDM point-to-multipoint networks are usually called broadcast and select (B&S). Broadcast and select networks can be constructed as physical stars by using optical fibre couplers (OFC). Other multiplexed configurations are also possible such as bus and (ring) networks, which will be discussed in section 2.2. A number of transmitters are connected to a number of receivers via the broadcast medium and, when the traffic is sent out from one node, it automatically becomes present for all other connected nodes. This can be used for broadcast and multicast services (which was demonstrated in [***A***]), high-speed computer interconnect networks [6][7], and access networks [8]. Most of the ideas in these types of networks come from local data networks, such as FDDI (fibre distributed data interface) and Ethernet, where a media access control (MAC) layer, is usually used. The MAC protocols, which states when the nodes are allowed to transmit, are used to minimise congestion and prepare the receiver that a packet will arrive. An advantage of B&S networks is the network simplicity. This can be seen from an optical technology point of view (it uses only passive optical devices between the end-nodes) and in some cases from a routing point of view because non-routing decisions are performed in the optical network layer. The transmitters and receivers in the B&S network can be fixed (static) or tuneable (dynamic). Tuneable transmitters and filters are used to reconfigure or save wavelengths, at the cost of a more complex access method. If every node in a local network only has one fixed transmitter and one fixed receiver, then it is difficult to justify WDM from a cost perspective, because non-specified wavelength interfaces, together with short distance parallel fibre, cost less. Furthermore, the efficiency of the MAC protocol is usually limited by distance [9]. In contrast, the use of WDM only makes sense for longer distances. To scale the star network, the stars can be interconnected. Optical interconnects are very limited by the number of wavelengths. Electrical interconnects, called multi-hop, have been analysed for regular network such as shuffle-net [10],[11].

2.1.1 Wavelength dependent network elements

Optical channel Terminal Multiplexer

To originate and terminate information of in an optical network, optical (channel) terminal multiplexers (OTMs) are utilised. The OTMs are used to assure that channels are compliant to the network, e.g. single/multi mode, power, wavelength, and coherent/direct. Generally, an OTM has an array of input ports and an array of output ports where at least the network interface ports, are optical. If both the input and output ports are optical on the transmitting side, the terminal is called transponder based (TET: transmit-end-transponder/RET: receive-end-transponder). Otherwise the terminal is called transceiver based (TX: transmitter/RX: receiver). The transponder can be made all optical with an optical wavelength converter, e.g. a semiconductor optical amplifier [12]. The transponder can add overhead channel information, e.g. via a pilot tone [13] or via an optical frame (digital wrapper) [I], onto the optical channel. The receiving side will select the channel to terminate, de-multiplex if necessary and sometimes also supervise the connectivity, continuity and performance of the channel. The OTMs can be divided into four categories: a single or multi port with static or dynamic wavelength assignment, Figure 2.1. A static wavelength assignment is usually fixed to a specified grid, e.g. ITU G.692, while dynamic assignment implies that different wavelengths can be set up on demand. A 100-wavelength channel static multiplexing system was demonstrated in 1990 [14]. A reconfigurable (dynamic) multi-port OTM offers the opportunity to select which wavelength the information should be modulated on. This is accomplished with a switch in front of the transmitters. The switch can also be utilised to loop-back the signals and protect the transmitters. Another alternative to protect the transmitters is to use an extra transmitter with dynamic wavelength assignment, which is able to protect all the wavelengths in use.

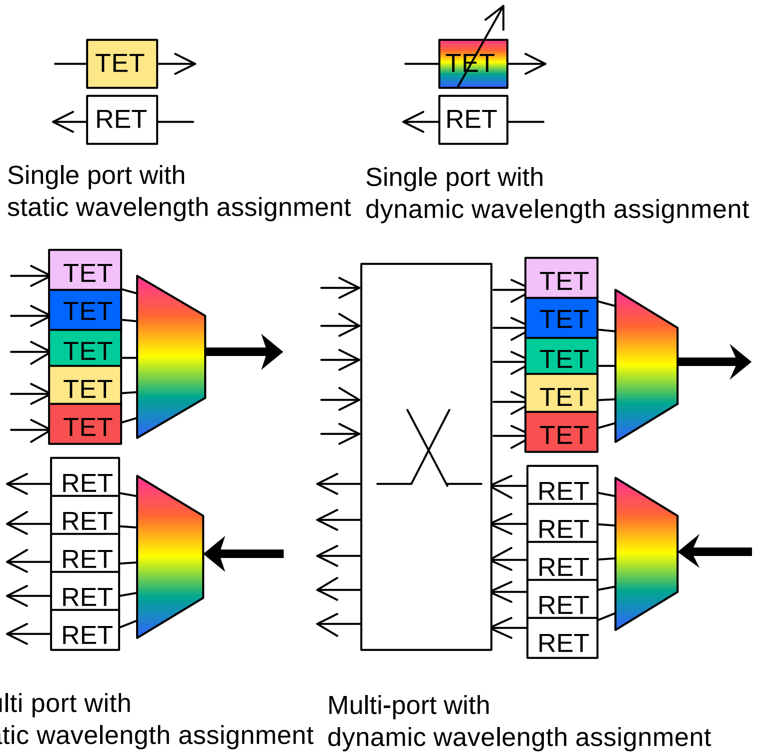


Figure 2.1 Optical terminal multiplexers: single/multi port with static/dynamic wavelength assignment.

Additional OTM functions can be to control and monitor the wavelength and power on the transmitting side as well as to control and monitor the power on the receiving side of the OTM. The system demands on the OTMs, can contradict each other. For example, the transmitting side demands no temperature control and yet must still have high wavelength accuracy, low bias and yet high output power, ECL levels and yet high extinction ratio, and finally high capacity and long distance while maintaining a low cost.

2.1.2 Wavelength independent network elements

Optical Fibre Amplifier

One of the enablers of the WDM network is the optical fibre amplifier (OFA) [15], which makes WDM extremely cost effective for longer distances (>80km) when compared to utilising N channel repeaters. Optical fibre amplifiers can be divided into pre-amplifier, line amplifier and booster. As usual the pre-amplifier should have low noise, and high gain, the booster should have high output power, and line amplifier should achieve a flat gain spectrum. Despite the fact that the OFAs compensate for transmission loss, it is still crucial to keep down the loss between OFAs, in order to maintain an acceptable signal-to-noise ratio (SNR). This emphasises the importance of minimising the insertion loss of optical network elements, used in optical networks. The OFA monitor points used are total input/output/pump power, pump current and pump laser temperature. The most significant parameter for the OFA in a WDM system is the gain flatness over the multiplexed spectrum [A]. Variations over 1dB can destroy the system performance in a cascaded system. Most of the amplifiers are usually optimised for a certain total input power, however, when the input power is changed the amplified spectrum starts to tilt due to homogenous broadening [16]. Several gain equalisation methods exist such as inverse filtering [17], pre-emphasis [18] and fibre cooling [19].

Optical Fibre Coupler

The basic network element to support broadcast and select networks is the optical fibre coupler. OFCs can either be used as a wavelength independent N:1 combiner, 1:N splitter for broadcast or monitoring or combined as a M:N star.

One of the arguments for broadcast and select networks is the reliability and nearly ideal OFC performance, e.g. fused fibre couplers. The monitor points of an OFC are the output power and optionally the input power. In linear lightwave networks [20], the coupling factor of the OFC is used to route the optical power in the network.

2.2 Bus and ring

A bus is defined as a link where the traffic can be accessed at many points along the link. When the two ends are connected to each other a ring is created. This gives the ring inherent protection ability, because a connection can always be set up in two geographically different ways, Figure 2.1. The ring can be open [A] or closed [E]. An open ring is always terminated at some location on the ring. This prevents the light from oscillating at the expense of decreased connectivity for the optical channel add drop multiplexers (OADMs). Both the ring and the bus can either be unidirectional or bidirectional. All configurations except unidirectional bus can manage duplex communication. The bidirection can be achieved either by an extra fibre or an extra wavelength channel.

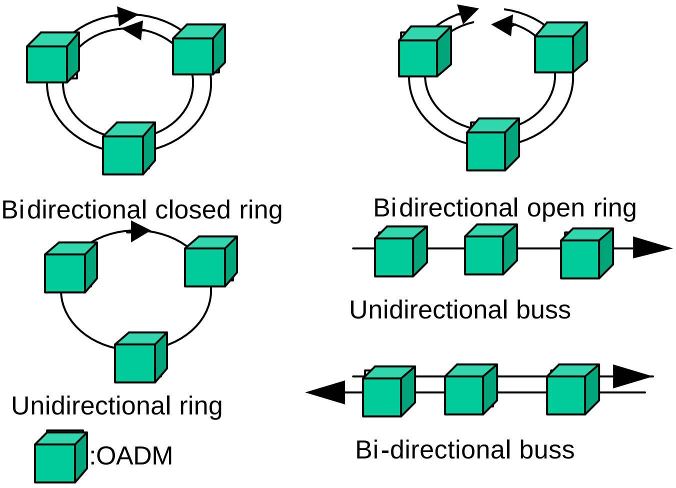


Figure 2.1 Five types of topologies where OADMs can be utilised

2.2.1 Optical Add Drop Multiplexer

The introduction of optical add drop multiplexers into optical networks allows traffic to be inserted, removed and, most importantly, bypassed. Additionally, functions such as protection, drop/continue, loop-back and wavelength reuse of the optical channels can be supported by the OADM. Wavelength reuse means that the dropped channel does not pass through to the next OADM. Instead a new channel of the same wavelength can be added. Drop and continue means that the channel is both dropped at the node but also allowed to pass through to the next OADM. Depending on, which network the OADM should be used in, different requirements are set, based on cost, capacity, redundancy and flexibility.

OADMs can be realised in various technologies [E]. From a transmission point of view OADMs can be classified into notching and demultiplexing [F]. The DMUX based solution separates all the incoming wavelengths and then combines them again after dropping and adding wavelengths. The notch type only separates the wavelength(s) to be dropped. Because the notch type doesn't affect bypassed channels, the cascaded passband and crosstalk performance can be improved compared to the demultiplexing OADM. The crosstalk component at the OADM output port originates from poor suppression of the drop channel (assumed wavelength reuse), which leads to interferometric crosstalk, see section 2.6.2. At the drop port, crosstalk comes from low suppression of the other channels.

Similar to the OTM, the OADM can be divided into a single port with static wavelength assignment, a single port with dynamic wavelength assignment and a multi port with static and dynamic wavelength assignment. The single port with static wavelength assignment is mainly used in hubbed structures, where the OADMs are connected to a central hub, e.g. in the metropolitan network. In order to utilise network resources in a more efficient way, the OADMs with dynamic wavelength assignment are preferred when traffic variations are comparable to network capacity. The multi port OADMs can be utilised when the network is characterised by a uniform traffic distribution and high capacity. This leads to a fully connected meshed network. The number of wavelengths N in the hub structure network grows linearly with the number of OADMs around the ring, contrary to the fully meshed network which grows as N^2. The OADM consists of 1 to 4 input ports (due to protected/unprotected and/or unidirectional/bidirectional links), that are connected to a ring or a bus, Figure 2.1.

