WDM THE TRANSMODE WAY
The text you have started to read describes how optical networks using wavelength division multiplexing (WDM) are built with Transmode products. The focus is set on the fundamentals of optical networking and on the optical and layer 1 functions of the TM-Series. Native Packet Optical networking – a key feature of the TM-Series platform – is briefly touched upon, but more detailed information about the higher layer functionality of the products in the TM-Series is found elsewhere. The description is kept as product release independent as possible. Those interested in specific product details are referred to the most current TM-Series Datasheets available at: www.transmode.com

The reader is assumed to have a basic knowledge of telecommunications, but all subjects specific to optical networking as well as the key layer 1 features of the TM-Series are thoroughly explained.

*Unique features of the TM-Series and the Transmode portfolio are highlighted by this marker.*

*The information included is subject to change without further notice. All statements, information and recommendations are believed to be accurate but are presented without warranty of any kind.*
1. OPTICS AND COMMUNICATIONS
1.1 Executive summary of chapter 1
Chapter 1 outlines the general structure of telecommunications networks and describes the fundamental role that optical technologies play in these networks. This chapter also positions the TM-Series packet-optical transport system in this context.

1.2 Telecommunications networks, now and in the future
Our century is undoubtedly a century where telecommunications have become a central element of life, both in a private and a professional sense. The continuing, relentless need for more network capacity is one of the clearest technical trends, whether you are a network operator in Sweden or in Bangladesh. Where telecommunications once meant using the telephone network, today the Internet, TV and various computer networks make up the vast majority of information transported over the electronic web, spanning the globe.

Bandwidth demand is fueled by the tremendous growth of the Internet, both in terms of number of users and by the amount of data they transfer. Although hard to measure, the total bandwidth consumed by Internet traffic alone is estimated to grow some 50% annually during the next decade. Meanwhile, residential broadband access technologies with data rates of 1 – 100 Mbit/s have been widely deployed. With access technologies supporting 1 Mbit/s per user and more, traditional broadcasted TV become challenged by video on-demand, delivered to our homes over the telecommunications network. (Figure 1)

At the same time, business operations today rely upon high speed data networks, interconnecting sites, companies, suppliers and customers. Where once large companies were satisfied by using leased telephone lines with a capacity of some Mbit/s between their sites, the current demand is to interconnect offices with Gbit/s or 10 Gbit/s and use data centric protocols such as Ethernet, rather than transport formats that were originally optimized for carrying voice traffic from telephone calls. Furthermore, technological innovation, mass production and cost rationalization have gradually reduced the cost of components used in telecommunications, thereby reducing the cost of bandwidth. A lower bandwidth cost spurs innovation of more bandwidth hungry applications – think of Spotify and YouTube – creating demand for still more bandwidth. The shift towards higher capacity telecommunications networks is in a positive feedback loop, and will roll on for many years to come.

All these factors drive the development of high capacity telecoms networks, and optical transmission techniques have become the standard technology to use. Optical fiber can carry much more bandwidth than copper wires and is less susceptible to electromagnetic interference and signal attenuation. Consequently, from a technical perspective optical fiber is the preferred medium for transmission of data at anything more than a few Mbit/s over any distance more than a kilometer. It is also the preferred medium for shorter interconnections requiring ultra-high capacity within computer systems, e.g. in Storage Area Networks (SAN).

The evolution of new, innovative techniques to carry data over optical fibers is a core technology in building up our current and future telecommunications networks. Transmode is at the forefront of this development seeking
Figure 1. Internet traffic 2000 – 2015. Source: Cisco 2011. (1 exabyte = 1018 byte)
to help operators, wholesale carriers and private companies to make the most efficient use of their optical fiber assets, may they be fully owned or leased. Transmode is leveraging the latest technologies in carrier class products, creating flexible and future proof optical networks worldwide.

1.3 Telecommunications network architecture

The larger telecommunications networks are public networks, run by service providers and network operators which sell capacity and related services to their customers. Service providers typically specialize in the provisioning and marketing of end user services such as mobile telephony to consumers and enterprises. Network operators normally own their own infrastructure, i.e. the ducts, fibers, microwave links, switches etc. of the telecommunications network, and provide transport capacity and more specialized services based on those assets. Network operators and other carriers often resell their transport capacity in bulk to service providers, other smaller operators and enterprises. Private networks, i.e. telecommunications networks built and used by an enterprise or governmental agency for internal purposes, are typically smaller, but organized in similar structures as the public networks. These private networks frequently rely upon capacity (fiber, Ethernet services etc.) rented from the network operators.

The following figure shows an architectural overview of a typical public, national fiber network structure. (Figure 2)

In reality, a public fiber network is very extensive and its structure more complex than depicted, often with different carriers owning and operating different parts of the network. The nodes of the network are central offices (telephone exchanges) or other locations where the respective carrier has a point of presence (POP) and can create a hub where fibers can be interconnected. The links between the nodes in the network consist of a single optical fiber, a fiber pair, or multiple fiber pairs, typically deployed in an underground duct, but for example, sometimes spun around the wire of a high voltage electrical distribution system on poles.

1.3.1 Long haul, metro and access

When discussing optical networks, the separation of the network in a long haul (sometimes called core) part, a metropolitan (metro or regional) part and an access part is useful, since these networks have somewhat different technical and operational requirements.

The long haul network interconnects different regions and countries, often covering distances of 1000’s of kilometers. Such long distances between nodes require amplification and regeneration of the transmitted optical signals at intermediate points. A long haul network may serve one or more network operators, each having millions of users and many services; hence the requirement on availability (up time) for the connections between the nodes becomes extremely high. Long haul networks therefore have alter-
native paths between nodes and some scheme for protection switching that can re-route traffic on an alternative link with minimal delay. From a topology perspective, the long haul network is normally designed as a mesh of alternative links between important cities/hubs, each link being implemented with multiple fiber pairs using highest quality, single mode optical fiber.

The *metro network* consists of interconnections between central office locations in a large city or cities in a region (*metro-core*), but normally it also comprises the links to mobile cell sites, large enterprise users, industrial campuses and groups of residential homes (*metro access*). The metro-core network spans anything from 10 to 1500 kilometers and the metro access network, which accumulates traffic towards the central parts of the structure, typically spans a few kilometers. Protection switching is normally required from a reliability point of view, so metro networks are sometimes meshed but more often built as rings to save on fiber deployment costs. The ring allows an alternative route towards the central office node “in the other direction”, should the fiber accidentally be cut. A ring is also an efficient way of collecting traffic from many sites and therefore sometimes referred to as a collector ring. Metro networks are normally built with one or more pairs of single mode optical fiber, but structures using a single fiber also exist.

The *access network*, finally, refers to the “last mile” (i.e. km) from a node in the metro network out to the individual user of a telecom service. The access network comprises a significant part of the overall fiber mileage especially in residential area fiber deployments, where a fiber is pulled to each individual home (*Fiber to the Home, FTTH*) or multi dwelling building with apartments (*Fiber to the Building, FTTB*). Since this part of the optical network is costly to deploy, several schemes where a single fiber or a single fiber pair are used to pass multiple homes have been conceived, for example several types of Passive Optical Networks (*PON*), which can use various means of sharing the available bandwidth.

### 1.3.2 Deploying the fiber

Fiber is deployed physically in many different ways today – fiber cables are buried underground in ducts, strung on overhead poles and buried along railroad lines – all with different deployment cost characteristics. Typically more than 60% of the investment in a new optical network relates to the civil works (excavation, ducts etc.) needed. Hence, the links between nodes are normally created by installing *fiber cables*, each cable containing many fibers (10 – 20) and sometimes also copper wires for power supply of intermediate amplifiers. Initially only a few fibers are used (or *lit*), and the rest are available for possible future expansion needs or lease to other users as *dark fibers*. (Figure 3)

The efficient utilization of already deployed fibers becomes of utmost importance for the economy of any carrier, given the large investments done when originally deploying ducts and installing the fiber. Not only does adding additional fiber pairs cost money, digging up street requires right-of-way privileges, planning and permits. It is very obvious that the optical fiber infrastructure must be given a long life, and should be kept unaltered as long as possible, despite growing capacity demand, new protection schemes and changing usage patterns.

#### Fiber deployment costs – examples

<table>
<thead>
<tr>
<th>Description</th>
<th>Cost (€/m)</th>
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<tr>
<td>Heavy trenching</td>
<td>10</td>
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<td>Micro trenching</td>
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<tr>
<td>Aerial deployment</td>
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<td>Reuse of existing ducts</td>
<td>10</td>
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<tr>
<td>Drop costs</td>
<td>300</td>
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<tr>
<td>Vertical build</td>
<td>200</td>
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*Figure 3. Examples of fiber deployment costs. Source: Ericsson 2010.*
Today’s advanced optical technologies provide the means to increase the capacity of the deployed or leased fiber, make that capacity available to multiple services in a secure and manageable way, and cater for further capacity upgrades. Furthermore capacity can be added in a “pay as you grow” manner without fork lift upgrades of already installed switches and routers. Thus, optical networking becomes the universal solution to the need for more capacity at any network operator.

1.4 The Transmode TM-Series

Transmode specializes in optical transport products giving network planners the maximum freedom in leveraging already deployed and new fibers when designing their telecommunications network. The TM-Series family of WDM based packet-optical products are optimized for building the most cost efficient and flexible metro interoffice and metro access networks possible. And as the optical technologies evolve, the TM-Series becomes increasingly attractive also for networks previously requiring specialized long haul equipment. In the access, the TM-Series provides solutions for the “2nd mile” connections, i.e. the transport of data from fiber access points in housing areas, enterprises, cell sites and local exchanges, and leverages advances in standardized WDM technology to serve enterprises and residential subscribers. (Figure 4)

Key to the TM-Series is its flexibility and how passive and active units may be combined to adapt to the requirements at hand. For example, the TM-Series is applicable for use on single fibers, fiber pairs and multiple fiber pairs in mesh, ring and point-to-point topologies, enabling protection switching where necessary. Cost efficient, simple networks with only passive elements are easily designed, while still enabling an incremental, fully compatible upgrade path to the highest capacity DWDM solutions.

The TM-Series supports a very wide range of passive and active units and the total compatibility where any plug in unit can be located freely in any chassis minimizes initial investments while still maintaining the option to accommodate virtually any need. The completeness of the Transmode offering is further strengthened by the accompanying management suite Enlighten™, which includes both network planning and management tools for the Transmode products.

The TM-Series family belongs to a fourth generation of packet-optical products. In the first and second generations optics was essentially only performing signal transmission, upgrading the capacity and performance of previous installed copper wires. All switching and other higher order network functions were done by electronics in external equipment. Examples of typical first and second generation optical systems are the PDH and SDH networks deployed in Europe and SONET networks deployed in North America during the latter part of the 20th century. Third generation optical products can route and redirect the optical light paths and form an integrated optical networking system, significantly reducing the signal conversions and equipment needed and thus also the network cost.
The TM-Series fourth generation packet-optical networking products take the integration of functionality one step further by including Ethernet aggregation and other packet mode functions optimized for data traffic into the optical network equipment, creating one integral, centrally managed, packet-optical network. The integration of higher layer functionality makes it possible to handle traffic according to predefined levels of quality, security and bandwidth. By eliminating the need for separate switching equipment in the metro and access networks, the TM-Series reduces overall costs and improves efficiency of data traffic transmission for the network operator.

*Figure 4.* The Transmode target network (blue).
2. WDM NETWORKING TECHNOLOGIES
2.1 Executive summary of chapter 2

Optical fiber is a remarkable communications medium, providing almost loss-less transmission over an enormous frequency range, making it capable of carrying enormous levels of traffic, such as over a million simultaneous HDTV video streams over a single pair of fibers. This chapter looks at how this wealth of bandwidth can be tamed and put to use. The chapter discusses:

- How electrical signals are converted to pulses of light, sent over an optical fiber and retrieved again.
- The role of amplification and regeneration of the signals.
- How multiple signals are multiplexed over one single fiber or a pair of fibers with coarse and dense wavelength multiplexing (CWDM and DWDM).

2.2 Transporting the information

In an optical network, information is converted to a series of light pulses, which are transported along optical fibers and retrieved at a remote location. Theoretically, any light source could do as the information transmitter, but to achieve the distinct shapes of pulses needed for high speed data transfer and to restrict the light to a particular wavelength ($\lambda - \text{lambda}$), only lasers are used in telecommunications systems. (Figure 5)

The TM-Series is a fourth generation packet-optical transport system, that builds on the above basic transport principle, but also integrates information aggregation, multiplexing, switching, automatic protection, amplification and other functions into the optical domain. This integrated approach has several fundamental benefits:

- It multiplies the transport capacity of the optical link by several powers of ten.
- It reduces the total cost of the equipment.
- It enables intelligent routing and management of information flows from different subscribers at the optical layer.

Before we go deeper into how the TM-Series achieves this intelligent use of the optical layer, we need to discuss how information can be “condensed” i.e. multiplexed, on a single optical link.

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1 A regenerator is an optical – electrical – optical (O-E-O) converter with electrical amplification of the signal.
The need for multiplexing arises from the fact that it for most applications is less costly to transmit data at a high bitrate (e.g. Gbit/s) over a single fiber than it is to transmit it at lower rates (e.g. Mbit/s) over multiple fibers. There are two fundamentally different ways of multiplexing the lower bitrates onto a single fiber – time division multiplexing (TDM) and wavelength division multiplexing (WDM). (Figure 6)

In time division multiplexing (TDM), the lower speed input channels are each allocated a defined timeslot on the outgoing higher speed channel – physically they are “taking turns” on the outgoing fiber. Using a framing mechanism in the data stream or by other means of synchronization, it is possible for the receiving end to extract the respective lower speed channels again.

Time division multiplexing has been used in telecoms since the 1960s and was also the first technique employed in optical networks. Standards like the Synchronous Digital Hierarchy (SDH), with data rates denoted STM-1, STM-16 etc. and SONET with optical data rates denoted OC-3, OC-48, etc. are typical examples of TDM systems used in the second generations of optical networks. (Figure 7)
In wavelength division multiplexing (WDM) each input channel is assigned a unique wavelength (i.e. color of light), thus the channels can traverse the fiber “in parallel”. This technique enables multiplication of the capacity, but also bidirectional communication over one single fiber – a fact of significant importance when fiber is scarce or expensive to lease. Nothing stops a network designer from combining the above multiplexing techniques into a hierarchy as indicated in the following figure. (Figure 8)

The TM-Series is optimized for the above situation, where circuits from legacy applications are to be combined with new streams of data traffic and transported in the most cost efficient way over the fibers of an optical network. Before we consider how this is implemented, we need to have a deeper understanding of the optical fiber, and how light signals are generated and detected.

### 2.3 Basics of optical transmission

#### 2.3.1 The optical fiber and its characteristics

An optical fiber is a very thin cylindrical glass waveguide consisting of an inner core material and an outer cladding, all encompassed by a protective outer coating. The core and cladding have different refractive indexes and are designed to guide the light signals by successive reflections along the inside of the fiber core. The core and the cladding are usually made of high-quality silica glass, although they can both also be made of plastic (rarely used in telecommunications systems). Connecting two optical fibers is done by fusion splicing or mechanical splicing and requires special skills and interconnection technology due to the microscopic precision required to align the fiber cores. Two main types of optical fiber are used in communications: Multi-mode optical fibers and single-mode optical fibers. (Figure 9)
A multi-mode optical fiber has a larger core (50 - 85 micrometers), allowing less precise, cheaper transmitters and receivers to connect to it as well as cheaper connectors. Multi-mode signals, typically having a wavelength of 850 or 1300 nm, are distributed in waves that are dispersed into numerous paths, or modes, as they travel through the fiber’s core. However, in a long cable run, the multiple paths of light cause signal distortion at the receiving end, resulting in unclear and incomplete data transmission. Multi-mode fibers are therefore not suitable for distances over about a km, and are seldom used in public networks. But for shorter distances, e.g. interconnections between IP routers and in home entertainment systems, multi-mode fiber is common.

A single-mode optical fiber has a much smaller core (< 10 micrometers) through which only one mode of light will propagate. The small core and single light-wave virtually eliminate any distortion that could result from overlapping light pulses, which allows much longer, high performance optical links of several hundred kilometers. Hence, single mode fibers are used in telecommunications systems, and their characteristics have been extensively standardized by e.g. ITU-T.²

Two characteristics are of significant importance when classifying the optical fiber: attenuation and dispersion.

