Chapter 2

Optical technology and standards

2.1 Enabling technologies

The field of optical communication encompasses various disciplines, ranging from physics and photonics to topologies, protocols and even economics. The use of lasers for communication purposes was first proposed in the 1960's. Remarkable advances in technology over recent years have had an incredible impact on the rapid growth of this field and the subsequent popularity of optical communication technology as a whole.

Developments such as low-loss optical fibers, erbium-doped fiber amplifiers (EDFAs), solitons, dense wavelength division multiplexing (DWDM) and micro electro-mechanical systems (MEMS) enable the optical communication networks of today, while the theoretical all-optical networking node boasting multi-protocol label switching (MPLS) and the all-optical processing of header information, will enable the optical communication networks of tomorrow.

Enabling technologies and their development influence the design of wide-area optical communication networks due to the technical context which they define. Aspects such as data rates, number of wavelengths, propagation delay and link span are all functions of the underlying technology as well as critical parameters in the design of optical communication networks. From a purely mathematical point of view, a certain network topology or protocol might be superior to others based on its robustness or load balancing characteristics, but if the technology required for its implementation does not exist, it will be nothing more than a theoretical dream.

The manufacturers of modern network equipment tend to base their design philosophies solely on the technologies that they want to sell. This approach makes sense from a business point of view, but fails when considering that its very nature does not stimulate or encourage novel solutions to old problems, solutions that could enable the consideration of new problems and better ways of solving them. It is for this reason that a network designer should tread lightly through the myriad of design philosophies preached by the vendors of network equipment. Throughout this investigation a neutral approach is taken towards the issue of enabling technologies. The focus is on the theoretical aspects of network design, while considering the influence of enabling technologies and the technical limitation that they impose.

2.1.1 Basic building blocks

A dichotomy of elementary geometric ray theory and advanced electromagnetic wave theory, governed by Maxwell's equations, describe the principles behind the propagation of light in optical fibers. Wavelengths of 1310nm and 1550nm are predominantly used due to their favourable attenuation and dispersion characteristics. As with all communication systems, the basic building blocks of an optical fiber link is a trans-

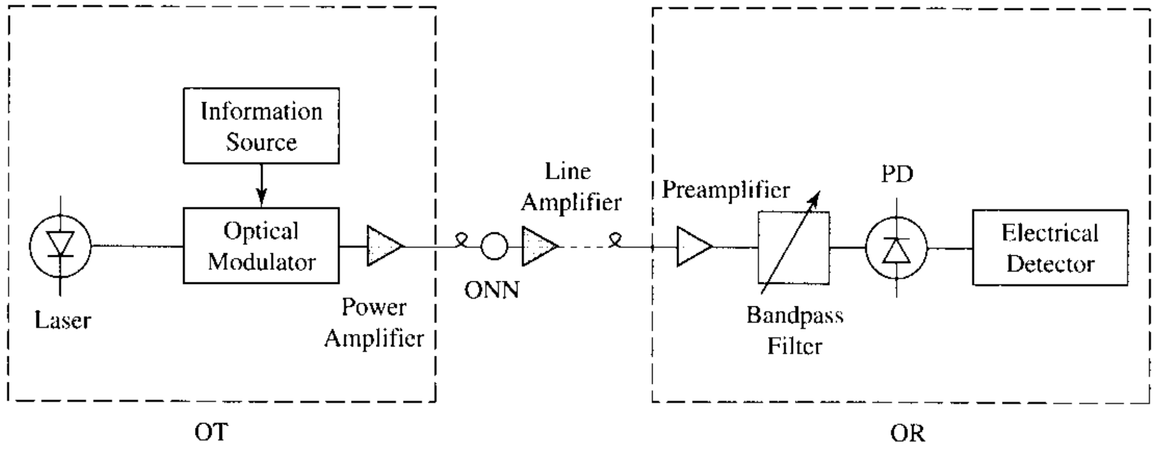

Figure 2.1: A generalised point-to-point optical connection [18].

mitter, a medium (the optical fiber) and a receiver. Figure 2.1 shows a generalised point-to-point optical connection comprising an optical transmitter (OT) and optical receiver (OR), with a transmission medium that could contain optical network nodes (ONNs) and line amplifiers in conjunction with the implicit optical fiber.