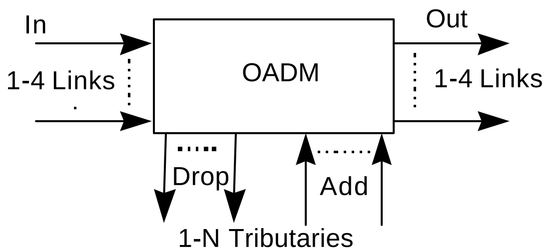


Figure 2.1 A generic optical add drop multiplexer

Broadcast and select OADM

Similar to SDH/SONET a physical ring inherently provides the ability to protect and multiplex traffic. One of the most straightforward implementations of a WDM ring is to have an open ring, which broadcasts the traffic at each node and then selects the channel at the receiver [21]. The advantages with this approach are, among others, flexible adaptation of the logical traffic pattern, multicast, independence of end terminal failures (does not affect the network), and a smooth and flexible ability to upgrade end terminals. A disadvantage to the broadcast ring solution is that it is affected by excess optical power loss and waste of wavelengths, which requires extra fibre amplifiers and dense channel spacing. Additionally, there could be a security risk to have the broadcasted optical channels present at all nodes instead of, only where the traffic is terminated.

Wavelength reuse OADM

Wavelength reuse (WR) can be utilised to decrease optical splitting loss and, to some extent, the number of wavelengths. This can be achieved with wavelength selective devices such as notch filters or (de)multiplexers, Figure 2.1. The notch filter can be implemented as dielectric multi-layer filters or as Mach-Zehnder grating configuration in fibre or in silica on silicon. It is preferably used in hubbed and adjacent logical structures. A meshed structure, on the other hand, is preferably accomplished by (de)multiplexers, which can be implemented in dielectric multi-layer filters or silica on silicon by arrayed waveguide gratings.

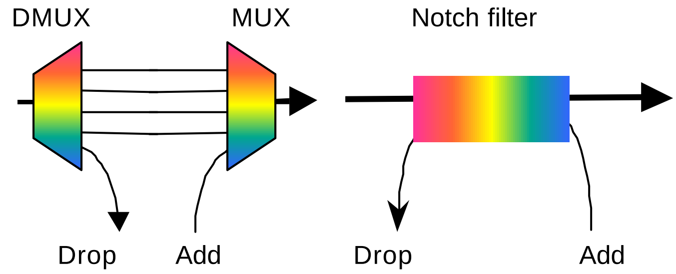


Figure 2.1 (De)multiplexer and notch, DMUX: demultiplexer, MUX: multiplexer

The main wavelength reuse feature is the ability to support an establishment of connections. This is possible because the dropped wavelength slot is always available to the added channel, just as SDH/SONET ADM. From a transmission point of view two aspects are worth considering: intra channel crosstalk between the dropped and added channel, and filter alignment of the cascaded (de)multiplexers [F]. Master and slave locking can calibrate wavelength and channel power to the grid of the other channels [22].

Dynamic OADM

Regardless of the logical traffic pattern, it may be desirable to utilise the same network element for the dynamic OADM as that for the ADM of SDH/SONET. Even if a dynamic OADM can respond to traffic changes (e.g. upgrading) it will probably be configured once and for all. One realisation of the dynamic OADM is comprised of (de)multiplexers and an array of 2x2 switches, Figure 2.1. For a large number of cascaded OADMs, transmission limitations require equalisation to be used. For the bypass channel, this can be implemented either by attenuators or transponders [23]. The transponders give the opportunity to implement electrical 2x2 switches between the receiver and the transmitter. The 2x2 switch array can, of course, be exchanged by manually connecting the two (de)-multiplexers with fibre jumpers and terminating the channel from the (de)multiplexer or forwarding them to the multiplexer. The advantage with this approach is that ordinary OTMs can be utilised. On the other hand supervision of the configuration state of the OADM will be rather rudimentary, e.g. lack of the MIB (management information base) which provides the management system with the configuration status of the optical channels (add, drop, drop/continue, bypass or not present). The array of 2x2 switches can be exchanged by an NxN switch, which enables wavelength conversion.

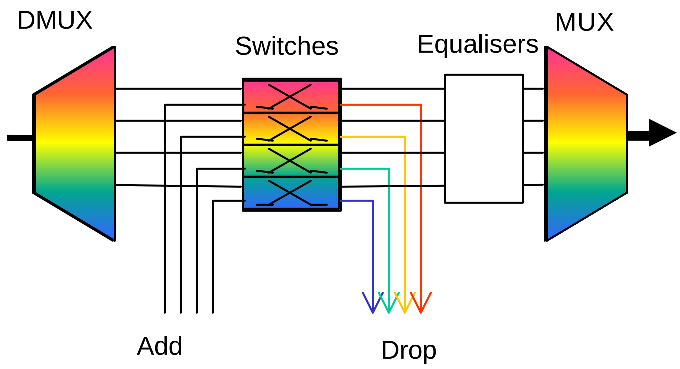


Figure 2.1 Dynamic OADM

Ring interconnect

When a number of sites have been connected in a WDM ring, a situation where sites want to establish connections outside the ring will occur. Most of the time these connections can be handled in the electrical layer, but for large traffic flows it could be an advantage to establish a direct optical connection, which bypasses the electrical clients. Depending on the infrastructure, it could be beneficial to divide the network into physical sub-rings, in order to avoid all wavelengths from propagating around all nodes. On the other hand, optical channel connectivity between the rings could still be required. This can be solved by a bridging function between the rings. One implementation of this interconnection is to connect two dynamic OADMs back to back directly or via point-to-point links. A benefit with ring interconnection is that the maximum number of alternative paths are limited to two, which simplifies the transmission design.

2.3 Mesh

In the next stage of the optical network evolution, multiple rings and links are interconnected to each other via optical crossconnects. The meshed network offers the shortest path, which saves fibre and relaxes the transmission requirements (less dispersion and attenuation). Crossconnection of optical channels can be used to set up high-speed links between routers/switches according to the actual traffic pattern, without being locked into the physical fibre connections. This is similar to what can be accomplished with SDH, but can be done more efficiently for higher bit rates by using optical channel crossconnects (OXCs). Furthermore, an OXC can be used to groom the optical channels (decide which fibre the wavelength should be multiplexed). The net result is to minimise the number of router hops and hopefully reduce delay and jitter. The time scale for this is rather long compared to the bit rate. It is only done if there is a significant change in the traffic pattern, which justifies the WDM layer to take action. Some operators pay more attention to OXCs than to OADMs, because their existing fibre infrastructures are not suitable for rings. In these networks, the OXCs are motivated solely by cost effective protection of the high capacity network. Even if the physical network is meshed, the logical connections can be established in rings [24], which enables local decision and automatic protection of the traffic. Flexibility of the network increases cost because the operator has to design the whole network for the worst case (longest) connection.

2.3.1 Optical CrossConnect

An OXC comprises a crossconnect core unit that either operates on the fibres (fibre crossconnect (FXC)) or on separate wavelengths (optical channel crossconnect) including ingress and egress parts that demultiplex/multiplex the wavelengths. Like the OADM, the OXC can perform wavelength add/drop simply by connecting OTMs to a few of the OXC ports [25]. Every architecture shown below is drawn with four input/output fibres and wavelengths, but all architectures are scaleable to N input/output ports and M wavelengths.

Static OXC

A configured wavelength router is the simplest form of unit that crossconnects wavelengths. It can be realised as fixed interconnections between a set of WDMs, or by an arrayed waveguide grating [26], Figure 2.1. The latter is integrated on one chip and realised as one device. Although the router is fixed, dynamic routing can be obtained if OTMs have dynamic wavelength assignment. Then, when shifting the wavelength of an OTM, the transmitted signal will find different outlets of the wavelength router. The Static OXC has a low connectivity, but it is non-blocking [27].

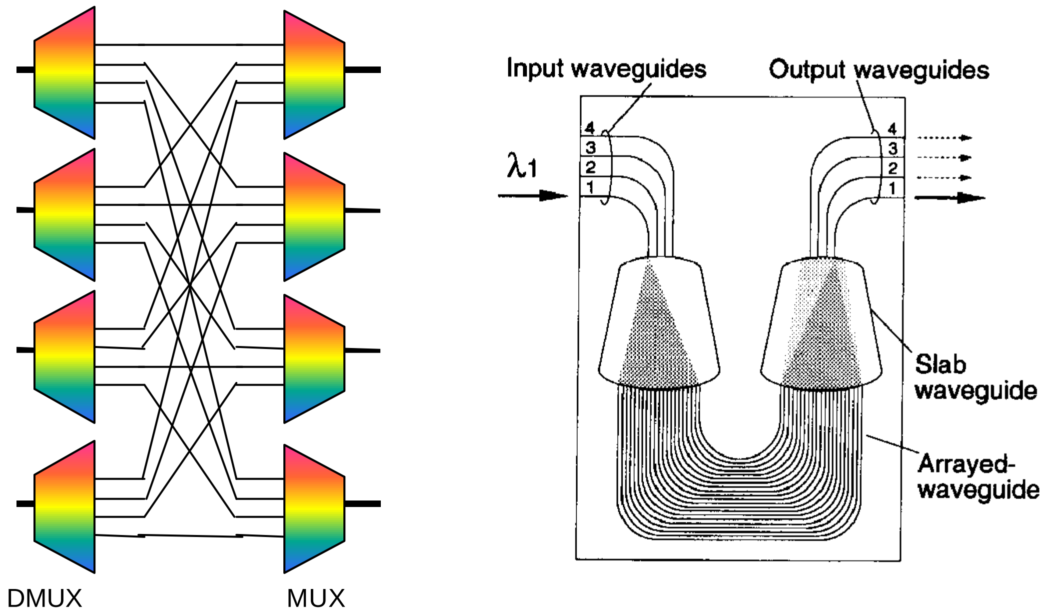


Figure 2.1 Static OXC implemented by (de)multiplexers or integrated as a phased array

Dynamic OXC

Wavelength Path

The wavelength path (WP) OXC establishes a connection through the WDM network with one wavelength (wavelength conversion not allowed). A higher level of functionality is achieved when replacing the fixed interconnection within the static router with space switches. Hence, a reconfigurable wavelength router, or in other words, a dynamic OXC is obtained. In this way, an arriving wavelength from an input port, can be crossconnected to any output port. However, the same wavelength, from two different input ports can not be switched to the same output port. This limitation in crossconnection possibilities makes the OXC wavelength blocking. Under these circumstances, the switch core of an OXC can be divided into separated switch planes, one for each wavelength, Figure 2.1a. N input/output ports, each with M wavelengths, require M NxN switches to realise the OXC. Attenuators, transponders (wavelength converters) or amplifiers (mainly for the pre-equalisation on the optical multiplex section layer) can be used to equalise the signal. Two WP OXCs have been implemented and evaluated [C],[H] in the Stockholm gigabit network.

