Optical Fibre Transmission

Executive Summary

This paper aims at describing, in simple terms, optical fibre transmission technology fundamentals, history, current status and future perspectives:

1. Fundamental laws of physics limit usable bandwidth in an optical fibre. Maximum bandwidth is 12.5 THz (12,500 GHz). This translates into an ultimate capacity achievable on an optical fibre, which is 12.5 Tbit/s (12,500 Gbit/s)
2. DWDM is a recent technique developed to allow access to a large share of the fibre ultimate capacity. DWDM is also a flexible technique, as the available capacity can be increased as and when required by procuring additional terminal equipment.
3. In the last twelve years, optical fibre transmission industry has achieved striking progress in opening access to fibre ultimate capacity. Percentage of usable capacity as compared to the ultimate capacity (12.5 Tbit/s) has increased from 0.0025 % for first generation systems to 8 % for the latest generation, to be in service in 2001-2002. This has been made possible by the discovery of optical amplifiers (EDFA), by DWDM and by progress in terminal equipment electronics.
4. Axone is a DWDM system of the latest generation and will provide capacity of up to 1 Tbit/s per fibre pair.
5. Next generation of optical transmission systems is likely to be available for service in 2003-2004, and would provide limited improvement, with a capacity in the range of 1.5 Tbit/s to 2 Tbit/s.
6. Access to full 12.5 Tbit/s ultimate capacity is not foreseen in the near future, as major issues need to be solved, such as extension of optical amplifiers bandwidth and management of distortions effects in the optical fibre.

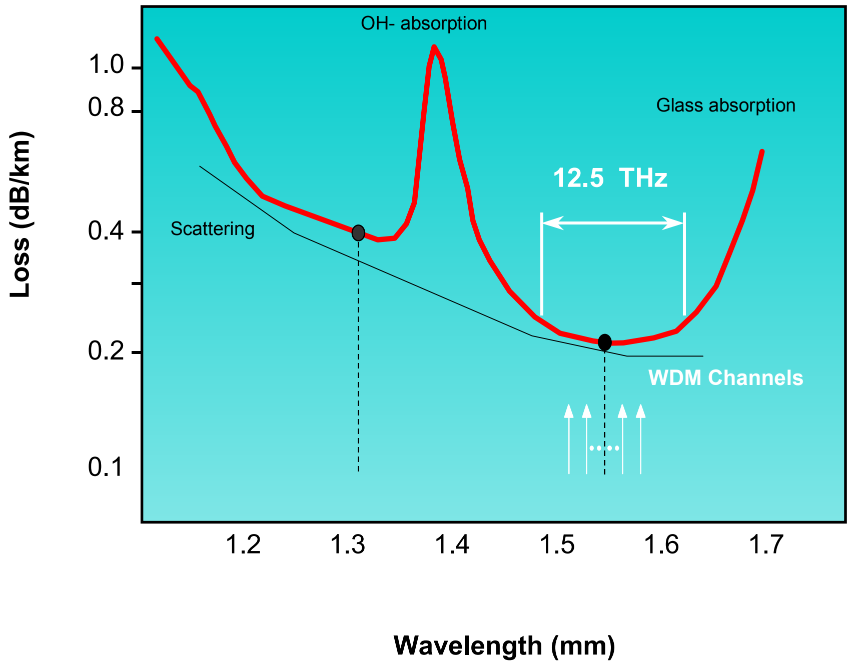
Optical Fibre Technology

1. Optical fibre transmission

Optical transmission is based on sending information in form of light pulse in an optical fibre. To keep information intact the received light pulse requires a minimum energy. Energy of the pulse decreases with distance, due to attenuation in the fibre medium. As such, attenuation is a major limiting factor in optical fibre transmission.

Attenuation over the optical fibre is extremely low compared to other transmission means such as copper. Low as it is, attenuation still exists with different degrees depending on the colour (wavelength) of the optical signal. Figure 1 shows typical attenuation in a glass fibre as a function of light colour.