In wide-area optical networks narrow-band lasers are the most commonly used transmitters, while light emitting diodes (LEDs) are more prevalent in shorter distance low-cost applications. Positive-intrinsic-negative (PIN) photodiodes and avalanche photodiodes are the most well-known types of optical detectors. An in-depth discussion of these devices and their operation is beyond the scope of this investigation, and the interested reader is referred to the several introductory textbooks on optical fiber communication, of which some are listed in the bibliography section.

2.1.2 Combating transmission impairments

The two main phenomena that impact negatively on BER in digital systems and SNR in analog systems are attenuation and dispersion. The problem of attenuation is addressed by lowering the attenuation of the optical fiber or by amplification of the signal. Lowering of the attenuation in the fiber is not a trivial issue, and it has taken several decades for researchers to reduce the attenuation of optical fibers from several dB/km to well below 0.1 dB/km. Choosing the wavelength of the transmitted light carefully leads to lower attenuation due to the wavelength dependence of attenuation, which is shown in figure 2.2.

There are several techniques for combating dispersion and thereby limiting the occurrence of inter-symbol interference which negatively impacts system performance. The use of dispersion shifted fiber, dispersion compensating fiber and other dispersion management techniques are popular. On long-haul fiber links the use of soliton waves can potentially eliminate the need for the costly process known as regeneration with re-timing and reshaping (3R) that needs to be performed every few hundred kilometres above and beyond the signal amplification which is also required, but at typically more frequent intervals.

EDFA

The erbium-doped fiber amplifier revolutionised optical communication and is widely considered to be the most important enabler for wavelength division multiplexing. The EDFA is the most important amplifier in optical communications due to the fact that it has a relatively wide amplification bandwidth, around 35nm, and even more importantly operates in the very low attenuation window around 1550nm shown in figure 2.2.

The EDFA is a true optical amplifier as opposed to the earlier receive-amplify-retransmit amplifiers that require optical-to-electronic conversion at its input and electronic-