Attenuation refers to the fact that the strength of the light pulse is gradually reduced as it propagates along the fiber. The attenuation depends on the wavelength of the light. In the infrared spectrum used for optical transmission in a fiber it has a minimum at approx. 1500 - 1600 nm, where it is some 0.20 dB/km.³ “Useful” wavelengths have been grouped into standardized bands, and transmission equipment is often specified according to which band it is designed to operate in. The TM-Series active equipment uses pluggable optics to adapt to the widest possible range of wavelengths, irrespectively of what network function is to be performed by a node. (Figure 10)

² The ITU Telecommunication Standardization Sector (ITU-T) is one of the three divisions of the International Telecommunication Union (ITU) that coordinates standards for telecommunications. ITU-T Recommendation ITU-T G.652 describes the geometrical, mechanical and transmission attributes of a single-mode optical fiber and cable which has zero-dispersion wavelength around 1310 nm. The ITU-T G.652 fiber was originally optimized for use in the 1310 nm wavelength region, but can also be used in the 1550 nm region.

³ The decibel (dB) is a logarithmic unit that indicates the ratio of a physical quantity (usually power or intensity) relative to a specified or implied reference level. A ratio in decibels is ten times the logarithm to base 10 of the ratio of two power quantities.
For modern glass optical fiber, the maximum transmission distance is limited not only by direct material absorption (attenuation) but also by the dispersion, or spreading of optical pulses as they travel along the fiber. Dispersion is caused by the fact that the refractive index has a wavelength dependent factor; the higher frequencies travel faster than the lower frequencies. The resulting effect is a distortion of the signal shape and interference between signals at different wavelengths. (Figure 11)

Dispersion can be neutralized by regeneration, i.e. the light signal is detected and converted to an electrical signal that is amplified, reshaped and converted back to an optical signal for continued transmission. There is also special optical dispersion compensating equipment available for the TM-Series, as well as dispersion shifted fibers that compensate for the wavelength dependent refraction index. Another characteristic to be aware of is Polarization Mode Dispersion (PMD), where the two different polarizations travel at slightly different speed causing a similar spreading of the pulse.

### 2.3.2 The optical transmitters

Light that enters the fiber comes from an optical transmitter. The most commonly-used optical transmitters are semiconductor devices such as light-emitting diodes (LEDs) and laser diodes. LEDs produce incoherent light, while laser diodes produce coherent light, i.e. light of one wavelength with all the light waves being in the same phase. Coherent light is a prerequisite for long reach over fiber, and consequently lasers are used in telecommunications.

A semiconductor laser has high optical power (~100 mW) as well as other benefits related to the nature of coherent light. The output of a laser is relatively directional, allowing high coupling efficiency (~50 %) into single-mode fiber. The narrow spectral width also allows for high bit rates since it reduces the effect of chromatic dispersion. Furthermore, semiconductor lasers can be modulated directly at high frequencies. (Figure 12)

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**Figure 11.** Chromatic dispersion degrades the signal shape.

**Figure 12.** The semiconductor laser.
2.3.3 The optical receivers

Light pulses are retrieved from the fiber by optical receivers based on photodetectors. Several types of photodetectors are available including p-n photodiodes, p-i-n photodiodes, and avalanche photodiodes (APD). Metal-semiconductor-metal (MSM) photodetectors are also used due to their suitability for circuit integration in regenerators and wavelength-division multiplexers.

Optical receivers are typically coupled with a transimpedance amplifier and a limiting amplifier to produce a digital signal in the electrical domain from the incoming optical signal. Further signal processing, such as clock recovery from data (CDR) performed by a phase-locked loop, may also be applied before the data is passed on. (Figure 13)

2.3.4 The transceiver and the SFP/XFP

Optical transmitters and receivers are often combined into a single component – a transceiver – which has reached a high degree of standardization as the small form-factor pluggable transceiver (SFP). An SFP is a compact, hot-pluggable transceiver module that interfaces the electronics of a network element to an optical fiber. SFP transceivers are available with a wide variety of transmitter and receiver types, allowing designers to select the appropriate transceiver for each link providing the required optical reach and data rate over the available optical fiber type.

The original SFP standard was developed for data rates up to 4.25 Gbit/s and has recently been extended to 10 Gbit/s (the SFP+ standard). A complementing standard for high speed transceivers, the XFP (10 Gigabit Small Form Factor Pluggable Transceiver), is commonly used in high speed telecommunication systems. SFP/XFP transceivers are available as un-colored (having a broad spectrum), as tuned to a specific wavelength or as tunable for several wavelengths, all designed for use in CWDM and DWDM applications. (Figure 14)

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The receiver

Invented in 1950s.

Three main characteristics;
- Minimum receiver sensitivity
- Receiver overload
- Two main types of receivers; PIN & APD

Figure 13. The optical receiver.

SFP: CWDM, DWDM, & uncolored up to 4Gb/s
XFP: CWDM, tunable DWDM & uncolored for 8Gb/s & 10Gb/s

Figure 14. Examples of Transmode SFPs and XFPs.

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SFP transceivers are also available with electrical line interfaces for e.g. CAT5 Ethernet cabling and coax cables for video.
The TM-Series uses SFP, SFP+ and XFP transceivers on all active network elements interfacing the optical fiber to create maximum flexibility and adaptability to the fiber media at hand. By using pluggable optics, the same boards can easily be adopted to varying fiber qualities, channel formats and data rate requirements. This keeps the number of boards needed as spare parts low and allows for a smooth upgrade when more capacity is needed on the optical links. (Figure 15)

A further improvement is the use of a **tunable laser** in the XFP\(^5\). A tunable XFP provides the flexibility to choose the transmit wavelength at the source of a light path, which is a key feature in creating reconfigurable optical networks. With tunable XFP transceivers in a node, wavelengths can easily be set by command from a central management system and re-arranged remotely, should the network get more nodes and additional traffic streams. Being at the forefront of new technologies, the TM-Series includes the option to use tunable transceivers in proven products.

A traffic unit equipped with a tunable XFP is the ideal element for remote wavelength reconfiguration when colorless mux/demux and ROADM:s are deployed (see chapter 3).

All SFP, SFP+ and XFP transceivers provided by Transmode are validated to ensure:
- Optical performance over time and temperature.
- Interoperability towards hardware and software functions in the TM-Series transponders and muxponders.

To ensure performance, all SFP and XFP transceivers provided by Transmode are coded so that the software recognizes that it is a “certified” SFP/XFP. Unlike equipment from most other vendors, non-Transmode transceivers are accepted by the traffic units, but a warning will be raised in the management system and no guarantee of the functionality is provided. Allowing alien transceivers enables immediate repair in a situation where a Transmode qualified transceiver is not available. The warning will provide information on where the non-Transmode transceivers are located to ease replacement at an appropriate service occasion.

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\(^5\) Tunable SFPs are not yet available (Q4 2012).

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**Figure 15.** The TM-Series traffic units can be adapted to varying optical requirements thanks to the use of pluggable transceivers.
2.4 Making use of the wavelengths

Designing an optical network includes choices on topology, use of single fiber or fiber pairs, multiplexing techniques, interfaces to legacy services and more. The TM-Series is a true multi purpose system, allowing maximum flexibility in multiple design dimensions – all to the benefit of a smooth and easy growth and capacity upgrade of the network.

2.4.1 Single fiber and fiber pairs

A basic parameter is the use of single fiber or a fiber pair between network nodes. The TM-Series supports both alternatives, and also combinations of them.

- **Single fiber**, i.e. bi-directional communication on one single fiber. “Two-way traffic” is achieved by using one wavelength in the transmit direction and another in the receive direction. Using two separate wavelengths is the simplest and most stable way to distinguish between the two directions on the same fiber.

- **Fiber pair**, i.e. one fiber in the pair is used for the transmit direction and the other is used for the receive direction. In this configuration, the same wavelength is normally used in both the transmit and receive directions. The fiber pair configuration is the most commonly used one and the only configuration possible in long distance networks since optical amplifiers only operate in one direction.

The choice of a single fiber or fiber pair configuration depends on several factors, such as:

- Fiber availability – owned or leased.
- Network topology, i.e. ring, bus or point-to-point. A single fiber configuration enables easy network expansion from point-to-point to bus, ring and other more advanced topologies. Fiber pairs are best suited for more static point-to-point links.
- Traffic pattern.
- Expected network growth.

The TM-Series takes advantage of both single fiber and fiber pair configurations, using them with various types of multiplexing schemes – TDM as well as the two types of wavelength multiplexing: CWDM and DWDM.6

2.4.2 Coarse WDM (CWDM) and Dense WDM (DWDM)

Multiplexing of the wavelengths in a WDM system can be done in two different ways, depending on how much bandwidth each wavelength is allocated on the optical fiber: Coarse (CWDM) and Dense (DWDM).

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6 It is even possible to design nodes having links using both a fiber pair and a single fiber; a feature of value for example if intermediate sites in a direction require less capacity, and can be served by a CWDM system over a single fiber, while a more remote site in the same direction requires more capacity and is served by a direct DWDM link over the fiber pair.
2.4.2.1 **COARSE WDM (CWDM)**

Typically, CWDM systems provide up to 8 channels (i.e. wavelengths) in the 1470 to 1610 nm range. The TM-Series allows for 8 additional CWDM channels in the 1270 to 1450 nm range, fully in accordance with the ITU-T Recommendation G 694.2. i.e. a total maximum of 16 CWDM channels. (Figure 16)

The available 16 channels can be used for 8 full duplex (two-way) connections over a single fiber. Alternatively 8 channels are used on a fiber pair, with each fiber carrying the traffic in only one direction. Both designs are shown in the following diagram where 8 bidirectional channels are multiplexed onto a single fiber and a fiber pair respectively. The diagram also shows available *add-drop filters* for wavelength extraction and insertion at intermediate sites. (Figure 17)

*Figure 16.* CWDM channels using 16 wavelengths according to ITU-T G.694.2. As can be seen from the diagram the channels avoid the “water peak” of attenuation created by fiber imperfections.

*Figure 17.* CWDM with 8 bi-directional channels over single fiber and over a fiber pair.
2.4.2.2 DENSE WDM (DWDM)

Dense wavelength division multiplexing (DWDM) uses a smaller transmission window than CWDM but with much denser channel spacing. The DWDM channels are normally located in the 1530 to 1565 nm range the C-band; hence there is a certain overlap between the DWDM channels and the standard CWDM channels. An additional set of DWDM channels have been standardized for the 1570 to 1600 nm range, the L-band, making it theoretically possible to more or less double the capacity of a fiber. However, components for the L-band are not as common as for the C-band and there are virtually no pluggable transceivers available for the L-band, making the C-band the most economical alternative for DWDM. The TM-Series uses 40 channels at 100 GHz spacing or 80 channels with 50 GHz spacing in the C-band. (Figure 18)

DWDM systems have to maintain more stable wavelengths/frequencies than those needed for CWDM because of the closer spacing of the wavelengths. Precision temperature control of the laser transmitter is required to prevent “drift” from the central frequency and maintain a very narrow frequency window of the order of a few GHz. Initially, this translated into significant higher costs for DWDM systems than for CWDM systems, but technology innovation and mass production have now made it possible to provide DWDM functionality for close to CWDM prices, especially in systems optimized for metro applications.

The TM-Series supports DWDM links using pluggable and software-tunable transceiver modules capable of operating on 40 or 80 channels. Tunable transceivers dramatically reduce the need for discrete spare SFP/XFP transceivers, since a handful of pluggable devices can handle the full range of wavelengths. A further advantage is that TM-Series’ 80 channel DWDM links are created by combining the output from two 100 GHz standard mux/demux units using a passive, optical interleaver.

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7 The DWDM frequencies (wavelengths) are specified in ITU-T Recommendation G.694.1 and positioned in a frequency/wavelength grid having exactly 100 GHz (about 0.8 nm) spacing in optical frequency, with a reference frequency fixed at 193.10 THz (1552.52 nm). DWDM systems use 100 GHz, 50 GHz or even 25 GHz channel spacing for up to 160 channel operation.
The interleaver provides 80 channels at 50 GHz channel spacing by combining odd and even channels from the 100 GHz mux/demux units. This reduces cost since standard pluggable transceivers can be used on all traffic units. Interleavers also open for additional networking options where even and odd 50GHz channels can be used to structure the traffic flows of the network. (Figure 19)

The TM-series supports DWDM networking over.

- Single-fiber configurations with optical add/drop filters.
- Fiber-pair configurations with optical multiplexers/demultiplexers.

The single-fiber configuration enables powerful DWDM metro/regional networks to be built when there is no need for optical line amplifiers. The optical add/drop filters also enable a network to be designed to the exact capacity and still provide a high flexibility in scalability and connectivity. This is the perfect choice for point-to-point, bus, ring and any other network topology.

The fiber-pair configuration is more effective to bridge point-to-point connections at medium range distances (up to ~1500 km) when all wavelength channels need amplification. It is possible to mix both single-fiber as well as fiber-pair configurations within the same network and within one network node. (Figure 20)
2.4.2.3 WHEN TO USE CWDM AND WHEN TO USE DWDM

The actual choice of multiplexing technology – CWDM or DWDM – depends on multiple factors such as:

- Distance to bridge.
- The number of channels needed.
- The data rate used per channel.
- The number of fibers available.

(Figure 21)

The standardized CWDM wavelengths do not fit well with optical amplification techniques; hence the optical (fiber) distance that can be bridged is typically limited to some 60 – 100 km for a 2.5 Gbit/s signal, without use of an optical-electrical-optical regenerator. DWDM can be optically amplified, hence bridging up to some 1500 km before electrical regeneration is required.

A DWDM system provides 40 or 80 channels, while CWDM is restricted to 8 or 16 channels, a factor to consider when planning for future channel growth.

Traditionally transmission of higher data rates (10 Gbit/s) was only possible with DWDM transponders and muxponders. But a significant feature of the TM-Series is that it supports the same traffic unit data rates up to 10 Gbit/s on both CWDM and DWDM, i.e.

- 100 Mbit/s – 2.7 Gbit/s via SFP transceivers.
- 1 Gbit/s – 4.2 Gbit/s via SFP transceivers.
- 8 Gbit/s via XFP transceivers.

It is thus easy to upgrade a CWDM network to 10Gbit/s transport without converting the network into a DWDM network as was the case before the 10 Gbit/s CWDM XFP’s were available.

The CWDM filters in the TM-Series also enable a mix of CWDM and DWDM on the same fiber to further enhance the ability to scale a CWDM network to higher capacity, without unnecessary interruptions of services.

(Figure 22)

![Figure 21. Applicability of CWDM and DWDM.](image-url)

![Figure 22. Using the appropriate TM-Series filters, the DWDM wavelengths can be interleaved with the CWDM wavelengths, enabling combined use of CWDM and DWDM over the same fiber.](image-url)
Generally speaking, CWDM solutions give the lowest entry costs for metro access networks while DWDM is more cost-effective in metro/regional networks due to the higher number of channels and longer distances. The cost of CWDM equipment operating at lower data rates, e.g. 2.5 Gbit/s is lower than for DWDM, but for data rates of 10 Gbit/s costs of CWDM and DWDM equipment is becoming comparable.

In fiber-scarce areas DWDM solutions can also be a suitable option if more than four channels are required. Alternatively, a more “dense packaging” of the information transported over each wavelength may reduce the number of wavelengths required. Such increased packaging can be achieved by increasing the data rate used and by using the TM-Series Muxponders and Ethernet Muxponders that perform electrical multiplexing of multiple client signals onto one wavelength. The 10Gbit/s data rate capability on CWDM wavelengths makes such multiplexing an even more viable option. (Figure 23)

2.5 Amplification and regeneration

When the optical signal travels along the fiber, it gets attenuated and distorted, as the fiber is not a perfect waveguide for light. How far the information may reach and still be correctly detected depends on the transmitter strength, the type of fiber used, and the data rate of the signal.

Current technologies allow optical signals with Gbit/s data rates to travel up to 275 m – 2 km over multimode fiber, hence such fibers are less common in telecommunications and storage area network (SAN) applications. However, the versatility of pluggable optics makes it possible to equip the TM-Series traffic units also for use on multimode fiber, if needed. On a single mode fiber, an unamplified 2.5 Gbit/s or 10 Gbit/s signal from a high quality SFP/XFP can easily travel more than 100km and be correctly detected. This is however not always enough, hence optical amplification and electrical regeneration of the signal may be needed along the way. The TM-Series offers both possibilities.