Figure 1: Optical fibre bandwidth



The selection of the optimal wavelength window for fibre transmission comes from desire to optimise against the three different factors which contribute to fibre attenuation:

- ***Scattering***. Light (photons) interacts in a very feeble manner with glass molecules on a random basis. From time to time photon path is deviated up to a point where it is ejected from the optical fibre. The higher the photon wavelength, the lower the interaction, and the less the scattering of data.
- ***OH^- Absorption***. Molecules are present as impurities in the fibre and absorb light at specific wavelengths. The most critical absorption is located between wavelengths of 1400nm and 1500nm and is due to presence of OH- ions.
- ***Glass absorption***. At high wavelengths (above 1600nm), the glass molecules themselves start to strongly absorb light, creating a natural limit in the wavelength chosen for data transmission by light pulse.

The three factors above are direct consequences of some fundamental laws of physics and are very unlikely to be overcome by any technological innovation. Indeed, any modification would require a complete change in type of material used to manufacture fibres. All attempts have been generally abandoned and in any case would result in new designs, new developments, new qualification efforts, new manufacture techniques and plants for fibre, as well as lasers, photodiodes and other opto-electronic components.

As a result of the above, fibre can be used within two “windows”:

- 1300nm window with a range/bandwidth of 50nm and attenuation around 0.4 dB/km
- 1550nm window with a range/bandwidth of 100nm and attenuation around 0.2 dB/km

1300 nm window has high attenuation, but cheap associated components (lasers and receivers) and is therefore still used for short range/low capacity telecommunication applications, optical local loop or metropolitan networks.

1550 nm window is universally used for long distance, high-speed transmission applications, as the lower attenuation allows a much larger spacing between costly regenerators or amplifiers.

2. 1550 nm optical fibre window range/bandwidth implications

A range of usable wavelengths can be translated into a range of usable bandwidth, as would be used in radio-wave applications such as mobile phone or satellite. The main difference is the huge amount of bandwidth available in an optical fibre:

- Wavelengths and frequency are linked by: Wavelength x Frequency = speed of light.
- As a result of the above formula, 1 nanometer (around a wavelength of 1550 nm) corresponds to a 125GHz bandwidth.
- 1550nm optical window corresponds to a total bandwidth of **12.5 THz (12,500 GHz)**.

3. Bandwidth and capacity

Available capacity on any transmission medium is directly linked to the available bandwidth. This is a fundamental result of the Information Theory: capacity corresponds to a number of potential transitions (between 1 and 0) in a given time. When capacity increases, the number of potential transitions increases as well, i.e. transition frequency increases. This is illustrated in various domains:

- FM radio and TV broadcast: in the US, a given bandwidth in the spectrum is licensed by FCC, which limits the total number of channels that can be broadcasted, and the frequency spacing between two channels, so as to avoid signal conflicts
- Mobile phones: bandwidth limitations limit the number of mobile licences that can be granted to any one frequency range.

As an upper theoretical limit, the number of bits per second that can ultimately be transmitted in binary (1-0) transmission is equal to number of Hertz available in the bandwidth. Such a rule does not take into account other limitations such as noise, distortion, wavelength differentiation, etc.

Ultimate capacity available in the optical fibre 1550 nm window is **12.5 Tbit/s** for a binary transmission.

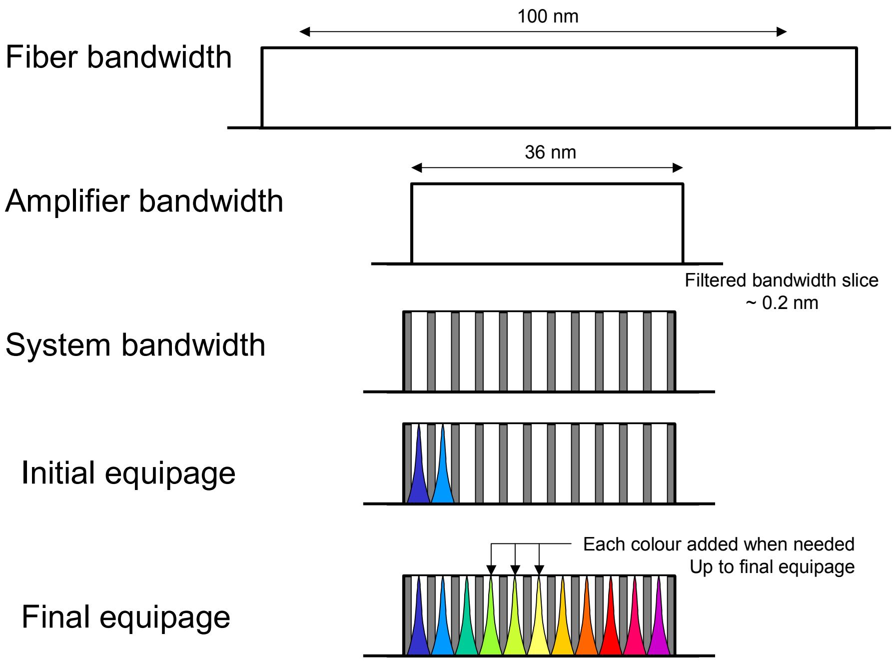
4. DWDM to make the most of fibre bandwidth