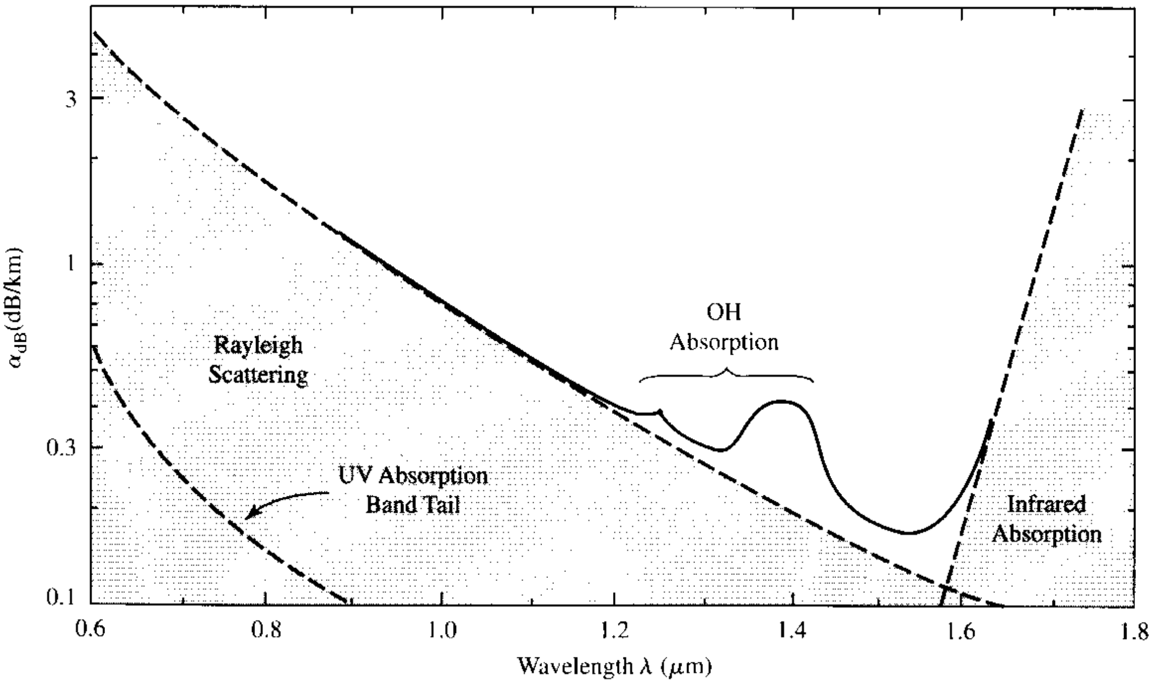

Figure 2.2: Graph showing attenuation as a function of wavelength in a conventional glass optical fiber [18].

to-optical conversion at its output. This enables the EDFA to amplify signals at virtually any data rate and at any wavelength in its amplification window. In WDM systems an EDFA is thus able to amplify several adjacent wavelengths simultaneously, even though it is with gains that vary according to the gain profile shown in figure 2.3.

Solitons

Long before optical fiber communication, it was known that a special wave shape exists that can propagate in certain media without experiencing dispersion. This phenomenon was first recorded by John Scott Russell in 1838 based on observations that he made at a canal in Scotland. This soliton wave is fundamentally stable, meaning that any wave approximating a soliton wave launched into a fiber will tend towards a soliton wave as

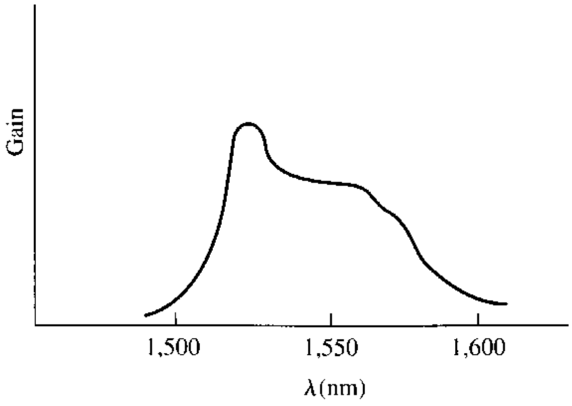

Figure 2.3: The gain profile of an erbium-doped fiber amplifier [18].

it propagates down the fiber, and consequently assume the unique soliton characteristic of dispersion immunity.

Solitons used in optical communication systems are narrow, high powered pulses that do not exhibit pulse broadening normally associated with dispersion. The shape of the soliton can be constant as it propagates through the fiber, this being referred to as a fundamental soliton. A soliton of which the shape periodically changes is referred to as a higher-order soliton. Due to a soliton's dependence on a high pulse energy, optical amplifiers are however required at more regular intervals than would normally be necessary.

2.1.3 DWDM

Dense wavelength division multiplexing is to optical communication what frequency division multiplexing (FDM) is to the conventional communication fraternity, the only exception being that the bandwidth available in the optical frequency domain is orders of magnitude greater, hence translating into orders of magnitude greater potential data rates. In the EDFA window around 1550 nm alone, there is around 4 THz of bandwidth.

This incredible bandwidth translates into volumes of capacity unheard of in conventional communication technology. At an aggregate data rate of 1 Tbps, a single optical fiber with a diameter of less than 250 μm can accommodate around 40 million 28 kbps data connections, 20 million digital voice channels, or half a million compressed digital video channels [19]. Although commercial installations do not yet possess this kind of capacities, the popularity and commercial success of DWDM technology is apparent when it noted that in 1998 already more than 90% of the networks of long-haul carriers in the United States utilised DWDM technology [20].

With the inherent limitations of electronic modulation circuitry, it is impossible to harness this immense bandwidth while operating at a single wavelength, thus the motivation for wavelength division multiplexing. Figure 2.4 shows how several wavelengths are simultaneously used when the spectrum of a single fiber is analysed. The four indicated wavelengths are in the 1550 nm band, with signal powers in the region of 6 dBm and an optical rejection ratio of 38 dB. It is customary to specify optical rejection ratio at a distance of one-half the wavelength spacing from the carrier wavelength.

