ENHANCEMENT OF THE CAPABILITY OF OPTICAL NETWORKS BASED ON WDM TECHNIQUE

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This article discusses the possible applications for optical networks based on wavelength division multiplexing and how they compete and complement current high speed networks (SONET, ATM). We first outline the best-case scenario for this technology and describe the spectrum of optical networks (WDM links, passive optical access networks, broadcast-and-select networks, and wavelength routing networks). Then we focus on wavelength routing networks and describe their advantages and disadvantages relative to other competing alternatives for very-high-speed networks. Finally, the paper speculates on how capacity might evolve the future to handle the undoubtedly new services that are on the horizon

1. INTRODUCTION

Wavelength division multiplexing (WDM) is the technology of transmitting multiple data streams independently on a single fiber using different light wavelengths. This technology, in the form of point-to-point multiplexer/ demulti-plexer systems, has successfully passed its first real-world test, and has moved from laboratories and testbeds into commercially available and deployed systems. WDM technology clearly has great advantages for the long distance telephone companies, since it enables them to dramatically increase their (currently almost saturated) trunk capacities without going into the painful process of laying more fiber in the ground.

On the other hand, from the research point of view, optical networks based on WDM hold great promises for the future of both tele- and data communication networks, since they currently appear to provide one of the only solutions that overcomes the inherent limitations of electronics and probably the simplest solution in sight to enable high-speed networks to become really high-speed (say, above 10 Gb/s). However, the reasons a given technology becomes successful lie not in its theoretical merits, but in how well it competes with alternative solutions, both potential ones as well as those already in use. We then present a brief technical overview of the field, and narrow down the discussion to the current commercially viable solutions: WDM links and wavelength routing networks. Next we compare all-optical networking with competing electrical solutions for very-high speed networking

2. THE TECHNOLOGY BEHIND THE OPTICAL NETWORKS

This section briefly outlines the current architectures of optical networks. It also serves to filter out from the rest of the discussion directions that are beyond the scope of this article. An in-depth discussion of the optical devices used to build these networks, as well as some networking aspects, can be found.

Optical networks can be divided according taxonomy tree in Fig 2.The main distinction between various types based on the multiplexing scheme: whether it is done in the frequency domain (WDM) or the time domain, as in optical time division multiplexing (OTDM). WDM networks may be further split into:

- Point-to-point links — in which both ends of the link have identical equipment to transmit and receive the channels
- Access networks — in which one side of the link gets split among different locations (homes) and requires simpler equipment at the home
- Broadcast-and-select systems—in which the signal is broadcast to multiple endpoints rather than a single endpoint

- More scalable and complex networks, in the form of wavelength routing networks, realized by introducing switching nodes to connect multiple point-to-point links.

2.1. Broadcast-and-Select Networks

Broadcast-and-select networks are based on a passive star coupler device connected to several stations in a star topology .[1] This device is a piece of glass that splits the signal it receives on any of its ports to all the ports. As a result it offers an optical equivalent of radio systems: each transmitter broadcasts its signal on a different wavelength, and the receivers can tune to receive the desired signal (see Fig. 1 for a schematic drawing of such a system).

The main networking challenge in such networks pertains to the coordination of a pair of stations in order to agree and tune their systems to transmit and receive on the same wavelength [2]. One design issue that must be determined before deciding on these protocols is the tunable part of the system. It is possible to either have tunable receivers and fixed transmitters than the other way around. The advantage of these networks is in their simplicity and natural multicasting capability. However, they have severe limitations since they do not enable reuse of wavelengths and are thus not scalable beyond the number of supported wavelengths. Another factor that hinders the scalability of this solution and disables it from spanning long distances is the splitting of the transmitted energy to all the ports.

For these reasons the main application for broadcast-and-select is high-speed local and metropolitan area networks. However, the relatively high costs of WDM transmitters and receivers compared to the low costs (less than $1000/port) of other technologies (e.g., ATM and switched Ethernet) do not enable broadcast-and-select networks to be competitive in this arena currently. The few niches that appear to be appropriate for such networks are in broadcast studios and supercomputer centers. Due to these reasons we will ignore broadcast-and-select networks for the rest of the discussion.

