Managing the Optical Networking Solution

Is Increased Bandwidth Enough to Reduce Delays?

Although the supply of raw bandwidth has been leveling out since early 2000, the demand for bandwidth-intensive applications is relentlessly increasing. Users are burdening corporate networks and the Internet with requirements to transport real-time applications like voice and video—applications that are extremely sensitive to end-to-end delay and to jitter, caused by gaps between arriving packets. Interactive corporate applications such as voice-over Internet Protocol (VoIP) and video conferencing are particularly vulnerable. If a transmitter sends a packet once every 33 ms, ideally, the receiver would get a new frame at the same rate. If the packet arrives early or late, the network has introduced jitter. Worse, if a frame arrives late after its intended playback time, it is considered useless.

To meet user demand, corporate networks are rapidly evolving from a classic client-server paradigm to an intranet- or extranet-based model, founded on information sharing and Web navigation. The popularity of corporate virtual private networks (VPNs) is increasing because they are relatively inexpensive and easy to implement. At the same time, rapid advances in access technologies such as digital subscriber loop (DSL) and hybrid fiber-coaxial (HFC) cable are giving rise to an unprecedented user appetite for downloading multimedia content. All these trends point to increased bandwidth supply as essential to the successful operation of corporate networks and the Internet.

Many corporate network managers and service providers believe that more capacity can address bandwidth demands as well as delays in message transfer. As the sidebar “Optical Technology and Wavelength-Division Multiplexing” briefly describes, the solution of choice is optical technology that uses wavelength-division multiplexing (WDM). The implication of WDM is that network managers can improve their Internet application and network response time by leasing more capacity from service providers—response time being the sum of message (request and response) and application-processing delays. But although WDM transmission is promising, it presents a tradeoff between bandwidth and message-transfer latency—a tradeoff that is particularly significant for long-haul networks where latency begins to dominate and offset any additional bandwidth advantage for single-message transfers.

To help IT network managers get the most from WDM-based technology, we have derived a model that establishes a boundary bandwidth for single message transfers. The boundary represents the point at which latency begins to offset any advantage from additional bandwidth. Our model clearly shows that bandwidth management is as
critical to the success of this technology as having access to a large supply of raw bandwidth.

**BANDWIDTH DRIVERS**

In addition to challenges from applications like VoIP and video-conferencing, two major limitations of current networking technology are driving the need for more bandwidth. First, bandwidth availability is unpredictable in quantity and quality. Applications that require a certain bandwidth and delay cannot currently reserve the needed quality of service, because end-to-end Resource Reservation Protocol is still unavailable.

Second, applications and users might not get the appropriate bandwidth allocation because the technology cannot discern traffic type. DiffServ and traffic shaping provide only limited help, so an application or a user could thus be consuming all the available bandwidth, effectively shutting out other applications or users on that network. Or an unaware application could stream a 5-Gbyte video file over a 14.4-Kbits per second (Kbps) cellular data link or send a text-only version of a Web site over a 100-Mbps link. An application that “knows” the bandwidth along a path can avoid such mistakes by adapting the size and quality of its content or by choosing a Web server or proxy with higher bandwidth.

According to Larry Roberts, father of the Arpanet, (“Beyond Moore’s Law: Internet Growth Trends,” L. G. Roberts, *Computer*, Jan. 2000, pp. 117-119), for 18 years Internet hosts doubled every 15 months, and network traffic doubled every 12 months. Then, in 1997, after dense WDM began cutting communication costs in half every 12 months, the market responded by doubling the traffic rate every six months, reflecting a market elasticity of two. This was the first time that network performance had to improve at a rate faster than the 2x-per-18-months rate of Moore’s law. Now the maximum speed of core routers and switches must match a 4x-per-year growth rate.

**A BANDWIDTH BOUNDARY MODEL**

With a WDM-based optical network, theoretically, at gigabit speeds and beyond, response time should improve significantly. In practice, however, this is not always the case because, as Klienrock noted, light speed can affect latency so much that it becomes a severe limitation (“The Latency/Bandwidth Tradeoff in Gigabit Networks,” L. Kleinrock, *IEEE Communications*, Apr. 1992, pp. 36-40). Of course, WDM still makes sense in metropolitan areas, where light speed has only a negligible effect on latency.

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**Optical Technology and Wavelength-Division Multiplexing**

For the past several decades, optical fiber transmission has played a key role in increasing the bandwidth of telecommunications networks. Optical fiber offers much higher bandwidth than copper cables and is less susceptible to various kinds of electromagnetic noises and other undesirable effects. In 1996, local exchange carriers in the US had already deployed more than 360,000 sheath miles, containing more than 12 million fiber miles, and since then Internet-exchange carriers have deployed more than 106,000 route miles of fiber containing more than 2.9 million miles of optical fiber.