Optical amplifiers are used to regain optical power and enable bridging of distances up to the point where the chromatic dispersion of the fiber sets the limit. Dispersion compensating devices (DCU’s) can then be introduced to extend the distance to the point where optical noise etc. have deteriorated the signal quality to a level where electrical regeneration is needed before bridging another segment of the link.

The optical amplifier works fully in the optical domain. There are several different physical mechanisms that can be used to amplify a light signal. In doped fiber amplifiers and bulk lasers, stimulated emission in the amplifier’s gain medium causes amplification of incoming light. In Raman amplifiers, Raman scattering of incoming light with photons in the lattice of the gain medium produces photons coherent with the incoming photons. (Figure 24)
The erbium-doped fiber amplifier (EDFA) is the most deployed fiber amplifier as its amplification window coincides with the third transmission window around 1550nm (C-band) of silica-based optical fiber. (Figure 25)

As can be seen from the amplification diagram, the EDFA is only applicable for wavelengths in the C-band used by DWDM; hence only DWDM can be used in optically amplified networks. CWDM networks are optically unamplified networks.

The power balance, i.e. ensuring that the signal levels of all transmitted wavelengths are equal and not interfere, is of utmost importance in amplified DWDM systems. The TM-Series therefore includes variable optical attenuators (VOA) to balance the laser output power from the transponders. The VOA is normally used together with an optical channel monitor (OCM) unit which automatically measures optical power levels of wavelengths in the C-band. The VOA can be an integrated part of a TM-Series network element or an external unit, the latter enabling control also of the signal levels for wavelengths from other sources. (Figure 26)
Unfortunately optical amplification adds noise to the signal at every amplifier, which reduces the *signal to noise ratio* (S/N). Consequently, after a number of optical amplifications, the signal is hidden in noise. Optical amplifiers can extend the optical reach over single mode fiber from about 100 km to some 800 km, and even up to 1 500 km if the link has *forward error correction* (FEC).\(^8\)

For even longer distances the optical signal must be converted to an electrical equivalent that can be reshaped and retransmitted. This conversion is normally done by the same types of transponders that are used to convert other signals into the wavelengths for WDM. Re-time, re-transmit, re-shape (so called 3R) regenerators can easily be created by the various TM-Series Transponders and Muxponders described in the next chapter. Since the signal is converted from optical (O) to electrical (E) and back to optical (O) again, an electrical regenerator is sometimes referred to as an *OEO regenerator*. (Figure 27)

**IN SUMMARY**

Optical amplifiers can extend the transmission range of a signal. An optical amplifier amplifies all DWDM wavelengths, and therefore becomes a less costly alternative than an OEO regenerator, which has to have discrete circuitry for each regenerated wavelength. The optical amplifier is also independent of any type of bit rate and framing of the signal, i.e. it is fully bit rate transparent.

However, optical amplifiers add some complexity and cost. The DWDM wavelengths need to be power balanced, which makes bus and ring networks complex and expensive. It is also harder, although not impossible, to mix CWDM and DWDM on the same fiber, if amplifiers are to be used.

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\(^8\) Forward error correction (FEC) is a technique for controlling errors in data transmission over unreliable or noisy communication channels. The sender encodes the message in a redundant way by using an error-correcting code, which can be used to restore one or more identified bit errors if such have occurred.
Figure 27. The principles of 3R regeneration.

Degraded signal

Re-amplification

Re-shaping

Re-timing (clock recovery)

Regenerated signal
3. CREATING THE TOPOLOGY
3.1 Executive summary of chapter 3

Using the transmission and multiplexing technologies described in chapter 2, end-to-end light paths passing multiple intermediate nodes can be created. The light paths act as “optical circuits” that are routed through the network permanently or set up by demand. In chapter 3 the focus is on these light paths:

- Using WDM wavelengths to create a complete optical transport network.
- Routing of wavelengths between network nodes using add drop multiplexers (OADM and ROADM) and why there are multiple types of ROADMs.
- WDM in the access network.
- How WDM light paths can be configured to protect the transport network and make it more resilient.

3.2 Transport networks in telecom

The equipment and fibers handling the physical transport of signals in the telecommunications network are often referred to as the transport network. How should such a network be designed and operated? There are different ways to solve this task.

Whether a nationwide or metropolitan network is being constructed, the network designer must consider two different aspects of network life – its planned expansion over time and its day to day operations.

PLANNED EXPANSION – THE LONGER TERM PERSPECTIVE

Planning of the network is a longer term activity typical performed “off-line” in an office environment. When planning the transport network, factors such as these are important:

- Location of nodes based on site availability and cost.
- Availability and cost of fibers – single fiber, fiber pairs, own cables, leased dark fiber.
- Customer/user locations, types of traffic, capacity needs now and in the future.
- Future expansion of the network – topology and capacity.
- Need of redundant links and equipment for protection against faults.

OPERATIONS – THE SHORTER TERM PERSPECTIVE

The operational perspective covers the day-to-day operations of the network. These tasks are performed in direct contact with the optical network, typically from a network management center (NMC). Examples of operational tasks that influence the network design and put requirements on the flexibility of the network are:

- Procedures for connecting users to the network.
- Procedures for expanding the network and adding more links.
- Manual or automatic procedures for protection switching, i.e. the re-routing of traffic on alternative links in case of a node failure or link outage.

Both the longer and shorter term activities require a set of flexible and manageable network elements that can form the transport network: These elements are the TM-Series.
3.3 WDM as the transport network

The TM-Series is a fourth generation optical networking system that combines the most advanced optical transmission technologies with the switching of light paths and the packetization of information into a multifunctional packet-optical transport network. Its principal elements are the transponders and muxponders that allow traffic to enter and leave the optical network and the optical filters, multiplexers/demultiplexers and reconfigurable optical add drop multiplexers that multiplex and send wavelengths of light in different directions as directed by the controlling management system. (Figure 28)

An optical network provides circuit-switched end-to-end optical channels or light paths between network nodes and their users, the clients. A light path is made up of a wavelength between two network nodes that can be routed through multiple intermediate nodes. The intermediate nodes direct the wavelengths. The optical network may thus be thought of as a wavelength-routing network. Light paths are set up and taken down as required by the users of the network.

It is important to remember that the light paths in a WDM network are end-to-end connections, and should be considered as the equivalents of uninterrupted “wires”, stretching from one point in the network to another while passing one or several nodes. This is a significant difference from the principles of classical TDM optical transport networks, such as SDH and SONET, where the signals are regenerated at each node – the equivalent uninterrupted “wire” stretches only between two nodes. Hence, a WDM network requires careful wavelength planning, to define where each wavelength (“wire”) starts and ends, while an SDH/SONET network makes all signals available in every node passed. The end-to-end aspect also affects how the power budget (i.e. signal attenuation) is calculated: In a WDM network, the optical transmission characteristics for a wavelength has to be calculated for the complete distance the light path traverses; for SDH/SONET a new power budget is calculated for each hop between two adjacent nodes. (Figure 29)
The light paths of the optical network have several important characteristics:

- They are transparent, i.e. they can carry data at various rates, with different protocols etc. This enables the optical layer to support a variety of higher layer protocols concurrently.

- Wavelength and data rate used are set by the terminating nodes. Hence an individual light path may be upgraded to higher capacity by simply changing traffic units in the start and end nodes, without affecting any equipment in intermediate nodes. This is a fundamental difference to SDH/SONET as well as networks of interconnected Ethernet switches.

- Light paths can be set up and taken down on demand, equivalent to the establishment of circuits in a circuit switched network.

- Alternative light paths can be configured and kept in “standby mode” so that in the event of a failure, traffic may be re-routed and the service maintained.

- Wavelengths can be reused. If a light path using a particular wavelength ends in one node, the same wavelength can be re-used in another light path heading in another direction.

- The whole concept of WDM and light paths is based on analog optical transmission techniques, making parameters such as dispersion, signal attenuation, optical signal to noise ratio and interference over the whole length of the path important to control.

### 3.4 Nodes and network elements

The light paths of the optical network pass nodes of different types, each comprising one or more managed network elements. The principal nodes of the optical network from a topology perspective are the terminal multiplexer, the optical add/drop multiplexer (OADM) and the reconfigurable optical add/drop multiplexer (ROADM). These nodes allow light paths to enter the optical network and to be routed to any desired point of exit.9

#### 3.4.1 The terminal multiplexer

Clients of the WDM optical network are interfaced to the network via transponders and muxponders. The principal difference is that a transponder is a signal/wavelength converter (one signal in and one signal out), while the muxponder has circuitry that combines several client signals into one line signal and vice versa. The transponder/muxponder and an associated multiplexer/demultiplexer are often referred to as a terminal multiplexer (terminal mux) or terminal node.10

The transponder/muxponder is an optical-electrical-optical unit that adapt the incoming signal to a format for use inside the optical network. The incoming wavelength may need to be converted. Overhead for network management, forward error correction and other purposes must be added. Bit errors counted and statistics forwarded to the management system. And in the case of the muxponder, several bit streams are time division multiplexed into a higher rate bit stream. The next chapter describes the functions of the transponders and muxponders in more detail. (Figure 30 and 31)

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9 The optical cross connect (OXC) is sometimes also referred to as a principal node of an optical network. However, in most cases the same functionality can be achieved with combinations of ROADM units; hence the OXC is not described here.

10 The terminal multiplexer is sometimes called an optical line terminal (OLT), especially in residential broadband access network applications.
**Figure 30.** Block diagram of a terminal multiplexer with a transponder and a muxponder.

**Figure 31.** A TM-Series terminal multiplexer combining 2.5 Gbit/s and 10 Gbit/s data rates on CWDM and comprising two muxponders, a transponder and a CWDM multiplexer/demultiplexer. All units are housed in one single chassis.
3.4.2 The optical add/drop multiplexer (OADM, ROADM)

The light path that has entered the optical WDM network via a terminal multiplexer must be routed to its destination via intermediate nodes that can direct the wavelength towards the desired point of exit. The task of routing the light paths is performed by the optical add/drop multiplexer (OADM) and the reconfigurable optical add/drop multiplexer (ROADM). (Figure 32)

Consider, for example, the situation depicted in the following diagram. A fiber ring spans a metro area, with traffic originating and leaving the ring at 10 locations, where locations HUB A and HUB B are acting as central hubs for the traffic. (Figure 33)

Such a ring topology requires an optical element that can remove and add wavelengths from the ring at demand and forward them towards the client facing equipment – it requires an add/drop multiplexer. Several approaches can be used when implementing an add/drop multiplexer, and the TM-Series comprises optical filters, band splitter units, mux/demuxes and complete ROADMs for this purpose.
3.4.2.1 THE OPTICAL FILTER AS OADM
A fully passive optical filter can be used in CWDM and DWDM networks to add/drop one or more wavelengths. The main advantage of the optical filter approach is its simplicity and direct scalability – only when more channels are to be dropped, more filters need to be installed. The main disadvantage is the attenuation that is introduced at each filter point and the planning required in assigning wavelengths to the desired light paths. (Figure 34-35)

Figure 34. Principle of a passive, filter based, optical add/drop multiplexer. One wavelength (λ1) is passed through the OADM, and another wavelength (λ2) is dropped. New signals are then added when the wavelength is continued.

Figure 35. The optical filter used as an OADM

Three main characteristics:
- Pass band
- Isolation
- Attenuation/losses
3.4.2.2 THE MUX/DEMUX AS OADM

An alternative approach for adding and dropping channels at an intermediate site is to demultiplex all the line wavelengths and extract/add the desired channels, while letting the rest of the wavelengths pass through. (Figure 36)

This approach is more efficient than filters if many channels are to be dropped at one location. Since all wavelengths are catered for “from the beginning” and the mux/demux has a fixed attenuation, this approach also becomes more flexible and requires less advance planning than with optical filters in series. However, the amount of equipment needed and thus the cost is higher than for a filter solution. Also, the amount of patch cords for interconnecting the wavelengths to be passed through adds to the complexity and can create handling problems.

For the TM-Series’ add/drop with optical mux/demux can be used on both single fiber and fiber configurations with CWDM and on fiber pair configurations with DWDM.

When larger numbers of channels are to be dropped the above principle can be extended by use of a band splitter unit, which extracts/inserts a whole band of wavelengths for demultiplexing by a mux/demux as shown in the following diagram. (Figure 37)

3.4.3 The ROADM

In a small and static optical network, OADM nodes of the above types may be the best solution. However, in larger networks, the frequent establishment and re-assignment of light paths make remote reconfigurability a very desirable attribute in an OADM. Reconfigurability refers to the ability to select the desired wavelengths to be dropped and added “on the fly”, as opposed to having to plan ahead and deploy appropriate
Creating the topology

© transmode

Equipment. Reconfigurability allows light paths to be set up and taken down dynamically as needed between network nodes and is the task of the reconfigurable optical add/drop multiplexer, the ROADM. (Figure 38)

ROADMs are used in bus and ring networks to enable flexible add/drop of wavelengths and “hitless” expansion where wavelengths can be added without interruptions of traffic on adjacent channels. When used in a meshed optical network, ROADMs can provide total flexibility in the routing of light paths. The flexibility of ROADMs thus benefits the operator wanting to adapt to changing subscriber requirements, as well as increasing network availability by simplifying protection switching and restoration of light paths. It can even be used for setting up light paths dynamically “on demand” in special applications, for example if there is a major media event at a site requiring bandwidth just for a few hours. (Figure 39)

A ROADM based network decreases the operator’s time to revenue since services can be provided rapidly when light paths are set up remotely without the need of dispatching technicians to network nodes. Commissioning and operation of the entire network becomes simplified and the centralized management of ROADM nodes enables more automation, reducing the risk for manual errors.

ROADM nodes also have significant advantages from a network planning perspective. Free wavelength allocation with ROADM nodes simplifies network planning and reduces the effects of inaccurate traffic forecasting. ROADM nodes simplify traffic engineering and optimization of network use. They allow for better wavelength utilization since wavelengths are managed separately rather than in complete bands. The TM-Series ROADM units also include integrated variable optical attenuators (VOAs) for each wavelength, which greatly simplifies power balancing of the light paths.

Figure 38. The adding of new light paths with red and blue wavelengths requires changes in node configurations.

Figure 39. Example of a meshed optical network. With multi-degree ROADM nodes in the nodes the light paths can be directed to any destination, providing maximum flexibility for the network operator and superior resilience to link outages.
### 3.4.3.1 ROADM PRINCIPLES

ROADM units can be designed around mux/demuxes and optical switches, but the most common architecture today makes use of a $1 \times N$ wavelength selective switch (WSS) that individually can switch the wavelengths on its inputs to its output. (N denotes the number of inputs to the switch.) The TM-Series ROADM units have a WSS on the “add side”, i.e., where added signals are combined with the line signal. This arrangement gives full control of all signal levels on added and passed channels, a prerequisite for secure network operations without any transmission level problems.

Recent technology developments have made WSS-based ROADM units affordable, not only in long haul networks, but also in the metro networks. Having the capability to deploy ROADM nodes in metro applications is of significant value since configuration changes are normally quite frequent in metro and metro access. Hence the TM-Series ROADM nodes are an optimal choice when implementing a regional, metro or metro access optical network. (Figure 40)

As shown in the figure above, the incoming wavelengths from “west” are all split via an optical coupler and made individually available locally via a demux when using the TM-Series $1 \times 2$ ROADM plug in unit. Local wavelengths to be added are multiplexed and added to the incoming signal from “east” in the $2 \times 1$ WSS. Each of the incoming WSS ports is set to accept one or several wavelengths, the only limitation being that no two wavelengths overlap, i.e., are the same. Thus, the WSS can for each wavelength decide if it should be taken from line “east” or be locally added.

The ROADM unit in the diagram above has fiber links in two directions, as for example in a ring topology. The number of fiber link directions to/from a ROADM (or any other optical network node) is often referred to as the degree of the ROADM. In mesh networks and interconnected ring topologies there are nodes that have a higher degree, for example 3 or 4, referred to as multidegree ROADM nodes.