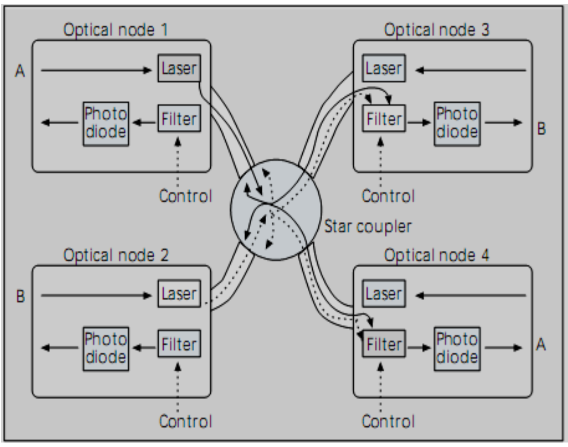

Figure 1 A broadcast-and-select system

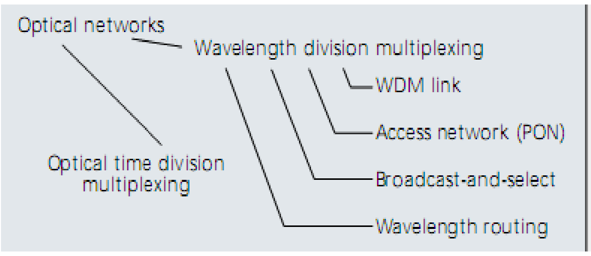

Figure 2.A.taxonomy of optical networks

2.2. Wavelength Routing Networks

A scalable optical network can be constructed by taking several WDM links and connecting them at a node by a switching subsystem. Using such nodes (also called wavelength routers) interconnected by fibers, diverse networks with complex and large topologies may be devised [3, 4]. Each wavelength router makes its routing decision based on the input port and wavelength of a connection going through it. Thus, if a light signal of □□□enters a router at a port x it is switched to some output port y. At the other end of the fiber, attached to y, the signal enters another router in which a similar routing decision is made. This process continues until the signal is switched to an output port of the system (Fig. 3). Another optical signal coming into the same router on a different □2will be routed differently. Such an end-to end connection is called a light path, and it provides a high-speed transparent pipe to its end users. At the same time, another light path can reuse the same wavelength in some other part of the network, as long as both light paths do not use it on the same fiber. Since such "spatial reuse" of wavelengths is supported by wavelength routing networks, they are much more scalable than broadcast-and-select networks. Another important characteristic which enables these networks to span long distances is that the energy invested in a light path is not split to irrelevant destinations. There is a large diversity of capabilities that a wavelength router can provide, depending on the components in use and design of the node. Most notably, nodes may provide configurable light paths versus fixed routing, full wavelength conversion versus limited conversion versus no conversion at all, fault tolerance in the optical layer versus reliance on higher layers. Nodes may also vary in their scalability to increasing numbers of local or network ports

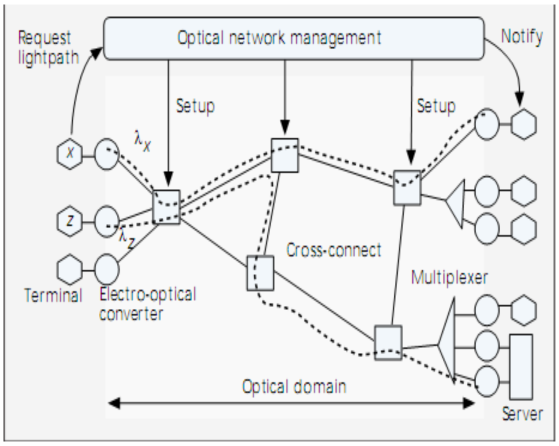

Figure 3 An all-optical network

3. NETWORK CAPACITY

There are generally two approaches for increasing the fiber capacity: increase the number of wavelengths supported on a fiber or increase the bit-rate of each wavelength. Historically, both approaches have been used. During the late 1980s, quasi- supported on a fiber, each one carrying rates of tens of Mb/s. By the mid-1990s, 8 t o 1 6 2.5-Gb/s wavelengths were supported on a fiber, where the wavelengths were located in the 1500-nm region of the spectrum, with wavelength spacing on the order of 100 to 400 GHz. This rapidly increased to 80 to 200 10-Gb/s wavelengths by year 2000, with 25- to 50-GHz wavelength spacing. Current benchmarks are 40 to 80 40-Gb/s wavelengths per fiber. Thus, in roughly a 20-year span, the capacity per fiber has increased by more than four orders of magnitude.
Increasing the fiber capacity beyond

these numbers will require advanced modulation formats, e.g., multilevel amplitude and/or phase modulation . Assuming that higher capacity is possible, it is interesting to consider whether it is more desirable to increase the number of wavelengths or increase the bit-rate of each wavelength.

