Optical Transmission Network Upgrade Using WDM

George Milosevic

Telecommunication traffic has experienced exceptionally fast growth during the last few years (roughly doubled each year). This growth is fueled by the increase in the usage of existing services and emergence of new services covering both voice and data traffic. By the end of year 2000, data traffic will surpass the volume of the voice service due to the growth of the Internet and other interactive services (Fig. 1)[1]. So, a dual phenomenon is present, on one hand we have a growth in traffic and on the other hand the nature of the traffic is changing from voice to data [2].

Thus, there is a need for a reconstruction and upgrade of the transmission network covering the increase in the capacity, higher data rates, better usage of the available bandwidth, more efficient data transfer, ease of oversight and maintenance, robustness to failures, compliance to new standards and better pricing strategies. These are some of the options to explore in pursuit of the optical transmission network upgrade:

A. Increase the number of fibers

The increase in the capacity and performance of the transmission network via the increase in the number of optical fibers in the existing and future cable infrastructure is not recommended because of high capital expenses and a relatively long time needed for the completion of the work. It requires a large number of fibers, and use of regenerators to increase the reach of a link. This option is acceptable only if the existing optical fibers exhibit high or shifted chromatic dispersion, or the overall quality of the cable is poor. Sometimes in big metropolitan networks and on short distances it is easier to use available telephone cabling infrastructure to increase the number of fibers than to install expensive WDM equipment. However, overall, this option is neither effective nor economically feasible.

B. Transmission systems with higher bit rate

An increase in the capacity of a telecommunication network can be achieved through the use of transmission systems that are able to handle higher bit rates. The development of the transmission systems is partially driven by the need for higher capacity. The following is a brief chronology of the development of transmission systems.

1915 - The first transcontinental telephone call (in North America) is made over an analog network of cooper cables.
1936 - The first coaxial cable route with multiplexed analog voice signals is implemented.
1947 - The first microwave route is used as it is less expensive than the coaxial cable route.
1962 - The first telecommunication satellite link is finished.
1980 - The fiber-optic cables are able to support the shift from analog to digital networks. Fiber-optic

The following text will address all of the above-mentioned options with the emphasis on the benefits that WDM technology brings to the pursuit of an upgraded optical network.

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1 Regenerators convert an optical signal to an electrical signal, and a convert the result of electronic processing back into an optical signal. Regenerators are not necessary with WDM because the optical amplifiers perform their function.
cables begin replacing copper pairs, coaxial cables
and microwave routes [3]. Time Division
Multiplexing (TDM) based Plesiochronous Digital
Hierarchy (PDH) is introduced to replace the analog
multiplexing of voice signals. Typical capacity of
TDM-PDH equipment is:
(1) N. America  — DS0-64kb/s, DS1-1.544Mb/s,
DS2-6.312Mb/s, DS3-44.736Mb/s, and not
standardized DS4-274.176Mb/s, and
(2) Europe  — E1-2.048Mb/s, E2-8.448Mb/s, E3-
34.368Mb/s, E4-139.264Mb/s and not standardized
E5-564.992Mb/s.

PDH transmission technology showed significant
disadvantages in:
(1) add/drop insertion (inability to recognize the higher
level channels),
(2) routing,
(3) usage of bandwidth,
(4) complexity of scalability,
(5) small overhead for services functions, and
(6) long self-healing.

1990 – Widespread use of TDM-based Synchronous
Optical Network/ Synchronous Digital Hierarchy
(SONET/ SDH) digital network that uses fiber-optic
cable as a transmission medium. In 1988, the
American National Standards Institute (ANSI)
standardized SONET while the International
Consultative Committee on Telephony and
Telegraphy (CCITT) adopted SDH recommendations
G.707, G.708 and G.709 with the International
Telecommunications Union (ITU-T) joining at 1993.
SONET/SDH standards are nearly identical and
allow a wide range of transmission rates:
OC-1/STM-0  = 52Mb/s
OC-3/STM-1 = 155.52 Mb/s
OC-12/STM-4 = 622.08 Mb/s
OC-48/STM-16 = 2.488,32 Gb/s
OC-192/STM-64 = 9.95328 Gb/s
OC-768/STM-256 = 39.81312 Gb/s

