The Future of WDM: An Engineering and Economic analysis

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1. Introduction:

The advent of new information technologies has created both opportunities and challenges. These opportunities and challenges are both economic and engineering in nature. Creation and application of any new technology depends on both economic incentives and engineering ingenuity. Any meaningful analysis of a new technology should, therefore, address at least the engineering and economic aspects.

The purpose of this paper is to look at a recent technology of information transmission in the fiber optics area. The technology in question is known as WDM or wavelength multiplexing. The engineering aspects known to us and discussed in the next section already indicate tremendous potential for both producers and consumers. However the integration of an engineering analysis with an economic analysis will be crucial for estimating the possible paths of diffusion and the costs and benefits for the society of this new technology. Accordingly this paper begins with an engineering analysis in section 2 and then moves to an economic analysis in section three. The latter analysis is both general in terms of addressing the economics of high technology sectors and specific to the characteristic features of WDM. Our analysis thus helps uncover the links between the engineering and economic aspects. On the basis of this interdisciplinary analytical effort we try to ascertain both the short term and the long run prospects and implications of WDM.
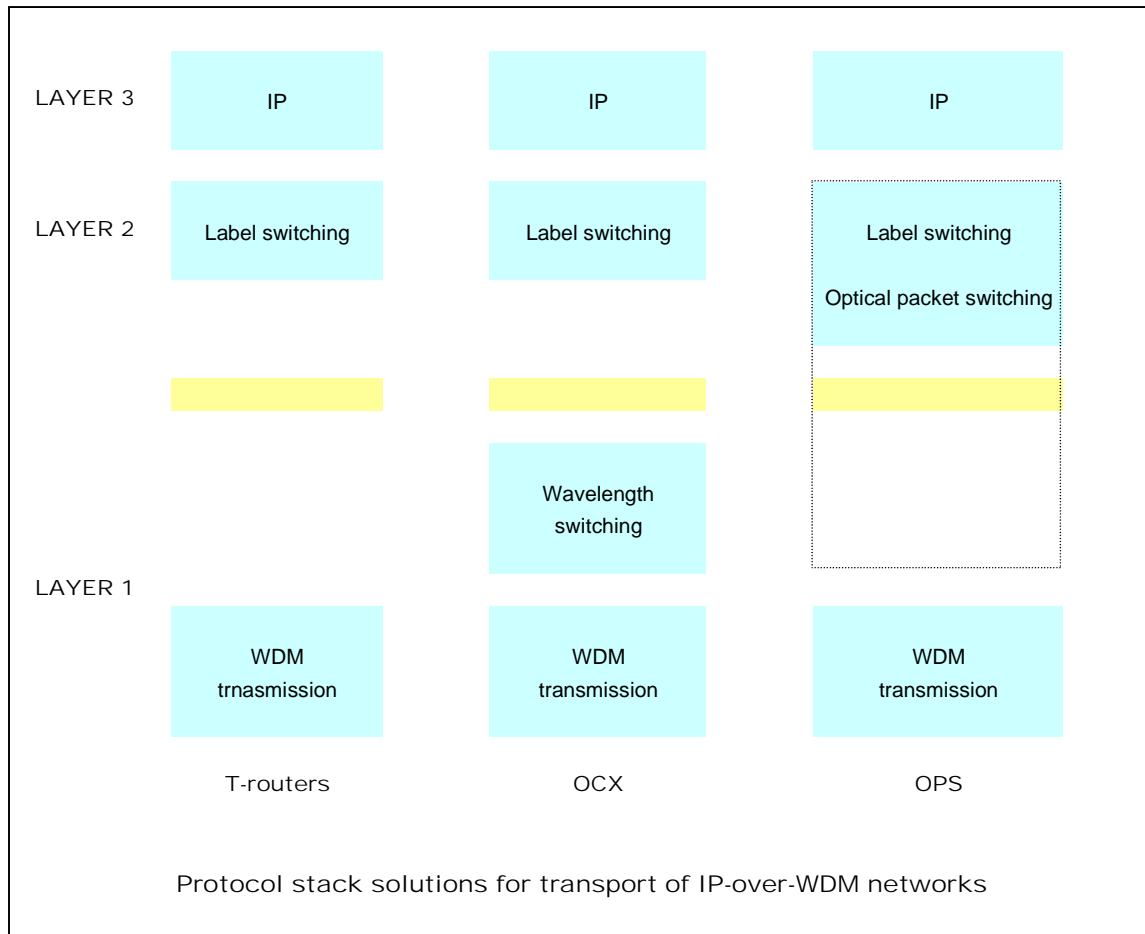
2.WDM and Beyond: Engineering Aspects

WDM:

Wavelength-Division Multiplexing (WDM) is the technology of combining a number of wavelengths in a single fiber.