3.1. Increasing the Bit Rate of a Wavelength

Thus far, the transport bit-rates have followed the SONET/SDH hierarchy, with each successive bit-rate representing a four-fold increase; e.g., 2.5 to 10 to 40 Gb/s. Historically, one of the advantages of increasing the bit-rate has been cost. With each quadrupling of the bit rate, the cost of the associated transponders has increased by a factor of 2 t o 2.5, yielding a steadily decreasing cost per bit/sec. Furthermore, the power and space requirements per bit/sec have decreased as well with increasing bit-rate, thus improving the network operating costs. Give n the challenges posed by high-speed electronics, however, it is not clear that this trajectory will continue. While the cost target for a 40-Gb/s transponder is 2.5 to 3 times more than a 10-Gb/s transponder, the current cost is actually more than four times greater (i.e., increased cost per bit/sec). Moving beyond 40 Gb/s will be even more difficult. Originally, the industry favored 160 Gb/s as the next transport rate; however, the standards bodies have now settled on 100 Gb/s instead to coincide with the Ethernet hierarchy.

WDM was implemented, where just two wavelengths (at 1310 nm and 1550 nm) were A second advantage of increasing the bit-rate relates to switching. Photonic switches are generally limited in the number of supported ports; e.g., 320. For a give n level of traffic, increasing the bit rate decreases the number of wave lengths entering a node (assuming the wavelengths are well packed), resulting in a smaller required switch size. Thus, from a switching perspective, increasing capacity through increased bit rate is more readily scalable.

One of the disadvantages of higher-rate wavelengths is that the signals are more susceptible to optical impairments such as chromatic dispersion, polarization mode dispersion (PMD), intra-cross-phase modulation (IXPM), and intra-four-wave mixing (IFWM). Thus, the optical reach decreases as the bit-rate increases. For example, a system may have a 4,000-km reach for 2.5-Gb/s signals, a 3,000-km reach for 10-Gb/s signals, and a 2000-km reach for 40-Gb/s signals. Shorter reach translates to more regeneration, which may nullify the benefits achieve d through lower-cost-per-bit/s transponders.

Another disadvantage to increasing the wavelength bit-rate stems from the fact that the required bit rate of most services is less than that of a full wavelength. Thus, these sub rate services need to be bundled together, i.e., groomed, in order to pack the wavelengths efficiently. Grooming is currently implemented in the electronic domain, typically using fine-granularity O-E-O switches. For a give n traffic set composed of subrate demands, a higher line-rate requires that the traffic undergo more grooming to achieve the same, or close to the same, level of wavelength efficiency. This translates to larger grooming switches and more Howeve r, a higher bit rate does provide an advantage with respect to the grooming of bursty traffic. With a low bit rate, a small number of flows are carried on a wavelength, where the wavelength can only be partially filled to account for the burstiness of the traffic. With a higher bit rate, more flows are packed together, allowing the system to take advantage of statistical multiplexing. As a percentage of the wavelength capacity, less spare capacity needs to be reserved to accommodate the traffic burstiness, thereby resulting in an overall higher rate of network efficiency.

3.2. Increasing the Number of Wavelengths

Rather than increasing the bit-rate, one can boost the fiber capacity by increasing the number of wavelengths while decreasing the spacing between channels and maintaining, or possibly lowering, the bit-rate. For example, in the future, this might imply implementing a 1000 10-Gb/s system as opposed to a 100 100-Gb/s system. The biggest advantage of this approach is the reduced need for electronic grooming. More services are likely to be delivered to the network that are already at the rate of a wavelength, thereby requiring no grooming. For those services with rates less than that of a wavelength, an appreciably smaller amount of electronic grooming is required to achieve efficiently packed wavelengths.