WDM (Wavelength Division Multiplexing) technique was developed to optimise translation of the huge fibre bandwidth into a huge capacity. In WDM, the bandwidth "cake" is divided in bandwidth slices in each of which a colour carries a bit stream. Colours are transmitted together (optically multiplexed) in the fibre. On the receiving side, optical filters are used to separate colours, each colour is then processed to extract capacity it carries.

Space between colours is dependent on transmission and filtering techniques. Size of the colour (i.e. size of the slice) is directly linked to the capacity transmitted (the more bit/s the larger bandwidth).

D (Dense) of DWDM refers to the recently developed techniques aiming at packing as many wavelengths into the fibre as possible.

Figure 2: Principles of WDM transmission



Advantages of DWDM are the following:

- Breaking fibre capacity (up to 12.5 Tbit/s) into capacity slices manageable by the terminating electronic equipment: Silicium chips cannot process 1 Tbit/s capacity units! Current capacity units are 2.5 Gbit/s and 10 Gbit/s. 40 Gbit/s should be available in 3 or 4 years, using Moore's law as a rule of the thumb.
- Flexibility of equipage: Equipment terminating slices of capacity can be procured progressively on a per colour basis.

DWDM perspectives:

- The exact extent of the total capacity that could be transmitted using DWDM is not easily computed as one must consider interactions between colours and capability of terminating equipment such as selection filters.

- The theoretical maximum extent in the number of colours is simply the total capacity available, as described in §3 (12.5 Tbit/s), divided by capacity carried by each colour. See the following table for examples.

	2.5 Gbit/s per colour	10 Gbit/s per colour	40 Gbit/s per colour
Maximum number of colours	5,000	1,250	312
Total capacity available	12.5 Tbit/s	12.5 Tbit/s	12.5 Tbit/s

Capacity per colour

- Recent industry past has shown that cost of terminating equipment is multiplied by 2.5 when capacity terminated is multiplied by 4.
- Silicium chips capabilities on the one hand and optical distortions in fibre on the other hand will be technology limiting factors. For long distance applications, distortions are likely to be the main constraint. As an example, use of 40 Gbit/s is currently problematic on long distance systems (>1000 km).

5. Brief history of optical submarine systems

G1 (Generation 1): 1989 - 1991.

First optical submarine cable systems were using silicium-based in-line submarine repeaters to regenerate the signal attenuated within each fibre span. Capacity was limited to 0.28 Gbit/s per fibre pair.

G2 (Generation 2): 1992 - 1995.

G2 improved the technology of G1, by increasing capacity to 0.56 Gbit/s per fibre pair. This was achieved by various improvements in the silicium circuits within the repeater and switching from 1310 nm to 1550 nm window.

G3 (Generation 3): 1995 - 1997.

G3 corresponds to a major evolution in optical transmission: Erbium Doped Fibre Amplifier (EDFA). Such optical amplification technique, avoiding regeneration in each repeater, was much cheaper, efficient and reliable, and provided access to higher bandwidth. Limitation due to the use of silicium circuits in repeaters was overcome, and capacity increased to 5 Gbit/s per fibre pair.

G4 (Generation 4): 1998 - 2000.

In G4, EDFAs have been improved by increasing their optical bandwidth. In association with other technological progress on optical filters, this allowed deployment of first WDM systems, with capacity up to 40 Gbit/s (16x2.5 Gbit/s) per fibre pair.

G5 (Generation 5): 2000 - 2002.

First G5 systems are currently under deployment. G5 further improves EDFA bandwidth and is based on colours carrying 10 Gbit/s. G5 systems provide capacity of up to 160 Gbit/s (16x10 Gbit/s) per fibre pair.

