Optical Networking Enabling Technologies

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ABSTRACT **— The rapidly increasing demand on bit rate has taken the technology to its limit for supplying that rate. A relatively new technology is optical networking which is capable of supplying bit rates up to several Terabits/sec.**

This paper presents components of optical networks that make such high bit rates possible. It also discusses basic principle parameters of optical fibers such as dispersion, attenuation and types of fibers used and gives a brief review of the current state of the art devices that are vital for optical transmission. The devices include optical amplifiers, multiplexers, optical filters and wavelength converters. It also introduces some basic concepts in dense wavelength division multiplexing (DWDM) and provides the limitation and capability of the various devices that are used in this technology. It also surveys some tests that were preformed to get a bit rate up to 5 Terabits/sec.

1. Introduction

Visions of optical network have captured the imagination of researchers and network planners alike since the rapid and successful commercialization of Wavelength Division Multiplexing (WDM) in the early 1990's and the traffic boom in telecommunication industry associated with the view of merging multimedia and the Internet. A study in North America has shown that the bit rate demand in the year 2003 will reach up to 15 Million Terabits/month [1] which if assumed uniform will result in 5.787 Terabits/second. The only technology that can support such huge bit rates is optical networking. Many experiments have been reported that showed the possibility of several Terabits/second transmissions using Dense WDM (DWDM) and optical amplification [2]-[4].

2. What is Optical Networking?

Optical network is a data-optimization network infrastructure in which switching and routers have integrated optical interface and are directly connected to the fiber and/or optical network elements such as Dense Wavelength Division Multiplexers with no form of opto-electronic conversion. An optical transport network infrastructure is capable of meeting the rapid bandwidth increase by replacing time slots with wavelength (optical channel) as the medium of providing reliable transfer of high bandwidth services across the network [5]. An optical channel in an optical network is capable of carrying much more information than the conventional time division multiplexed networks [6]. DWDM is the technology that enables the propagation of more than one wavelength in a single fiber possible, thus increasing its aggregate bandwidth per fiber to the sum of bit rates of each wavelength [7].

3. Components of Optical Networks

This section discusses the main elements that help in constructing an optical network. The main elements are sources and detectors, optical fibers, optical amplifiers and wavelengths selective devices.

3.1 Optical Sources and detectors

Optical sources used in a fiber optical communication systems must posses certain features such as small size, sufficient and stable power coupling into the fiber, small linewidth, fast response and suitable wavelength. There are two types of sources that convert electrical signals to optical signals efficiently. Namely, they are Light Emitting Diode (LED) and Laser Diode (LD). Since LDs provide higher coupling efficiency and a smaller linewidth, they are widely used in fiber-optic systems. The most widely used type of LD is the Distributed Feed Back Laser (DFB). DFB lasers have narrow linewidth, a stable power output and a broad band. DFB structure can be combined with multiple quantum structure to improve the linewidth of the produced laser light. DFB laser is a reliable source with center frequencies in the region around 1310 nm and also in the 1520 nm to 1565 nm range which makes them compatible with erbium-doped fiber amplifier (EDFA) and excellent sources in DWDM application [7].

Optical detectors are the counter verse of optical sources. That is optical detectors convert optical signals into electrical signals. Optical detectors must be sensitive, having a large electrical response to the input optical signal, with fast response time and the internal noise must be minimum [8].

3.2. Optical Fibers

Optical fibers are waveguides that are made of a dielectric media. Most of the optical fibers are pure silica-based fibers that consist of two concentric cylinders. The inner cylinder is called the core which has a refractive index of n_1 and an outer cylinder with a refractive index n_2 called the cladding. For a fiber to confine the optical wave n_1 should be greater than n_2.

3.2.1. Types of Optical Fibers

Fibers can be classified into three main categories depending on their modal and physical properties [9]. These categories are multimode step index fibers, multimode graded index fibers and single mode fibers. Since the lateral one is the most widely used in optical networking the other types are disregarded.