Initial WDM systems utilised less than nine different wavelengths simultaneously. Technology however improved so rapidly and the popularity of WDM with it, that the term *DWDM* was coined and is used for systems that utilise in excess of 8 wavelengths on single fibers simultaneously. The family of multiplexing techniques that utilise the wavelength domain has three main members:

WDM refers to initial systems utilising 8 or less wavelengths, typically the current implementation of wavelength division multiplexing

DWDM refers to systems utilising more than 8 densely packed wavelengths, typically

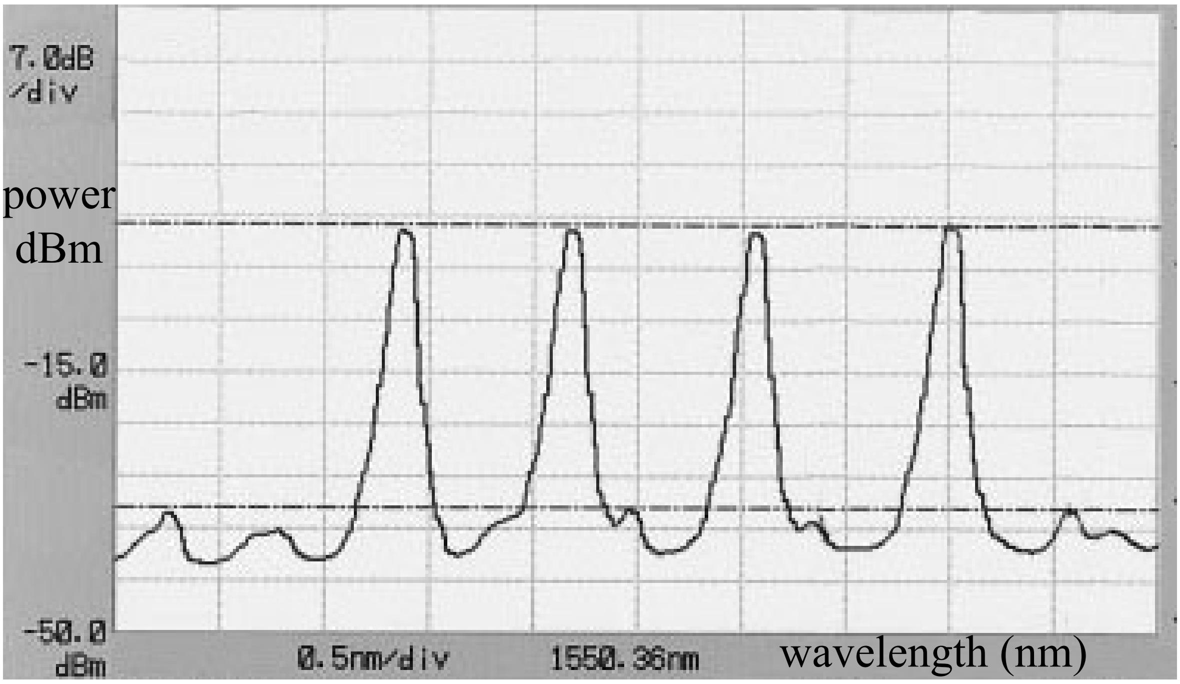

Figure 2.4: An example of an optical fiber's spectral occupancy in a WDM system as displayed on an optical spectrum analyser [21].

used in new wide-area and long-haul networks

CWDM refers to systems utilising more than 8 coarsely packed wavelengths, typically used in new metropolitan area networks

Since there is often not a clear distinction in literature between WDM and DWDM systems, the term *WDM* is used throughout to refer to systems utilising wavelength division multiplexing irrespective of the number of wavelengths. This investigation is however aimed at the application of wavelength division multiplexing in future wide-area optical networks, hence the focus, although not in name, on what has been described as DWDM. Section 2.2.2 provides more information on the standards that govern WDM.