Examples of first-generation optical networks are the synchronous optical network (Sonet) and synchronous digital hierarchy (SDH), which form the core of telecommunications infrastructure in North America, Europe, and Asia. A 10-mile-long route using three fiber cables has 10 route miles and 30 sheath miles. If each cable has 20 fibers, that route essentially has 600 fiber miles. On average, more than half these miles are lit (in use), with the rest dark (not used).

Because the cost to lay additional fiber is relatively high, service providers are extremely interested in increasing the capacity of existing cables, and many see wavelength-division multiplexing (WDM) as a promising solution. WDM is essentially the same as frequency-division multiplexing, which radios have used for more than a century. The idea is to transmit data simultaneously at multiple carrier wavelengths over a fiber and to ensure that the wavelengths do not interfere with each other.

Even though WDM has become commercially available only recently, its deployment as a point-to-point transmission technology has been fast-paced. Systems are available in 8, 16, and 32 channels, and service providers are deploying OC-192 (10 Gbps). WDM transmission systems employing up to 32 wavelengths at 2.5 Gbps each over a single fiber are commercially available, and vendors are currently developing 40-channel WDM systems. Recent research has also produced up to 80 wavelengths transmitting simultaneously.

Economic and reliability considerations make the case for WDM particularly compelling for long-haul networks. For service providers, WDM-based technology is the preferred choice for deploying bandwidth and meeting traffic requirements across service provider networks. Multi-wavelength optical networking, for example, is expected to play a significant role in the next-generation transport networks.
Figure 1 shows two cross-country (3,000-mile) links connecting two pairs of transmitters and receivers. The first link operates at 100 Mbps; the second, at 1 Gbps. Propagation delay from light speed in the optical fiber is approximately 8 µsec per mile. If each transmitter wants to send a 1-Mbit message, it will take 24 ms (8 µsec per mile \times 3000) for that message to reach the corresponding receiver. As Figure 1a shows, each transmitter starts to transmit its 1-Mbit message at 0 ms. In Figure 1b, the leading edge of the messages on both links arrive at 10 ms simultaneously, even though transmitter 1 takes 10 times longer than transmitter 2 to complete its transmission. In Figure 1c, at 24 ms, both messages start to arrive at their respective receivers. Again, because the 100-Mbps link is 10 times slower, receiver 1 takes 10 times longer to completely receive its message.

The point is that, regardless of bandwidth, the propagation delay is the same for both links; the leading edges of both messages are at the same place at 0 ms, 10 ms, and 24 ms.

Now suppose the same links are part of a packet-switching optical network with \( h \) switches. To link these switches, the diameter path through this network will have \((h - 1)\) links. Given that propagation delay is 8 µsec per mile, the propagation delay through the network is then \( 8L(h - 1) \) µsec where \( L \) is the average length of each link in miles. These switches can be electro-optical switches that provide light paths and usually have switching times of a few milliseconds to a few subnanoseconds. In Sonet (Synchronous Optical Network) architectures, these switches could be either add/drop multiplexer (ADM), digital cross-connect (DCS) or ATM switches. Today’s DCSs have OC-3 or OC-12 ports (155 Mbps to 622 Mbps) and typically interconnect Sonet rings.

In a packet-switching optical network with more than one switch, multiple messages will be arriving and leaving each switch—in contrast to the situation in Figure 1, in which the 1-Mbit message is the only link traffic. Consequently, delays will occur from the queuing of the various messages. Given that \( C \) is the capacity of each wavelength link in Mbps and \( n \) is the number of wavelengths that WDM uses, the server capacity at each switch is \( Cn \) Mbps. The interdeparture time of packets \( 1/\mu \) (in µsec) is then \( b / Cn \), where \( \mu \) is the average service rate, and the utilization factor \( \rho \) at each queue is \( \rho = b / Cn \). We assume that the queuing delay in this scenario follows a Poisson distribution at a rate of \( \lambda \) messages per µsec, and that each message length is exponentially distributed with a mean of \( b \) bits—in other words, a classic M/M/1 queuing system. In this system, queuing delay is \( \rho (h - 1) / \lambda (1 - \rho) \). Hence for a single-message transfer, the end-to-end delay is \( \rho (h - 1) / \lambda (1 - \rho) + 8L(h-1) \).