It is difficult to predict the overall effect on optical reach with high-wavelength counts. While the bit rate may be lower, which lowers the susceptibility to the impairments mentioned earlier, the closer channel spacing may lead to problems with impairments such as crosstalk and cross-phase modulation (XPM). Additionally, functions such as receiving a signal may be more difficult with the tight spacing. Techniques such as coherent detection at the receive r may be needed.

While this approach may not appear to offer the advantages in cost, power, and space historically realized through higher-speed transponders, and may present scaling challenges for wavelength-level l switches, there are alternative means of addressing these issues. To address the first set of issues, one can consider the PIC approach mentioned in Section IV-D, where several transponders are integrated on a chip. For r example, one chip could include ten 10-Gb/s transponders. A goal would be to have this chip be no more costly, and require no more space or power, than a single 100-Gb/s transponder. Note that, in principle, PIC technology does not imply an O-E-O architecture; however r, supporting tunability with integration may be challenging, which would limit its efficacy i n a network with optical bypass. Additionally, meeting the tight spacing between channels (e.g., 10-GHz) may be difficult with PIC technology. As an alternative, hybrid integration of individual, miniature, low-cost components may be a more suitable solution rather than monolithic integration With respect to the challenges of switching, one solution is to implement waveband switching, where groups of wavelengths are treated as a single unit for switching purposes, thereby reducing the size of the switch fabric. Waveband switching has been considered in the past for economic reasons, especially in the cost-sensitive metro area. One objection that has been raised to coarse switching is that it may reduce the flexibility of the network somewhat. However, studies have shown that, with good algorithms, the network efficiency lost due to waveband switching as opposed to wavelength switching is small. Furthermore, if the options are switching ten 10-Gb/s wave lengths as a unit versus one 100-Gb/s wavelength, the switching granularities are the same.

Moreover one can improve the flexibility of waveband switching by implementing a hierarchical switch architecture (e.g., [5] and [6]), with waveband grooming. In a two-level switch hierarchy, the bulk of the switching occurs at the wave band level, but a small amount of switching is also supported at the wavelength level t o improve the network efficiency. The wavelength-level switch allows the wavebands to be groomed. For example, the frequency of a specific wavelength can be converted, which move s the signal to another waveband. Conversion may also be possible at the waveband level, where the frequencies of all wavelengths comprising a band are shifted as a unit . It is expected that these functions of wave length and waveband conversion will ultimately be performed in the optical domain. Essentially, the paradigm of increased number of wavelengths, at possibly lower rate, trades O-E-O wavelength grooming for all-optical waveband grooming.

3.3. Flexible Bit-Rate Wavelengths

One of the drawbacks of a system composed of purely low bit-rate wavelengths is that inverse multiplexing is required for the services that require a higher rate. With inverse multiplexing, multiple wavelengths are used to carry a single service; e.g., four 10-Gb/s wavelengths are used to carry one 40-Gb/s service. To avoid the added operational complexity of this solution, an alternative approach is to support a mix of bit-rates on a single transmission system; e.g., a range from 10-Gb/s to 100-Gb/s wavelengths. This allows the bit-rate of the wavelength to better match the service that is being transported. Thus, low bit-rate services can undergo minimal grooming, whereas high bit-rate services can be carried without inverse multiplexing. Depending on the distribution of the wavelength bit rates, the switches may be able to operate on a wavelength granularity. However, if wavebands are used, then one can consider variable sized wave bands that adjust depending on the system configuration.

4. CONCLUSION

Clearly, networking has undergone tremendous changes over the past 25 years. This has been drive n b y the push–pull of services and networking capabilities. With a chiefly homogeneous service (i.e., voice), network evolution was centered on providing more capacity in a cost-effective manner. With respect to transmission, this meant more wavelengths and higher line rates . With respect to switching, this generally meant switching traffic at coarser granularities when possible.However, the surge in data, and, more recently, video services, has taken networking in different directions. Providing large-capacity static pipes was no longer sufficient to meet the needs of the application layer. This led to the introduction of a configurable optical layer and the control plane, which has further encouraged the growth of more dynamic services.

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