G6 (Generation 6): 2001 - ….

G6 systems have similar design as G5 systems, but the EDFA characteristics have been improved and terminal equipment has higher performance. G6 systems can provide capacity of up to 1 Tbit/s (100x10 Gbit/s) per fibre pair for medium and short haul systems (< 4,000 km) and 400 Gbit/s (40x10 Gbit/s) per fibre pair for long haul systems. G6 systems can be built today for operation in 2001-2002.

G7 (Generation 7)

Some Suppliers R&D centres mention DWDM using 40 Gbit/s colours, with a typical initial target of 40 colours per fibre pair, while others believe that G7 may only be a further improvement of G6, with additional 10 Gbit/s colours (up to 150-200x10 Gbit/s). G7 definition is rendered difficult by physical limits on the maximum bandwidth of EDFA, as well as propagation difficulties for colours carrying 40 Gbit/s.

Generation	Systems	Capacity improvement factor (compared with previous generation)	Cumulated improvement factor
G1	TAT-8, TPC-3, EMOS	Not applicable	Not applicable
G2	TAT-9, TAT-10, TAT-11, TPC-4, SMW-2, SAT-2, ITUR	2	2
G3	TAT12/TAT13, TPC-5, APCN, FLAG	8	16
G4	Gemini, AC-1, SMW-3, Atlantis-2, Columbus-3, SAFE, China-US, MAC, PAC	4 to 8	128
G5	TAT-14, Japan-US, PC-1, SAC, SAM-1	4	512
G6	Hibernia, Yellow, FA-1, EAC, APCN-2, AJ, FP-1, Axone	2.5 to 4 6.25 for Axone	3,200
G7	Axone-2 (?)	1.5 to 2	6,400
GU	Ultimate capacity systems (12.5Tbit/s ?)	6.25	40,000

Technology perspectives

Previous system generations have been hugely improving access to the available fibre bandwidth, thanks to EDFA technology and improvements in terminal equipment (filtering, lasers, etc.). The easily usable fibre bandwidth has now been exploited to a very significant extent. Next technology systems (G7) will probably consist of further improvements of available technology (G6), but with limited advantages in terms of maximum capacity.

Beyond G7, progressing towards the ultimate capacity will require a number of major technical issues to be cleared, among which the following:

- ***Line bandwidth***. Line bandwidth is nowadays limited by amplifier bandwidth and not fibre bandwidth. Amplifier are currently based on well established EDFA technology. New amplifiers (C and L-band amplifiers) are under development and would have bandwidth larger by a typical 60%, thus still accessing less than half of the fibre bandwidth.
- ***Colour spacing***. Ultimate capacity of 12.5 Tbit/s assumes no spacing between two adjacent colour slices. In the current design, spacing between colour slices is about 3 times the size of each slice. Minimising colour spacing is limited by the four-wave mixing (a physical non-linear distortion induced by the fibre). Four-wave mixing increases strongly when spacing is reduced.

Taking into account that the two above issues are related to physical limitations, either in fibre or amplifier, it is most likely that they will not be solved to a full extent. As such, the ultimate capacity of 12.5 Tbit/s shall only be considered as theoretical and a lower value could be expected as ultimate limit of optical fibre transmission capacity.

Conclusions

- Fundamental physical limitations exist on the optical fibre bandwidth that lead to an ultimate capacity of 12.5Tbit/s per fibre pair.
- Other physical limitations (on optical amplifiers and in fibres) exist that tend to indicate that this ultimate capacity of 12.5 Tbit/s is an ambitious target for the industry.
- Next generation Systems will come around 2004, and can be guessed to offer design capacities in the range of 1.5 to 2Tbit/s
- Since the birth of submarine optical fibre system, design capacity has been increased by a factor of 3200 in 12 years.
- Due to the fundamental physical limits, it is concluded that a similar 3200 capacity increase in the 10 years to come is impossible, and that best factor improvement would be in the range of 10.

As a general conclusion, optical fibre technology has made huge progress in the last 10 years, that have allowed to access to a significant share of the ultimate capacity induced by the fibre bandwidth. Further progress will be limited by the fibre media itself. As such, there is little probability that a 1Tbit/s/fp system such as Axone be technologically burned-out by huge future improvements in fibre optics transmission.

Figure 3: System capacity over time