2.1.4 Micro electro-mechanical systems

MEMS is a platform technology that enables the fabrication of microscopic structures by micro-machining. The structures range in size from a few hundred micrometers to several millimetres and are fabricated on silicon substrates using mostly existing semiconductor processing techniques. Use of the same efficient and proven mass-production processes that were developed for the semiconductor industry during the last 30 years, is one of MEMS technology's great motivators. Although MEMS technology utilises similar fabrication processes to that of semiconductor devices, its operation is electromechanical in nature, which makes reliability one of its greatest challenges.

The micro-machines are formed on silicon substrates using epitaxial growth, patterning, and etching processes developed for manufacturing integrated circuits. Where an acid wash etches away layers of oxides, mechanical parts are released and moving pieces are created. Researchers have made three-dimensional micro-machines crafted so that flaps or mirrors spring into place when the parts are released. Figure 2.6 shows a scanning electron microscope (SEM) image of a two-axis electro-statically actuated micro-mirror.

The MEMS anti-reflection switch can be used as a micro-mechanical modulator, and MEMS 2-axis micro-mirrors which can be used in routing applications, shows potential for drastically reducing the cost of future fiber access applications. At an end point such as a customer's home such a device, when used in conjunction with a local modulator, could impose signals on a stream of light generated by a laser somewhere else in the network. In practice, eliminating the need for large numbers of expensive lasers with cheap silicon devices is a very appealing prospect. Similar devices, configured as wavelength-selective attenuators, could be used to flatten amplifier gain across a band of wavelengths, even providing active equalisation in real time. A mode-eclipsing

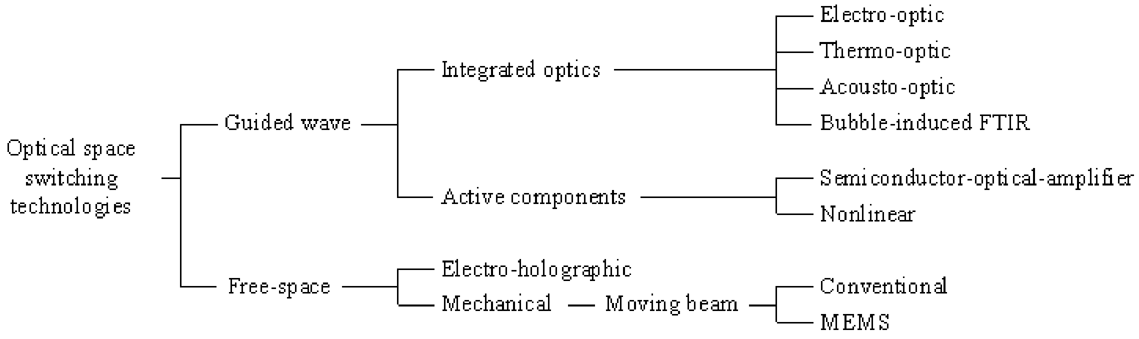

Figure 2.5: Taxonomy of optical switching technologies [22].

optical switch can be used as an on-off switch, a shutter, or an attenuator to control signal power and protect components.

More than a dozen types of MEMS devices have been designed, prototyped, and demonstrated for optical communications, and each of these could serve a number of different purposes. Such potential applications have enabled this technology, though still in exploratory stages, to make the leap from a research curiosity to a serious contender for large-scale deployment in revolutionary network architectures.

Of the various optical switching technologies shown in figure 2.5, MEMS is now pursued by more researchers than any other, as the most viable technology for optical switching in optical networks. The reasons for this are: MEMS's inherent batch fabrication characteristics and the related economic benefits; insensitivity to bit rate or data protocols due to optical transparency; and the high performance that characterises transparent optical networking components.