If we want to create a complete 2 degree ROADM node where any wavelength can be added or dropped in both the “west” and “east directions, two of the just described $1 \times 2$ ROADM plug in units are combined “back to back”. (Figure 41)
3.4.3.2 COLORLESS ROADM

Further flexibility can be added to the ROADM by making the mux/demux units wavelength independent, i.e. making it possible to add or drop any $\lambda$ at any of their ports, creating a *colorless ROADM node*. (Figure 42)

When combined with tunable transceivers in the attached transponders/muxponders, the operator can now change the wavelength for a service without moving the transponder/muxponder to a new port on the mux/demux. For the TM-Series ROADM nodes, such wavelength reconfigurations can be made completely remotely from the Transmode Network Manager (TNM) system without the need to visit the site. (Figure 43)

Figure 42. A colorless 2 degree ROADM node.

Figure 43. Management of wavelengths with the Transmode Network Manager (TNM).

A further advantage of the TM-series ROADM units is that they are all implemented as plug in units which may be located in any of the available chassis. This means that any node, large or small, easily can be upgraded with ROADM functionality when the network grows.
3.4.3.3 DIRECTIONLESS ROADM
In the ROADM node configurations in the previous chapters, a particular added $\lambda$ is physically determined to go either in the “east” or “west” direction, depending on which of the two muxes the transponder/muxponder is connected to. This can be a disadvantage, for example in protective switching and may mean a waste of available wavelengths. By adding one more 1 x 2 ROADM, it is possible to create a directionless ROADM node where traffic from any added port can be sent in either “east” or “west” directions. (Figure 44)

3.4.3.4 HIGHER DEGREE ROADM NODES
Using 4 x 1 and 8 x 1 WSS units it is possible to design ROADM nodes for meshed networks, with nodes of higher degree than two and with more than two incoming and outgoing fiber directions. The TM-Series comprises one 1 x 4 ROADM unit for 40 channel DWDM systems and two 1 x 8 ROADM units for 40 or 80 channel DWDM systems, all suitable for these applications.

The 4 or 8 add ports use a wavelength selective switch (WSS) to dynamically select which of the DWDM channels on the ITU-T C-band grid to be added to the line signal for each add port. An Optical Coupler is used to distribute the incoming line signal to the drop ports. A DWDM add-drop filter or Mux/Demux unit is always used for the locally terminating traffic.

Similarly to the 1 x 2 ROADM plug in unit, the TM-Series 1 x 4 and 1 x 8 ROADMs also include variable optical attenuator (VOA) functionality on all wavelengths added to the line signal by the WSS. This facilitates channel power balancing in amplified networks.

Grouping of ports on different units can be made in the node management software to enable the setting of identical channel selection. Also restrictions on channels selection can be made on individual or grouped ports to simplify commissioning and minimize risk for faulty handling.

Both the 1 x 4 and the 1 x 8 ROADM units consumes less than 6W. Low power consumption in combination with a small footprint reduces site costs and enables more capacity to be handled at sites with restrictions on power consumption, cooling and space.

3.4.3.5 CONTENTIONLESS ROADM
Using a combination of 1 x 4 and 1 x 2 ROADMs a fully contentionless ROADM node for 2 degrees may be designed. As shown in the following diagram, wavelengths cannot be assigned arbitrarily in the directionless ROADM described earlier: If one wavelength $\lambda 1$ is sent in e.g. the “west” direction, the same wavelength $\lambda 1$ cannot be re-used in the “east” direction. By adding an extra set of 1 x 2 ROADM units full freedom of wavelength allocation is possible; the ROADM node becomes both directionless and contentionless. However, especially for higher degree nodes, the amount of equipment needed for a contentionless ROADM may make its cost prohibitive, although expected to decrease as new components become available. (Figure 45)
Figure 45. A directionless and contentionless 2 degree ROADM node. The mux/demux units can be made colorless and combined with traffic units having tunable transceivers for additional flexibility.

The four individual add-drop ports of the 1 x 4 ROADM enable hitless redirection of traffic in multi-degree nodes. By grouping four units and interconnecting the add-drop ports, a 4 degree node is created, where traffic from any line can be directed to any other line or be locally dropped. (Figure 46)

Figure 46. A four degree node implemented by four 1 x 4 ROADMs.
The 8 individual add-drop ports of the 1 x 8 ROADM enable hitless redirection of traffic in even higher degree nodes. By grouping up to 8 units and interconnecting the add-drop ports, up to 8 degree nodes can be created, where traffic from any line can be directed to any other line or be locally dropped. A 50GHz compatible Mux/Demux is used to separate the terminated channels. (Figure 47)

It is possible to create directionless higher degree nodes by using an extra 1 x 8 ROADM unit to direct the local traffic to the preferred line fiber. Each wavelength can be directed as required on an individual basis. It is possible to have both fixed and directionless add/drops in the same node. (Figure 48)
3.5 Wavelength management
Traffic units with plug in and tunable transceivers, multi-degree ROADMs and colorless mux/demux units enable a tremendous flexibility in optical network design and operations, but also put stringent requirements on wavelength management. The Transmode Enlighten® software suite for planning, design, commissioning and management of an integrated packet-optical network includes the necessary tools for this task. Centralized wavelength management is performed from the Transmode Network Manager (TNM), a comprehensive, carrier class Element, Network and Service Manager for Transmode’s integrated layer 1 and layer 2 networking solutions.

TNM includes several features of high value for efficient wavelength management, for example:
- The extensive inventory module.
- The ROADM provisioning application.
- The Optical Control Plane with its applications.
- Integrated handling of alien wavelengths.

Not only does the inventory module of TNM keep track of all active equipment in a TM-Series optical network. The inventory may also be used to register every filter, mux/demux and other passive unit in the network and then keep track of how the various wavelengths are allocated. Having also the passive elements available in the inventory greatly simplifies planning and allocation of wavelengths throughout the optical network.

The ROADM provisioning application in TNM automatically reads ROADM parameter settings from the nodes and enables the operator to remotely add channels to an add/drop port. If the ROADM provisioning application is activated, the TNM automatically identifies potential channels through the un-configured ROADMs of the network. TNM checks that no wavelength conflicts occur through-out the optical path and then automatically configures the ROADMs to create the optical path, including starting necessary control-loops. This highly automated process greatly reduces the risk for misconfigurations while reducing the configuration time by up to 90%.

3.5.1 The Optical Control Plane in TNM
The Optical Control Plane (OCP) in TNM provides advanced functionality to simplify centralized commissioning, tuning and planning of the optical network. Currently, the TNM Optical Control Plane comprises two modules: Transmission Control and Channel Control.

3.5.1.1 TRANSMISSION CONTROL
Transmission Control is a TNM application that supports commissioning and tuning of amplified optical networks, thereby reducing the operational costs associated with setting up and maintaining such networks. Transmission Control works in concert with the Optical Channel Monitoring (OCM) units, the Variable Optical Attenuators (VOAs) and the transceivers in the network to measure and present power levels at various points of an optical light path. Transmission Control allows the operator to select one or more light paths in the network, show the power level in each point that has measurement capability and then make the optimal power settings in attenuators and amplifiers.

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11 Enlighten and the Transmode Network Manager are further described in chapter 5.
3.5.1.2 CHANNEL CONTROL

*Channel Control* is a TNM application that allows the operator to select a number of optical links and show the routing of used and available channels (λ) and sub-channels (sub-λ) through-out the selected light path.

Channel Control provides routing information for channels and sub-channels and identifies channels as:

- **Active Channels** – channels that are carrying traffic. Active channel have transponders connected and client entries defined.
- **Possible Channels** – pre-provisioned channels that are available to be taken in service. Possible channels may or may not have transponders connected but no client entries are defined.
- **Reserved Channels** – pre-provisioned channels that have been dedicated for particular future purpose. Reserved channels may or may not have transponders connected but no client entries defined.

3.5.1.3 HANDLING OF ALIEN WAVELENGTHS

An *alien wavelength* is a standard CWDM or DWDM wavelength that transports traffic that does not originate and terminate in Transmode equipment, e.g. IP packets sent between two routers having optical interfaces connected directly to the ports of two mux/demux units. Such traffic does not pass any TM-Series traffic units and is only transported through the optical network between two passive ports. Although not being of TM-Series origin, the following TNM management features are still available for alien wavelengths:

- Transmission Control, i.e. the alien wavelength is power balanced in the same way and together with the TM-Series native wavelengths.
- Optical provisioning.
- A separate “passive” administrative state.
- Service topology.
- Service alarms if the wavelength passes an optical channel monitoring (OCM) unit.

(Figure 49)

![Diagram showing an alarm if λ₁ disappears](image)

*Figure 49.* An alarm can be triggered also for an alien wavelength if it passes a node with an optical channel monitoring (OCM) unit.
3.6 WDM in the access network

Modernization of the access network is a pressing issue for many operators, due to the rapidly increasing traffic volumes generated by new applications demanded by their subscribers and users. Mobile operators are deploying fourth generation (HSDPA, LTE) mobile networks to support smartphones, tablets and mobile computing, thus requiring links with Gbit/s data rates to the cell sites. Enterprises are increasingly dependent on centralized cloud computing, while the resources “within the cloud” need to be interconnected by high capacity links; both trends driving up the need for more data transport capacity in the access network. In parallel, consumers subscribe to video on demand and other Internet based media services, making 100 Mbit/s access and more a requirement for each household.

WDM as a technology answers many of the operator’s demands and has an important role in the modernization of the access network.

3.6.1 WDM aggregation rings

An important application of WDM and the TM-Series is for efficient capacity upgrades of the aggregation networks, carrying traffic from multiple remote access sites to/from a central hub site. For examples, the remote sites may be a mobile cell site, a DSLAM serving residential Internet users or an Ethernet demarcation unit in an industry campus. With WDM, each such remote node can be allocated a dedicated wavelength over the ring, carrying its traffic to/from the central hub. (Figure 50)

In a WDM ring, all the remote nodes have their own pre-determined capacity on the link towards the hub, resulting in a deterministic traffic pattern and easy bandwidth management. Ethernet rings, on the other hand, share the available link capacity between all the remote nodes. An increase in capacity on one node steals capacity from the rest.

**Figure 50.** Comparison of an aggregation network built with Ethernet switches and a WDM aggregation network.
Ethernet rings also require the same uplink interface on all switches/nodes which leads to expensive fork-lift upgrades, should capacity on any of the nodes need to be raised. In a WDM network each node uplink is independent from all the others and each node can be upgraded individually when needed.

In a WDM ring each node equipment is independent of the others (no shared hardware) and the protection can be handled directly on layer 1 with less than 50ms delay. Ethernet rings are sensitive to single unit failure and need complex layer 2 or layer 3 redundancy schemes to overcome this.

With WDM aggregation it is easy to combine Ethernet and TDM traffic backhauling on the same fiber, while Ethernet rings need more complex remapping solutions (pseudowire etc.) or separate fiber pairs to cope with legacy TDM traffic. This is of specific value to mobile operators which often require transport of both legacy TDM traffic and new Ethernet traffic from the cell sites.

The TM-Series is ideally suited for building WDM aggregation rings. Low cost CWDM ring solutions using only passive optical filters and colored interfaces on already existing routers and switches are easily implemented. By including active transponders and muxponders, the traffic aggregation, protection and monitoring can be made more efficient. And for longer distances and more channels, complete DWDM systems, if necessary with amplifiers, can be deployed. In addition, the packet-optical functionality of the TM-Series transponders and muxponders enables integration of layer 2 functions previously residing in the Ethernet switches directly into the optical aggregation ring.

3.6.2 Point-to-point and Passive Optical Networks (PON) in access

Expanding the telecommunications network to each and every house- hold and each and every enterprise is the real challenge of any network designer. The number of end-points terminating the network becomes massive, and so does the associated cost of civil works and equipment needed. While most larger and medium sized enterprises have had dedicated connections (“leased lines”) for data traffic to their premises since the 1980s, residential Internet users have primarily been restricted to use access networks that take a “free ride” on the already installed infrastructure of telephony lines or CATV HFC networks.

The cost of deploying new fiber is obviously a prohibiting factor for a more rapid expansion of high speed access, and various schemes are used to reduce the number of fiber miles in the access networks. The two main competing categories are point-to-point fiber access networks and passive optical network (PON) access networks. As we will see, WDM has an important role in extending the capacity, security and flexibility of these networks.

A point-to-point fiber access network is a fairly straight forward structure that mimics the classical telephony access network in that it has a central node with individual fiber cables reaching out to each subscriber. The network is star shaped; sometimes ending in the basement of a multi-dwelling building, where an optical electrical conversion is done and a traditional star shaped, electrical Ethernet LAN is installed reaching out to each and every apartment. (Figure 51)

The main advantages of a point-to-point access architecture are its topological simplicity and the strict separation of traffic to/from each subscriber. Significant disadvantages are the deployment cost of all the

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12 Cable TV (CATV) using hybrid fiber and coax (HFC) distribution networks.
Two main types of PON systems have been standardized: TDM-PON and WDM-PON. TDM-PONs (i.e. BPON, EPON, GPON) use separate wavelengths for the downstream and upstream directions on the single fiber and time division multiplexing between the individual subscribers connected to the fiber. Downstream signals are broadcast to all premises sharing multiple fibers and only received by the appropriate ONT. Upstream signals are combined using a multiple access protocol, usually time division multiple access (TDMA). The OLTs allows a time slot assignments for upstream communication from each of the OLTs in turn. Because a TDM-PON relies upon time-sharing, it has an inherent capacity limitation, as well as a security problem, since all information is theoretically available at every endpoint.

A WDM-PON combines the dedicated bandwidth of a point-to-point network with the fiber sharing architecture inherent in the PON topology. A WDM-PON uses a filter to separate the wavelengths of a WDM stream for delivery to each individual subscriber ONT. Thus, only one fiber is required at the central site while the wavelength (channel) topology is point-to-point.
A key advantage of WDM-PON is the use of a completely separate downstream wavelength for each of the subscribers. This separate wavelength provides more bandwidth to each subscriber, better security, and enhanced operational control since there is no potential interference between wavelengths. Similarly, a dedicated upstream wavelength provides almost unlimited capacity to each subscriber, covering all potential future growth. (Figure 53)

Transmode has therefore selected an alternative approach to WDM-PON: Using the same basic elements as for metro and long haul WDM, Transmode’s iWDM-PON solution operates in the C-band. By using the same wavelengths for access as those used in the metro and long haul networks, it is possible to develop a common WDM access structure that combines legacy enterprise traffic, mobile backhaul, residential Internet access and high capacity WDM-PON users in the same optical network. (Figure 54)

The advantages of using ITU standard WDM in the access network are varied:

- Easy to combine FTTB, mobile backhaul, Enterprise leased lines and more in the same infrastructure. Provides one solution for all types of data rates and applications.
- Each service (SDH/SONET, GbE, FC, FICON) can be allocated its own wavelength.
- Open and standardized DWDM grid and use of the standard ITU C-band makes it possible to capitalize on standard component development curve and price reductions.
- Optical transparency from access to core eliminates the need for optical electric conversions.

Transmode’s iWDM-PON solution leverages the passive and active components already described, but also includes special elements to facilitate wavelength allocation to subscribers, according to normal WDM-PON principles. A key element is the use of pluggable, colorless DWDM SFPs with injection locked FP lasers in the ONT at the customer site. The colorless SFP is automatically tuned to the incoming “seeding” wavelength, thus eliminating manual tuning at each subscriber. (Figure 55)
Figure 54. A Transmode iWDM-PON access network. Using one wavelength from access to core provides optical transparency and eliminates optical electric conversions.

Figure 55. Wavelength allocation in iWDM-PON: The seeding board installed in the TM-Series central office OLT broadcasts a broadband light source. A filter forwards a single wavelength to the SFP, which locks on the correct frequency.
3.7 Network topologies

Optical networks can be classified according to their topologies: Line or point-to-point, star, ring and mesh shaped. The line and star topologies have single points of failure, and should be avoided when resilience against outages is important. There are many arguments about which are the best: Ring or mesh. Very often, the debate mixes up the topology of the physical fibers installed and the logical connectivity that can be achieved by switching and routing over the fibers at higher layers. The physical connectivity matters most when resilience, distance and delay are being considered.

Many metropolitan networks start as rings and evolves gradually to mesh – the crossover depends on fiber costs, equipment costs, traffic loading, degree of mesh required for resilience etc. As can be seen from the diagram below, the cost of a meshed network is high at lower traffic volumes, but becomes increasingly attractive as traffic grows. The diagram is based on simulations.