Manufacturers, vendors, suppliers and
telecommunication companies started replacing the
existing PHD fiber-optic equipment with
SONET/SDH. The advantages of SONET/SDH over
PHD are:
(1) enables direct multiplexing of the tributary
signal in the Synchronous Transfer Mode
(STM)-n for n = 0, 1, 4, 16, 64, 256, so called
single stage multiplexing,
(2) the STM-n payload can be used for the transfer
of signal of mutually different rates, so called
bandwidth flexibility,
(3) visibility and direct access to STM-n virtual
containers that allows easy routing through the network,
(4) reduction in the network facilities due to the change in the topology of hierarchical levels
(cost-effective topology),
(5) better self-healing capabilities using the ring
protection topology,
(6) central oversight and network management
using the Data Communication Channels
(DCC),
(7) high capacity interfaces (10 Gb/s, 40Gb/s and higher) compared to PHD (565Mb/s),
(8) generous service channel overhead,
(9) transparency of new services,
(10) transparency of vendor equipment
(standardized STM-n interface),
(11) lower cost per channel compared to PHD due to
simplification of the equipment and networking,
(12) the basis (non-ideal) for inter-working of packet
technologies such as ATM, IP, Frame Relay
(FR) is in the STM-n and WDM level,
(13) international acceptance of the standards,
(14) many networks elements as Digital Cross-
connects System (DCS), Add-Drop
Multiplexers (ADM) and Digital Carrier Loop
(DCL) are already available, and
(15) SONET/SDH transmission systems make up
nearly all of local and inter-exchange carrier
transmission facilities in the world [2].

The main disadvantages of SONET/SDH are:
(1) TDM transport may not be an ideal solution for the inherently burst nature of data traffic
(2) restoration of routes when problems occur
(3) the use of only 10-15% (on average) of the maximum provided bandwidth when TDM is
used to carry data traffic services [7], and
(4) high-speed systems (2.5, 10, especially 40 Gb/s
and higher) experience severe difficulties and
limitations due to the presence of non-linear
distortion in the optical fiber and optical equipment
and in the electrical devices5.

SONET/SDH is a flexible and effective technology of
transmission and it supports, but not efficiently
enough transport all kinds of data signals (ATM, FR,
IP, etc.) However, the future high-bit rate and large
bandwidth demands cannot be satisfied using to-date
SONET/SDH bit rates or future (very expensive and
technically difficult) upgrades of SONET/SDH

5 Mapping and framing do not use the bandwidth effectively because of the STS method (multiplexing is realized with a
digital TDM (64kb/s) voice signal, which only gives an
opportunity for data transport but it is not efficient enough [4]).

6 The SDH ring back-up switch takes about 50 ms, whereas WDM-
based optical networks will be able to switch to back-up routes
within a few µs [5].

Bit rate is inversely proportional to the square of the length of the link not requiring regeneration [6]. The march toward greater
speeds in TDM SONET/SDH will continue though limited by the
length of the link.
systems. The solution to this problem is the WDM technology.

C. WDM - Better usage of the available fiber bandwidth

An increase in the capacity of a transmission network can be achieved by utilizing the available spectrum of the optical fiber better. Signal multiplexing methods used today in optical transmission systems are:

1. Time Division Multiplexing (TDM),
2. Sub-carrier Division Multiplex (SCM),
3. Code Division Multiplexing (CDM),
4. Space Division Multiplex (SDM), and
5. Wavelength Division Multiplexing (WDM).

TDM – forms a high-speed channel by time multiplexing of a number of lower-speed channels. This method of multiplexing can be accomplished in the electrical or optical domain [10]. TDM has found wide acceptance in digital electronic transmission systems and networks and is fairly straightforward to implement in an optical network carrying up to 10Gb/s [10]. The systems with bit rates of 40Gb/s and higher will be less developed and used for two reasons:

1. It is easier to reach the desired link capacity using WDM than to develop new electrical devices that can handle such data rates, and
2. ATM and IP are more suitable data transfer technologies compared to SONET/SDH and will be more used and developed.

SCM – a baseband signal (data, voice or video) modulates sub-carriers at a GHz level and the resulting signal is imposed on a THz optical carrier wavelength. Multiplexing and de-multiplexing of SCM signals is accomplished electronically, not optically. SCM is a less expensive method then WDM, because electrical components and circuits are cheaper then optical components. However, SCM is limited because it can be used effectively only for low-cost, low-speed multi-user systems.

CDM – a channel-specific coded sequence of pulses is transmitted on multiple sub-channels. These short pulses are placed within chip times with the longer bit time. All sub-channels, each with different code, can be transmitted over the same fiber and asynchronously de-multiplexed. However, this method is complex and very expensive.