The field of optical Wavelength Division Multiplexing has experienced explosive growth over the past few years, in a relatively short time. This growth has been fueled mainly by the demands for enormous bandwidth on our data networks, namely the Internet, to satisfy the high-speed applications of the network users. WDM has proven to be the current favorite technology for building optical networks. The promise of metro networks/access networks and their ability to flourish as a huge market for fiber optics is a popular topic for discussion in terms of technology and economical point of view. Experts of the field have identified the high cost of components, and specifically dense wavelength division multiplexing (DWDM) components, as the primary reason for delay in the rapid growth of this market.

The use of optical technology in wired telecommunications networks is widespread, and interest in optical networking is widespread, and interest in optical networking has abruptly increased in the last few years. While the role of optics in networks is often limited today to the realization of transmission functions, next-generation networks will also perform some or all of the switching and control functions in the optical domain. It is well known that one of the major advantages of optical technology is that it provides a huge amount of bandwidth. Interesting properties of optical networks are great flexibility in network design and configuration, and the fact that the cost of switching optical channels can largely independent of their data rate.

The current trend in development of networking systems for the core of the network is based on two different approaches (the two left protocol stacks of Figure 1 below)

LAYER 3	IP	IP	IP
LAYER 2	Label switching	Label switching	Label switching
			Optical packet switching
		Wavelength switching	
LAYER 1			
	WDM trnasmission	WDM transmission	WDM transmission
	T-routers	OCX	OPS

Protocol stack solutions for transport of IP-over-WDM networks

The IP Multiterarouter Approach (T-Routers):

Based on current technology, Internet Protocol / multiprotocol label switching (IP/MPLS) routers are now reaching capacities in the sub-terabit-per-second throughput range, with 10 Gb/s line cards. Reaching multiterabits-per-second throughputs requires massive parallelism, and complex interconnection, which, although probably feasible in the medium term as claimed by several vendors for a third generation of router (see figure below), are not likely to drive the cost down significantly. However, this approach has the merit of being completely IP-driven, and therefore obviously compatible with traffic engineering and distributed management techniques developed for IP networks.

The Wavelength Cross-connect Approach (OCX):

Introducing wavelength crossconnects, closely associated with edge IP routers: this approach is the most likely to be introduced soon, since it provides scalability at a reasonable cost. It introduces two new features: optical switches (e.g., micromechanical switches, MEMs) for direct crossconnection of optical channels without electrical demultiplexing, and MPLS-based control plane, for enhanced management flexibility. Application of MPLS techniques, allowing switching and transport of IP over service-sensitive lower-layer technologies, on top of optical crossconnects for dynamic wavelength allocation (also called multiprotocol lambda switching, MPλS) provides some flexibility and rapidity in the redistribution of resources along the network, to cope with the massive traffic pattern variations core networks experience over long periods of time. However, it may not be sufficient in the long run to cope with the large and rapid fluctuations expected from data traffic, even when entering the backbone. The size of the edge routers associated with these crossconnects will still be very large, in the vicinity of 20-30 percent of the crossconnect itself, to provide efficient traffic aggregation, and to take into account the expected multihop traffic due to the lack of efficiency generated by the crossconnect rigidity.

The Optical Packet Switch Approach (OPS)

Optical switching has more than 10 years of research behind it, with recently increased efforts, fueled by the new attraction around optics in general. Such technologies have not yet been widely used in actual products, and it is worth analyzing that the most often quoted reasons for this situation:

- The lack of deep and fast optical memories, preventing us from implementing in optics the same router architectures as in electronics
- The poor level of integration, due to some intrinsic limitations and also the limited effort devoted to the subject compared to the mature silicon industry

Now, these issues can be overcome, not only through recent technical breakthroughs, but also through clever network design, making optimal use of optics and electronics wherever they fit best.

Optical fibers offer huge bandwidth at a reasonable cost, and optical devices for multiplexing and switching in simple configurations are now available Bostica, et al. (1997). These facts are making optical networks a very appealing solution for development of telecommunication networks, changing some of the optimizations and cost effectiveness evaluations made by network engineers Hiramatsu et al (1997).