With the advent of today’s cost efficient ROADM nodes, it is now possible to implement resilient and flexible meshed networks also in the metro area and metro access areas. (Figure 56)

3.8 Resilience and protection

3.8.1 Calculating the availability

Being a fundamental part of the telecommunications infrastructure, the optical network must always be operational. Three variables define the quality of a network from a resilience perspective:

- **Availability** is the fraction of total time that a function, for example a network connection, is available i.e. what the users experience as a “working system”. Availability is measured in % of time and typically lies in the range of 99.999% (“five nines”) or more.

- The **reliability** of a network element is the fraction of total time that an object is working. Reliability is often measured as mean time between failures (MTBF) – a time that should be as long as possible. The **repair time** defines how quickly an object can be repaired and put back in service. Repair time is measured as mean time to repair (MTTR) and should preferably be as short as possible.

Let us look at a concrete example on how protection switching and ring topologies can help improve the availability on an optical light path from Glasgow to London. The calculation is based on SDH technology and purely for illustrative purposes, i.e. the values used for active components are not directly applicable for the TM-Series.

![Network cost vs. traffic loading](image)

*Figure 56. Simulation of network cost as a function of traffic for different topologies.*
Looking first at an unprotected light path, the physical network can be drawn in a more easily understood form. The total availability of the unprotected path is simply found by multiplying the availabilities of each of the elements in the 'chain'. (Figure 57)

Using *protection switching* in the nodes, the light path may find alternative routes between its endpoints, for example, should a fiber break occur. (Figure 58)

Calculation of the availability in a protected network is a bit more complicated than in an unprotected network:

1. First multiply the availabilities of the unprotected parts together (in this case the tributary card at either end of the path).
2. Calculate the availabilities of the two diverse paths by multiplying the availabilities of each of the elements in both ‘chains’.
3. Combine the two chains by multiplying their *unavailability*’s together (unavailability = 1 - availability).
4. Finally multiply the availability from step 1 with the availability from step 3.

The restored example breaks the single, long, diverse route into several, shorter, diverse sections. The result of this is that it can survive multiple simultaneous failures whilst the protected design can only survive a single failure.

© TRANSMODE

Figure 57. Availability for an example network.

Figure 58. Availability for a protected and a restored example network.
### 3.8.2 TM-Series resilience features

The TM-Series includes numerous features that can be used to minimize the impact of both fiber breaks and failures in individual components on the overall network availability.

One live and one redundant client system may, for example, be connected to two separate and independent transponders or muxponders sharing the same optical fiber via a passive optical coupler unit. In case of failure of the live client system or the corresponding transponder/muxponder traffic, the redundant path is automatically made active in less than 50ms. The transponders/muxponders may even be located in separate TM-Series chassis to further minimize the risk of single point of failure. (Figure 59)

Transponders can be equipped with multiple outputs for alternative fiber routes and signals from incoming fibers can be split into two or more paths. Switching between the working path and the alternative path is fully automatic and takes less than 50ms. Therefore, multipath line protection can easily be achieved in TM-Series optical networks without the need for GMPLS/ASON software. (Figure 60)

If several fibers are available on a given link, the TM-Series also allows for fiber protection, by using a mechanical fiber protection unit. (Figure 61)

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**Figure 59.** Client and equipment protection with the TM-Series.

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13 Generalized Multi-Protocol Label Switching (GMPLS) is a protocol suite extending MPLS (see chapter 4) to manage further classes of interfaces and switching such as time division multiplexers, layer-2 switches and wavelength switches. ASON (Automatically Switched Optical Network) is a concept for the evolution of transport networks which allows for dynamic policy-driven control of an optical or SDH network based on signaling between a user and components of the network.
Figure 60. Three examples of line protection with transponders.

Figure 61. Fiber protection.
4. ADDING TRAFFIC
4.1 Executive summary of chapter 4

This chapter describes the various external systems that use the optical WDM network to transport information and the transponders and muxponders acting as interfaces between the external systems and the WDM network. This chapter also explains how the information is framed when it is forwarded between the network nodes over the WDM light path. A closer look at how the Transmode unique internal framing (Intelligent WDM - iWDM) can be leveraged in mobile backhaul and Gigabit Ethernet access networks. The chapter explains:

- SDH, SONET and OTN.
- Fast Ethernet, Gigabit Ethernet, 10 Gbit Ethernet and higher speed Ethernet.
- Storage Area Networks (Fiber Channel and ESCON).
- Line side data rates with iWDM or OTN framing.
- iWDM applications.

4.2 Introduction

The preceding two chapters describe how continuous connections of wavelengths – light paths – are established and managed in a WDM optical network. The light paths are the “circuits” of the optical network, circuits which are put to work and used by traffic units – the transponders and the muxponders. The light paths make up the “physical” transmission links between the client systems attached to the optical network. (Figure 62)

A light path in a WDM network relies upon analog technology and therefore requires a strictly controlled optical environment for error free transmission. The transponders and muxponders serve as buffers between the served traffic layer and the optical (WDM) layer. As a result, client equipment of different types (e.g. SDH multiplexers and IP routers) and from different vendors can be connected to the TM-Series network without impacting the parameters of the transmission path through the optical domain.

When designing the optical layer of the network, i.e. the grid of light paths between endpoints, two main parameters are fundamental:

- The number of wavelengths needed to establish the desired connections without “collisions on the way”, i.e. each light path must have its own wavelength(s) assigned for the entirety of its route.
- The distances involved, which affects the type of transceivers (SFP/XFP) to be used and if the WDM network must include amplifiers.
In the traffic layer(s), i.e. the end to end logical connection between the client systems, digital signals are processed in the electrical domain, with transponders/muxponders performing functions such as fixed time division multiplexing or statistical time division multiplexing (packet switching). Transponders/muxponders aggregate and bring a variety of lower-speed voice, data and leased line services into the WDM network. Each of these client networks is important in its own right and can typically operate over point-to-point fiber links as well as over a more sophisticated optical layer, using the light paths of WDM. Finally, the transponders/muxponders also add management and control information for the link and network to the bits sent over the light path.

When designing the traffic layers of the network, an additional set of parameters become important:

- The data rate (Mbit/s) of the signal to be transported. In time division multiplexing, the outgoing line rate of the transponder/muxponder must be sufficient to accommodate all the incoming multiplexed data streams. The line rates currently available with the TM-Series are 2.5 Gbit/s, 4 Gbit/s, 10 Gbit/s, 14, 40 Gbit/s and 100 Gbit/s.
- The format (framing) of the client signal and how signaling between the end points is done, i.e. the protocol employed.
- If data can be “manipulated”, e.g. compressed by the transponder/muxponder or if the connection must be fully transparent.
- How and if exact time synchronization is to be maintained between the digital signal at the sending and receiving ends of the connection.

A key feature of the TM-Series is its flexibility in adapting to the shifting traffic layer requirements. The TM-Series includes a wide range of transponders and muxponders either dedicated to a particular client system protocol or capable of serving multiple protocols in the same traffic unit.

Transponders and muxponders for various protocols and for different data rates can be combined in the same chassis and one single chassis can be equipped with multiple control units, making it into several nodes from a management perspective. The versatility of the traffic units in combination with the modularity of the optical filters and multiplexers allows the design of highly cost efficient networks optimized for any transport requirement today, while still allowing for an easy and incremental upgrade to coming needs.

This chapter concentrates on the traffic layer functionality of the TM-Series and describes how the transponders and muxponders in the TM-Series can meet all the varying requirements of the client systems connected to the network.

4.3 Clients of the optical layer and their protocols

Using the terminology of optical networking, a client system is any digital communications equipment that is connected to and makes use of the optical network. A client system can be an SDH/SONET multiplexer, an IP router or an Ethernet switch, all capable of sending and receiving digital signals. The connection between the client system and the network (i.e. the interface between the client system and the transponder/muxponder) can be optical over a multimode or single mode fiber, or electrical, e.g. a coaxial cable.

The client system exchanges data with its peer client systems according to a given set of rules for how data shall be formatted when being sent and received – it follows a communications protocol. Since each communications protocol has its own characteristics, it becomes an important parameter when selecting a suitable transponder or muxponder. It is

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14 Additional data rates may be made available in the future.
therefore necessary to understand the basics of the most common telecommunications protocols, when designing an optical network with the TM-Series.

4.3.1 SDH and SONET

Synchronous Digital Hierarchy (SDH) and Synchronous Optical Networking (SONET) are standardized protocols for time division multiplexing of multiple bit streams over an optical fiber. Both protocols were developed for the first generations of optical networks and has been widely deployed, SONET in North America and SDH in the rest of the world. Originally, SDH/SONET was designed to support the multiplexing of real-time, uncompressed, circuit-switched voice circuits (telephony), but it can now also be used for data networking with packet mode traffic at Gbit/s speeds using data link protocols that adapt packet traffic for its connections.\(^{15}\)

SDH and SONET employ a sophisticated multiplexing scheme taking advantage of the fact that all clocks in the SDH/SONET network are perfectly synchronized to a single master clock. The perfect synchronization allows lower speed signals to be added/dropped from the SDH/SONET stream without de-multiplexing the entire stream into all its individual components. Consequently, less equipment is needed and the management of multiple, real time, bit streams become less costly than with earlier multiplexing schemes. Furthermore, the SDH/SONET multiplexing is fully compatible with earlier standards such as PDH\(^{16}\), allowing the encapsulated data to have its own frame rate and be able to “float around” relative to the SDH/SONET frame structure and rate. Another important feature of SDH/SONET is that it has been designed for use in public networks and includes extensive network management capabilities to provide a carrier grade service of high availability. When WDM is used to upgrade the capacity of a public metro or long haul network, it is very likely that some of the client systems are SDH/SONET multiplexers, due to the frequent use of this technology.

The basic unit of framing in SDH is the STM-1 (Synchronous Transport Module, level 1), which operates at 155.52 Mbit/s. SONET refers to this basic unit as an STS-3c (Synchronous Transport Signal 3, concatenated) or OC-3c, depending on whether the signal is carried electrically (STS) or optically (OC), but its high-level functionality, frame size, and bit-rate are the same as STM-1.

In packet-oriented data transmission, such as Ethernet, a packet frame usually consists of a header and a payload. The header is transmitted first, followed by the payload (and possibly a trailer, such as a CRC\(^{17}\)). In synchronous optical networking, this is modified slightly. The header is termed the **overhead**, and instead of being transmitted before the payload, is interleaved with it during transmission. Part of the overhead is transmitted, and then part of the payload, then the next part of the overhead, then the next part of the payload, until the entire frame has been transmitted. (Figure 63)

The STM-1 and OC-3 signals can be further multiplexed into higher, synchronous bit streams, designated as indicated in the following table. (Figure 64)

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\(^{15}\) The Generic Framing Procedure (GFP) is an SDH/SONET and OTN adaptation method that works for a variety of data networking protocols, including IP, Ethernet and Fibre Channel.

\(^{16}\) Plesiochronous Digital Hierarchy. An ITU-T standard from the mid-1960s for the multiplexing of digital voice circuits without requirement on full signal synchronization.

\(^{17}\) Cyclic Redundancy Check, an error detection or correction bit pattern.
Figure 63. The STM-1 frame is the basic transmission format for SDH and the first level of the synchronous digital hierarchy. The STM-1 frame is transmitted in exactly 125 µs. The STM-1 frame consists of overhead and pointers plus information payload.

SONET/SDH Designations and bandwidths

<table>
<thead>
<tr>
<th>SONET optical carrier level</th>
<th>SONET frame format</th>
<th>SDH level and frame format</th>
<th>Payload bandwidth (kbit/s)</th>
<th>Line rate (kbit/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>OC-1</td>
<td>STS-1</td>
<td>STM-0</td>
<td>50,112</td>
<td>51,840</td>
</tr>
<tr>
<td>OC-3</td>
<td>STS-3</td>
<td>STM-1</td>
<td>150,336</td>
<td>155,520</td>
</tr>
<tr>
<td>OC-12</td>
<td>STS-12</td>
<td>STM-4</td>
<td>601,344</td>
<td>622,080</td>
</tr>
<tr>
<td>OC-24</td>
<td>STS-24</td>
<td>-</td>
<td>1,202,688</td>
<td>1,244,160</td>
</tr>
<tr>
<td>OC-48</td>
<td>STS-48</td>
<td>STM-16</td>
<td>2,405,376</td>
<td>2,488,320</td>
</tr>
<tr>
<td>OC-192</td>
<td>STS-192</td>
<td>STM-64</td>
<td>9,621,504</td>
<td>9,953,280</td>
</tr>
<tr>
<td>OC-768</td>
<td>STS-768</td>
<td>STM-256</td>
<td>38,486,016</td>
<td>39,813,120</td>
</tr>
</tbody>
</table>

Figure 64. The SONET and SDH multiplexing hierarchies.

SDH and SONET networks have been in existence for several decades and often encompass complex structures of the public telecom network. The following figure shows a typical example of such a SONET network, comprising fiber links between add/drop multiplexers (ADM), digital cross connects (DCS) and optical line terminals (TM). When designing a WDM-system for this network, light paths carrying signals with sufficient data rates have to be created between all the individual SONET network elements.

4.3.1.1 OVERVIEW OF SDH/SONET CLIENT INTERFACES IN THE TM-SERIES

The TM-Series traffic units can be grouped according to what line rate they support, i.e. 2.5 Gbit/s, 4 Gbit/s, 10 Gbit/s, 40 Gbit/s or 100 Gbit/s. SDH/SONET uses a fixed time division multiplexing scheme which implies that the outgoing line rate must be higher than the sum of the data rates coming from the client system(s).

Currently the TM-Series includes transponders and muxponders with client interfaces for the following SDH/SONET levels: (Figure 65)

<table>
<thead>
<tr>
<th>Line rate</th>
<th>2.5 Gbit/s</th>
<th>4 Gbit/s</th>
<th>10 Gbit/s</th>
<th>40 Gbit/s</th>
<th>100 Gbit/s</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transponder</td>
<td>STM-1/OC-3</td>
<td>STM-1/OC-3</td>
<td>STM-64/OC-192</td>
<td>STM-256/OC-768</td>
<td></td>
</tr>
<tr>
<td></td>
<td>STM-4/OC-12</td>
<td>STM-4/OC-12</td>
<td>STM-64/OC-192</td>
<td>STM-64/OC-192</td>
<td></td>
</tr>
<tr>
<td>Muxponder</td>
<td>STM-1/OC-3</td>
<td>STM-1/OC-3</td>
<td>STM-16/OC-48</td>
<td>STM-64/OC-192</td>
<td>STM-64/OC-192</td>
</tr>
<tr>
<td></td>
<td>STM-4/OC-12</td>
<td>STM-4/OC-12</td>
<td>STM-64/OC-192</td>
<td>STM-64/OC-192</td>
<td></td>
</tr>
</tbody>
</table>

Figure 65. SDH/SONET client interfaces of TM-Series Transponders and Muxponders.
4.3.2 Optical Transport Network (OTN)

The Optical Transport Network (OTN) is a more recent addition to the standards for public telecommunications networks and is sometimes referred to by its ITU-T name G.709. The standard was designed to transport both packet mode traffic such as IP and Ethernet, and legacy SDH/SONET traffic over fiber optics. It supports forward error correction (FEC) and management functions for monitoring a connection end-to-end over multiple transport segments.

The amount of installed OTN equipment is currently still limited in many regions but OTN is becoming more widely deployed as SONET/SDH solutions reach end of life. Today, OTN has its main application in the long haul network where error correction and interoperability between several operators’ equipment are important.

OTN is a digital wrapper technology that wraps any client signal in overhead information for operations, administration and management. The basic unit of information transport in the protocol is the Optical Channel Data Unit (ODU) which is carried within an Optical Channel Transport Unit (OTU) defining the line rate of the connection. The line rates of OTN are referred to as OTU1, OTU2 and OTU3 and are different from the SDH/SONET line rates. (Figure 66)

<table>
<thead>
<tr>
<th>OTN (G.709)</th>
<th>Line rates</th>
<th>SONET/SDH</th>
<th>Line rates</th>
</tr>
</thead>
<tbody>
<tr>
<td>OTU1</td>
<td>2.666 Gb/s</td>
<td>STS-48/STM-16</td>
<td>2.488 Gb/s</td>
</tr>
<tr>
<td>OTU2</td>
<td>10.709 Gb/s</td>
<td>STS-192/STM-64</td>
<td>9.953 Gb/s</td>
</tr>
<tr>
<td>OTU3</td>
<td>43.018 Gb/s</td>
<td>STS-786/STM-128</td>
<td>39.813 Gb/s</td>
</tr>
</tbody>
</table>

Figure 66. OTN line rates compared with SDH/SONET line rates.