Two major components make up the end-to-end delay: propagation delay and queuing delay. (A third, less important component is switch-processing delay.) These two terms define two regions: latency-limited and bandwidth-limited. If propagation delay is greater than queuing delay, then the delay from light speed dominates the end-to-end delay, which means latency limits transmission speed, the latency-limited region. If the queuing delay is greater than propagation delay, then queuing and transmission time dominate the end-to-end delay, which means bandwidth limits transmission speed, the bandwidth-limited region. The boundary is where propagation delay equals queuing delay, which occurs when the channel bandwidth (\( C \)) takes on the following boundary value:
Figure 2 shows the boundary bandwidth versus system load, again assuming a long-haul network with a total length of 3,000 miles. $L$ is then 120 miles, because when you send a packet on the Internet, the maximum number of hops (routers) it would traverse to reach its destination is 25 ($h = 25$), and packet size $b$ is 1,024 bits. In the figure, we have arrived at a boundary by fixing $n$ as 4, 8, or 12 and varying the load. Above the boundary, propagation delay effects dominate the system; below the boundary, additional bandwidth will help reduce the end-to-end delay. As bandwidth becomes large ($n = 12$), the region below the boundary shrinks, which means more bandwidth is not likely to reduce the end-to-end delay.

These boundary curves imply that at a certain point, latency impediments offset any benefit received from more bandwidth—an insight that should benefit those planning to use optical networks.

**EFFECTIVE BANDWIDTH MANAGEMENT**

Traffic patterns of newer applications such as B2B and peer-to-peer (P2P) contribute new complexity that IT network managers and service providers must consider when planning their network and offering services:

- The demand for bandwidth is skyrocketing. Corporate users and customers stay on the Internet for longer periods and download larger amounts of data. More and more data comprises images and video.
- The deployment of mission-critical applications on intranets and extranets is becoming more common. These include enterprise resource planning (ERP) applications such as SAP on the intranet and e-commerce and business-to-business (B2B) transaction packages on extranets.
- User attitudes are changing. Corporate users and customers expect instant access to information without delays or restrictions, especially if that information is critical to their work.
- Very different traffic types with different quality-of-service requirements must coexist. Traffic types include interactive telnet traffic, real-time voice and video traffic, and bulk FTP traffic. Almost all network links have more than one user or application, which means they must share available bandwidth.

As our model demonstrates, simply leasing more wavelengths or adding connections might not be enough to reduce message response time. Instead, IT network managers and service providers should look closely at the balance between bandwidth and latency, using the boundary curves as a planning model. The model, however, should be one of many bandwidth management techniques and tools that aid in planning and controlling the allocation of available bandwidth.

If a network link is continuously congested, the network manager must upgrade it to provide greater capacity. In many cases, however, the typical load is within the link’s capacity, and the link is congested only temporarily. If the link’s average use is below its capacity, a network manager can considerably improve the link’s performance by managing the available bandwidth capacity. Three techniques, caching, prefetching, and logistical networking, are effective techniques in reducing latency. The model supports all three of these by allowing the network to preload or pre-deliver more objects.

**Caching**

A cache is located between servers and clients and keeps copies of requested objects. If there is a repeated request for the same object, the cache (instead of the server) delivers the object to the client. Because a cache is closer to the client, it takes less time for the client to receive the requested object. A cache can be either at the browser (local cache) or at a proxy (proxy cache).
Prefetching
Prefetching objects into local caches involves recognizing patterns in a user’s past actions and predicting the next object that the user will select. Then before the user asks, the application loads the object either from caches nearer the user, from the server, or from some combination of these. As such, prefetching effectively exploits the idle time between user requests to deliver the object.

Logistical networking
A relatively new approach to moving and storing data on the network, this technique globally schedules and optimizes data movement, storage, and computation using a model that accounts for the network’s underlying physical resources. An example is the Internet Backplane Protocol (IBP), which uses depots on the network and implements a storage service that applications can use for logistical purposes, including object caching and distribution. Such characteristics make logistical networking useful in reducing latency effects.

Observing an intricate relationship
We have made a case for making bandwidth management part of the optical technology solution and offered a boundary bandwidth model to aid in planning. Our analysis is not meant to minimize the advantages of increased wavelengths for service providers, because greater bandwidth clearly helps them carry more traffic and thus generate more revenue, as well as helping reduce the variance in queuing delay variance. Rather, from an IT network’s perspective our analysis underscores the intricate relationship between optimizing message response time and leasing more bandwidth in WDM networks. For simplicity, we did not account for the other delays that occur at the protocol layers; the interaction among TCP/IP and ATM and Sonet protocol layers along with operating-system-related processing could greatly increase actual delays. Our point was to underline the importance of controlling delay effects and of managing bandwidth. Both are critical if network managers and service providers hope to use the network infrastructure to its fullest potential.

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