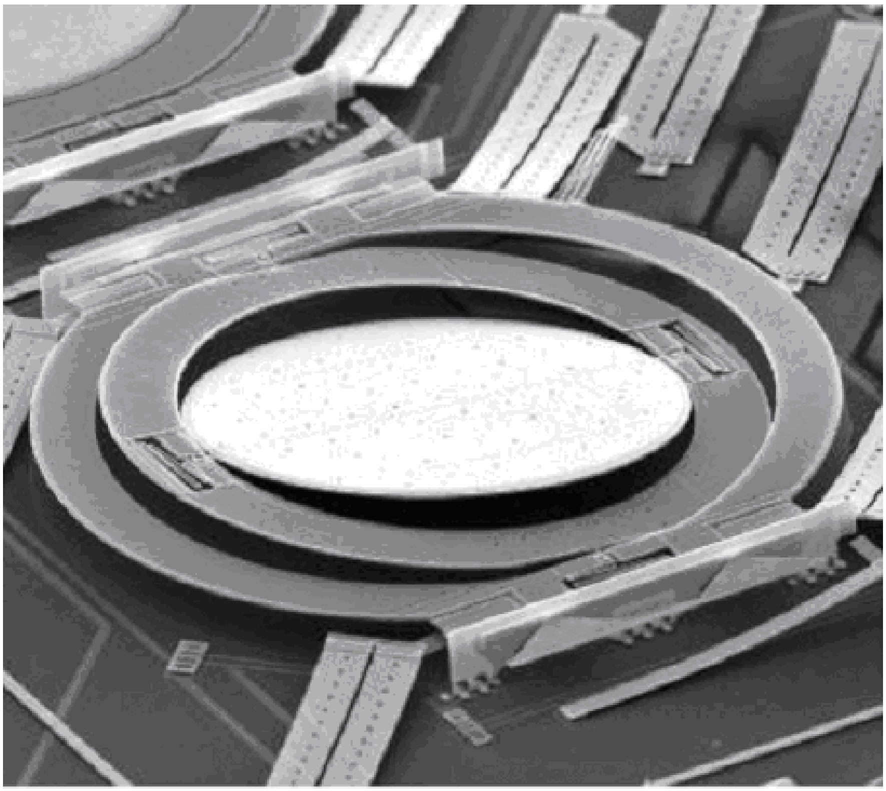

Figure 2.6: A SEM image of one of the 256 free-rotating 2-axis electro-statically actuated micro-mirrors used in Lucent's WaveStar LambdaRouter [23].

2.1.5 All-optical network node

The all-optical network node is a theoretical device similar to the switches, routers and exchanges that we are familiar with in modern communication networks. The network node is a place in a network through which physical connectivity with adjacent nodes in the network is established. Logical connectivity between any combination of nodes in a network is achieved through the wavelength dimension that WDM and optical networking exploit. This enables logical connectivity to be obtained through an infrastructure on which various protocols can be implemented, as opposed to through the protocols themselves as in conventional communication networks. Figure 2.7 shows a theoretical ONN, with an emphasis on the wavelength selectivity and spatial switching characteristics thereof.

Network nodes are the basic building blocks of a network and are defined as being responsible for all traffic on the network. The all-optical network node is one of the basic building blocks of the wide-area WDM optical network. It should not be confused with the network access station (NAS), which serves as interface between the electronic and optical parts of the network. In the context of a multi-level network where local, metropolitan and wide-area networks co-exist on different levels of the network, it is important to be aware of the different distribution, access and transport functions that network nodes perform.

The concepts of a network edge and a network core should be handled with care, since they do not explicitly define the function of a network node. These edge and core concepts have a place when the communication infrastructure is considered as a whole, with a user's mobile communication device being close to the network's edge and far from the network's core. As a matter of fact there would be various networks that interconnect to provide this seemingly singular connectivity solution.

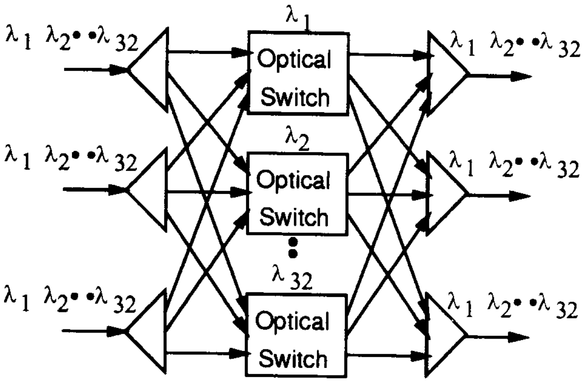

Figure 2.7: The theoretical optical network node showing wavelength selectivity and spatial switching [24].