The ITU-T G.709 standard defines the format and data rates for the ODU signals. (Figure 67)

<table>
<thead>
<tr>
<th>Signal</th>
<th>Data Rate (Gbit/s)</th>
<th>Typical Applications</th>
</tr>
</thead>
<tbody>
<tr>
<td>ODU0</td>
<td>1.24416</td>
<td>Transport of a timing transparent transcoded (compressed) 1000BASE-X signal or a stream of packets (such as Ethernet, MPLS or IP) using Generic Framing Procedure.</td>
</tr>
<tr>
<td>ODU1</td>
<td>2.49877512605042</td>
<td>Transport of two ODU0 signals or a STS-48/STM-16 signal or a stream of packets (such as Ethernet, MPLS or IP) using Generic Framing Procedure.</td>
</tr>
<tr>
<td>ODU2</td>
<td>10.0372739240506</td>
<td>Transport of up to eight ODU0 signals or up to four ODU1 signals or a STS-192/STM-64 signal or a WAN PHY (10GBASE-W) or a stream of packets (such as Ethernet, MPLS or IP) using Generic Framing Procedure.</td>
</tr>
<tr>
<td>ODU2e</td>
<td>10.3995253164557</td>
<td>Transport of a 10 Gigabit Ethernet signal or a timing transparent transcoded (compressed) Fibre Channel 10GFC signal</td>
</tr>
<tr>
<td>ODU3</td>
<td>40.3192189830509</td>
<td>Transport of up to 32 ODU0 signals or up to 16 ODU1 signals or up to four ODU2 signals or a STS-768/STM-256 signal or a timing transparent transcoded 40 Gigabit Ethernet signal or a stream of packets (such as Ethernet, MPLS or IP) using Generic Framing Procedure.</td>
</tr>
<tr>
<td>ODU3e2</td>
<td>41.7859685595012</td>
<td>Transport of up to four ODU2e signals</td>
</tr>
<tr>
<td>ODU4</td>
<td>104.79444581497</td>
<td>Transport of up to 80 ODU0 signals or up to 40 ODU1 signals or up to ten ODU2 signals or up to two ODU3 signals or a 100 Gigabit Ethernet signal.</td>
</tr>
<tr>
<td>ODUflex (CBR)</td>
<td>239/238 x client bit rate</td>
<td>Transport of a Constant bitrate signal such as Fibre Channel 8GFC, InfiniBand or Common Public Radio Interface</td>
</tr>
<tr>
<td>ODUflex (GFP)</td>
<td>any configured rate</td>
<td>Transport of a stream of packets (such as Ethernet, MPLS or IP) using Generic Framing Procedure.</td>
</tr>
</tbody>
</table>

Figure 67. ITU-T G.709 ODU definitions and application examples. Source: Wikipedia
The TM-Series includes the following traffic units for transparent transport of OTN/ODU signals. (Figure 68)

<table>
<thead>
<tr>
<th>Line rate</th>
<th>10 Gbit/s</th>
<th>40 Gbit/s</th>
<th>100 Gbit/s</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transponder</td>
<td>OTU2</td>
<td>OTU3</td>
<td>OTU4</td>
</tr>
<tr>
<td>Muxponder</td>
<td>OTU2</td>
<td>OTU2</td>
<td>OTU2e</td>
</tr>
</tbody>
</table>

*Figure 68. TM-Series traffic units for transport of OTN/ODU signals.*

OTN systems are often divided into two categories; transport systems and switches. Systems that use OTN transport use the OTN standards to frame signals for a specific route. This utilizes the sections of the OTN standards that relate to transmission such as framing, Forward Error Correction (FEC) and Performance Monitoring etc, in a very similar way to the SONET/SDH standards. These systems use transponders or muxponders to terminate the signal. OTN Switches take this one stage further and add an OTN switching fabric that is capable of demultiplexing incoming OTN signals and switching the lower speed components to other high speed interfaces.

4.3.3 Ethernet

*Ethernet* is a family of protocols and networking technologies originally designed for local area networks (LANs) in the 1980s but now also widely used for other topologies and distances. Standardized by IEEE in the IEEE 802.3 family of standards, Ethernet has largely replaced competing wired LAN technologies and is today the dominating link layer protocol also for wide area data networks (WAN).

Ethernet can be used in bus, star and mesh topologies and over a variety of physical media, including coaxial cable, twisted pair copper cable, wireless media, and optical fiber. Typical data rates today are 10 Mbit/s, 100 Mbit/s (Fast Ethernet), 1 Gbit/s (Gigabit Ethernet or GbE) and 10 Gbit/s (10-Gigabit Ethernet or 10 GbE). New standards for higher speed transmission at 40 Gbit/s (40 GbE) and 100 Gbit/s (100 GbE) have been developed and are now starting to be deployed in high capacity networks.

4.3.3.1 ETHERNET MODE OF OPERATION

Systems communicating over Ethernet divide a stream of data into individual packets called *Ethernet frames*. Each frame contains source and destination addresses and an error-checking code so that damaged data can be detected and re-transmitted. (Figure 69)

<table>
<thead>
<tr>
<th>6 Bytes</th>
<th>6 Bytes</th>
<th>2 Bytes</th>
<th>46-1,500 Bytes</th>
<th>4 Bytes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Destination</td>
<td>Source</td>
<td>Length/Type</td>
<td>Data</td>
<td>FSC</td>
</tr>
</tbody>
</table>

*Figure 69. The basic Ethernet frame (FCS, Frame Check Sequence).*

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18 IEEE, Institute of Electrical and Electronic Engineers.

19 For Gigabit Ethernet some vendors provide equipment that support a jumbo frame option, where frames can have a data payload of up to 9 000 bytes.
While the original Ethernet standard was designed for operation on a single transmission medium – a coaxial cable connecting a set of computers – practically all LAN and every WAN Ethernet design today is based on switched Ethernet. In **switched Ethernet** all Ethernet stations have their own, individual, full duplex, connection to a central switch (sometimes called multiport bridge). The switch has a forwarding table which matches Ethernet addresses with a corresponding port, and sends the frame to the correct destination. Switches are then interconnected and form more or less complex mesh structures. (Figure 70)

In a meshed Ethernet, there are several paths between nodes, and frames could be forwarded in infinite loops within the network, if no countermeasures were taken – there must be one and only one open route between each node of the network, and all other interconnecting ports of the switches must be blocked. Such a network topology is called a **spanning tree**. (Figure 71)

The **Spanning Tree Protocol (STP)** in the Ethernet standard is a distributed algorithm run by the switches to form a spanning tree. The switches identify alternative routes, use “weights” assigned to the links to select the shortest/fastest link, and block ports not to be used. In case of link failure, a recalculation is done and an alternative route for the frames is selected. The original protocol has been further improved (**RSTP, Rapid Spanning Tree**), to reduce the convergence time to compute a new spanning tree when there is a topological change. It could take the STP protocol 30 – 50 s to recalculate the spanning tree after a link outage, but RSTP and further refinements have taken the recovery time down to some milliseconds.

Another important Ethernet feature is the possibility to define a **virtual LAN (VLAN)**. A VLAN allows bandwidth to be divided up between groups of nodes, and in a way so that users in each group can only communicate within its own VLAN. All Ethernet frames in a VLAN have a distinct identifier called a **VLAN tag**. VLANs can be used to implement **virtual private networks (VPN)** and VLAN frames include priority fields that can be used to support a differentiation of quality of service. (Figure 72)
The 100 in the media type designation refers to the transmission speed of 100 Mbit/s. The “BASE” refers to baseband signaling, which means that only Ethernet signals are carried on the medium. The TX and FX refer to the physical medium that carries the signal.

The TM-Series traffic units support both the electrical 100BASE-TX and the optical 100BASE-FX client interfaces.

**GIGABIT ETHERNET (GbE) PHYSICAL LAYER**

Gigabit Ethernet (GbE) can be transmitted over shielded fiber cables and over shielded copper cables. It can also be transmitted over unshielded twisted pairs of copper. The transmission is set up to operate in full duplex (most common) or half-duplex mode. The standard defines a physical medium dependent (PMD) sub layer which specifies the transceiver for the physical medium in use. There are three types of PMDs for GbE:

- **Short range**: Uses 850 nm light with a reach of 220 – 250 m on multimode fiber. The long range PMD uses 1310 nm light with a reach of 550 m on multimode fiber and 5 km on single mode fiber. The PMD for shielded copper reaches only 25 m.
For unshielded copper, which is common in many office installations, multiple twisted pairs are used to send multilevel signals in a way that extends the reach to 100 m. (Figure 73)

### Ethernet in the First Mile later added 1000BASE-LX10 AND -BX10

<table>
<thead>
<tr>
<th>Name</th>
<th>Medium</th>
<th>Specific distance</th>
</tr>
</thead>
<tbody>
<tr>
<td>1000BASE-CX</td>
<td>Twinaxial cabling</td>
<td>25 meters</td>
</tr>
<tr>
<td>1000BASE-SX</td>
<td>Multi-mode fiber</td>
<td>220 to 550 meters dependent on</td>
</tr>
<tr>
<td></td>
<td></td>
<td>fiber diameter and bandwidth</td>
</tr>
<tr>
<td>1000BASE-LX</td>
<td>Multi-mode fiber</td>
<td>550 meters</td>
</tr>
<tr>
<td>1000BASE-LX10</td>
<td>Single-mode fiber using</td>
<td>5 km</td>
</tr>
<tr>
<td></td>
<td>1,310 nm wavelength</td>
<td></td>
</tr>
<tr>
<td>1000BASE-ZX</td>
<td>Single-mode fiber at 1,550 nm</td>
<td>~70 km</td>
</tr>
<tr>
<td></td>
<td>wavelength</td>
<td></td>
</tr>
<tr>
<td>1000BASE-BX10</td>
<td>Single-mode fiber, over</td>
<td>10 km</td>
</tr>
<tr>
<td></td>
<td>single-strand fiber:</td>
<td></td>
</tr>
<tr>
<td></td>
<td>1,490 nm downstream</td>
<td></td>
</tr>
<tr>
<td></td>
<td>1,310 nm upstream</td>
<td></td>
</tr>
<tr>
<td>1000BASE-T</td>
<td>Twisted-pair cabling (Cat-5,</td>
<td>100 meters</td>
</tr>
<tr>
<td></td>
<td>Cat-5e, Cat-6, or Cat-7)</td>
<td></td>
</tr>
<tr>
<td>1000BASE-TX</td>
<td>Twisted-pair cabling (Cat-6,</td>
<td>100 meters</td>
</tr>
<tr>
<td></td>
<td>Cat-7)</td>
<td></td>
</tr>
</tbody>
</table>

The TM-Series traffic units support both the electrical (1000BASE-T) and the optical (1000BASE-L) variants for single and multimode fiber in the GbE physical layer when interfacing to client systems.

### 10-GIGABIT ETHERNET (10GBe) PHYSICAL LAYER

10-Gigabit Ethernet (10GbE) can be transmitted over fiber optics and copper cables, but copper cables are only used over very short distances such as interconnections within a chassis.

For fiber optic cables, the physical layer can be implemented in two main variants: LAN PHY and WAN PHY, optimized for use in local area and wide area networks respectively. Both the LAN PHY and the WAN PHY operate over a short range, long range, extended range or long reach PMD. Short range uses 850 nm over multimode fibers up to 300 m; long range uses 1310 nm and reaches 260 m on multimode and 10 km on single mode fiber. The extended reach PMD uses 1550 nm and has a maximum reach of 40 km on single mode fiber.

The TM-Series traffic units can be equipped with client system interfaces that support both the LAN PHY and WAN PHY over the various PMDs on single and multimode fiber.

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4.3.3.3 CARRIER ETHERNET
With the pervasiveness of Ethernet in enterprises, many operators today offer Ethernet connectivity across multiple sites as a service. Services are often standardized as E-Line, which is an Ethernet point-to-point connection, E-LAN which is a multipoint connection that operates as a virtual switched Ethernet LAN over many locations and E-Tree which is an Ethernet point-to-multipoint connection.

The Ethernet standard has been extended with options to support such carrier offerings: Provider Bridges and Provider Backbone Bridges (PBB). Both these mechanisms extend the VLAN concept described earlier so that a VLAN can span more than one single location and data can be “tunneled” between the VLAN islands. A further extension of PBB called Provider Backbone Bridge – Traffic Engineering (PBB-TE) has been defined for use of Ethernet as a connection oriented transport technology with some of the characteristics of SDH/SONET and OTN. The Metro Ethernet Forum (MEF) is an industry body that produces standards for these Ethernet services and associated network hardware.

4.3.3.4 CARRIER ETHERNET 2.0
The MEF has announced the next evolution of Carrier Ethernet services with the Carrier Ethernet 2.0 standards. CE2.0 brings three powerful and standardized features, Multiple Classes of Service (Multi-CoS), Interconnect and Manageability. The new specifications expand from the three services available in CE 1.0 to eight services – two of each respectively in E-Line, E-LAN, E-Tree, and E-Access – dedicated Ethernet and shared Ethernet Virtual services per type.

4.3.3.5 OVERVIEW OF ETHERNET CLIENT INTERFACES IN THE TM-SERIES
The TM-Series traffic units support a wide range of Ethernet interfaces, both on dedicated Ethernet traffic units and on units combining SDH/SONET and other client interfaces with Ethernet ports. In addition, the TM-Series includes “Ethernet aware” traffic units that can act upon the Ethernet frames and manage the traffic even more intelligently. (Figure 74)

<table>
<thead>
<tr>
<th>Line rate</th>
<th>2.5 Gbit/s</th>
<th>4 Gbit/s</th>
<th>10 Gbit/s</th>
<th>40 Gbit/s</th>
<th>100 Gbit/s</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transponder</td>
<td>100 Base-T</td>
<td>GbE</td>
<td>10 GbE LAN</td>
<td>100 GbE LAN</td>
<td></td>
</tr>
<tr>
<td>Muxponder</td>
<td>GbE</td>
<td>GbE</td>
<td>GbE</td>
<td>10 GbE LAN</td>
<td>10 GbE WAN</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>10 GbE WAN</td>
<td>10 GbE LAN</td>
</tr>
</tbody>
</table>

74. Ethernet client interfaces in TM-Series traffic units.
### 4.3.4 IP and Multiprotocol Label Switching (MPLS)

IP is by far the most widely used wide area data networking technology today. IP networks rely upon the Internet protocol suite of communications protocols commonly known as TCP/IP from its most important protocols: Transmission Control Protocol (TCP) and Internet Protocol (IP). TCP/IP is used for the all-pervasive Internet and in most private intranets that link up computers.

IP is a networking protocol designed to work over a multitude of lower data link layers, a fact that has contributed to its widespread success. Several layering structures are possible to map IP into the optical layer and WDM, i.e. the term IP over WDM may refer to several alternative approaches. (Figure 75)

From the TM-Series perspective, it is important to note that IP relies upon underlying physical layer protocols and that these protocols (e.g. SDH/SONET and Ethernet) are the ones that are interfaced to the transponders and muxponders. The TM-Series WDM optical network is completely transparent to all IP packets, which are forwarded “inside” the selected physical layer protocol.

**Multiprotocol Label Switching (MPLS)** is a technology that can be used in IP networks to simulate more permanent “connections” between end points. MPLS simplifies the implementation of routing and packet processing in the IP routers, and enables quality of service mechanisms of value to network operators. MPLS can be thought of as a layer “sandwiched in” between the IP layer and the physical layer, hence the TM-Series is also completely transparent also to MPLS traffic.

### 4.3.5 Storage Area Networks (SAN) with Fibre Channel and ESCON

A storage area network (SAN) is a dedicated data network that connects storage devices, such as disk arrays, tape libraries, and optical jukeboxes to mainframe computers and servers, so that the devices appear like locally attached devices to the operating system. A SAN typically has its own network of storage devices that are generally not accessible through wide or local area networks by other devices. In the early days, the entire SAN was located at one data center, but today a SAN is often distributed over a wider metropolitan area to duplicate data and provide resilience against disasters. (Figure 76)

SANs often utilize a Fibre Channel fabric topology – an infrastructure specially designed to handle storage communications. A typical Fibre Channel SAN fabric is made up of a number of interconnected Fibre Channel switches. The Fibre Channel protocol adds overhead data to the vendor specific data storage protocols and adapts the signal for transmission over fiber and copper wires (the latter seldom used). Fibre Channel trans-

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**Figure 75.** Alternative implementations of IP over WDM: a) Packet over SONET with HDLC framing. b) Packet over SONET with GFP framing. c) Ethernet framing.
receivers operating at 1300 nm and 1550 nm can reach tens of kilometers on single mode fiber. 850 nm transceivers are used for multimode fiber with a reach of a few hundred meters. Just as for SDH/SONET and OTN, Fibre Channel is available in a hierarchy of data rates, from 100 Mbyte/s up to 1 000 Mbyte/s. (Figure 77)

Another common legacy protocol for attaching peripheral equipment to mainframe computers is ESCON, (Enterprise Systems Connection), originally created by IBM. ESCON is an optical fiber, half-duplex, serial interface. It originally operated at a rate of 10 Mbyte/s, which was later increased to 17 Mbyte/s. The current maximum distance specified is 43 kilometers.