SDM – the optical output of a fiber is split into N different and parallel optical beam paths, each of which passes through a light-modulating switch and goes to a different input fiber. SDM creates a high-bandwidth space-switching matrix however, all sub-channels cannot be transmitted simultaneously on the same fiber thus wasting the high bandwidth of fiber. SDM allows transmission of single signal on an individual fiber.

WDM – several baseband channels are transmitted along a single optical fiber with each channel located at a different wavelength. Transmission is done primarily in the regions of the optical fiber wavelength spectrum where the attenuation is the smallest (Fig. 2) [8]. We can recognize three such regions (optical windows) in the attenuation plot of Fig. 2 at 850 nm (1st), 1300 nm (2nd) and 1550 nm (3rd).

When only one wavelength is used for transmission (single channel - done in the early development of optical transmission systems) less than 1% of optical fiber bandwidth capacity is used [9]. Later solution used one wavelength in the 2nd and one wavelength in the bandwidth of the 3rd window. This was the beginning of WDM and multi-

Figure 2: The attenuation coefficient $\alpha$ of silica fibers
wavelength usage of fiber bandwidth. These kind of optical links have significant weaknesses:

1. they only use a fraction (on the order of GHz) of the enormous bandwidth of fiber, and
2. they connect two district end-points and do not provide for a multi-user environment.

Further progress in the development of stable, narrow-line Distributed Feed-Back (DFB) lasers, Erbium-Doped Fiber Amplifiers (EDFA) and other elements of an optical transmission system enabled the use of a larger number of wavelengths as carriers of a TDM signal thus covering a larger portion of the optical fiber bandwidth.

The principle behind the WDM technology is simple but the development has been complex and construction of a working WDM system required a very long time. WDM was not used until late 80’s due to fiber attenuation that required periodic regeneration. EDFA eliminated the need for repeaters and covered more than one information-carrying wavelength. EDFA can provide gain and cover all the channels in the available spectrum in the 3rd window (from 1530 to 1565 nm). There is a possibility to use the 2nd window (1310 to 1350 nm) [11], but the 3rd window is mostly used.

Multiplexing signals at different wavelengths increases the transmission capacity of an optical fiber significantly. WDM offers much better utilization of the optical fiber’s Tb/s bandwidth (Fig. 3) [12] and can be combined with the TDM.

Some of the optical signal impairments that limit system performance in a WDM network are:

1. dispersion of optical fibers and WDM multiplexing/de-multiplexing filters,
2. coherent and incoherent signal cross-talk from imperfect WDM channels filtering,
3. polarization-dependent signal cross-talk from imperfect WDM channels filtering,
4. finite optical signal extinction,
5. wavelength chirp of modulated laser transmitters,
6. WDM filter pass-band narrowing of filter cascading [13],
7. optical fiber non-linearity,
8. additive spontaneous emission noise of optical amplifiers, and
9. non-flat gain profile of optical amplifiers.

Signal dispersion, optical amplifier impairments and inter-channel crosstalk are probably the most important signal degradation mechanisms in WDM.

In a WDM system (Fig. 4 [8]), each laser transmitter emits light at a different wavelength. Multiplexer (combiner or coupler) multiplies all the laser wavelengths and transmits into a single optical fiber. On the other side of the link, after the transmission through the optical fiber, the combined optical signal is de-multiplexed and the receiver optical filter selects only one desired wavelength.

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5 In the 2nd window we have a bandwidth of about 18 THz and in the 3rd window about 25 THz (Fig. 2).

6 They cover the entire bandwidth of the 3rd window.
This method solves the capacity problem caused by the limited ability of SONET/SDH transmission systems. WDM systems are designed according to the ITU-T recommendation G.692 (Optical Interfaces for Multichannel Systems with Optical Amplifiers). G.692 recommendation defines bi-directional 4, 8, 16 and 32 channel systems. All data channels in a WDM system should fall within a specified 100GHz grid (Fig. 5[8]). Smaller channel spacing (such as 50GHz and 25GHz) is possible, too. DWDM systems typically use 4, 8, 16, 32 channels; sometimes 6, 10, 20, 40 and experimentally 60, 64, 80, 100, 128 and more (Fig. 6 [12]).

Non-ideal wavelength filtering in the receiver results in the appearance of inter-wavelength cross talk. Increase in the number of channels reduces the separation between wavelengths and raises the inter-wavelength crosstalk. This reduces the number of carrier wavelengths that can be used. A decrease in the number of channel leads to the decrease in the total TDM rate. In general, there is a tradeoff between the number of channels and the inter-wavelength crosstalk so that the capacity of the fiber is used optimally. WDM systems that multiplex TDM signals of 40Gb/s with 64, 80, 100, or 128 channels need to overcome a score of imperfections before their wider acceptance.