2.2 Standards

The establishment of standards by organisations that govern and regulate the telecommunications industry has advantages as well a disadvantages. Advantages of standards include the resultant compatibility of conforming vendors' equipment and focused efforts of researchers and developers. Disadvantages of standards on the other hand include the cumbersome support required for legacy equipment and unfashionable or impractical parts of these standards. The existence of several seemingly uncoordinated regulatory bodies negates the potential advantages of inter-vendor compatibility to such an extent that one of the main selling points of new networking equipment is its promised compatibility with other vendors' offerings. In a marketplace fearing monopolies and proprietary bindings, standards have become nearly as important if not more important than the technologies that they describe.

2.2.1 SONET/SDH

Synchronous optical network (SONET) is the well-known standard for high data rate digital transmission in North America, published by the American National Standards Institute (ANSI). Its sibling, used in most other countries including South Africa, is published by the International Telecommunications Union (ITU) and is known as synchronous digital hierarchy (SDH). These similar standards are jointly referred to as SONET/SDH and supersede an earlier standard called plesiochronous digital hierarchy (PDH). SONET/SDH is capable of transporting a myriad of digital traffic types including PDH and asynchronous transfer mode (ATM), but has as one of its most important features a very organised protection method known as automatic protection switching (APS) whereby traffic is efficiently rerouted, i.e. self-healing rings (SHR), to avoid damaged or malfunctioning links and nodes.

PDH is still predominant in conventional telephony networks with the basic building block known as digital system - level 1 (DS1), which is the framing format and interface specification with its transmission medium known as T1. This nomenclature is used throughout the four levels of PDH with data rates for each level differing slightly based on the region of implementation, with ANSI and ITU being the references for PDH standards as shown in table 2.1.

The first level of the SONET hierarchy is known as the synchronous transport signal - level 1 (STS-1), with the synchronous transport module - level 1 (STM-1) being the first level of the SDH hierarchy. The data rates at which these level 1 building blocks of SONET and SDH operate are however different. Table 2.2 shows the difference between the levels of SONET and SDH as well as where they fit into the OC-x classification system with an optical channel (OC) as its basic building block.

ANSI			ITU		
Signal	Bit rate (Mbps)	Channels	Signal	Bit rate (Mbps)	Channels
DS-0	0.064	1 DS-0	64 kbps	0.064	1 64 kbps
DS-1	1.554	24 DS-0	E1	2.048	30 64 kbps
DS-2	6.312	96 DS-0	E2	8.448	4 E1
DS-3	44.736	28 DS-1	E3	34.368	16 E1
N/A	N/A	N/A	E4	139.264	64 E1

Table 2.1: PDH levels and data rates defined by ANSI and ITU.

The STS-x and STM-x nomenclature applies to signals while still in their electrical state. The OC-x classification system applies to optical signals used at equipment and network interfaces, with OC-1 being the lowest level of the hierarchy, obtained from a scrambled STS-1 bit stream being converted from electrical to optical. Although it is commonly used, SDH does not officially make use of the OC-x classification, but rather extend the STM-x naming convention to signals in the optical domain, with STM-1, in its capacity as optical domain descriptor, being the equivalent to the optical OC-3. Higher data rate optical signals are created through multiplexing by the interleaving of lower level STS or STM bytes.

2.2.2 WDM

The ITU standardised the nominal centre frequencies for use in multi-wavelength systems with the G.692 recommendation. Table 2.3 shows the ITU frequencies and wavelengths for use in the 1550nm band of wavelength-division multiplexing optical communication networks for spacings of 50GHz and 100GHz anchored around the 193.10 THz reference. It is important to note that wavelength values are indicated relative to fre-

Data rates (Mbps)			SONET		SDH	
Line	Payload	Overhead	Electrical	Optical	Electrical	Optical
51.840	50.112	1.728	STS-1	OC-1	STM-0	STM-0
155.520	150.336	5.184	STS-3	OC-3	STM-1	STM-1
622.080	601.344	20.736	STS-12	OC-12	STM-4	STM-4
1244.160	1202.688	41.472	STS-24	OC-24	N/A	N/A
2488.320	2405.376	82.944	STS-48	OC-48	STM-16	STM-16
9953.280	9621.504	331.776	STS-192	OC-192	STM-64	STM-64
39813.120	38486.016	1327.104	STS-768	OC-768	STM-256	STM-256

Table 2.2: SONET/SDH levels and data rates [25, 26].

quency through the $c = f\lambda$ relationship, where c is the speed of light in a vacuum, $2.99792458 \times 10^8 ms^{-1}$, f is frequency and λ is wavelength.