Single mode fibers support only the lowest mode at the wavelength desired. It is used for high data rate transmission and long distance communication because of its low attenuation at the desired wavelength. The single mode fiber is subdivided into four types as recommended by the International Telecommunication Union (ITU). These types are:

i. Dispersion Unshifted Fiber (USF)

This type is the most widely used [9]. It has zero chromatic dispersion at wavelength of 1310 nm. It has a dispersion of 17 ps/nm-km at a wavelength of 1550 nm, which limits the bit rate transmitted to 2.5 Gbps.

ii. Dispersion Shifted Fiber (DSF)

In this fiber the zero chromatic dispersion is relocated at the wavelength of 1550 nm where the fiber losses are minimal. These types of fibers find application in long distance transmission with single wavelength transmission.

iii. 1550 Loss Minimized Fiber

This is a special type of USF that has losses minimized to 0.18 dB/km in a 1550 nm wavelength. Because they are difficult to manufacture they are expensive and seldom used.

iv. Nonzero Dispersion Fiber (NZDF)

These types are specially designed for the use in Dense Wavelength Division Multiplexing (DWDM) system. NZDF has both the minimum and maximum amount of chromatic dispersion specified over a portion of the third wavelength window. The dispersion of these fibers suppresses the non-linearity and allows individual channel rate of 10 Gbps to distances of 250 km without dispersion compensation. NZDF are widely used in submarine and long haul terrestrial transmission.

3.2.2 Fiber Properties

There are two main properties that are considered. Theses properties are attenuation and dispersion [10].

A) Attenuation

Attenuation leads to a reduction of signal power as the signal propagates through the fiber over some distance. Attenuation can be classified into three main categories, namely, intrinsic, scattering and waveguide imperfections. Intrinsic attenuation is due to absorption of the fiber. It occurs because of resonance of silica molecules as well as the impurities (OH^-) in the fiber. Impurities cause the major peak at 1390 nm as well as several minor peaks. Scattering is mostly due to the molecular structure of fiber material because of the medium is not absolutely uniform. Waveguide imperfections are caused by non-ideal fiber geometry, which occurs due to manufacturing imperfections and small bends and distortion in the fiber.

B) Dispersion

Dispersion is the widening of pulse duration as it travels through a fiber. This can lead to intersymbol interference if it was not taken into consideration while designing, thus limiting the bit spacing and the maximum transmission rate on an optical fiber channel. One form of dispersion is the intermodal dispersion. This type of dispersion is caused when multiple modes of the same signal propagate at different velocities along the fiber. Since in a single mode fiber only one mode is permitted to propagate. It follows that single mode fiber does not exhibit this type of dispersion. Another type of dispersion is the chromatic dispersion. This occurs because generated photons in a transmitter are not produced at a single wavelength. Since each wavelength propagates at a velocity that differs from other wavelengths, signals arrive at different times even if they follow the same path, which causes broadening of a pulse. A third type of dispersion is the waveguide dispersion. This type of dispersion is caused by the structure of the waveguide itself.

3.3 Optical Amplifiers

In traditional optical communication systems amplification was obtained by amplifying the electrical signal obtained by converting the optical one into electrical and then retransmitting it by converting it back to optical. A new era started by the introduction of the first optical amplifier called erbium doped fiber amplifier (EDFA) in 1987 [11]. EDFA's have very attractive features such as high power transfer efficiency, high gain, amplification of wide wavelength region, low noise figure and very low dependency on light polarization. They are also transparent to the optical signals propagating in the fiber. Other optical amplifiers depend on the nonlinearity possessed in the fiber itself. Such optical amplifiers include stimulated Raman scattering and stimulated Brillouin scattering amplifiers.