D. Advanced performances devices for WDM

The improvement of an optical transmission network may be achieved with WDM system. One way for that is to develop and advance the performances of devices used in a WDM system. WDM systems consist of devices such as: lasers in multi-channel transmitters, optical modulators, multiplexers and couplers, optical amplifiers (semiconductor or fiber), optical fibers, passive and active routers and splitters, tunable optical filters, de-multiplexers, photo-diodes, attenuators, add-drop multiplexers, cross-connectors, etc.) All of these devices have to fulfill the requirements of WDM/DWDM systems such as:

1. large wavelength tuning range,
2. wavelength stability,
3. low cross-talk,
4. high extinction ratio,
5. multi-user capability,
6. fast wavelength tuning,
7. minimum access losses,
8. high-speed modulation,
9. low residual laser chirp,
10. low noise,
11. high selective wavelength filters,
12. potential low cost,
13. commercial availability, etc.

Transmission lasers, optical amplifiers and optical fiber are key elements in WDM transmission systems and we will be described in the following text.
Lasers: Semiconductor lasers are used in transmitters for multichannel systems. Widely available lasers are fixed-wavelength distributed feedback (DFB) semiconductor lasers with wavelengths on the standardized wavelength grid (ITU-T G.692). Lasers tunable over as much as 40 nm (4.6 THz) are also becoming available on the market. The main characteristics of lasers are:

1. precisely controlled wavelengths,
2. wavelength stability with time and temperature,
3. tuning ability of laser, tuning range, tuning speed,
4. low power consumption, and
5. low cost.

A WDM system has multiple wavelengths at the input of an optical multiplexer. This is achieved using multiple lasers, each with a fixed, tunable or variable wavelength. Fixed-wavelength lasers are manufactured with a particular wavelength; tunable lasers are adjusted to the desired wavelength during the installation process while the variable lasers can be changed as the need arises. However, the most desirable option is a laser that can emit simultaneously a spectrum of separated wavelengths. Some categories of monolithic tunable lasers are:

1. index tuned lasers,
2. arrayed lasers and
3. integrated cavity lasers.

Index tunable lasers tune the wavelength by changing the refractive index in the lasing cavity. Distributed Bragg Reflection (DBR) is an example of this kind of laser that can emit only one wavelength at a time.

Arrayed lasers are an ensemble of fixed-wavelength lasers combined in an optical power splitter such as Distributed Feed-Back (DFB) lasers array. Arrayed lasers can emit on several wavelengths simultaneously.

Integrated-cavity lasers consist of a multi-port optical multiplexer integrated with optical amplifiers. Integrated-cavity lasers can emit on several wavelengths simultaneously and are also known as multi-frequency lasers (MFL) [14].

A DFB array is a monolithic device. It can deliver multiple wavelengths simultaneously. Each individual DFB can be modulated at a very high-speed bit rate. It is smaller then an MFL and can provide the desired optical spacing. An MFL is physically larger because it involves more elements like optical amplifiers, multiplexer, waveguide grating router and applications with a small number of wavelength channels will favor a DFB because of its compactness. However, as we increase the number of wavelength channels, the inherently controlled optical channel spacing of the MFL may outweigh its size disadvantage. Also, DFB suffers from an intrinsic loss and needs a fine grating period, which makes manufacturing more complicated than for an MFL. Fig. 7 shows an overlay of nine lasing spectra of an MFL. The channel spacing is exactly 150 GHz.

Amplifiers: A precursor for the great strides in the development of WDM systems were and still are optical amplifiers. The amplification of the optical signal can be achieved at transmission with booster amplifiers or on the line with line amplifiers or at the receiver with pre-amplifiers. All functionality is realized in the optical domain. The amplification seeks to include most of the spectrum where the channel has a flat frequency response. Years of research in this area laid ground for the intense development of WDM and DWDM systems that we see today. Optical amplifiers can be separated in two groups:

1. Semiconductor optical amplifiers – laser diode with a Fabri-Pero resonator and progressive waves (TWA), and
2. Doped Fiber Amplifiers (DFA) with Erbium, Praseodymium, Fluoride or rare-earth element and Non-linear effect (Raman, Brillouin),