Wavelength converters have been observed earlier as a key technology to resolve wavelength congestion in optical networks. Wavelength conversion can be compared with Time Slot Interchange (TSI) in TDM switching [27], where it is fundamental to obtain non-blocking circuit switches. However, studies, e.g. [28], have shown that the probability for wavelength congestion in core networks is limited and can to a large extent be avoided with appropriate routing algorithms. An alternative to introducing wavelength converters within the OXC is to drop the blocked wavelength at an OTM that retransmits the signal again on a different wavelength. While this approach will save wavelength converters it will, however, allocate capacity of the switch core since the signal is being connected twice through the crossconnect [29].

Virtual Wavelength Path

Virtual wavelength path OXCs can switch any wavelength to any output port. In the event of wavelength congestion, one of the wavelengths is simply converted before multiplexing at the egress. An OXC with this architecture is non-blocking [30].

Rearrangeable non-blocking

A virtual wavelength path OXC can be realised by introducing wavelength converters immediately in front of the egress part and tuneable WDMs [G](alternatively optical coupler with tuneable bandpass filters at the output [C]). This solution would also improve the equipment redundancy [31], Figure 2.1b. The rearrangeable virtual wavelength path OXC is non-blocking, but unfortunately not strictly, which means that for multiplexed high capacity circuit switched networks this is not an alternative.

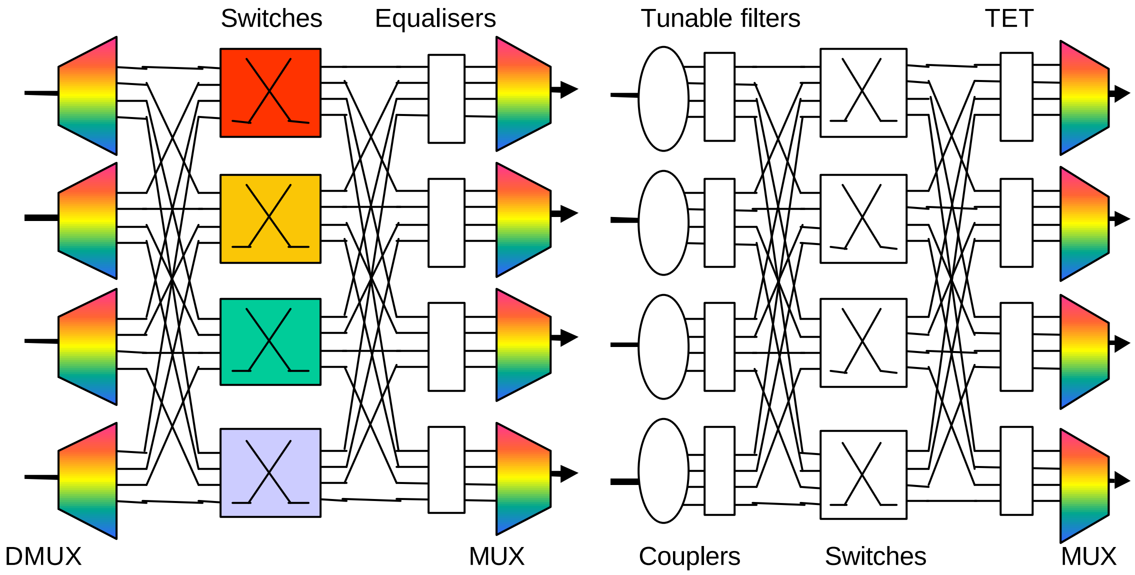


Figure 2.1a) Wavelength path OXC, b) rearrangable virtual wavelength path OXC

Strictly non-blocking

Three main architectures exist to implement a strictly non-blocking OXC, Figure 2.1. The first architecture utilises only the space domain to crossconnect the channels. An electrical switch surrounded by receivers and transmitters can achieve the crossconnection [J]. Another option is to use an optical switch with transponders at the output ports and optional receiver transponders at the input ports. The switch matrices can be divided into Clos network [32] and still preserve the non-blocking performances. The electrical switch solution is the most scalable, provided that interconnections to the switch are solved.

Another approach is to use both the wavelength and space domain to crossconnect the channels, e.g. parallel lambda switch [33], which uses tuneable filters or the reversed solution [34] using tuneable transmitters. The last approach utilises only the wavelength domain, by e.g. wavelength expansion [35].

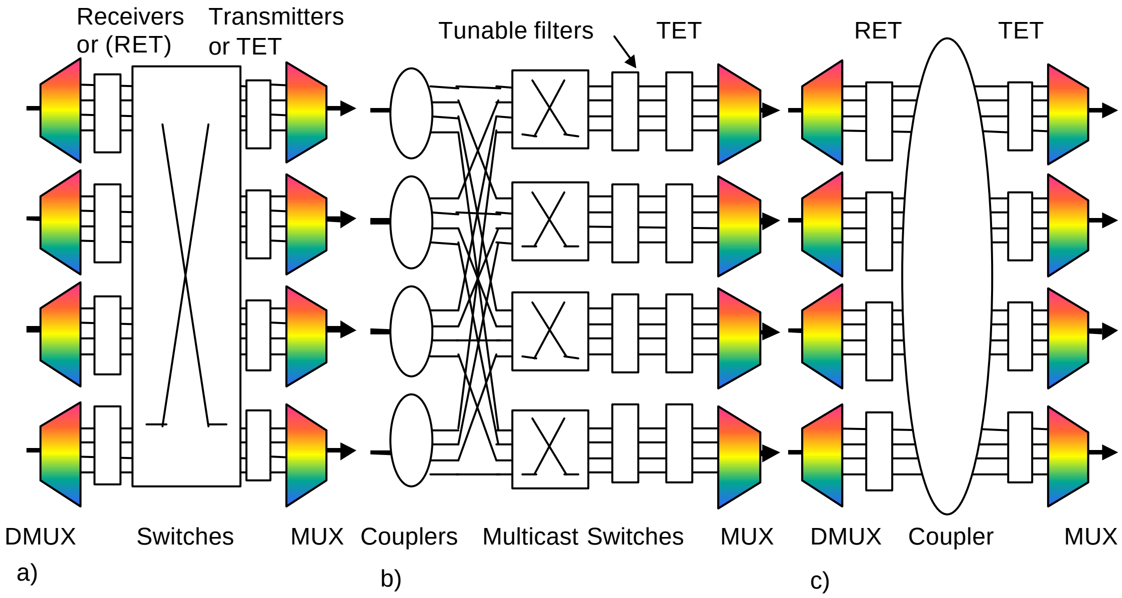


Figure 2.1 Three principal architectures for constructing a non-blocking OXC, a) space switch OXC, b) wavelength and space switch OXC, and c) wavelength switch OXC.

2.4 Transparency versus regeneration

The operators' investment in their WDM transport networks has to be "future proof" for several years. When the WDM system extends from point-to-point to reconfigurable networks all the network elements have to be compliant with each other. This means that channel spacing, bit rate range and number of channels should be the same in the WDM network, else the wavelength selective and bit rate dependent devices will have to be exchanged.

Transparency is a concept that has been a strong selling argument for optical networks [36]. However, the degree of transparency is limited both by transmission rate and by network extension [37]. Transmission formats can have very diverse characteristics and are affected differently by perturbation. It is a challenge to design an optical network that is fully transparent to transmission format and at the same time obtain certain coverage of the network.

For example, a separate OFA is transparent to bit rate and code format, but when cascading a number of the same OFAs in a chain the transparency will be considerably reduced [38]. Transparency is dependent on the OFA operating condition, e.g. signal level, gain, and noise accumulation, and these are dependent on the OFA span. It is not realistic to change the span of the OFAs afterwards to adapt the network for new operating conditions as higher bit rate. Therefore it will not be possible to upgrade to higher bit rates if this was not taken into account in the original design. However, a network design should be limited to those transmission formats that can be expected within a foreseeable time frame, to avoid over engineering. In essence, the worst path (weakest link of the chain), taking into account the evolution, determines the scalability of a transparent and reconfigurable network.

2.4.1 Level of transparency

The transparency within the optical layer can be divided into several levels [39], Table 2.1. All levels are comprised of two transparency sub-levels, ingress and egress transparency, Figure 2.1. The ingress is the interface from the client towards the optical layer, which task is to be independent of the client characteristic. The egress is the interface from the optical layer towards the client, which assures that the client signal characteristics are preserved. Independence of the electrical characteristics leads to preservation of the characteristics.

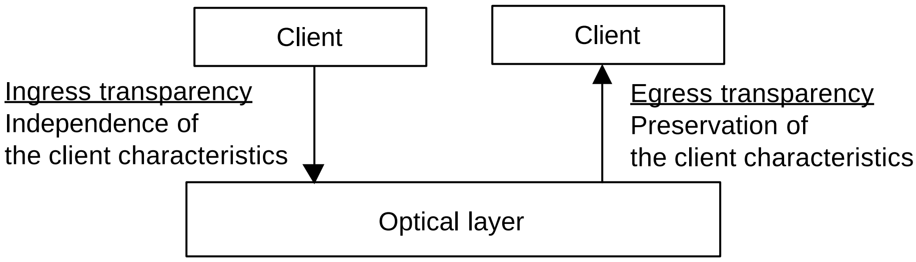


Figure 2.1 Ingress and egress transparency of the optical layer

2.4.2 Level of regeneration

Several levels of manipulation have to be considered when adapting the characteristics of a signal to the optical network [40]:

- reamplification (1R)
- (phase- and wavelength-regeneration) + reamplification (1.5R)
- reshaping + reamplification (2R)
- retiming + reshaping + reamplification (3R)
- resynchronisation, coding or service regeneration + retiming + reshaping + reamplification (+3R)

Usually there are two kinds of regeneration in optical networks, 1R provided by the OFA and 3R provided by the OTM. There are two reasons to minimise the number of 3R repeaters, and exchange them to lower order repeaters when possible: to simplify the design and decrease the cost of high-speed 3R repeaters (one per wavelength), and to improve network transparency for the client signals. However, 3R repeaters are still required at many different levels in the network, e.g.

- At the boundary of the electrical backbone to control the quality of the signal coming from different clients
- Within the optical network to increase the propagation distance, and to achieve a modular concatenation of transmission links
- In the interconnection of optical networks to create a bridge between two networks operating at different bit rates
- In the interconnection of optical networks to create a bridge between two network operators

The only means to obtain full recovery of the digital signal is by 3R regeneration of the signal. This requires clock extraction to recover the clock rate from the signal, and a decision circuit to recover the original bit pattern. Non-optimal recovery of the clock results in jitter. The jitter requirements depend on which application it should be used for. For example, connecting routers or switches with buffers relax the jitter specifications compared to an entire synchronous network, such as SONET/SDH (despite the pointer adjustment). Jitter accumulates if the 3R repeaters are cascaded. This increases the requirements even more. Jitter can be compensated for if the signal is synchronised with an external clock source (+3R).