**Figure 76.** Architecture of a storage area network (SAN).

**Figure 77.** Fibre Channel storage area network data rates. Source Wikipedia.

### 4.3.5.1 OVERVIEW OF STORAGE AREA NETWORK CLIENT INTERFACES IN THE TM-SERIES
(Figure 78)

<table>
<thead>
<tr>
<th>Line rate</th>
<th>2.5 Gbit/s</th>
<th>4 Gbit/s</th>
<th>10 Gbit/s</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transponder</td>
<td>ESCON</td>
<td>1GFC</td>
<td>8GFC</td>
</tr>
<tr>
<td>1GFC</td>
<td>2GFC</td>
<td>10GFC</td>
<td></td>
</tr>
<tr>
<td>2GFC</td>
<td>4GFC</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Muxponder</td>
<td>ESCON</td>
<td>1GFC</td>
<td>1GFC</td>
</tr>
<tr>
<td>1GFC</td>
<td>2GFC</td>
<td>2GFC</td>
<td></td>
</tr>
<tr>
<td>2GFC</td>
<td>4GFC</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*Throughput for duplex connections.

**Figure 78.** SAN client interfaces in the TM-Series.
4.3.6 Video protocols
Transport of video signals over long haul and metropolitan networks is an important application for WDM networks. Standards for digital broadcasting have been developed by the Digital Video Broadcasting (DVB) Project, an industry consortium of broadcasters, network operators and the TV industry. The first phase of DVB’s work involved establishing standards to enable the delivery of digital TV to the consumer via the “traditional” broadcast networks. Thus, the three key standards during this phase were DVB-S for satellite networks, DVB-C for cable networks and DVB-T for terrestrial networks. In addition to these, a whole range of supporting standards was required covering areas such as service information (DVB-SI), subtitling (DVB-SUB), interfacing (e.g. DVB-ASI), etc. The TM-Series traffic units include interfaces for DVB-ASI/-SDI/HD-SDI.

4.4 Combining protocols in one traffic unit
Real world metropolitan transport networks are characterized by a mix of different traffic layer protocols. Computer centers are to be interconnected in a Storage Area Network, a cable TV operator wants to distribute broadcast TV content, household Internet users’ traffic is aggregated over Gigabit Ethernet lines and legacy telephony traffic is in SDH format. The diversification of protocols and data rates makes it of utmost importance that the underlying WDM network can be adapted to the needs in a granular way, so that ports are not left empty in the traffic units. (Figure 79)

The TM-Series has a unique flexibility. Multiple traffic unit cards with different protocols and data rates can be combined in the same chassis. Also the individual transponder and muxponder card has versatility in the protocols supported. The cards are designed for multi-protocol operation, and furthermore, they can be adapted to multiple configurations by downloadable software. To simplify operations, many traffic unit ports are capable of automatic protocol recognition.

Figure 79. A typical metropolitan area network and the traffic layer protocols employed between nodes.

Figure 80. Example of a TM-Series multi-protocol and multi-configurable transponder.
4.5 Line side data rates and framing
After having discussed the various traffic layer protocols of the client systems connected to the WDM optical network, it is time to look into the line side of the Transmode traffic units. (Figure 81)

- Insertion of path information that can be used to validate the connection.
- Safety and security features like Automatic Laser Shut-down (ALS) that shuts down the laser upon a fiber cut.

The TM-Series traffic units – the transponders and muxponders – are designed to operate at a specific date rate on their line side: 2.5 Gbit/s, 4 Gbit/s, 10 Gbit/s, 40 Gbit/s or 100 Gbit/s. This is the data rate of the digital signal transmitted on the WDM wavelength \( \lambda \), a wavelength that is created by the SFP/XFP of the traffic unit and that enters the filters, multiplexers, ROADMs etc. of the optical network. The line side data rate thus defines the highest client side data rate and the number of client systems that can be time division multiplexed upon one single wavelength forming a light path between two traffic units.

Just as client systems interact with each other according to different protocols, the two traffic units at the end of a given light path interact with each other according to a specific framing format and protocol (signaling). The framing and the signaling specify how data from the clients is multiplexed and allows for the management information to flow between the traffic units. (Figure 82)

As stated earlier, the transponder/muxponder adapts the client signal to the WDM network. It also encapsulates the client signal into a digital wrapper, i.e. extra bytes are added to the client signal at the client ingress point and removed at the client egress point. These OH-bytes can be used for a number of features, such as

- Introduction of quality check of the WDM signal enabling Performance Management (PM) as well as Fault Management (FM) in the transmission domain.
- Insertion of management channels that are used to connect to other nodes in the network for management purposes \( \lambda \). Embedded or in-band management channels.
- Insertion of coding that detects and corrects bit errors; Forward Error Correction (FEC). There are different variants of FEC and these are sometimes needed for long-haul transport of 10/40/100 Gbit/s signals in amplified networks.

Figure 81. Definition of the line side of a traffic unit.

Figure 82. The traffic units at each end of a light path interact with each other according to a line side framing format and a signaling protocol.
4.5.1 SONET/SDH and OTN Framing

As previously described in this document in the section on client side protocols, both SONET/SDH and OTN support the necessary framing for transmission over fiber or WDM networks.

SONET/SDH and OTN framing can be particularly useful in long-haul applications where equipment from several vendors has to interwork in the same optical network, other protocols may be required.

The TM-Series Transponders provide fully transparent transport of OTN OTU1 signals at 2.5 Gbit/s and for OTN OTU2 signals at 10 Gbit/s. The TM-Series also supports transparent transport of SONET/SDH signals, i.e. it is possible to use SDH framing on the line side of selected transponders.

Furthermore muxponder options are available that multiplex lower speed signals onto an OC-48/STM-16, an OC-192/STM-64 line or an OTU2 OTN line.

4.5.2 Native Ethernet Framing

Transmode also supports a Native Packet Optical architecture that integrates Layer 2 Ethernet switching into the TM-Series optical platform. This solution is outside the scope of this document as it is a wide ranging subject in itself. But it is worth noting in this section that the TM-Series also supports Native Ethernet as a protocol for line framing.

4.5.3 Transmode iWDM™ Framing

In addition to the SDH/SONET, OTN and Native Ethernet framing options outlined above, Transmode has also developed Intelligent WDM framing to provide additional options to address some of the flexibility and cost efficiency challenges that need to be addressed in metropolitan networks, Transmode provides this additional optional framing format – iWDM framing – for traffic unit interaction, i.e. for point to point wavelengths over a fixed or ROADM based optical network. The iWDM framing was invented by Transmode and provides cost-optimized transport of multiple services while simplifying the provisioning and operations of the optical transport network. (Figure 83)

The ability to support multiple services, and the quality of these services, is vital for transport networks. iWDM framing provides aggregation at the physical transmission layer and at higher layers to the most cost-efficient transport bit rate that includes 2.5 Gbit/s, 4 Gbit/s or 10 Gbit/s depending on the application. With iWDM framing, it is for example possible to multiplex up to 10 independent GbE signals into one 10 Gbit/s stream on a single wavelength, while still maintaining full transparency for both data and individual synchronization per GbE signal.
The iWDM framing also provides options for forward error correction which extends the reach of a system, while maintaining the quality of the services and performance monitoring for service level agreement maintenance. iWDM provides a patented automatic client side protocol and bit-rate detection scheme that reduces an operator’s OPEX by removing the need for complex installation, commissioning and provisioning. The iWDM framing furthermore provides in-band management capabilities that simplify the management of remote network elements.

### 4.5.4 OTN and iWDM comparison

Transmode WDM solutions provide operators with a broad range of networking options, including line framing protocols. All protocols have advantages and disadvantages and are therefore more suitable in different networks or parts of networks.

Using iWDM framing can be an optimal solution in regional, metro and access networks, where versatility and cost are first in demand, especially in optical sub-domains (see 5.5). The use of an all TM-Series based network with iWDM provides the operator with the highest flexibility when mixing and matching varying client system requirements in one optical network.

However, OTN can be more suitable in networks where line rate (as opposed to client level) multi-vendor interworking is required.

The table below compares the differences between the two protocols for transport networks. (Figure 84)

<table>
<thead>
<tr>
<th>OTN feature</th>
<th>iWDM feature</th>
</tr>
</thead>
<tbody>
<tr>
<td>Management by embedded management channels</td>
<td>Management by embedded management channels</td>
</tr>
<tr>
<td>Increased transmission performance by forward error correction (FEC)</td>
<td>Increased transmission performance by forward error correction (FEC)</td>
</tr>
<tr>
<td>Transparent transport of STM-16 and STM-64 signals in G.709 framing</td>
<td>Transparent transport of STM-16 and STM-64 signals in G.709 framing</td>
</tr>
<tr>
<td>End-to-end management through multi-vendor networks</td>
<td>Not supported</td>
</tr>
<tr>
<td>Only for STM-16/-64/-192 (OTU1/2/3)</td>
<td>iWDM supports data rates from STM-1 to OC-3 transparently</td>
</tr>
<tr>
<td>High amount of overhead makes use of bandwidth for management functions</td>
<td>Efficient use of available bandwidth. and low delay</td>
</tr>
<tr>
<td>No special features for multiple synchronization signals in current OTN standard</td>
<td>Transparent transport of up to 10 data channels including synchronization over one 10 Gbit/s channel</td>
</tr>
<tr>
<td>OTN is an OSI Layer 1 framing standard</td>
<td>iWDM provides for OSI Layer 2 functions such as VLAN management and Layer 2 performance monitoring</td>
</tr>
</tbody>
</table>

*Figure 84. Comparison of some OTN and iWDM framing characteristics.*
4.6 Two applications taking advantage of iWDM framing

The versatility of the iWDM framing enables much more than the basic multiplexing and management of several client signals over a WDM network. The iWDM framing can for example be optimized for specific applications, such as mobile backhaul and residential broadband access.

4.6.1 Synchronization and transparency in mobile backhaul

The booming use of smartphones and tablets create a true traffic explosion in every mobile network today. Conventional mobile backhaul networks based on microwave radio links cannot affordably scale to meet this demand. The trend is that more and more mobile operators use optical fiber to connect a growing proportion of their cell sites. Most of the traffic is data, so the use of Ethernet and IP protocols all the way out to the cell site has become the norm. This in turn creates complexity in the handling of synchronization for legacy voice circuits and the wireless networks.

Transmode’s Mobile Backhaul Solutions respond to the requirements of mobile operators by pushing Intelligent WDM (iWDM) technology to the cell site, to cost-efficiently increase the backhaul capacity. This is a successful way to utilize standard WDM technology and provides mobile, fixed and wholesale operators with a speedway to the cell site and cost efficient transport of Ethernet as well as legacy TDM traffic. (Figure 85)

The figure illustrates how traffic from a number of cell sites covering a region is aggregated over WDM and handed over to a long haul network for transport to the central nodes of the mobile network. The bulk of the traffic is IP packets over Ethernet, but there are also streams of SDH/SONET E1/T1 or E3/T3 time division multiplexed circuits for voice calls. In addition, the wireless transceivers need to maintain an exact synchronization to handle the radio protocol with the mobile devices. Thus, maintaining synchronization while transporting large amounts of Ethernet traffic becomes a key problem to solve.
Figure 85. Principles of a WDM mobile backhaul network.
One simple solution is to assign separate wavelengths in the WDM network for different types of traffic and use individual wavelengths for synchronization. Such an approach is, however, not very feasible because of the waste of bandwidth, the associated complexity in light path planning and, not the least, the sheer cost.

As mentioned earlier, iWDM framing allows for cost efficient time division multiplexing of both Ethernet and SDH/SONET traffic on the same wavelength. But how can the synchronization required be achieved?

Several standards have been proposed for how to transport synchronization information within the Ethernet protocol – so called pseudo-wire emulation (PWE). However, the standards lack on accuracy, latency or possibility to handle several parallel synchronization flows. Transmode has therefore developed a solution within the TM-Series uniquely adapted to the needs of mobile backhaul.

The Transmode solution enables native – i.e. 100% transparent – transport of up to 4 independent TDM E1/T1 circuits and 4 independent Ethernet connections within the same iWDM frame using one single wavelength. Synchronization for the E1/T1 circuits is derived from STM1/OC-3 and transported within each E1/T1 signal, which enables up to 4 different TDM clocks to be present in the same iWDM frame. In the same way, each of the four Ethernet connections is fully transparent for transport of data and synchronization, and can support PWE-standards such as sync-E (G.8262/Y.1362) and Timing over Packets (1588v2) for its own, independent synchronization. (Figure 86)

A typical example of how this capability can be applied is shown in the following figure. (Figure 87)

20 More than one synchronization clock may be needed in a wholesale business model, where a network operator transports traffic for different mobile operators, each with their own “time,” within the same WDM network.
Synchronization is a generic strength of the iWDM protocol and this is just one example where multiple transparent sync domains on a single wavelength can be useful. Other iWDM muxponders also support multiple transparent sync domains which is something that is very difficult to implement using other protocols.

**4.6.2 Gigabit Ethernet broadband access**
Demand for very high speed broadband access services is rising, putting a requirement on operators to offer Gigabit Ethernet to selected subscribers. Thanks to the flexibility and efficiency of Gigabit Ethernet and the iWDM protocol, it is possible to design a TM-Series muxponder that can transport 10 full GbE links over one single 10 Gbit/s channel. (Figure 88)

![Figure 88. Transport of 10 full GbE links over a 10 Gbit/s channel with iWDM.](image)

Ethernet aggregation is just one of several possible applications of this 10G muxponder MS-MXP/10G. The MS-MXP/10G implements a true multi-service concept, enabling a traffic unit to be configured and used in multiple applications. Instead of having traffic units that are dedicated for a certain service and application, the TM-Series comprises units that can be reconfigured to support different traffic formats as well as being configured to provide various functions. This flexible capability in combination with pluggable optics gives the lowest total cost of ownership (TCO).

When the MS-MXP/10G traffic unit is used as a 10 x Ethernet muxponder all client side Ethernet ports support:
- Optical and electrical Gigabit Ethernet.
- Electrical Fast Ethernet.
- Individual Sync-E (G.8262/Y.1362) when using optical SFP’s.

The transport between two MS-MXP/10G units is fully synchronization and information transparent, and can be given improved availability with 1 + 1 line protection, using the two available line side ports of the traffic unit.
5. OPERATING THE NETWORK
5.1 Executive summary of chapter 5
This final chapter is dedicated to the operational aspects of the packet-optical network. The text describes the standardized management model for telecommunications networks and how it has been implemented in the network elements of the TM-Series and by the Transmode Network Manager (TNM). Some of the practical aspects of handling the network hardware are also touched upon:
- Management architecture for telecommunications network.
- Transmode’s Enlighten.
- Transmode Network Manager (TNM).
- Embedded Node Manager (ENM).
- Installation, commissioning and repair.
- Low Power Design.

5.2 Introduction
Looking at the total life cycle cost of a communications network, i.e. the cost of both the equipment and the resources spent over time to keep the network operational, the recurring operational and management expenses dominate. Capable network management tools and network equipment designed for cost efficient maintenance are vital to make the communications network investment profitable and the business case attractive. Furthermore, management systems must be well integrated with both operational processes and business support systems to provide maximum value. Rather than acting on isolated “islands” per technology, region etc., management systems covering multiple OSI layers and enabling end-to-end overview are required for today’s complex networks.

Transmode’s Enlighten multi-layer management suite provides network operators with full control of their integrated packet-optical network, from planning and design, to implementation and commissioning, through to full network operation. The Enlighten applications include the Transmode Network Manager (TNM), the Embedded Node Manager (ENM), the Transmode Network Design Tool, the Transmode Planning Tool, and the Enlighten Ecosystem. Together, these applications provide superior tools for planning, deploying and operating a Transmode packet-optical network.

And from the overall operations perspective, all TM-Series hardware and software components have been designed with high availability and easy handling as the guiding principles. Rigorous quality control procedures and extensive testing ensures minimum risk of failures.
5.3 Managing the optical and Ethernet domains

Management of a communications network comprises many diverse actions, which classically have been grouped into five main categories, the FCAPS suite:

- **Fault management (F)** encompasses functions for detecting failures and isolating the failed equipment, including the restoration of connectivity.

- **Configuration management (C)** refers to functions for making orderly and planned changes within the network. An important part of configuration management is keeping an inventory of equipment, software releases etc. in the nodes.

- **Accounting (or administration) management (A)** deals with functions that make it possible to bill users for the network resources they use.

- **Performance management (P)** comprises functions for monitoring and fine tuning the various parameters that measure the performance of the network and forms the basis for service level agreements with the network users.

- **Security management (S)** refers to administrative functions for authenticating users and setting access rights and other permissions on a per-user basis.

A great deal of standardization of management procedures has taken place among operators and their vendors to facilitate network operations. Organizations such as TeleManagement Forum (TM Forum), formerly the OSI/Network Management Forum, have developed extensive specifications of management functionality, interfaces and protocols.

The Transmode network management philosophy fully adheres to the relevant TM Forum standards. The network management system offered by Transmode is a fully TM Forum Frameworkx compatible multi-layer service manager, i.e. it allows for end-to-end configuration of services over multiple OSI-layers, i.e. both the optical equipment and the Ethernet functionality. The capability to seamlessly manage wavelengths, light paths and Ethernet parameters on an end-to-end basis is the one and only way to make commissioning, maintenance and monitoring of services in large scale optical networks feasible.

5.4 The management model for communications networks

Over time, a typical structure – an architecture – has evolved for how to organize management systems for communications networks. To facilitate interoperability between equipment from multiple vendors, the architecture has been standardized by ITU-T in recommendation M.3010 “Principles for a telecommunications management network”[21], and is now widely used.

Communications network management is performed in a hierarchical way, most often involving multiple, interacting management systems. The individual pieces of equipment to be managed are referred to as the network elements, i.e. the amplifiers, transponders and switches of the optical network are all network elements. Each network element is managed by its own element management system (EMS). The network element itself has a built-in agent – a piece of software – which communicates with the corresponding element manager, and acts upon other functions within the network element. Some local management functionality is normally always provided by the network element itself, to enable service personnel to configure individual elements from a locally attached terminal or laptop computer.

[21] ITU-T Recommendation M.3010 refers to the architecture as the TMN architecture.
The element manager can be implemented by software within the network element, or in a stand-alone computer which then communicates with the network element over a data communications network (DCN) of some kind. Element managers may control just one single network element, or via the DCN a whole group of elements, forming a sub-domain, e.g. all the optical equipment. In a simple case, multiple element managers may be used to handle the whole network, typically using one EMS per each vendor’s equipment.

An EMS can only view one network element at a time, and lacks the more comprehensive “overview” of what is going on in the entire network. The EMS therefore in turn normally communicates with a higher level network management system (NMS) or an operations support system (OSS). The NMS views the entire network and can manage many different types of network elements through the intermediation of the element managers. Even higher levels in the hierarchy are possible: The NMS/OSS may be part of an integrated business support system (BSS) or a web based self-provisioning system interfacing operator sales people and end-users.

The hierarchy of management systems is illustrated in the following figure. (Figure 89)

5.4.1 Enlighten™
Transmode’s Enlighten is a whole life-cycle multi-layer management suite for managing Transmode’s transport networks. It provides a common management framework for multi-layer networks, simplifying the task of managing and operating Layer 1 and Layer 2 based transport networks.

Enlighten consists of a set of applications, all playing an important role in service and network management throughout the service and network lifecycle. The applications included are:
- Transmode Planning Tool (TPT).
- Transmode Network Design Tool (TNDT).
- Transmode Network Manager (TNM).
- Embedded Node Manager (ENM).
- Transmode Enlighten Ecosystem.
(Figure 90)

In this document we will focus on the Embedded Node Manager (ENM) and Transmode Network Manager (TNM).

Figure 89. Telecom management architecture.

Figure 90. Enlighten provides service and network management through the plan, deploy and operate phases of a network.
5.4.1.1 THE EMBEDDED NODE MANAGER
The Transmode management systems are designed in accordance with the above ITU M.3010 architecture. Local management of the individual nodes in the packet-optical network can be performed by the Embedded Node Manager (ENM). The node manager provides the foundation for the management of the packet-optical network and has sufficient capabilities to manage a small and simple network such as an enterprise network or point-to-point links.

The Embedded Node Manager has a web-based graphical user interface and a command line interface for configuration and provisioning of an individual network element. The graphical user interface can be executed from any common web-browser running UNIX or Windows. The node manager stores all fault, configuration and performance data in a Management Information Base (MIB) that contains the status for the set of objects accessed by higher order management systems. The node manager also includes an open interface for integration towards higher level management systems.

5.4.1.2 THE TRANSMODE NETWORK MANAGER (TNM)
As part of Enlighten, Transmode Network Manager (TNM) is a multi-layer network and service management system for Transmode’s optical and packet optical networking solutions. TNM provides one multi-layer management system with complete topology awareness across both Layer 1 and Layer 2, resulting in a simplified management architecture and more efficient management of the transport network.

TNM is built around a multi-layer TMF608 model according to TMForum specifications. This model has complete topology awareness of the network and services across Layer 1 and Layer 2, enabling multi-layer management in one system for fast cost-effective provisioning, fault isolation and resolution without the need for extensive integration to other OSS systems. With TNM, the user can, in minutes and from one graphical interface, configure an optical channel and add a Layer 2 service on top of this channel or find the root-cause for a problem detected for a Layer 2 service even if the fault occurs on Layer1. (Figure 91)
The versatile TNM can be used as:

- Stand-alone management system for the packet-optical network, providing a complete end-to-end management solution for Transmode’s integrated packet-optical networks.
- Mediator to higher level management systems, hiding the complexity of the underlying packet-optical network.
- Complement to higher order network management systems, simplifying troubleshooting and daily operations and maintenance activities of the packet-optical network.

A key capability of TNM is its topology awareness of optical light paths as a basis for customer centric service management. The fault and performance modules in the TNM leverage this topology awareness to provide connection oriented management of optical end-to-end circuits rather than management of single network elements. Connection oriented management is a prerequisite for end-to-end performance monitoring and time saving features such as root-cause analysis for fault-isolation.

While the TNM is a fully complete network manager for the packet-optical network, it also has an important role as a mediator of information e.g. towards higher order inventory and provisioning systems. It complements other network management systems, simplifying troubleshooting and daily operations and maintenance activities for the optical part of an integrated network. The TNM northbound interfaces are TMForum Frameworx compliant. (Figure 92)

Figure 92. Northbound interfaces of TNM.

TNM offers a full-featured graphical user interface with real-time alarm monitoring, multi-layer root-cause analysis, performance monitoring and point-and-click provisioning and activation.

With its modular architecture, TNM provides management for all aspects of the network and service life-cycle including commissioning, provisioning and assurance. For integration to back-office OSS, TNM provides TMForum Frameworx compliant web-services interfaces based on the TMF608 model to hide the complexity of the underlying optical network and reduce the time, risk and costs associated with integration. (Figure 93)
TNM provides point-and-click provisioning and activation, including automatic path-finding. TNM allows the user to select nodes from the map and the provisioning module lists all available capacity. The user can then select a connection and TNM automatically provisions the service. The user can also activate, deactivate and remove a service through point-and-click.

A feature of specific value in TNM is the connectivity view. It provides visibility of the network and service topology by showing a graphical view of the network, reducing the time to resolve networking problems. (Figure 94)
5.5 Multi-vendor optical networks

Larger operators prefer to deploy equipment from two or more vendors in the same network to avoid single vendor dependence and stimulate competition. It is however extremely challenging to achieve interoperability between WDM equipment from different vendors, since their interfaces convey rather complex analog signals, rather than digital signals. The set of parameters that need to match between network elements are for example optical wavelength, optical power, signal-to-noise ratio, bit rate and more.

Rather than trying to solve the complexity of standardizing all the analog interface parameters, a more practical solution often used is to create separate optical subnets, each with its own vendor equipment. The subnets are then interconnected via transponders or regenerators having standardized digital interfaces. Although this approach may require more equipment, the clear-cut boundaries between domains make fault isolation much simpler. (Figure 95)

5.6 Transporting the management information

The data communications network (DCN) used for management of the network must have a means of “reaching out” to the individual network elements. This can be solved in various ways, and the TM-Series leverages several of them.

5.6.1 Management VLAN

Traffic units and other active equipment with ISO layer-2 functionality and installed at central office locations are normally connected to a dedicated IP-network (a VPN implemented by VLAN technology). This IP-network can only be accessed from the management systems, and has its data transported over the optical network in the same way as other data streams from end users. In the TM-Series some of the transponders and muxponders normally only involved in layer-1 activities have been given additional layer-2 functionality to enable this VPN-type of management.

5.6.2 Embedded management channels (OH-bytes in digital wrappers)

Most TM-Series traffic units multiplex the incoming client signals into a digital frame enabling both transport of the connected client signals, performance monitoring of the line signal and an embedded management channel for remote management connectivity (i.e. transport of OH-bytes in digital wrappers). The latter removes the need for separate wavelengths or a separate data communications network for the TM-Series management traffic. The line signal can also be coded using Forward Error Correction (FEC) to enable long haul transmission over amplified networks.

Figure 95. Interoperability between optical equipment through transponders.

When several optical subnets are constructed in this way, the Transmode Network Manager (TNM) makes an ideal manager of the Transmode subnet, providing open and standardized management interfaces towards higher level management systems.
Figure 96. The TM-Series has full support for a separate Optical Supervisory Channel (OSC), which is made available at each amplifier location.

5.6.3 Optical Supervisory Channel (OSC)
In an amplified optical network, special mechanisms to carry the DCN signals out to the amplifiers located between the nodes are required. This can be realized in many ways, but the best alternative is to dedicate a separate wavelength to monitoring and control functions, i.e. to create an optical supervisory channel (OSC). The OSC is carried on a wavelength different from the wavelengths used for traffic. It is separated from the other wavelengths at each amplifier location and processed and retransmitted to the next amplifier as shown in the following figure. ITU-T has selected the 1510 nm wavelength outside the C- and L-bands used for DWDM as the preferred OSC choice, a standard which is supported by the TM-Series. (Figure 96)

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22 Other signaling methods include use of modulations of the optical carrier (pilot tone) and use of the overhead bytes inherent in SDH/SONET and OTN.
5.7 Installation, commissioning and repair

Providing network services to demanding users requires resilient network elements of high quality with minimum time to repair. The TM-Series is designed with an extremely flexible architecture, allowing for pluggable replacements all the way from the optical SFPs/XFPs, to traffic units and entire chassis. Dual AC or DC power supplies, duplication of control units and hot swap of transponders and muxponders secure the highest possible service availability.

The plug in units of the TM-Series are designed as “system on a blade”, i.e. each plug in unit performs a complete function without dependencies on other cards or an active back plane. Hence, all TM-Series passive optical units and traffic units fit into any of the 10U, 3U or 1U height chassis for 19” and 23” mounting available, making upgrades and spare part handling simple. All chassis are compatible with all units, and the choice of enclosure is primarily governed by the number of card slots required and the expected upgrade demand. (Figure 97)

Furthermore all chassis are designed so that all plug-in units can be inserted in-service without affecting ongoing traffic. A dedicated Control Unit (CU) within each node contains the software of all swappable plug-in units. This means that when a failed plug-in unit is replaced, the new unit can automatically be provided with both the correct SW version as well as the configuration of the unit it replaces. The control unit is not actively involved in the traffic flow and a control unit failure will thus not affect the ongoing traffic.

All the traffic units within a node have their own copy of the configuration data stored in the control unit. Thus, a replacement control unit is automatically provided with the current configuration files. There is therefore no need to locate documentation on current software versions or configuration files when performing maintenance activities on a TM-Series network element. All the required data is provided automatically from within the network element itself. Through providing single board and self-contained design, the TM-Series avoids unnecessarily complicated backplanes on the chassis. The TM-Series’ multi-service Muxponders and high density transponders 2x10G, 4x2.5G and 4x4G are just some examples.

Functionality upgrades and software corrections can be done remotely as upgrades on network element or entire sub-network level. There is thus no need to make a site visit to perform software and functional upgrades of a node. The control unit is equipped with two separate memory banks. One is used for the current version of the software, and one for next (newly downloaded) software.

The microprocessor on each traffic unit can be restarted without affecting the traffic flow. This ensures that a shift to newer traffic unit software can be done without affecting the traffic. Many of the traffic units support multiple software images, thus it is possible to remotely change the functionality of a transponder or muxponder.

![Figure 97. The TM-Series chassis.](image-url)
5.8 Low Power Design

Energy efficiency has become both an economic and environmental imperative in telecommunications. With energy savings of up to 80% as compared to similar solutions, Transmode Low Power Design takes out a significant part of network operational costs.

The TM-Series power consumption of less than 7W per Gigabit Ethernet and less than 10W per 10 Gigabit Ethernet in transport solutions offers an immediate and long-time benefit. An advantage that will grow with time in light of rising energy costs. Also, since it takes almost 5W to cool 10W of heat generated in a typical telecom environment, air-conditioning requirements can be lowered, a further 50% saving on energy.

The low power consumption enables more compact network elements, and also makes it possible to serve more customers per chassis. An example from the UK showed that an additional 50 broadband customers could be connected at each of more than 100 sites – meaning over 5000 extra customers were connected at no extra cost to the operator. All thanks to a low power backhaul solution provided by Transmode.

The Transmode in-depth knowledge of optical networks, coupled with a consistent focus on metro WDM and low-power hardware design, means that the TM-Series is designed with power efficiency and a small footprint right from the start.
Summary
As telecom networks evolve towards ultra-high speed transport of data, video and audio, WDM technology has become a vital component to leverage the capacity inherent in optical fibers.

The TM-Series family of CWDM and DWDM carrier class products is optimized for building the most cost efficient and flexible metro core, interoffice and metro access packet-optical networks possible. Key to the entire TM-Series is its flexibility and how passive and active units may be combined to adapt to the requirements at hand. The very wide range of TM-Series passive and active units and the total compatibility where any plug in unit can be located freely in any chassis minimizes initial investments while still maintaining the option to accommodate virtually any need. The completeness of the Transmode offering is further strengthened by the accompanying management suite Enlighten, which includes both network planning and management tools for TM-Series networks.

The TM-Series family is a fourth generation packet-optical product. In the first and second generations optics was essentially only performing signal transmission. All switching and other higher order network functions were done by external equipment. Third generation optical products route and redirect the optical signals, reducing the signal conversions and equipment needed and thus also the network cost.

The TM-Series fourth generation packet-optical networking products take the integration of functionality one step further by including Ethernet aggregation and other packet mode functions optimized for data traffic into the optical network equipment, creating one integral, centrally managed, packet-optical network. The integration of higher layer functionality makes it possible to handle traffic according to predefined levels of quality, security and bandwidth. By eliminating the need for separate switching equipment in the metro and access networks, the TM-Series reduces overall costs and improves efficiency of data traffic transmission for the network operator.
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Transmode is a global provider of packet-optical networking solutions that enable fixed line and mobile network operators to cost effectively address the capacity needs created by the rapid growth in video and data traffic. These solutions are important building blocks in next-generation high-speed optical networks that support services such as broadband backhaul, mobile data backhaul, video delivery services and cloud computing. Transmode’s solutions are based on Wavelength Division Multiplexing (WDM) and packet optical transport technologies, which are designed to increase the capacity, flexibility and functionality of optical metro core and metro access networks. Transmode’s Intelligent WDM (iWDM™) approach gives key advantages to customers, such as ultra-low latency, low power consumption and innovative network design.

Transmode is headquartered in Stockholm, Sweden and is listed on the NASDAQ OMX Stockholm Exchange (TRMO). Since 2000, the company has installed more than 30,000 systems for over 400 fixed and mobile network operators, service providers, large enterprises and public institutions in over 40 countries across the globe.

For additional information about Transmode, please visit www.transmode.com