EDFA are widely used today. They compensate for the line attenuation of the optical fiber in the 3rd window (1530-1565 nm, so called C-band) with the amplification of 30 dB. EDFA work using the following method. A piece of doped optical fiber is inserted into the transmission with its own laser source, the pump. The pump raises the carrier signal energy level in the doped piece and that energy is transferred to the useful signal in the courses of transmission through the doped piece. The length of the inserted piece is approximately 20 m. The wavelength of the useful signal and the laser pump, the later one emitting at 0.82, 0.98 or 1.48 nm. EDFA are bi-directional amplifiers that work independently of the data rate or the signal format and are immune to polarization changes. EDFA add a cumulative amplifier spontaneous emission noise (ASE).
Therefore, another potential problem with EDFA is the variable amplification gain (gain slope), for light of different wavelengths. While passing through cascades of EDFA, some signals get an asymmetric boost compared to other signals. This causes a serious imbalance [15]. Better performance (wavelength flat and larger amplification) can be achieved using a combination of doped and non-linear Raman amplifiers in what is called hybrid amplifiers (Fig. 8 [16]).

It is possible to extend the spectrum to the L-band (1565-1605 nm). When C and L bands are used simultaneously with the filters of high selectivity (provide 25 GHz spacing between the channels or 0.2 nm) one can get 160 channels for a 35 nm spacing or 400 channels with a 80 nm spacing [17]. The low-loss region (transmission loss less than 0.3 dB/km) is very wide, ranging from 1450 nm to 1650 nm. Extending the optical amplifier bandwidth is an active research topic and wide-band optical amplifier with a bandwidth of over 80 nm has been reported. In the future, the number of channels used in the optical network may increase to a few hundred [18].

**Fiber:** Chromatic dispersion of the fiber limits the reach or equivalently limits the transmission data rate. This dispersion of the optical fiber becomes much more visible in DWDM than in the single-channel systems. This comes about due to the fact that the separation of carrier wavelengths is 0.8 or 0.4 nm or even smaller as more carriers are employed and the dispersion in the 3rd window (used by EDFA) is roughly 17 ps/nm*km (ITU-T G.652). This can be compared to zero dispersion at 1300 nm, the wavelength of the 2nd window, which is widely used. A fiber with the zero dispersion shifted into the 3rd window (Dispersion Shifted Fiber (DSF)) allows the use of the 3rd window for high-speed single-channel systems (ITU-T G.653). However, the requirements for the fiber dispersion change significantly for a DWDM system. ITU-T recommendation G.655, which sets the parameters for mono-mode fiber with Non-Zero Dispersion (NZD), specifies that the spectrum used by DWDM systems has non-zero dispersion. The chromatic dispersion (D) is 0.1 ps/nm*km < Dmin < |D| < Dmax < 6.0 ps/nm*km in the waveband from 1530 to 1565 nm. Thus, neither ITU-T G.652 nor G.653 are designed for DWDM systems because the chromatic dispersion is different than the one recommended by G.655.

Non-linear effects present in the frequency response of the optical fiber are more evident in WDM systems compared to single-channel systems due to the dense grid of wavelength used and higher power in the fiber due to the operation of the EDFA. Non-linearity in the frequency response generates new signals at the sum and the difference of neighboring wavelengths, which is known as Four-Wave Mixing (FWM). FWM is the strongest when the wavelengths involved are located close to each other (like in DWDM) and close to the zero dispersion wavelength. This results in a high level of crosstalk between the subchannels of DWDM. Thus, optical fibers that lack zero dispersion (ITU-T G.655) effectively suppress FWM (Fig. 9 [19]). Optical fibers manufactured according to ITU-T G.652 (chromatic dispersion in the 2nd window) have larger dispersion than allowed according to ITU-T G.655. These optical fibers limit the data rate of a DWDM system to 10 Gb/s due to the dispersion of 17 ps/nm*km. The limit can be overcome using dispersion compensation employing Dispersion Compensating Fiber Modules (DCFM) with negative dispersion (opposite to the fiber dispersion).
at 1550 nm [20]. Combination of fibers with positive and negative dispersion can result in a balanced optical link according to ITU-T G.655. Using this technique numerous existing optical links can accommodate DWDM systems. Non-linearity of the fiber can be avoided by using Non-Zero Dispersion Shifted Fibers (NZDSF). NZDSF have a low, but non-zero dispersion in the EDFA spectral window (the 3\textsuperscript{rd} window) ranging from 2 to 6 ps/nm*km with both positive and negative dispersion according to ITU-T G.655.

References: