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Optical Networks and the Future of Broadband Services

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ABSTRACT

The evolution of broadband services will depend on the widespread deployment of optical networks. The deployment of such networks will, in turn, help drive increased demand for additional capacity. In this world, service providers will have a growing need to be able to flexibly adjust capacity to accommodate uncertain and growing demand.

In this article, we present a cost model that highlights the advantages of new optical networking technologies such as Dense Wavelength Division Multiplexing (DWDM) over traditional architectures for optical networks. This analysis highlights the increased flexibility and scalability of DWDM networks, which lowers the deployment costs of such networks in light of growing and uncertain demand.

The DWDM architecture holds the promise of allowing the emergence of wavelength markets, where traffic could be switched between service provider networks at the optical layer (without the need for multiple costly and wasteful electronic/optical conversions). While the DWDM and Optical Cross-Connect (OxC) technologies provide a technical infrastructure for supporting wavelength markets, additional developments are also likely to be required. This paper also considers some of the impediments to the growth of wavelength markets, namely the need for secondary markets and standardized contracts.

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INTRODUCTION

Ubiquitous broadband backbone and access networks are considered by many to be necessary for the Internet to realize its full potential. But there is only limited understanding of the technology required for end-to-end broadband Internet services in today's nascent multi-service, multi-provider environment. In the United States, the penetration of broadband services is growing rapidly, reaching 10 percent or more of all Internet households.[1] Current consumer broadband services, however, still only offer at best about 1Mbps per subscriber,[2] and many subscribers experience far lower data rates because of upstream congestion. Optical networking technologies hold the promise of unlocking these bandwidth bottlenecks and the potential of supporting mass market services that offer an order of magnitude or more improvement in bandwidth available to consumers.[3]

This article examines the implications of recent developments in optical networking technologies such as Dense Wavelength Division Multiplexing (DWDM) and optical cross-connect systems (OxC) for the development of next generation communications infrastructure. A preliminary cost model of an all-optical network making use of these technologies is compared to older optical networking architectures to highlight the increased flexibility and scalability inherent in the newer architectures.[4] These technologies change the economics of broadband services, with important implications for industry structure and the sorts of service markets that could develop, and indeed, must develop if the Internet is to remain robustly competitive and retain its multi-provider, multi-service character.

The development of broadband services has been hampered by endemic congestion. Because optical infrastructure is still relatively new and because capacity could only be added in relatively large increments (*i.e.*, investment is lumpy), deploying optical solutions has been quite expensive. Service providers face the dilemma of investing in excess capacity ahead of current demand, or tolerating congestion until pent-up demand warrants investing in the next increment of capacity. Moreover, as the Napster-experience has taught us, forecasting where and how broadband services will be used is extremely difficult.[5] In the absence of robust secondary markets for broadband capacity, investments in physical facilities (*e.g.*, fiber in the ground) are

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[1] Dial-up access at 56Kbps or less remains the dominant mode for residential Internet access, but broadband access is growing rapidly. As early as 1998, less than 1% of US households had broadband service, but by November 2000, Harris Interactive estimated that 3.6 million of the 38.9 million homes that subscribed to Internet service had broadband connections (see 14).

[2] Typical downstream rates are in the range of 1.5Mbps per connection for DSL and cable modem services, while upstream rates are usually substantially less.

[3] Access connections supporting 10Mbps, 100Mbps, or even 1Gbps are feasible as optical networking technology is pushed further towards the home.

[4] The analysis of DWDM technologies and costs in this article is based upon work initially done by Ferreira et al in [1].

[5] Napster is a peer-to-peer networking service that allowed end-users to share large MP3 music files directly with each other, resulting in substantially more traffic both downstream and upstream then network planners had originally planned for. Providers of broadband infrastructure were especially surprised by the fact that traffic was much more symmetric than anticipated with almost as much upstream as downstream traffic.

largely sunk and so the increased demand uncertainty associated with broadband services has further increased investment costs and encouraged providers to delay deployments.[6]

The resulting congestion, in turn, degrades the user-experience and suppresses demand for enhanced services (after all, who wants to watch streaming video over a congested network?). There is a chicken-or-egg problem: without the infrastructure, the services cannot develop; but without the services, there is insufficient demand to justify incurring the high costs of deployment.

The new optical technologies examined in this article address this problem by increasing the scalability of capacity expansions, which changes the economics of providing broadband services. The costs of deploying optical networking technologies is dropping and it is becoming feasible to push these technologies from the core to the periphery of the networks where demand is more bursty and even more uncertain than it is in the core of the network.

For the potential of these developments to be fully realized, however, the industry will need to develop standardized service offerings for optical transport. Optical networks prove to be an attractive solution from both a technological and an economic perspective but do not obviate completely the problems of service specification. Standardized offerings will need to be available both in the core and at the edges of the network to allow for the increased commoditization of the underlying transport services.

In the business data services market and in the core of the Internet, this problem has been addressed, in part, by increased reliance on Service Level Agreements (SLAs). These SLAs provide a mechanism for service providers and customers to flexibly specify the quality of service (QoS) that will be delivered. When used in conjunction with the new standards-based technical solutions for implementing QoS, these SLAs are helping to facilitate the development of robust wholesale markets for backbone transport services and content delivery services for commercial customers. The emergence of bandwidth traders, brokers, and exchanges provide an institutional and market-based framework to support effective competition, but to date, most of these participants have focused on traditional transport and interconnection services (*e.g.,* switched minutes, leased lines, or IP services).

Lehr and McKnight in [4] anticipated many of the developments occurring in bulk transport markets. These include the maturation and growth of bandwidth exchanges, the emergence of bandwidth brokers and speculators, and the creation of derivative financial securities such as futures, options, and bandwidth indices. In conjunction with these developments, substantial progress has been made towards developing such standardized technologies as DiffServ, IntServ, and other mechanisms to expand the range and flexibility of QoS guarantees that may be supported.[7] Adoption of these technologies within service provider networks means that the

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[6] Real options theory tells us that, in the face of uncertainty, irreversible (*i.e.*, sunk) investments that may be delayed are more costly to make. See [2] for a general discussion of how real options affect investment decisions. For an application of this to Internet infrastructure costs, see [3].

[7] For more information on the Internet Engineering Task Force's work on quality of service-related protocols including RSVP, IntServ and DiffServ, see 15 and 16.

basic technical and physical infrastructure is emerging within the core of the network and in the access services available to large commercial customers to support the holy grail of end-to-end QoS across multiple carrier domains. The emergence of all optical networks may simplify the task of commoditizing transport which is a necessary precursor to the emergence of robust secondary markets. This is because trading based on wavelengths provides a natural unit for exchange, thereby avoiding much of the confusion and complexity that arises when one considers commoditizing IP-based services.[8]

The emergence of optical networking also increases the need for secondary markets to facilitate the reallocation of available capacity. The deployment of broadband technology that unlocks a capacity bottleneck at one stage, can often create a bottleneck at another stage because of the pent-up demand (and services) it supports. Fiber deployments that provide terabits of excess capacity along some routes co-exist in a national network that has severe scarcity along other routes. Moreover, because of the burstiness of Internet traffic,[9] localized congestion (geographic or time of day) can occur even in well-provisioned networks. Broadband accentuates this problem because it increases the potential burst size. And, uncertain demand means that it is difficult to accurately forecast how much capacity will be needed at which time in which part of the network. Secondary markets that allow providers to transfer rights to use available capacity can significantly lower adjustment costs for all providers and thereby increase suppliers willingness to invest in new broadband services and infrastructure.

NEW DEVELOPMENTS IN OPTICAL NETWORKING

Building out a facilities network takes a long time and a lot of money. While many providers have invested in deploying substantial amounts of fiber capacity, the coverage of this fiber is not ubiquitous and it is prohibitively expensive – and unnecessary – for facilities providers to install capacity everywhere. The biggest component in the costs for new fiber are associated with the installation of the fiber (acquiring the rights of way, installing the conduit, putting the fiber in the conduit, etc.). Because it is so costly to lay fiber, it makes sense to install a lot of fiber along each route (multiple fibers in each bundle, multiple bundles in each conduit). Firms like Qwest, Level 3, and Williams pioneered new business models for financing investment in massive fiber expansions by cleverly exploiting control of rights of way, new technologies for deploying fiber, and through forward-sales of fiber to help finance the large up-front investment. Through the

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[8] While commoditization is perhaps easier in an all-optical framework, there are likely to be additional contracting features that are likely to prove more difficult to standardize (*e.g.*, reliability, contract duration, etc.). The need for standardized contracts is greater if one considers trading in edge networks, especially involving individual consumers, because of the lower tolerance for contracting overhead. That is, wavelength swaps between backbone providers may be more readily customized because transaction costs are likely to represent a lower share of the potential gains from trade.

[9] Bursty traffic has a high peak to average data rate. This is typical of Internet traffic. The mixture of different applications (file transfers, email, telephony, etc.) and intermittent nature of some traffic (download a file and then spend time reviewing) means that traffic is not smooth. For example, when someone browses the web they download a page (burst) and then read it (no traffic). See [5] for a discussion of provisioning for bursty Internet traffic.

efforts of these firms and others, the amount of installed fiber capacity has increased substantially in recent years.[10]

In addition to installing new fiber, service providers can also upgrade the capacity of existing networks through technologies such as Time Division Multiplexing (TDM). TDM increases the capacity of a fiber by slicing time into smaller intervals. This has been the industry method of choice for upgrading the capacity of their fiber optic networks. However, carriers using this approach have to make the leap to the next bit rate all in one jump, thus having to purchase more capacity than they initially need.[11] Also, at higher data rates, TDM systems become more expensive to operate and install, and there are practical limits to how much capacity can be added via a TDM approach.[12]

Dense Wavelength Division Multiplexing (DWDM) offers a newer and superior solution for increasing the capacity of embedded fiber. DWDM operates by using different wavelengths of light for multiplexing multiple signals onto a single fiber that can be amplified and transported as a group over the same fiber. When TDM or other multiplexing strategies are layered on top, the ability to flexibly expand the number of lit wavelengths on a fiber makes it possible to expand the capacity of in-place fiber geometrically. This greatly extends the life of installed fiber (thereby lowering its cost).

A number of technological advances have proved crucial in the development of DWDM. These include exploitation of the new low loss of silica-fiber in the 1500 nm band and making use of powerful amplifiers to transport multiplexed channels of independent information over the same fiber. Key to the deployment of DWDM systems, is the development of the Erbium-Doped Fiber Amplifier - EDFA[13] - that lessens fiber attenuation.[14] Other key DWDM network technologies are the DWDM transponder[15], the Wavelength Add/Drop Multiplexer[16] and the Optical Cross-

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[10] For example, in the United States, the FCC reported that fiber capacity increased from 953 thousand to 19.8 million fiber miles from 1985 to 1998, or 26% per year. (See 17). The data on fiber deployed represents the sum of fiber miles deployed by interexchange carriers and local telephone companies, and is larger than the route miles of installed fiber because each sheath may include multiple fibers.)

[11] For instance, the next incremental step from a 10 Gbps TDM system based on a SONET hierarchy is a 40 Gbps system.

[12] Increased attenuation resulting from increased dispersion at higher bandwidth rates is an inherent problem for TDM systems. Countering this requires greater expense for amplification and repeaters. Dispersion refers to the smearing or broadening of an optical signal that results from the many discrete wavelength components traveling at different rates. The increased dispersion occurs because the bandwidth is inversely proportional to the pulse width in TDM networks. Therefore, a higher bandwidth in a TDM system will create a shorter pulse width or higher frequency, making it more susceptible to fiber dispersion.

[13] The Erbium-Doped Fiber Amplifier – EDFA -, which operates only in the 1500 nm pass-band, is a section of fiber optic cable that has been doped with erbium to amplify the optical signal. Strategically spaced across a fiber span, in-line EDFAs amplify the DWDM signals and boost them on their way to the next amplifier, or to a termination point.

[14] Attenuation is the reduction of signal strength or light power over the length of the light-carrying medium.

[15]The DWDM transponder consists in circuit boards and lasers that pack different colored wavelengths onto a single fiber. These extremely high-frequency signals in the 192 THz to 200 THz range are spaced anywhere between 50 GHz to 100 GHz and are sent in one direction down the length of the fiber.

Connect – OxC [6]. The OxC is the system component that provides cross-connect functionality between N input ports and N output ports, each handling a bundle of multiplexed single-wavelength signals, as shown in Figure 1.

The OxC is the most complex DWDM component, and only recently, have commercial versions become available in the market. In the absence of the OxC, the DWDM offers a more scalable way to lower the costs of expanding optical network capacity. OxC's make it possible to dynamically reconfigure optical networks at the wavelength level. This allows network providers to transport and manage wavelengths efficiently.[17]

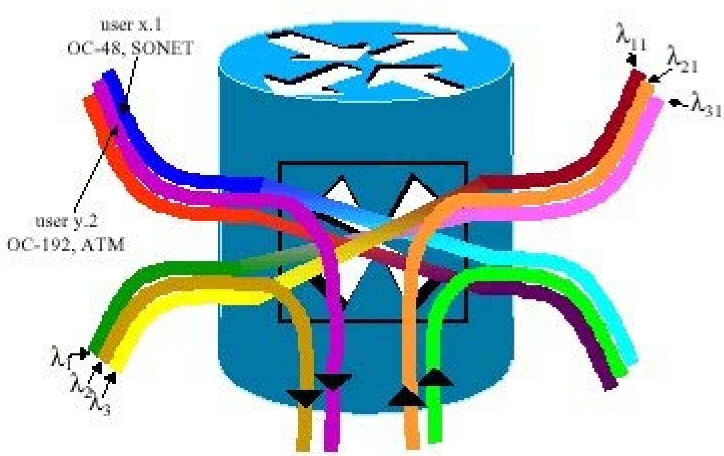

Figure 1- Schematic representation of an Optical Cross-Connect.

This ability to dynamically reconfigure optical networks makes it feasible to flexibly interconnect optical services provided by multiple providers, and thereby provides an important piece of the technical infrastructure needed to support secondary markets for broadband services based on a marketplace for wavelengths.

Networks are designed as a series of layers, each of which is associated with a different set of functions and responsibilities.[18] At the bottom are the physical facilities such as the wires, coaxial cables, microwave channels, satellite links, or fiber optic cable over which a signal is

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[16] The Wavelength Add/Drop Multiplexer – WADM - is the optical sub-system that facilitates the evolution of the single wavelength point-to-point optical network to the wavelength division multiplexed networks. It is responsible for selectively removing and reinserting individual channels, without having to regenerate the all of the WDM channels.

[17] In order to manage wavelengths efficiently an OxC should provide wavelength routing and space conversion (shift of sets of wavelengths across bands in the spectrum) still guaranteeing some level of protection.

[18] The classical layered architecture consists of the following (from bottom to top): (1) Physical; (2) Data link; (3) Network; (4) Transport; (5) Session; (6) Presentation; and (7) Application. The Internet Protocol (IP) is a layer (3) networking technology that is designed to operate on top of a wide range of underlying data link layers. It is this flexibility that provides the Internet with much of its strength as a technology for wide area, interoperable networking.

transmitted. At the top, are the end-user applications. The layers in between make it possible for multiple applications to operate over diverse types of network media. Each layer only needs to know about the layers immediately above and below it, so interoperability can be achieved via an intermediate layer protocol that supports multiple lower level protocols that are not directly interoperable. The Internet Protocol (IP), on which the Internet is based, offers an extreme version of this principle: IP can run on top of almost anything. This allows IP to serve as a spanning layer to provide wide area networking across heterogeneous infrastructure.[19]

Connectivity across traditional optical networks is provided by the SONET architecture.[20] SONET provides a framework for layering an electronic network on top of fiber optic channels. It is also possible to layer other networking technologies such as Asynchronous Transfer Mode (ATM) on top of SONET. For wider area networking, IP can be layered on top of ATM (IP-on-ATM-on-SONET). These strategies are useful in allowing legacy networks to interoperate and in integrating new technologies, but they can involve an excessive amount of administrative overhead and may not be very efficient in utilizing capacity.

With the develop of DWDM and complementary technologies such as OxCs, it becomes feasible to imagine a so-called "optical layer" that exists below the electronic interfaces supported by traditional networking technologies. It is inherently inefficient to de-multiplex an optical signal into an electronic signal for interconnection and switching and then re-multiplex back into an optical signal for transport. If switching and interconnection could be supported within the optical layer, this would increase efficiency, reducing end-to-end delays and networking costs. If switching and interconnection could be supported within the optical layer – without having to convert from optical to electronic signals and back again. The DWDM advances make this a more likely option.

The new optical layer is transparent to the SONET layer and provides restoration, performance monitoring, and provision of individual wavelengths[21]. This layered hierarchy is depicted in Figure 2.

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[19] See [7].

[20] The SONET layer provides lower-level functionality, including restoration, performance monitoring, and provisioning services to higher layer protocols such as those supporting the network.

[21] The optical layer provides point-to-point light-paths.

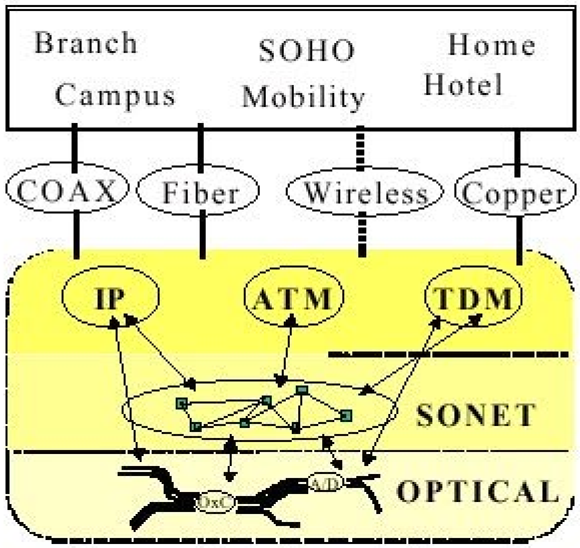

Figure 2- Layered perspective of a telecommunications network.

DWDM is based on wavelength routing and thus it allows the Internet Backbone Provider (IBP) to assign separate wavelengths to different customers facilitating the provision of different services over the same fiber [8]. Moreover, and as the incoming signals never terminate in the optical layer, the DWDM interface can be bit-rate and format independent, which allows the IBP to easily integrate DWDM solutions with existing equipment in the network still gaining access to the untapped capacity in the embedded fiber. Additionally, DWDM allows for a “grow-as-you-go” strategy. The IBP can add TDM systems on the top of a DWDM architecture as needed for virtually endless capacity expansion. IBPs can also enjoy the flexibility to expand capacity in any portion of their networks, addressing specific problem areas that are congested because of high capacity demands, which is usually the case where multiple rings intersect.

These advantages make DWDM technology more flexible and scalable than legacy optical technology. DWDM technology should also be able to support more flexible and rapid service provisioning, which is critical for the emergence of a wavelength marketplace. For robust secondary markets to emerge, optical transport will need to become commoditized which requires the development of Standardized Service Level Agreements (SLAs). These SLAs will be especially important to enable rapid provisioning in a multiprovider network environment. Developing such SLAs for an optical layer may prove easier than for IP services if trading is based on wavelengths because these provide a relatively unambiguous and well-understood unit for optical transport. However, there will still be other features that will need to be standardized to allow optical transport to be commoditized in a decentralized network environment. These will include features such as contract duration, reliability (and what happens in event of a system failure), and interconnection procedures and processes.

AN OPTICAL NETWORK COST MODEL

In this section, we present the results of a preliminary cost model for an optical network using DWDM technology and compare this with a legacy optical network.[22] The architecture of the model is depicted in Figure 3. We assume a static network architecture and we model its capital and recurring costs and the revenues. For the case of the capital costs, we consider in detail the structure of the Points of Presence (POPs) and of the links between POPs.

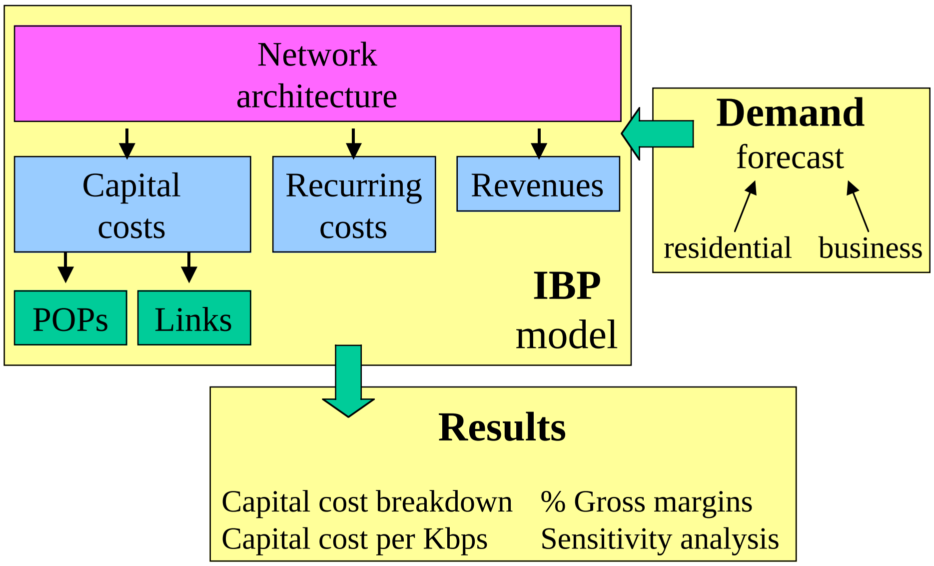

Figure 3- Architecture of the cost model.

A demand forecast module generates input parameters for the IBP cost model. The output of the IBP cost model includes a breakdown of capital costs per component, the capital costs per Kbps served and the percentage gross margins earned for different rates of demand growth. We also investigate the sensitivity of capital cost per Kbps served under various scenarios. The following sub-sections explain the model in greater detail.

Network Architecture

We model an optical network with 9 POPs. These POPs form 4 cells, each with a full-mesh SONET-based network, as shown in Figure 4. Two direct links between nodes far apart were also added for additional reliability and routing flexibility[23].

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[22] For a cost model on a traditional ISP with legacy technology, see [9].

[23] The architecture presented here is very typical of most nation-wide IBPs in the US. See for example PSINet Inc. and Sprint Corp. at http://www.boardwatch.com/isp/. Such a structure, with 9 major POPs, is usually deployed in conjunction with several second tier regional POPs, which we do not include in our model.

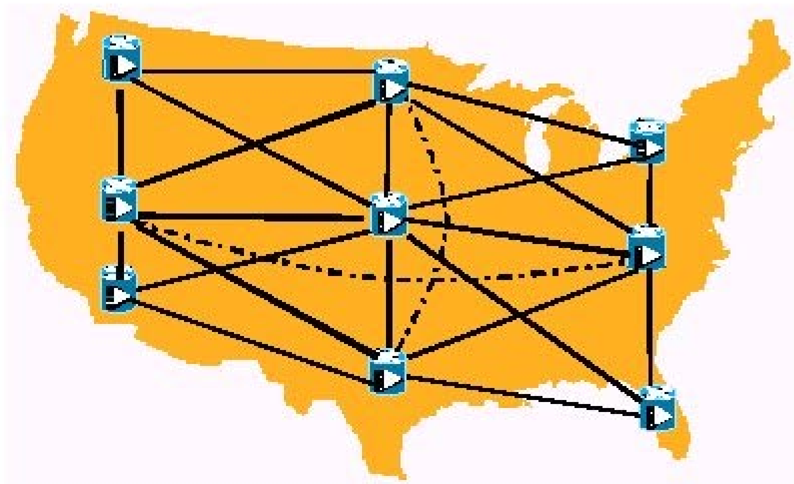

Figure 4- Network topology for a generic Internet Backbone Provider

Capital Costs

While the topology is the same for the legacy and DWDM networks, they differ in a number of important ways. First, the type and amount of equipment included in a POP are different in the two architectures, as shown in Figure 5. In both cases, the POP includes a Router. However, in the legacy network, there is an Add/Drop Multiplexer (ADM) that routes the long-haul traffic directly to the other POPs and drops the local traffic to the router, which routes this traffic to the metropolitan area served by the POP. In the DWDM architecture, the ADM is replaced with an OxC and a DWDM terminal. The DWDM terminal multiplexes several channels over the same fiber through different wavelengths and the OxC routes wavelengths separately and independently [10].

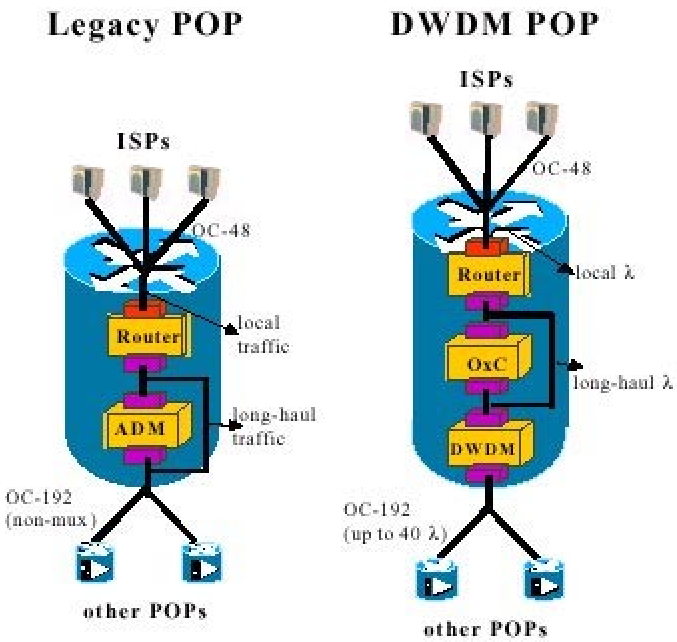

Figure 5- Generic Architecture for a POP in the legacy and DWDM networks.

The unit costs for this equipment are summarized in Table 1. The total capital cost for a DWDM POP is greater than for a legacy POP for a variety of reasons. First, the ADM is a more mature technology and so equipment prices reflect experience curve benefits. Second, the router in the DWDM POP requires more ports than the one in the legacy POP in order to handle the multiplexed channels.

Equipment	Legacy POP	DWDM POP	Units
Router	Ports to ISP: 80,000 Ports to ADM: 300,000	Ports to ISP: 80,000 Ports to OxC: 300,000	US$/port
ADM	40,000	-	US$/channel
Cross connect	-	75,000	US$/port
DWDM	-	79,500	US$/port

Table 1- Equipment costs for the components included in the POPs[24].

There are also systematic differences in the costs of the transmission links connecting the POPs in the two architectures. To estimate these costs we need to determine the number of amplifiers and regenerators required per link. The cost of amplifiers and regenerators in the legacy network is $80,000 for each pair of fibers; while in the DWDM network, these rise to $560,000 per fiber because they are substantially more complex devices that amplify and regenerate the multiplexed signal. The number of amplifiers and regenerators required per link depends on the length of the link and on the admissible attenuation between amplifiers. For the fiber itself, we have assumed

[24] The source for the costs presented in this table was private conversation with equipment vendor.

that the IBP leases fiber already in place through an Indefeasible Right of Use (IRU) contract, which grants ownership for 20 years, at a price of $4,800 per mile.[25]

Recurring Costs

We also included variable costs in the model. These included recurring network operating costs, retail-level sales and marketing costs, as well as general administration costs, as shown in Table 2. The recurring operating costs included monthly rental charges, personnel costs, and software licensing fees. We have also considered a low replacement rate for faulty equipment, applied to multiplexing equipment. **[modification]**

Item	**Value**	**Comments and sources**
Rent	4000 $/month	Average price offered by some collocation services: http://www.inway.cz/inway/eng/cenik_web.html http://hosting.marlabs.com/service_pricing.html
Technical Salary	110000 $/year	Bureau of Labor Statistics (www.bls.org) Average wage for IT-related manufacturing industries
Technicians	15	Average number of employees per POP for major IBPs (source: www.boardwatch.com)
Specialized Software	30000 $/month	Average price for software used to emulate routers (egs. www.cisco.com and www.ciena.com)
Replacement of Faulty Equipment	0.50%	Similar to reported network availability (source: www.band-x.com)
Sales, Marketing and Administration	25%	B. Cossa [19], who drew a regression using Boardwatch data on the major IBPs in the US [11]

Table 2- Recurring costs per POP and respective sources[26].

Revenues

Revenues were modeled by assuming that ISPs earn an operating margin of 20 percent and that they charge $20 per month per residential subscriber. Business customers are estimated to pay $1.5 per Kbps per month, which reflects a 40% discount off of the effective Kbps charge to residential consumers and is consistent with current pricing.[27] Prices are assumed to decline over time in accordance with Moore's Law.[28]

Demand

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[25] IRUs are granted by the company that builds the optical fiber cable. They provide temporary ownership of a portion of the capacity of a cable and are usually specified in terms of a certain number of channels of a given bandwidth. The estimate presented here is based on the price for an IRU for dark fiber in the state of Minnesota according to http://www.dot.state.mn.us/connect/rates.html. The price used in our model is an upper bound, since we expect the price of fiber to drop over time. The sensitivity analysis in the end of the paper captures the effects of such a decrease.

[26] The source for the costs presented in this table was private conversation with equipment vendor.

[27] As an example, MCI-WorldCom and AT&T charge 1.5 $US per Kbps for a T1 connection (see [20]*)*

[28] Note that Moore's law refers that prices fall 50% every 18 months, which entails a monthly decrease rate of about 3%, which was the figure used in the model.

Finally, the traffic handled by the IBP includes within state traffic as well as traffic from other IBPs that co-locate with the IBP's POP. Demand is forecasted separately for residential and commercial customers by state based on the residential population and workforce size, and using assumptions about Internet penetration and the market share captured by the IBP. The demand for the representative residential or commercial customer is parameterized by assuming an average bandwidth and a probability of being active during the peak period. The data used to parameterize the demand is shown in Table 3. Aggregated demand is assumed to growth 60% per year.

Item	**Value**	**Comments and sources**
Residential demand		
Population	5,200,000	Average population per state in the US (source: www.census.gov)
Internet penetration	34%	Average Internet penetration ratio in the US (source: Pulse Online [18])
Market share	10%	Assumed for the IBP modeled
% users active at peek	10%	Source: "Internet Telephony" [9]
Bandwidth/user	100 Kbps	Average given penetration of access technologies (source: "Internet Telephony[a] [9])
Business demand		
Population	2,000,000	Average number of employees per state in the US (source: www.bls.org)
Internet penetration	60%	Assumed about twice of the residential segment
Market share	40%	Assumed for the IBP modeled
% users active at peek	20%	Assumed about twice of the residential segment
Bandwidth/user	300 Kbps	Average assuming higher penetration of faster access technologies at work

Table 3- Assumptions to model demand for IP traffic per POP.

To account for interconnection traffic, we have also assumed that our IBP handles traffic from other IBPs. The amount of traffic that the other IBPs send to our IBP is proportional to their market share, 90% and 60% for the residential and business segments, respectively.

Results

The capital costs for a network to service a level of demand of 360 Gbps using the legacy architecture is $3.3 billion versus $4.4 billion for the newer DWDM architecture[29]. This reflects the higher capital costs inherent in deploying a new technology which has yet to benefit from experience effects.

An analysis of the composition of capital cost shares in the overall networks (see Table 4), demonstrates that a much higher share of the total costs is in the POPs rather than the transmission links for the DWDM network (74 percent) versus the legacy network (7 percent). Multiplexing up to 40 channels per OC-192 in the DWDM scenario reduces drastically the

[29] The level of demand of 360 Gbps is obtained by summing up the demand of all the sources in the model. According to the IP traffic estimates provided by Prof. Schulzrinne at the Department of Computer Science at Columbia University (available at http://www.cs.columbia.edu/~hgs/internet/traffic.html), this level of demand can correspond to the one we will find by the end of 2002 in the US backbone.

number of fibers deployed relative to the legacy network, which reduces the number of fiber pairs needed and the accompanying cost of amplifiers and repeaters.

Legacy Network		**DWDM Network**	
Fiber	57	Fiber	10
In-line amplifier	30	In-line amplifier	13
Regenerator	6	Regenerator	3
ADM	1	DWDM	25
Router	6	Router	37
		Cross connect	12

Table 4- Breakdown of initial capital costs for default scenario (percentage terms)

Although the DWDM system is more expensive in the default case, the reverse is true if demand turns out to be an order of magnitude larger. For a network capable of handling 3.6 TBps of traffic, the DWDM network costs $6B, while the legacy network costs $21B. Thus, the DWDM network is substantially more scalable than the legacy network, as is clear from Figure 6,which plots the capital cost per Kbps to build a network and extend it over time to meet growing levels of demand.[30] While a DWDM network is more expensive as long as demand is no more than twice the base demand, for higher levels of demand, the DWDM architecture is preferred. Although the cost per Kbps of capacity for the legacy network decreases as the installed capacity increases, it reaches a minimum value of $5.5.[31] This is not the case for the DWDM network. The cost per Kbps for this network decreases down to 0.5 $US and it is already significantly lower for terabit levels of demand.

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[30] In this figure the horizontal axis also represents time, as demand is assumed to grow 60% per year.

[31] The cost per Kbps oscillates with time because we have assumed that all equipment has an economic life of 5 years (expect for the fiber, which may be used without restriction during the entire lease period). These oscillations are not so clear for the DWDM case because the capacity of the network is already very large after the first 5 years, and the cost per Kbps low.

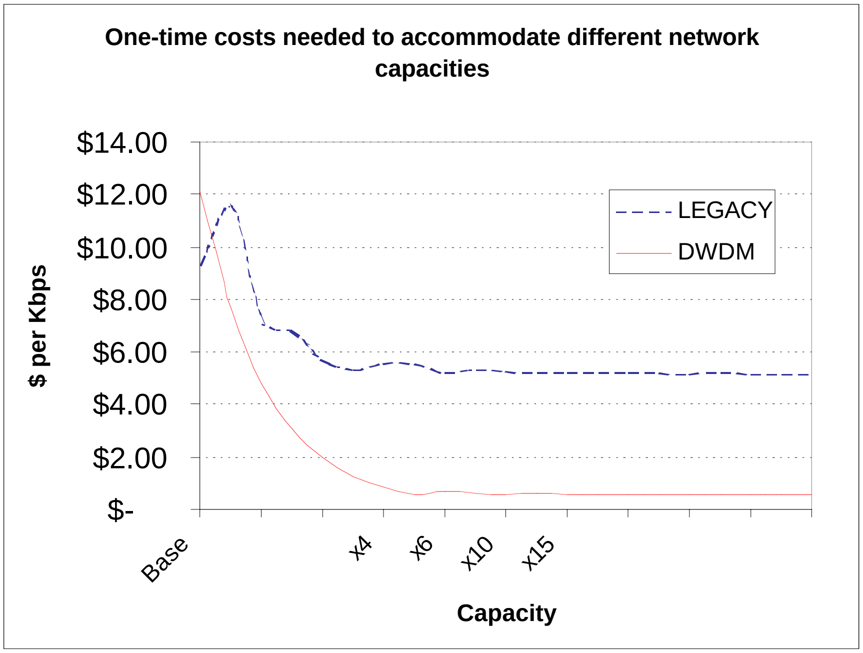

Figure 6- Capital costs incurred per Kbps over time.

An analysis of the percentage gross margin over 10 years for both the legacy and the DWDM networks is presented in Figure 7 for several yearly growth rates of demand.[32] Again, the scalability of DWDM networks is evident from the fact that the DWDM gross margin remains relatively constant over a wide range of demand growth rates, while the legacy network is high only if demand growth is relatively low (less than 15 percent) and drops precipitously for still higher rates which are actually closer to what we have been seeing in practice.

[32] The percentage gross margin is a ratio widely used to measure the percentage of revenues collected after all production costs have been paid. The dollar gross margin is defined as the sum of the discounted revenues over a certain period of operation minus the sum of discounted costs incurred over the same period. The percentage gross margin is ratio between the dollar gross margin and the sum of discounted revenues over that period.

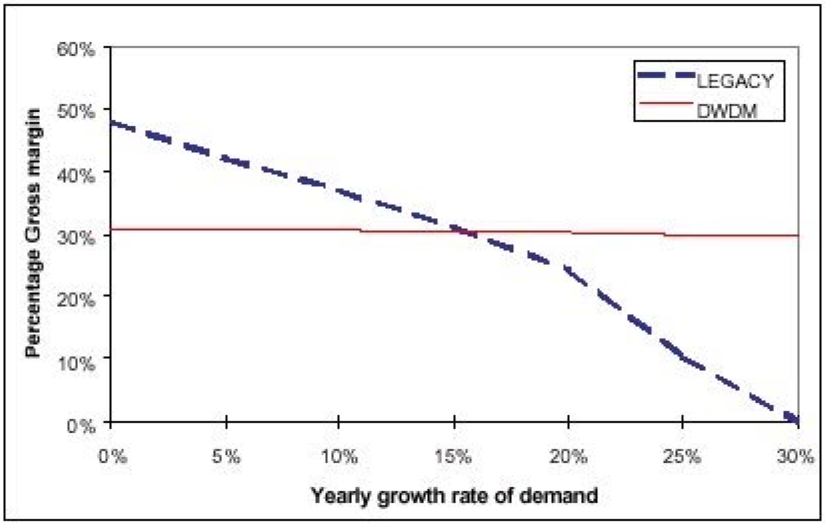

Figure 7- Percentage Gross Margins for different levels of yearly growth rate of demand.

We performed a Net Present Value (NPV) analysis for both networks over a period of 15 years. For the default scenario, the payback time is about 2.5 years for both networks. However, for the legacy network the cumulative NPV starts decreasing after year 4, which means that the legacy network is not able to cope with the increased demand and the IBP starts loosing money. The poor profitability of the legacy network is related to its inability to scale and accommodate more users and is a function of the demand growth rate, which we have assumed to be 60% per year. The poor scalability of the legacy network relative to the DWDM network is even more evident for growth rates above 60% per year, because for those cases its cumulative NPV never becomes positive during the 15 years period of analysis.

Finally, we performed a sensitivity analysis on the results obtained in order to understand how the capital costs per Kbps (the measure shown in Figure 6) are affected by the parameters of the model. Tornado diagrams[33] for both the legacy network and the DWDM network are shown in Figure 7. The modeling parameters with the largest effect on the capital cost per Kbps under variable demand are listed first. Business Internet penetration and the lease cost for a 20-year fiber IRU are the most important for both types of networks. This highlights the fact that the high price of dark fiber remains an issue for the deployment of optical backbones. In terms of equipment, the components at the POPs are more relevant for the DWDM network while the equipment along the fibers is more important for the legacy network. This reflects the relative cost of POPs and links as it was shown in Table 4.

[33] The Tornado diagrams shown indicate how the costs per Kbps change with changes in the parameters of the model. There is a horizontal bar for each parameter that indicates, down in the horizontal axis, the cost per Kbps for different values of that parameter holding all the other parameters fixed. Each parameter was modified in the range shown near to its horizontal bar.

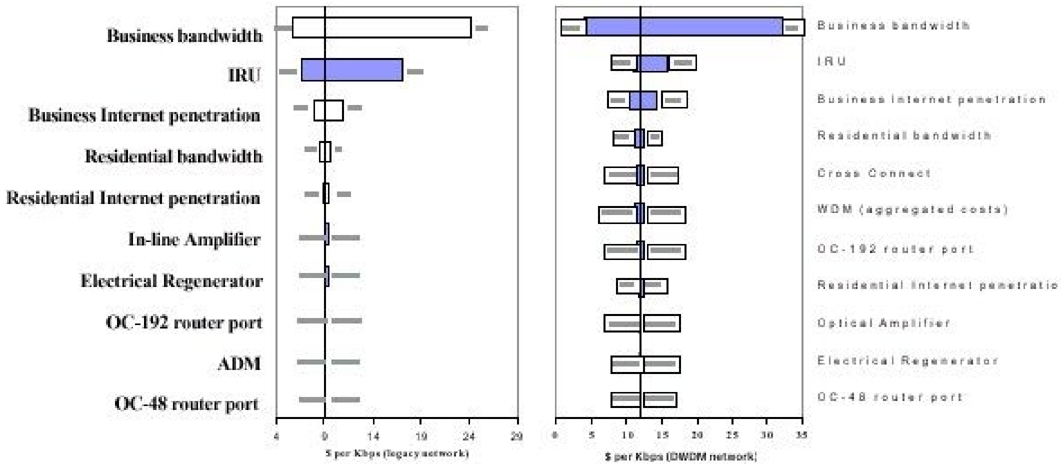

Figure 8- Sensitivity analysis of the capital cost per Kbps for both networks.

Finally, we observe that new and expensive equipment for the DWDM implementation, namely the OxC and the WDM terminal, impacts significantly the capital costs per Kbps incurred to build and maintain the network according to the estimated increase in demand. Consequently, decreases in the price of these components as they become widely accessible will certainly improve the scalability of DWDM networks. However, without standards and policies for wavelength trading, these capital cost reductions alone will do little to improve the efficiency of wavelength markets.

CONCLUSIONS

This article examines the implications for next generation communications infrastructure from the deployment of new optical networking technologies such as Dense Wave Division Multiplexing (DWDM). With the commercialization of DWDM and complementary Optical Cross-Connects (OxC), wide-spread deployment of all optical networks is becoming increasingly feasible. These new architectures have a number of important potential advantages.

We have demonstrated by a preliminary cost model that newer optical network architectures exploiting DWDM are inherently more flexible and scalable than traditional optical networks. This substantially lowers the lifecycle costs of provisioning for rapidly growing and uncertain demand. We have shown that wavelength provisioning is an attractive solution from a technological and economic viewpoint. In light of increased demand uncertainty (which applications? which locations? on which suppliers networks? from which customers?), there is an even greater need to more flexibly reallocate capacity among suppliers to address localized congestion bottlenecks. We have shown that DWDM technology can be successfully used for this purpose, because it provides a sophisticated control plane to assign and switch wavelengths across users independently of each other.

However, to make wavelength trading feasible in real time and in edge networks in a multicarrier environment, robust secondary markets will be needed which will require the commoditization of optical transport services. While the development of standardized wavelength trading contracts may be easier to develop than equivalent generic services based on IP transport layer services, there are still many issues which will need to be resolved. Carriers still need to agree upon a set of parameters in order to use each other's wavelengths, such as the bandwidth provided, the level of protection supported, the duration of and starting time of the service, the ingress and the egress nodes and the definition of penalties in case of failure. In other words, despite the significant flexibility of the control plane of OXCs to re-allocate wavelengths among users, parallel SLAs still need to be considered to parameterize the wavelength offers.

Broadband networks are likely to be even more bursty than narrowband networks and the implications of transitory bottlenecks will continue to pose a threat for the development of broadband services. This means that there will likely be a growing demand for secondary markets to allow owners of excess capacity to trade with providers or customers in need of additional capacity.

References

[1] report: Ferreira, P., Cossa, B. and Naud, F., *"A Cost Model for Optical Backbones*, submitted to DHPP232/ESD127/STP308, Telecommunications Modeling and Policy Analysis, Professors Lee McKnight and Jean Camp, Fletcher School-Tufts/MIT/Harvard Universities, Spring 2000.

[2] book: Dixit, Avinash and Robert Pindyck, *Investment Under Uncertainty*, Princeton, NJ: Princeton University Press, 1994

[3] journal: Hubbard, R. Glenn and William Lehr, "Telecommunications, the Internet, and the Cost of Capital," in The Internet Upheaval , edited by Ingo Vogelsang and Ben Compaine, Cambrige: MIT Press, 2000.

[4] journal: Lehr, William and Lee McKnight, "Next Generation Bandwidth Markets," in *Communications & Strategies*, 4th Quarter, October 1998.

[5] conference paper: Clark, David and William Lehr, "Provisioning for Bursty Internet Traffic: Implications for Industry Structure," paper presented to Workshop on Internet Service Quality Economics, Massachusetts Institute of Technology, December 2-3, 1999, Cambridge, MA.

[6] book: Ramaswami, R. and Sivarajan, K., *Optical Networks: A Practical Perspective*, Academic Press, Morgan Kaufmann, 1998

[7] chapter in book: Kavassalis, Petros and William Lehr, "The Flexible Specialization Path of the Internet," in *Convergence in Communications and Beyond*, edited by Erik Bohlin, Karolina Brodin, Anders Lundgren, and Bertil Thorngren, Amsterdam: Elsevier Science, October, 2000.

[8] book: Agrawal, G., *Fiber-optic Communication Systems*, 2nd Edition, New York, John Wiley & Sons, 1997.

[9] chapter in book: McKnight, L. and Leida, B., *"Internet Telephony: Costs, Pricing and Policy*", in McKnight, L., Lehr, W, and D. Clark, eds., *Internet Telephony*, MIT Press, 2001.

[10] report: Bell Labs, *Dense Wavelength Division Multiplexing Tutorial*, The International Engineering Consortium, Lucent Technologies, 2000.

[11] magazine: Boardwatch Magazine, *Directory of Internet Service Providers*, Spring 2000.

[12] conference paper: Lehr, William, and Lee W. McKnight, "A Broadband Access Market Framework: Towards Consumer Service Level Agreements," 28th Annual TPRC, Alexandria, VA, September 2000.

[13] book: Odlyzko, Andrew. "Internet pricing and the history of communications" in McKnight, L. and J., Wroclawski, *Internet Services*, MIT Press (forthcoming)

not yet in the right order:

[14] press release: "Plenty of Demand for Broadband, According to Harris Interactive Consumer TechPoll," *Press Release, Harris Interactive*, <http://www.harrisinteractive.com>, November 28, 2000

[15] webpage: www.ietf.org

[16] webpage: MIT/Tufts Workshop on Internet Service Quality Economics, available on-line at: http://www.marengoresearch.com/isqe

[17] press release: Kraushaar, J., *"Fiber Deployment Update: End of Year* 1998", Federal Communications Commission, September 9, 1999

[18] press release: Pulse Online:*"Carriers turn to DWDM for enhancing fiber optic networks", May 1999*

[19] thesis: B. Cossa, *"Economic and Policy Analysis of Mergers Among IBPs"*, MS. Technology & Policy thesis, MIT, 2000

[20] press release: Enck, J.,*"Windows NT Networking: A Collection of Topics"*, June 1998, 29th Street Press