Utilising limiters (2R) to achieve protocol transparency [40] for binary encoded systems add noise induced timing jitter to the signals, which actually limits the system to the same extent as ordinary 1R repeaters. Increasing the SNR and the bandwidth of the 2R repeaters, however, could reduce the timing jitter limitations [41]. The jitter of the 2R and 3R repeater can be divided into systematic and random. The systematic jitter can be pattern dependent [42]. When a 1R repeater includes a laser (1.5R), the phase, wavelength and polarisation will be regenerated, e.g. by linear opto-electro-opto (OEO) repeaters, crossphase or crossgain converters. An OEO-repeater is normally referred to as a transponder, which is comprised of fundamental elements such as a detector, electrical filter, amplifier, and a laser. 1R repeating is defined here as all optical. This is very effectively done today in the optical domain using EDFAs, due to low noise and multichannel amplification.

The intention of Table 2.1 below is to exemplify the potential misunderstandings that can occur when the word transparency is used. The important requirement of transparency, however, is client independence [I]. At present, most client interfaces can be summarised as binary NRZ, with a wide range of bit rates but mainly STM-1, 4,16, and 64, and either wavelength compliant to ITU G.692, or non-compliant (within the 1310 or 1550 nm window) [43]. Furthermore, no phase, linear, or polarisation demands are required as long as coherent communication or sub carrier modulation becomes widely deployed. Duo-binary modulation to improve bandwidth efficiency and RZ modulation to increase transmission distances could have a potential benefit to disturb the common standard. Finally, manageability is an important function of a reconfigurable network, because it, among other things, assures the transmission quality and the integrity of the client information. This requires access to the bits of the client. A solution to these contradictory requirements (transparency versus bit access) could be to deploy bit rate transparent 3R repeaters.

Characteristic	Ingress transparency	Repeater demand	Egress transparency	Repeater demand
Phase (coherent)	Independence of the optical phase	1-3R	Preservation of the optical phase, e.g. for coherent technique	All-optical 1R
Polarisation	Independence of the polarisation, e.g. no or small PDL or PMD		Preservation of absolute or relative polarisation.	
Frequency range	Independence of wavelength allocation within a certain range		Preservation of the carrier frequency wavelength path, e.g. no wavelength conversation	1-3R, presumed that the wavelength can be regenerated otherwise, 1R
Frequency grid	Independence of the wavelength allocation within a specific grid, virtual wavelength path			

Linear	Independence and preservation of the modulation spectrum	Electrical analogue 1-1.5R	Preservation of the modulation spectrum e.g. sub-carrier modulation,	Electrical analogue 1-1.5R
Modulation	Independence and preservation of the modulation format, e.g. NRZ, NRZI, RZ	Bit rate transparent 1-2R	Preservation of the modulation format	1-3R
Code and scrambling	Independence and preservation of the link protocol, e.g., 8B/10B		Preservation of the line code or scrambling	
Bit rate range	Independence and preservation of the bit-rate, e.g. 100-2700Mb/s		Preservation of the bit rate	
Bit rate grid	Independence and preservation of the bit rate grid, e.g. STM-1,4,16,	Multi-rate-3R, 2R, 1R		
Synchronisation	Independence and preservation of the synchronisation	Synchron +3R	Preservation of the synchronisation	Synchron +3R

Table 2.1 Different levels of transparency versus different levels of repeating

2.5 Reconfigurability

The functionality of reconfigurable networks can mainly be divided into protection of links and nodes, and dynamic configuration of logical networks.

2.5.1 Protection

Network protection, as a response to cable break or node failure is very important when designing a robust network. The demand for network survivability increases as more of the end-users share the same transport equipment due to multiplexing. Protection is a feature that optical networks can provide very efficiently [44]. The idea is to establish protection switching close to the origin of the fault, which would result in a smaller number of actions. This will make the protection switching fast and effective. Protection can be divided into network and equipment protection. Equipment protection is usually achieved by duplication of hardware, e.g. redundant pump lasers in an EDFA or redundant lasers, which can be tuned to a specific wavelength if a wavelength specific laser goes down. Network protection, which will be discussed in the following section, protects connections by always having at least one redundant and disjoint path within the network. Optical protection can be performed on each of the sub-layer, OCH, OMS, and OTS, Figure 2.1.

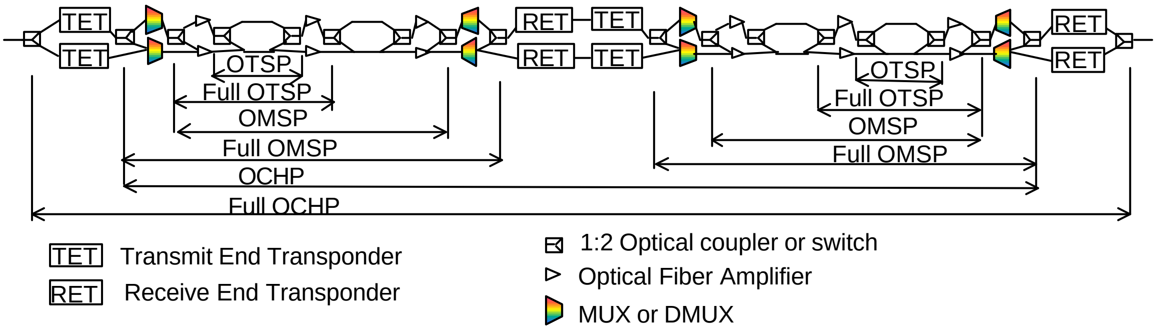


Figure 2.1 Optical channel protection (OCHP), optical multiplex section protection (OMSP), optical transmission section protection (OTSP)

Optical transmission section protection (OTSP) protects only the fibres, however, full OTSP includes the optical amplifiers as well. OTSP protection is seldom used because of how expensive it is to design a network with disjoint paths for each optical transmission section. Optical multiplex section protection (OMSP) assures the resilience between the multiplexer/demultiplexer, and full OMSP includes the multiplexer/demultiplexer. OMSP provides surveillance to cascaded OTS sections for all wavelengths. Finally, optical channel protection (OCHP) protects the entire optical channel path through the network, and full OCHP also includes the TET and RET into the protection. The advantage with OCHP is that it provides channel selective protection, yet it is more expensive than OMSP/OTSP protection due to the cost of more redundant equipment. The preferred optical protection (MCHP, OMSP, OTSP or no protection) is dependent on the network and on the client survivability. For example, OCHP for large networks is more efficient than OMSP/OTSP because many optical channels can share the same redundant path [45]. If the client protects the physical layer (layer 1), e.g. via SONET/SDH rings, then optical protection is useless. If the client layer provides protection on the link layer (layer 2), e.g. by multi protocol label switching or dynamic packet transport, then OMS protection could be a cost-effective complement. Finally, if the client layer provides protection on the network layer (layer 3) by rerouting, e.g. via routing protocol, then protection of the optical channel layer could be a good complement [K]. In essence, multiple layer protection should not be performed by adjacent layers in order to complement each other from a cost and functionality point of view. Depending on the network topology, i.e. link, ring, or mesh, further consideration of the protection scheme has to be made.

Link protection

There are two basic protection schemes to be considered for links: dedicated and shared protection. Dedicated protection means that a spare path is reserved as a backup for a particular path to be protected. This can be implemented in two ways, denoted 1+1 protection or 1:1 protection.

In 1+1 protection, the signal at the transmitter end is split into two paths which are directed towards the same receiving end. Typically these two paths are diverse in order to avoid both paths being affected by the same cable break. At the receiving end the signal is available from both paths. If the signal from the first path fails, the receiver simply switches over and selects the second path. This scheme is very simple, where the decision of protection switching is taken locally at the receiver end, without the need of signalling. It only costs a 1x2 splitter at the transmitter end and a 1x2 optical switch at the receiving end, but unfortunately, 1+1 protection allocates two paths, Figure 2.1a. In 1:1 protection, one path is dedicated to backup, but it is utilised for low priority traffic when not activated for protection. Thus the 1:1 protection scheme allocates one path only for the protected traffic. In order to switch in/out low prioritised traffic 2x2 optical switches must be implemented at the transmitter end as well as at the receiver end, Figure 2.1b. This makes the 1:1 protection scheme a bit more complex than 1+1 protection, because when the receiving end switches over to the protecting path it must signal back to the transmitter end to do the same. The simplest implementation of signalling is to switch the transmitter of the receiving node.

When the probability for simultaneous failure for the protected units is low, shared protection is used. This means that (n) protected units, paths or equipment share a number of protecting units (m). This scheme is denoted as m:n protection. In the special case when only one protecting unit is used, it is called 1:n protection. When one out of the (n) high priority units fails, the protecting unit becomes active. However, this means that there are no more spare units available if a second unit also fails, Figure 2.1c.

So far, protection switching has been discussed for the space domain only, but it can also be implemented in the wavelength domain. This usually requires a tuneable source. For example, in the case of a 16 channel OTM, one transmitter may act as a protecting unit to the other 15 transmitters. If one of these 15 transmitters breaks, the protecting unit goes active and replaces the failing source by tuning into the right wavelength (called 1:16 shared protection switching). The approach gives time to replace the failing unit, while the affected traffic is transmitted via the protecting unit. Later, when the broken transmitter has been replaced, the traffic is switched back to the original state and the protecting unit is available in case of new failures.

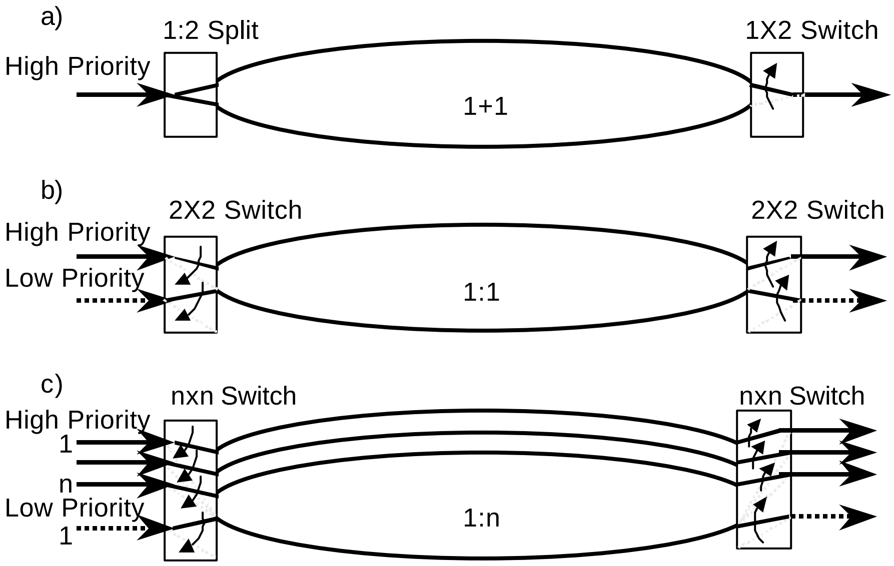


Figure 2.1: Protection schemes: a) 1+1 dedicated protection: the signal is transmitted on two paths simultaneously, protection switching is made at the receiving end only. b) 1:1 shared protection: protection switching needed at each end; the protecting path can be utilised for low priority traffic during normal conditions. c) 1:n shared protection: only one protecting path is used to protect (n) other paths.

Ring protection

Optical protection can be accomplished in different fibre topologies with several protection approaches. For example, in access networks with a star topology, one node (with only one circuit) will be affected if the link goes down, while link failures in rings will affect every node and on the ring. In the transport network where several circuits have been multiplexed to the same link, a ring offers cost-effective and simple network resilience, because it provides one diverse path for protection to all nodes, and it allows simple protection switching decisions, (because “east” or “west” directions are the only options). Rings can save link distances in a dense network, while stars can save link distances in a non dense network and provide protection via load sharing on 1+1 networks, thus giving both node and link redundancy. However, shared protection can be more effectively used for connections within rings, provided that wavelength reuse is utilised. Even if hardware requirements are the same as for

1:1 protection (1x2 switch at the sender and receiver), it can be shared between N connections, which utilise the same wavelength around one fibre ring. Therefore the ring structure will be treated in more detail here.

The ring may look very simple at first glance, but a closer look reveals that it can be designed in different architectural variations. The basic ring architectures include 2-fibre unidirectional (one working and one standby) [A], 2-fibre bidirectional, and 4-fibre bidirectional rings [46]. The latter is implemented as two reversed unidirectional rings. Shared protection for a 4-fibre ring with duplex traffic (bidirectional) has the advantage of never requiring wavelength conversion.

In a unidirectional ring all traffic propagates in the same direction, using one fibre. The second fibre is used solely as a protecting path in the opposite direction. From one node’s perspective, this means that, the return path will be to the “east” if the receive path is from the “west”, Figure 2.1a. In the case of a bidirectional ring the return path would be to “west” (in this example), using the second fibre, Figure 2.1b. Thus, the bidirectional ring uses the shortest path of the ring. The other path is used as a protecting connection. This difference between unidirectional and bidirectional rings also gives a different protection scheme.

In the case of unidirectional rings protection switching is accomplished by folding the ring to avoid the faulty section; the two nodes on each side of the fault switch over to the second ring, thus restoring the connection through the second fibre, Figure 2.1a. One of the two nodes on each side of the fault will become the head while the other will become the tail of the folded ring.

When providing a protecting path for a connection in a bidirectional ring, the ring sector not used for the principal connection is employed as a spare, alternative path. As in the example, this can be implemented as 1:1 protection, Figure 2.1b, or 1+1 protection by splitting the transmitted signal into both fibre rings, to “west” and to “east”. At the receiver end, the signal is available both from the “west” and the “east”. Thus, if the signal from the “west” fails, the receiver only has to switch to the “east” side.

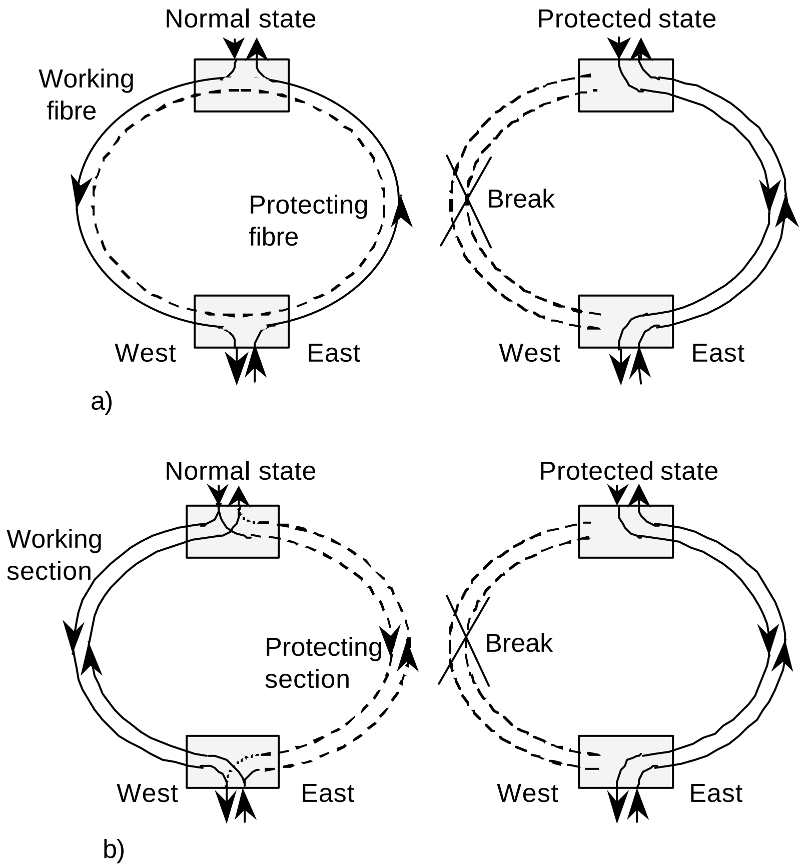


Figure 2.1 Ring protection a) shows unidirectional ring protection whereas b) shows bidirectional ring protection

Independent of which protection scheme the ring uses, the ring provides simple and at the same time wavelength effective protection.

Mesh protection

Protection in the meshed network can be provided either by dividing the network into protected sub-networks (e.g. rings), or protecting the path from the ingress to egress tributary. Sub-networks can be connected to each other and still preserve the protection by utilising dual homing [20]. Protected dual homing connections between the sub-networks can be seen as point-to-multipoint protection and multipoint-to-point protection within the sub-network. Alternatively, from an end-to-end point of view it can be viewed as an ordinary point-to-point protection. To avoid signalling between sub-networks connections can be broadcast to the two “homes” via drop and continue in the “homes”, at the cost of using 1+1 dedicated protection between the two sub-networks [47].

Rings can be created in meshed networks with point-to-point connections, and the same ring protection algorithms can be used [48]. However, due to the excess redundancy that a meshed network offers (more than two connections to the receiver) there usually exist more connection efficient solutions (rerouting), which take into account the present network status, usually using methods such as shortest path (modified Dijkstra, linear programming or simulated annealing) [11]. To continue providing fast network protection, the redundant connection should be reserved in advanced [45].

2.5.2 Logical networks

Multiplexing, transparency and reconfigurability enable the design of logical (or virtual) networks. The benefit is that the connectivity of the client layer and the functionality within the optical layer can be optimised (e.g. logical self-healing rings in meshed networks, section

2.5.1). The drawback is that more wavelengths and longer transmission distances are usually required, but as long as the transmission cost is decreasing and not the switching cost (Figure 1.1d) this is justified. The characteristics of the logical and physical network depend on how physical links and logical paths are connected [49].

Node connectivity

Nodes extend the connectivity in the optical network, by increasing the number of input/output ports, wavelength converters and switches. In Table 2.1 the degree of connectivity (C), defined here as the number of realisable distinct circuit connections between end node pairs [27], number of simultaneous active connections (A), and blocking characteristics (Bloc) is listed for different network elements.

Network Element	**C**	**A**	**Bloc.**	**Comment**
Fibre	F	F	SNB	
S-OTM-1ch	2	2	SNB	Figure 2.1, Static WC and filter
D-OTM-1ch	2F	2	SNB	Figure 2.1, Dynamic WC and filter
S-OTM	F	F	SNB	Figure 2.1WC (WP)
D-OTM	FF	F	SNB	Figure 2.1WC+FxF (VWP)
OFA	F	F	SNB	
OFC	NF	F	B	
S-OADM-1ch	F+1	F+1	SNB	1 static add/drop port, wavelength reuse
D-OADM-1ch	4F	F+1	B	1 dynamic add/drop port
D-WP-OADM	4F	2F	B	Figure 2.1, 2x2 D-WP-OXC,
D-VWP-R-OADM	4FF	2F	RNB	2x2 D-VWP-R-OXC
D-VWP-S-OADM	4FF	2F	SNB	2x2 D-VWP-S-OXC
S-OFXC	NF	NF	SNB	Static fibre connections
S-OXC	NF	NF	SNB	Figure 2.1
D-OFXC	NNF	NF	SNB	An optical NB switch
D-WP-OXC	NNF	NF	B	Figure 2.1a, [H]
D-VWP-R-OXC	NNFF	NF	RNB	Figure 2.1b
D-VWP-S-OXC	NNFF	NF	SNB	Figure 2.1 [30]

Table 2.1 Connectivity of network element, blocking (B), rearrangable non-blocking (RNB), strictly non-blocking (SNB) F=number of wavelength, N=number of fibres, S=static, D=dynamic, WP=wavelength path, VWP=virtual wavelength path,

Non-blocking means that it is always possible to set up an optical channel to one of the unoccupied channel slots at the output, independent of the wavelength. To increase the network connectivity, C should be larger than the node connectivity for a fibre. Dynamic network elements increase the connectivity, but can be blocking. Static network elements are inherently non-blocking, but have less connectivity. The connectivity for the OADM in Table 2.1 includes the loop-back state (the add port is connected to the drop port)

Network connectivity

Optical networks can be divided into virtual wavelength path and wavelength path networks [30]. In wavelength path networks the wavelength remains the same over the entire path. An advantage of WP is the possibility to set up all-optical connections, without requiring wavelength converters. In virtual wavelength path networks the path is independent of the wavelength. This means that wavelength blocking is avoided and the provision of connections for the network management system is simplified.

Reconfigurable networks enable the establishment of logical networks. Logical networks can be used to optimise the router/switch connectivity, to save ports and minimise the number of hops. By adopting the logical network as close as possible to a dense network [20], (e.g. the de Brujin graph) the number of nodes N, which can be reached within a maximum of number of hops D, for a specific number of ports Δ, is maximised. However, the usefulness of these dense networks in real networks is questioned because traffic patterns are seldom as uniform as the dense networks assume [50]. In Table 2.1, the maximum number of nodes, given Δ and D for some dense networks are listed and compared to basic networks such as, ring, bus, tree, star and mesh networks. Included is also Moores bound [20], which gives an upper bound of N.