When referring to wavelengths in the optical communication context, it is always with reference to the speed of light in a vacuum. Since the index of refraction, n in an optical fiber is typically in the region of 1.4, the actual wavelength in an optical fiber is $\frac{1}{n}$ of the wavelength specified. The frequency of an electromagnetic wave is however independent of the medium through which it propagates, hence the ITU's focus on frequencies in the standardisation of multi-wavelength communication channels.

Table 2.3 only shows 81 standardised frequencies in the 50 GHz spacing grid. The standard does however allow for implementors to extend the end-points of the grid above and below the outer frequencies. The basic prerequisite is that frequencies be integer multiples of the grid spacing factor around the nominal centre frequency of 193.10 THz. Experimental optical networking equipment utilising spacing factors of 25 GHz and even 12.5 GHz have been announced by several companies in the DWDM industry.

50 GHz spacing (THZ)	100 GHz spacing (THz)	Wavelength (nm)	50 GHz spacing (THZ)	100 GHz spacing (THz)	Wavelength (nm)
196.10	196.10	1528.77	194.05	-	1544.92
196.05	-	1529.16	194.00	194.00	1545.32
196.00	196.00	1529.55	193.95	-	1545.72
195.95	-	1529.94	193.90	193.90	1546.12
195.90	195.90	1530.33	193.85	-	1546.52
195.85	-	1530.72	193.80	193.80	1546.92
195.80	195.80	1531.12	193.75	-	1547.32
195.75	-	1531.51	193.70	193.70	1547.72
195.70	195.70	1531.90	193.65	-	1548.11
195.65	-	1532.29	193.60	193.60	1548.51
195.60	195.60	1532.68	193.55	-	1548.91
195.55	-	1533.07	193.50	193.50	1549.32
195.50	195.50	1533.47	193.45	-	1549.72
195.45	-	1533.86	193.40	193.40	1550.12
195.40	195.40	1534.25	193.35	-	1550.52
195.35	-	1534.64	193.30	193.30	1550.92
195.30	195.30	1535.04	193.25	-	1551.32
195.25	-	1535.43	193.20	193.20	1551.72
195.20	195.20	1535.82	193.15	-	1552.12
195.15	-	1536.22	**193.10**	**193.10**	**1552.52**
195.10	195.10	1536.61	193.05	-	1552.93
195.05	-	1537.00	193.00	193.00	1553.33
195.00	195.00	1537.40	192.95	-	1553.73
194.95	-	1537.79	192.90	192.90	1554.13
194.90	194.90	1538.19	192.85	-	1554.54
194.85	-	1538.58	192.80	192.80	1554.94
194.80	194.80	1538.98	192.75	-	1555.34
194.75	-	1539.37	192.70	192.70	1555.75
194.70	194.70	1539.77	192.65	-	1556.15
194.65	-	1540.16	192.60	192.60	1556.55
194.60	194.60	1540.56	192.55	-	1556.96
194.55	-	1540.95	192.50	192.50	1557.36
194.50	194.50	1541.35	192.45	-	1557.77
194.45	-	1541.75	192.40	192.40	1558.17
194.40	194.40	1542.14	192.35	-	1558.58
194.35	-	1542.54	192.30	192.30	1558.98
194.30	194.30	1542.94	192.25	-	1559.39
194.25	-	1543.33	192.20	192.20	1559.79
194.20	194.20	1543.73	192.15	-	1560.20
194.15	-	1544.13	192.10	192.10	1560.61
194.10	194.10	1544.53			

Table 2.3: ITU frequency grid for wavelength division multiplexing [27].