3.3.1 Erbium Doped Fiber Amplifier (EDFA)

EDFA's are basically a length of fibers heavily doped with erbium and a pumping laser connected to that fiber by a DWDM coupling component that combines the pumping signal into the doped fiber. The erbium doping provides gain for wavelengths of 1525-1560 nm and hence is perfect for use in DWDM system. Lasers with wavelength 980 nm or 1480 nm pump most EDFA's. The 3-dB gain bandwidth of EDFA is around 35 nm [12]. High gains of 30 to 40 dB are obtained with low noise with optical pumping powers in the range of 50 to 100 mW. The amplification is dependent on the material gain of a relatively short section of the fiber (1 to 100 m). Aluminum and germanium co-doping can be used to broaden the spectral bandwidth to around 40 nm and a total available bandwidth of 9 THz. EDFA's are available now that are capable of supporting 80 nm bandwidth with a potential wavelength capacity greater than 100 channels.

3.3.2 Stimulated Raman Scattering and Stimulated Brillouin Scattering Amplifiers

In these amplifiers the pumping laser takes advantage of non-linearity properties of the fiber. The most important feature or Raman amplifiers is that they have a bandwidth range that can extend over the complete useful spectrum from the 1300 nm to 1600+ nm that enables multi-Terabit transmission technology. Raman amplification requires a very long fiber and pump lasers with high optical power [7].

3.4 Dense Wavelength Division Multiplexing (DWDM)

In DWDM 1nm spacing separates wavelengths hence allowing a number of wavelengths to propagate in the same fiber. DWDM increases the aggregate bandwidth of a fiber to the sum of the bit rates of each wavelength. After transmission on the fiber each signal can be separated towards different detectors at the end of the fiber.

For the implementation of optical networks DWDM devices should be able to combine and separate closely spaced wavelengths to allow wavelength selection. The main DWDM devices that allow such selections include, and not limit, wavelength converters, multilayer interference filters and optical gratings. The definition of the above devices are given below:

A) Wavelength Converters
   Wavelength converters are devices that can convert input wavelengths λ_1 to another wavelength λ_2. These devices such as the four wave mixing (FWM) and difference frequency generator (DFG) (also known as three wave mixing) use some non-linearity in the fiber [13].
B) Multilayer Interference filter
   These types of devices are made of multiple dielectric layers. Each layer has a refractive index that defers from the other layers. The change in the refractive index causes a phase shift between the outputs of each layer and hence can select a single wavelength. Mach-Zehnder interferometer and acousto-optic tunable filter are examples for such devices.
C) Optical Grating
   Grating based devices use the diffraction property. These devices diffract the incident parallel light in a specific direction according to the angle of incidence and the optical wavelength of the incident light. If several wavelengths are incident on the gratings then the wavelengths are diffracted to different angles and thus different channels are demultiplexed.

4. Network Survivability

Survivability schemes can be classified into two forms, protection and restoration, where the former refers to preprovisioned failure recovery and the latter refers to more dynamic signaled recovery. A variety of protection levels can be provisioned depending on user demands and budgetary constrains, and recovery times under 50 ms can be provided [14]. Restoration on the other hand does not rely on previous backup channel and instead dynamically recomputes a new path for a broken channel upon failure detection, which makes restoration quite slow. For this reason after the protection function is completed, restoration is used to provide either more efficient routes or additional resilience against further failures before the first failure is fixed [10], [15]-[16].

5. Network Reliability and Management

The DWDM networks have a very large bandwidth throughput. It follows that such networks must be highly reliable. Reliability is expressed in terms of quality of signal, which is usually measured by the bit error rate (BER), downtime in seconds per year without service and traffic routing time in sec. For good reliability good network management is essential. To improve management of the network, protocols are used to give indications of network health and billing information to a remote station from where DWDM networks are managed [7].

6. Conclusion

Advances in DWDM component technology have heralded a new era in communications. The dramatic increase in network capacity coupled with improved cost effectiveness will likely lead to a large-scale deployment of such technology over the next few years. In this paper we have reviewed the operation principle of optical networking and discussed the vital network elements. In addition we have given a brief preview of survivability and reliability of optical networks. Research labs in different part of the world have demonstrated experiments with capacities up to 5 Terabits/sec and higher [1]-[4].

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