Network type	Number of nodes, N	Comments
N-cube	2^D	Δ=D
Manhattan Square Network	D^2	Δ=4, when D is even
de Brujin	$(\Delta/2)^D$	
Shufflenet and its Inverse	$0.5(D+1)\ (\Delta/2)^{0.5(D+1)}$	
Tree	$(\Delta(\Delta-1)^{D/2}-2)/(\Delta-2)$	Moore (D/2)
Ring	2D	Δ=2
Bus	D	Δ=2, or unidirectional ring
Full Mesh	Δ+1	D=1
Star	Δ	D=2, The hub has Δ=N
Moores	$(\Delta(\Delta-1)^D-2)/(\Delta-2)$	

Table 2.1 Regular (dense and basic) networks: number of nodes (N), number of hops (D), and number of ports (Δ) for bidirectional links.

Ring connectivity

Physical rings can always be configured in meshed networks where all nodes are bidirectionally connected to at least two nodes (Δ≥2), [24]. The connectivity pattern will respond to a certain traffic demand, and will impact the scalability of the ring in terms of number of nodes and available wavelengths. A basic logical pattern is the hub (star) (see Figure 2.1). In this case, one dedicated wavelength is used to connect each node in the ring to one hub node that is placed somewhere in the same ring. The hub node must handle all wavelengths in the ring and it therefore becomes more complex in realisation. The hub node has the task of regrooming the traffic to obtain high wavelength utilisation, and to serve as a gateway to other sub-networks.

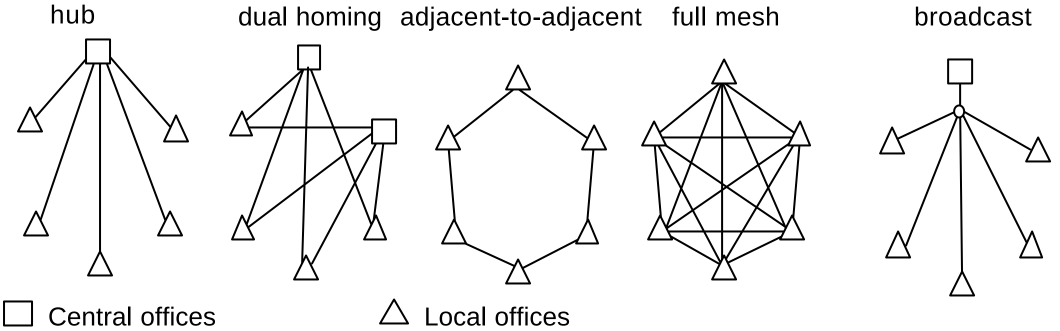
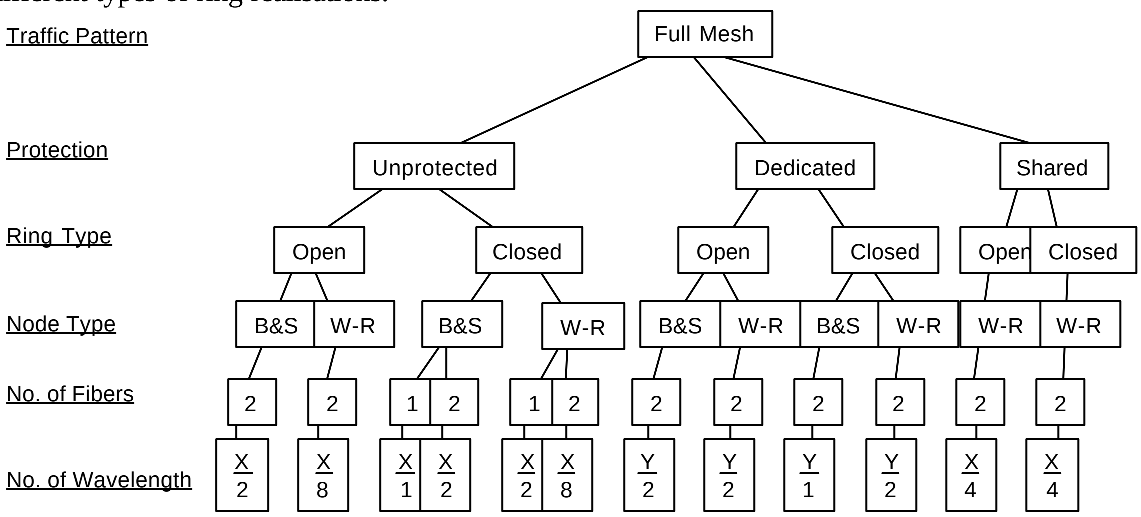


Figure 2.1: Different connection patterns that can be established within a constructed WDM ring, just by routing the wavelength appropriately.

To provide redundancy, dual homing is often practised (Figure 2.1). Then two hub nodes are placed in the same ring to improve redundancy in case of hub failure. Another simple pattern is the adjacent node pattern (Figure 2.1). This means that each node has only two connections, one to each of the two neighbours. The traffic is then routed with a multi-hop technique, which means that all nodes within the ring take part in a distributed regrooming process. The full mesh pattern is the most complex pattern (Figure 2.1), with all nodes interconnected. In this case the number of wavelengths is consumed rather rapidly (quadratically), and is therefore not as scaleable as the others. The full mesh pattern is useful when the availability requirement is very high, and the mutual traffic demands between individual nodes are sufficiently high to obtain acceptable wavelength utilisation without requiring client switching, routing or regrooming. Another pattern is the broadcast pattern (Figure 2.1). The node must, in this case, accomplish a drop and continue function.

In Figure 2.2, the number of wavelengths required for a full mesh pattern is shown for different types of ring realisations.



B&S= Broadcast and Select, W-R= Wavelength Re-use, **X=NN, Y=N(N-1)**,
N= No. of nodes in the ring, (for odd number of N, X should be decreased by one)

Figure 2.2 Number of wavelengths required for full mesh pattern

The pattern is divided into three types of protection: unprotected, dedicated and shared. The full mesh connectivity demands bidirectional connectivity. Only the closed unprotected ring can establish a full meshed pattern in a 1-fibre ring. The dedicated protection will under no circumstances have a spare wavelength available in the other ring direction. The number of wavelengths for the unprotected and shared rings scale with the number of wavelengths per link, while the dedicated and 1-fibre unprotected ring scales with the number of connections. A 4-fibre ring requires half the number of wavelengths than a 2-fibre ring.

The unprotected broadcast and select 1-fibre ring has as many wavelengths as the connections for the meshed pattern. Compared to a 1-fibre ring a 2-fibre ring with unprotected wavelength reuse, needs 1/8 less number of wavelengths due to the extra fibre, (wavelength reuse and bidirectionalty). When shared protection is provided on the same ring the number of wavelength doubles. With dedicated protection the number of wavelengths for the same ring nearly doubles when compared to the shared protection. Dedicated broadcast and select in an open ring is as efficient as wavelength reuse with the same protection, provided that the open part of the ring is at the same location as the failure, e.g. the Flexbus [21]. In an open ring (in this case equal to a bus), all wavelengths will always be terminated either at the head or at the tail of the ring. This prevents the light from oscillating as a ring laser, but at the expense of decreased connectivity.

The number of wavelengths is equal for dedicated and shared protection in a hub pattern because the wavelengths can only be reused once, which results in equally effective solutions, for a 2-fibre ring. However, the node-to-node pattern reuses each wavelength N times, which results in shared protection becoming N/2 more wavelength effective. In the dual homing pattern, shared efficiency depends on where the hubs (=homes) are located. If hubs are located next to each other, then wavelength efficiency will be the same as for the hubbed case. If the hubs are located with the maximum number of nodes between each other then wavelength efficiency will be 2 times better for the shared protection compared to the dedicated.

In essence, reconfigurable OADMs , utilising different logical patterns, enable the node to be logically shifted around the ring to appear next to the node with the highest mutual traffic demand. When the rings are configured in meshed networks where the number of ports $\Delta \geq 3$, several rings can be created through the same network element. The tributaries of the NE could then be efficiently exchanged between the rings to create new logical patterns.

2.6 Transmission limitations

The scalability of optical networks is partly set by transmission limitations (other restrains could be number of available wavelengths, manageability and cost-effectiveness). In addition to the traditional limitations for optical communication such as attenuation and dispersion, other limitations in optical networks arise from multi-channel propagation, e.g. cascading and crosstalk. One of the reasons behind these limitations is the analogue character of the transparent optical network.

When channel bandwidth and path distances increase the dispersion characteristics mainly of the fibre becomes more and more important. However, by including dispersion compensation methods in the network elements, the inter-symbol interference caused by dispersion could be decreased [3]. For metropolitan system (low cost and short distances) the adiabatic chirp from direct modulated lasers could be used to slightly enhance the fibre distance [51]. Dependence on the extinction ratio, which influences both the adiabatic and transient chirp has been experimentally investigated [52].

Non-linear effects in the fibre can also limit the system performance. Beside the single channel non-linear effects such as self phase modulation and stimulated Brillouin scattering, WDM systems can be affected by stimulated Raman scattering, crossphase modulation and four wave mixing [53]. These effects are one of the limits of maximum power and minimum channel spacing used in the optical network.

2.6.1 Cascading effects

When combining fibres with multiplexed channels in an all-optical crossconnect, power equalising is essential. The incoming multiplexed channels can be coarsely equalised (precompensation) by preferably optical (pre-) amplifiers, or attenuators. Secondly, the demultiplexed channels can be fine equalised after the crossconnect fabric (post-compensation) by attenuators or amplifiers. Another approach to equalise the optical channel levels is to regenerate the signal to a certain optical power in each node. The regeneration also reduces the wavelength stability requirement from globally to locally. Dynamic variations of the power levels, due to different number of wavelengths and different paths, will set harder constraints on the optical devices, especially the active devices, where the saturation power and small signal gain will be affected.

Reconfigurable WDM networks increase the requirements on wavelength stabilisation and accuracy in optical devices. As long as the requirements of centre frequency accuracy is lower than the stability of the temperature control circuits, indirect measurement of the temperature is enough, otherwise some sort of wavelength reference system is required.

When cascading (de)-multiplexers, alignment and the shape of the filter transfer functions (amplitude and phase) are essential [F]. The requirement of the filter function increases with the number of cascaded devices [54]. However, this can easily be solved for additional costs by introducing opto-electric converters [J].

Cascaded links in optical networks cause concatenation effects of e.g. the optical amplifiers or filters, which can decrease the bandwidth of the passband, and the amplified spectrum [F]. A number of different optical filter technologies exist to demultiplex optical channels. In Table 2.1 some of the filter technologies and corresponding transfer functions are listed. Cascading of filters results in a multiplication of their transfer functions.

Filter type	Approximated power transfer function T=|H(f)|^2	3dB bandwidth after n aligned filters
Fabry-Perot [55]	$\frac{1}{1+(2pft)^2}$, 1st Butterworth [56]	$\sqrt{2^{1/n}-1}$
Dielectric multilayer thin film [57]	$\frac{1}{1+(2pft)^6}$, 3rd Butterworth [56]	$\sqrt[6]{2^{1/n}-1}$
Acousto optical tuneable filter [58] (non apodised fibre grating)	$\frac{\sin^2(1.39\cdot 2pft)}{(1.39\cdot 2pft)^2}$, [59]	$\approx \frac{1}{1.39}\sqrt{6(1-\frac{1}{\sqrt{2^{1/n}}})}$
Mach-Zehnder	$\cos^2(\frac{p}{4}2pft)$, [3]	$\frac{4}{p}\arccos(\frac{1}{\sqrt{2^{1/n}}})$
Arrayed waveguide grating [60] (bulk grating)	$\exp(-\ln(2)(2pft)^2)$, Gaussian	$n^{-1/2}$

Table 2.1 Filter types and their approximated transfer functions and cascaded 3dB bandwidth

The multilayer filters have a very flat top, which preserves a wide 3dB bandwidth of cascaded filters, while the other filter types, especially the Fabry-Perot filter, decrease the cascaded 3dB bandwidth significantly.

Power fluctuations due to polarisation dependent loss of the optical devices can be a limitation in cascaded links. These effects require network elements, which have polarisation independent and flat power spectrum

Even if the attenuation bottleneck has been transferred to longer distances due to the optical amplifier, the loss between the amplifiers and the end-to-end points is still very crucial in order to maintain the signal to noise ratio within an acceptable level. This stresses the importance of minimising the insertion loss in the network elements and the noise figure of the optical amplifier. In the equation below, the effective noise figure of a link is shown where G is the net gain for each link and F_n is the noise figure for each amplifier.

$$F_n = F_{n1} + \frac{F_{n2}}{G_1} + \frac{F_{n3}}{G_1 G_2} + \frac{F_{n4}}{G_1 G_2 G_3} + \frac{F_{n5}}{G_1 G_2 G_3 G_4} + ... \text{ [61]}$$

When gain and loss are equal for each link the effective noise figure for the link will be the sum of the noise figures of all amplifiers. Moreover, the accumulated amplified spontaneous emission saturates the amplifier and decreases the available output power for the signal with high input power [B]. The saturation of the amplifier, e.g. semiconductor optical amplifiers, can also distort the signals in cascaded links

From a noise accumulation perspective there is no major difference between 1R opto-electrical repeaters and optical amplifiers. Cascaded 2R repeaters also degrade the signal, but here transferred to accumulation of timing jitter [41]. In the Table 2.2, the bit error rate accumulation for cascaded repeaters is shown. In essence, the BER of a 3R link increases linearly, while the BER of a 1R or a 2R link increases exponentially, whether the link is all-optical or opto-electrical.

Repeater type	BER accumulation over N cascaded repeaters
1R	$BER_{1R} \propto \sqrt{\frac{N}{2pSNR}}\exp(-\frac{SNR}{2N})$
2R	$BER_{2R} \propto \sqrt{\frac{N}{2pSNR\,k^2}}\exp(-k^2\frac{SNR}{2N})$ [41]
3R	$BER_{3R} \propto \frac{N}{\sqrt{2pSNR}}\exp(-\frac{SNR}{2})$

Table 2.2 Bit error rate performance of cascaded repeaters, N = number of cascaded repeaters, SNR = signal to noise ratio, and k = normalised steepness of the signal at the threshold crossing

The 2R repeater has the possibility to improve cascading performance by increasing the bandwidth via k (excess bandwidth). The improvements will not be very significant because SNR will at the same time be decreased. When k is equal to one the 2R repeater performs similarly to the 1R repeater. Finally, self-timed 3R repeaters will accumulate the clock jitter, both systematic jitter (usually pattern dependent) and random jitter [42].

2.6.2 Crosstalk

The multi-path (wanted or unwanted) propagation result in crosstalk, which can arise from reflections, demultiplexers, switches and non-linearities. Crosstalk can be divided into inter and intra channel crosstalk. Inter channel crosstalk, which is defined here as the crosstalk outside the electrical bandwidth of the optical channel, is often harmless, but if the number of channels are large and channel powers have large variations, it could be an issue. The intra channel crosstalk (inside the electrical bandwidth), on the other hand, can be very limiting, e.g. there is no linear way to suppress terms, which have been created. The reflections could be suppressed by inserting optical isolators. However, to decrease the crosstalk contributions from optical filters and switches, the isolation of these devices has to be sufficiently high. OEO converters, used in e.g. OADMs and OXC, prevent inter channel crosstalk from being multiplexed into intra channel crosstalk. 3R and 2R repeaters suppress the accumulation of intra channel crosstalk according to [62]. Electrical crosstalk in digital devices can usually be neglected [J], because the signal levels are well separated from each other.

In the equation below, the detected power is shown in case of crosstalk.

$$P(t) = 1 + \sum_{i=1}^{N} e_i^{\,2} + 2\sum_{i=1}^{N} e_i \cos(d_i)\cos(j_i) + 2\sum_{i=1}^{N-1}\sum_{j=i+1}^{N} e_i e_j \cos(d_{ij})\cos(j_{ij})$$

The power, phase and polarisation in the equation are normalised to the signal. e^2 is the crosstalk power, d is phase deviation and, j is the polarisation deviation between the beating signals. The first term in the equation corresponds to the signal power. The second is the sum of all non-beating crosstalk terms (equal to the inter-channel crosstalk). The third term is the beating between the signal and the crosstalk terms. The last term corresponds to the beating between the crosstalk terms.

It is commonly assumed that the phase deviation is uniformly distributed between 0-2π. This is true when the signal and the crosstalk are uncorrelated, but this is not valid for cases of homodyne crosstalk when the delay between the signal and the crosstalk is within the coherence length [D].

The polarisation deviation and the bit overlap have been assumed either to be uniformly distributed or worst case (polarisation and bit aligned). Several approaches to generate bit error rate estimation from the equation above have been done. Approaches, taking into account the beating between the signals (generating Rician and Rayleigh distributions) and convoluting these with the Gaussian distribution (in absence of any signal) generating the probability distribution function (pdf) have been done [63],[64]. Another approach has been to use the saddle-point approximation [65] and the Gram-Charlier Series [66]. In [67], the Gaussian approximation was used to calculate the pdf for many terms and the derivative of arcsin was used as the pdf for one crosstalk term. In conclusion, for many small crosstalk terms the Gaussian approximation is sufficiently good, however, when the number of crosstalk terms is few (<10), it is preferred to use the worst case (polarisation, phase and bit overlap).

2.7 Enabling technologies

The realisations of reconfigurable and transparent WDM networks rely on several technologies. For point-to-point system technologies, such as the fibre itself, fibre couplers, fibre amplifiers, receivers and lasers are required. Additional technologies needed to achieve reconfigurability are optical switches and optical filters.

Desired characteristics of tuning and switching devices are low insertion loss and loss variation, low crosstalk, polarisation independence, low unwanted reflections, reliability, fast tuning/switching speed, transparency (mainly bit rate), wide tuning range/large number of ports, and no tuning/switching interference.

Mechanical switching and tuneability of optical devices have been feasible for a long time with excellent transmission performance. However, these devices are usually associated with slow switching or tuning time and are unreliable due to moving parts. Integrated circuits have the potential to improve the reliability, cost and size of the optical devices.

2.7.1 Tuneable devices

Tuneable lasers and filters [59] can be used (as building blocks in tuneable WDMs and wavelength converters) for protection and for improving wavelength utilisation in wavelength path networks [45]. The OXC and OADM optical filter design are nearly the same as that of the OTM regarding channel spacing, insertion loss and isolation. However, if no wavelength converters (transponders) are used, the requirements of a flat bandpass and suppressed side band characteristics increase in order to avoid filter narrowing and intra-channel crosstalk. The response of the filters can be divided into bandpass and notch. The bandpass selects the channels, while the notch rejects them. Wavelength reuse requires both select and reject. This can be integrated into the same optical device. The tuneable and integrated devices, which have been evaluated in this thesis, are acousto-optic in $LiNbO_3$ [68] [C], and InP, which use either current injection [69] [C] or thermo-optic [G] to tune the frequency.

2.7.2 Switching devices

In addition to achieving the characteristics, which were mentioned above, switches should be non-blocking and wavelength independent. Multicast is an additional function, which can be desired. The switch technologies that have been evaluated in this thesis, are $LiNbO_3$ [70][A], InP [71][B], Polymer [72][H], and electrical GaAs [73][J]. Additional technologies, which recently have presented good results, are micro-machined [74] and silica on silicon switches.

Electrical switches, in contrast to most of the optical switches can multicast signals in 2R mode from DC up to their bandwidth limits (e.g. 1, 2.5 or 10Gb/s) [J]. The switching speed is usually proportional to the bandwidth. Power consumption and jitter are the main limitations of increasing the size (number ports of the switch). Several different technologies are available for realising electrical switches. The most commonly used are based on silicon, either CMOS or Bipolar. Advantages of silicon are the maturity level, integration level, and cost. Another technology is GaAs, which has the advantage of higher speed, but it is more expensive than silicon. The highest speed and lowest power is achieved using InP based transistors, however, the integration level is not sufficient today. A technology that promises the integration level of silicon, lower power and higher speed than Si bipolar technology is SiGe. Furthermore, electrical switches can easily provide 3R regeneration and monitoring of the channel overhead with the same technology.

2.8 RACE MWTN and ACTS METON projects from an evolutionary and an European perspective

In the introductory phase of the WDM era, USA followed by Japan, led the research efforts [75]. The computer industries, e.g. IBM and some ARPA sponsored programs, influenced the research on WDM networks. Furthermore, at the end of the 1980s penetration of the Internet was limited and local networks were believed to have the largest capacity demands e.g. between supercomputers. This led to a lot of work on broadcast and select networks [76].

Japan, represented by NEC and NTT, performed world-leading experiments with many WDM channels [14], and large optical switches [77] in the beginning of the 1990s. However, early deployment of dispersion shifted fibre delayed the introduction of WDM in the transport network. It was first with the optical path network [78] investigated by NTT, they started to seriously combine the technologies. Instead, long distance and high speed transmission solutions were led by Japan [79], closely followed by USA [80], especially for long-distance WDM. In this area Europe was far behind.

The belief in B-ISDN based on ATM was very strong [81] in the telecom industry in Europe and Japan. At the end of the 1980s Europe had developed world leading results of optical components, such as EDFA and switches and filters in $LiNbO_3$ [70] [68]. Combining this with the experience gained from SDH transport networks and WDM networks [82] the MWTN (Multi Wavelength Transport Network) project [iv-vi] was formed within the European research programme RACE. Compared to projects in USA [83] [84] and Japan [85] [86] the focus was from the start on management of the optical layer [87] implemented as a testbed in live fibre networks [88]. The impact of the MWTN project [13] [25] has mainly been to show that manageable and reconfigurable WDM networks can be accomplished in a cost efficient way.

During the same time that WDM point-to-point networks were commercially introduced in USA, (driven by the Internet capacity demands), the project MONET started [89]. This returned the research initiative to USA. Simultaneously, the METON (Metropolitan Optical Network) project [vii-xi] began within the Europe programme ACTS. This project focused on the requirements of the metropolitan WDM networks an area (low cost and short distances). The design of optical network within the METON project became pragmatic, focusing more on cost-effectiveness than pure all-optical solutions, by dividing the networks into sub-domains. This is an area, which has just started to be commercially explored.

3. Discussions and Conclusions

The first generation wavelength division multiplexing systems have now been commercially used for some years. The development of high bit rates systems saves the number of interfaces compared to WDM systems. However, WDM systems will in a foreseeable future be a good complement to high-speed systems, due to the better utilisation of the all-optical advantages.

The next generations WDM networks and network elements, which add more functionality to the transport networks, have started to be designed. In this thesis reconfigurable WDM networks have been evaluated. The functionality required by the network elements in the optical layer have been defined and discussed, Figure 3.1.

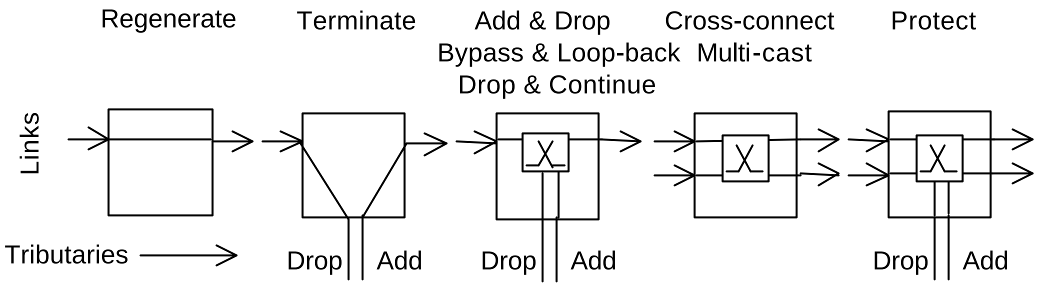


Figure 3.1: Node functionality: regenerate connects the in link to the out link, terminate connects all wavelength from the in link to drop and from add to the out link, add & drop connects the tributaries with the links per wavelength, crossconnect requires more than one in/out link and protect requires redundant links, which can be connected to the tributaries.

These functions can be mapped to different optical network elements. The network elements can be divided into wavelength selective and wavelength independent network elements [I]. The wavelength dependent network elements defined in this thesis are the optical channel terminal multiplexer (OTM), optical channel add drop multiplexer (OADM), and optical channel crossconnect (OXC). The wavelength independent network elements are the optical fibre amplifier (OFA), optical fibre coupler (OFC), and the optical fibre crossconnect (OFXC). Some of the network elements can include several functions, e.g. an optical crossconnect can include all the functionality above. These network elements can be used in physical networks to form logical networks, such as stars, rings and meshed networks, depending on the fibre infrastructure and traffic demands. The wavelength independent network elements have to be all-optical, while the wavelength selective network elements can either be all-optical or opto-electrical. In a static network with few cascaded wavelength selective network elements, all-optical is the most cost effective approach. However, when the number of links, cascaded network elements, and reconfigurations increase, a mix between optical and electrical technologies becomes more attractive, in order to relax the requirements on the transmission characteristics of the network elements. Especially crosstalk and cascadability effects limit the extents of the all-optical networks. The cascadability and crosstalk performance of transparent network elements and their switch and filter technologies, optical or electrical, have been experimentally investigated in this thesis.

The transparency of the optical network is used to achieve a future proof transport network, which can be adapted to new clients. The management system of the transport network demands bit access, in order to assure the transmission quality and integrity of the clients.

In the metropolitan network, the number of hops and reconfigurations are limited and the number of different clients can be large. On the contrary, in the core transport networks the need for fault location and isolation is important and the number of clients has usually been multiplexed to a few. This implies that the client transparency can preferably be supported in the metropolitan network. Furthermore, the larger the reconfigurable transport networks become, the larger the cost to provide transparent connectivity in the network.

The transport network has so far been very semi permanent and this is feasible for multiplexed telephone traffic, which also is very predictable. However, in scenarios with bursty computer to computer communication, and squeezing of several layers into two layers, such as layer 3 (IP) and layer 1 (WDM), the reconfigurabililty of the transport (WDM) network could be utilised, e.g. by WDM multi protocol label switching, to accomplish protection and optimised logical networks. At present, the combination (or perhaps even the integration) of the robust and simple service integrator IP and the coarse but power full transport technique WDM are an attractive alternative [K]. However, all previous ambitions to predict and construct one uniform network have so far failed [90]. One of the reasons is the difficulty to optimise one network to all new and unknown services.

4. Summary of the Original Work

Paper A: A Unidirectional Self-Healing Ring using WDM technique

Ring architecture with single channel optical protection had already been evaluated and multi-channel protected rings had been proposed. However, this paper presents the architecture and describes the implementation and the characteristics of a wavelength division multiplexed ring. The ring supports hubbed and multicast traffic simultaneously in the ring. The main transmission limitation was the gain tilt of the EDFAs, especially when the unidirectional ring was folded in the protected state. To achieve survivability in the ring 4x4 $LiNbO_3$ switches were used. Furthermore, a fault network management system was developed, which visualised the link status of the ring and gave the opportunity to reconfigure the ring to the working mode after failure.

Contributions by the author of the present thesis: Design, implementation and evaluation of the self-healing ring and its nodes.

Paper B: Experimental and analytical evaluation of packaged 4x4 InGaAsP/InP semiconductor optical amplifier gate switch matrices for optical networks

Initial transmission experiments on 4x4 InGaAsP/InP switches had already been performed. This paper investigates the transmission limitations and possibilities of a 4x4 packaged InGaAsP/InP switch. The cascadability, multi-wavelength performance, and polarisation dependence of the switch have been experimentally evaluated over the dynamic range of the input power to the switch. A numerical time domain model confirms the experimental results. One severe transmission obstacle of the switch was residual reflections, which was also confirmed by the numerical model. However, transmission experiments with three cascaded switch paths were successfully looped around the Stockholm gigabit network at 2.5Gb/s.

Contributions by the author of the present thesis: Experimental evaluation of the InGaAsP/InP switch

Paper C: Results from the Stockholm gigabit network-WDM networking

This paper gives a summary of the results achieved in the Stockholm Gigabit Network field trail, within the area of reconfigurable wavelength division multiplexed networks. Compared to previous demonstrations within the area of optical network, the network elements (OXC and OADM) were integrated into a management system. Advanced optical switches and filters in $LiNbO_3$ and InP were evaluated, according to their crosstalk, insertion loss, polarisation and wavelength characteristics, and compared to bulk optics performances.

Contributions by the author of the present thesis: Experimental evaluation of network, nodes and sub elements. Minor influence on the node design.

Paper D: Time dependence of interferometric crosstalk in all-optical networks

Crosstalk and in particular interferometric crosstalk had been investigated before. However, so far the assumption had been that the phase of the signal and the crosstalk terms were either strictly correlated or completely uncorrelated. In this paper the phase influence on the interferometric crosstalk is taken into account. It is shown that for a DC coupled receiver the quasi-correlated crosstalk can be the worst case for the bit error rate performance.

Contributions by the author of the present thesis: Experiments and part of the modelling.

Paper E: The concept and technologies behind a metropolitan optical network

Most of the WDM network research had so far been focus on long distance and high capacity. In this paper the utilisation of WDM in the metropolitan network is outlined. The metropolitan is characterised by short distances and many nodes. The cost benefits by reconfiguration, bypassing and protection within the optical layer is investigated. A unidirectional and a bidirectional ring are connected together via an optical crossconnect. Several optical technologies were evaluated from a functionality and transmission point of view.

Contributions by the author of the present thesis: Design of some node architecture and evaluation of network and nodes.

Paper F: Cascadability of optical add/drop multiplexer

In the previous papers the transmission experiments were performed on one node at a time or optionally by combining the different technologies. By utilising the loop experiments different kinds of transmission limitations of different nodes could be isolated. Six different optical add drop multiplexers were investigated in a loop experiment. For most of the experiments the gain tilt of the optical amplifiers were the limiting factor. One of the OADM, which utilised power equalisation, could be cascaded 28 times, which corresponded to a distance of 1120 km.

Contributions by the author of the present thesis: Categorising the optical add drop multiplexers, and major part of defining and performing the cascading experiments

Paper G: Experimental evaluation of novel tuneable MMI-MZI demultiplexer in InP

In a similar way as in Paper F this device was evaluated from a transmission point of view. Unfortunately the crosstalk of this device was too large to configure it as an optical add drop multiplexer. However, because of the functionality and integration, this device was still very interesting to evaluate as a tuneable WDM.

Contributions by the author of the present thesis: Influence on the experiments

Paper H: An optical crossconnect node prototype

The design of the wavelength path optical crossconnect presented in this paper performed except protection, crossconnection, add/drop and bypassing. Also performance monitoring of the wavelength channels, wavelength and power control, and finally channel identification were performed. The OXC, was constructed of polymer switches and fixed di-electrical multilayer filters, and had a Web based management.

Contributions by the author of the present thesis: The design and evaluation of the crossconnect

Paper I: Internetworking with domains and all-optical islands

This paper presents a pragmatic approach to scale the optical network and still preserve the desired transparency. To permit non-standardised domain and initially limit the standardisation to the inter-domain interfaces support the establishment of optical networks. Different transport techniques for the management information are described in the paper. The transmission requirements set by the reconfigurable and transparent networks are discussed.

Contributions by the author of the present thesis: The discussion concerning transmission and service transparency and the part concerning optical network elements.

Paper J: Experimental comparison between optical and electrical switches for transparent networks

Earlier works on electrical switches used in optical crossconnects have presumed that regeneration of the clock always will co-exist together with the switch. However, with the existing technologies this will limit the transparency of the network. This paper investigates the cascadability of the optical crossconnect with optical or electrical switches included, when the OXCs worked in a transparent mode. The crosstalk in the electrical switch was founded to be negligible, but the noise induced jitter limited the number of cascades to ten. The optical switch had to have –21dB as worst case crosstalk to achieve the same performance.

Contributions by the author of the present thesis: Modelling the optical crossconnect and the optical electrical crossconnect, and major part of defining and performing the cascading experiments.

Paper K: Evaluating the technical feasibility of transporting IP and ATM traffic through WDM

This paper describes the required functionality to map Internet protocol packets onto the WDM layer. The benefits of an optical layer for IP/ATM networks were outlined. Protection in the optical layer can be a strong complement to the rerouting of the upper layer. This was verified by experiments that showed no interference of the client layer surveillance when optical protection was performed. Finally, the management integration of the transport and the switching layer was described.

Contributions by the author of the present thesis: Main ideas concerning IP/WDM integration, protection experiments, and cost analysis

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The noble art of uniform networks defeated by the service giants driven by the wind of changes