One of the main issues investigated in ATM networks has been bandwidth optimization because bandwidth was an important limited resource for services. Today, optical fibers provide almost unlimited bandwidth, which means that most of the implementation complexity and cost typical of ATM can be remarkably reduced.

In this paper we consider a network scenario in which TCP/IP are the communication protocols among other things. In LANs we believe that IP over ATM will hardly be competitive with gigabit Ethernet. At the same time, this emerging technology will warrant the development of high-speed optical backbones to carry the increased capapubs / freety. Our focus, then, will be on fast WAN connections for TCP/IP remote LANs by means of an optical transparent packet network (OTP-N) as a possible future scenario.

Solutions for Optical Transparent Networking

In order to interconnect remote applications and subnetworks by means of optical technology, different solutions are possible (Green 1996). Due to the variety of networks and related protocol standards already existing, the main characteristic required is transparency in terms of protocol used and subsequent data format.

Wavelength-division multiplexing (WDM) rings are a possible solution, using optical add-drop multiplexers (OADMs) and optical cross-connect (OXC) for access and switching. This provides WDM transparent pubs/free rcuits between network access points. The circuits may be permanent or switched, but do not involve any protocol and/or data processing inside transport network nodes. Not even data regeneration is performed within the network, which only manages the light paths. The number of different pubs/freercuits that can be established on a network link is related to the multiplipubs/freety of wavelengths (typically 16 or 32/fiber with present or upcoming technology) and multiplexing on a wavelength is allowed only for traffic between the same set of network access points. Wavelength allocation

and path configuration are critical design problems that should take into account the variety of services, network topology, and their changes in time. In any case the pubs/freercuits suffer from the ineffipubs/freeency typical of circuit transfer modes. Moreover, the available bandwidth granularity is restricted to the fixed bandwidth of one wavelength pubs/freercuit, typically 2.4 or 10 Gb/s.

A more general approach is based on the idea of using a combination of time and wavelength multiplexing, introdupubs/freeng an optical packet transfer mode. Advantages can be foreseen taking into account that packet networks are flexible by nature regarding bandwidth exploitation. The design of an Optical Transparent Packet Network (OTP-N) should recall some of the options considered in the design of ATM. The information flow at a network access point is organized in packets, and the network delivers packets through virtual connections that can be permanent or switched. The link capapubs/freety is shared in time among packets, thus achieving a multiplexed use of network links. Different options can be considered for packet definition, and its management at the access and through the network (Gambini P. 1996). In any case, with this approach the problem of transparent transport can be effipubs/freeently solved in the time domain, holding the wavelength domain for further increase of network capapubs/freety or packet traffic load reduction. Also, the wavelength domain could be used to carry control and signaling information on the same data path (fibers) but on a different logical channel.

As an example, let us consider the connection of two remote IP routers through a high-capapubs/freety transport network. In the first solution a WDM circuit (i.e., a concatenation of wavelength) must be set up, or chosen if permanently configured, to carry IP packets among these routers. All TCP connections between the same routers exclusively use the assigned pubs/freercuit, with utilization related to the aggregate activity of the TCP connections themselves. Pairs of peer-to-peer routers must use different WDM pubs/freercuits for their information transfer when sharing the same physical infrastructure. The number of wavelengths on each network link thus limits the number of pubs/freercuits (and router connections) that can be active at the same time.

With the second solution, IP packets directed to the same remote IP network are gathered in optical packets carried by the network on an appropriate virtual connection to the destination IP router. Network capapubs/freety is

dynamically shared by different higher-level connections and used in relation to the aggregate traffic generated. Improved utilization of network capapubs/freety and better network flexibility is achieved with respect to the previous solution.

Network Architecture

Figure 1 shows the reference structure for the OTP-N, putting the emphasis on the basic building blocks and the interfaces required for interconnection with other networks.

It is assumed that the customers of the OTP-N are standard networks (LANs and WANs) where the user traffic is aggregated, and the OTP-N is mainly used as a very-high-capapubs/freety interconnection fapubs/freelity. In the long term, with the emerging of desktop applications natively requiring very high bandwidth for communication, it can be imagined to give direct access to the end users. All these "customers" form the so-called electrical switched layer.

The figure shows that, to interconnect the switches of the OTP-N, two different options are available:
- ***Direct optical connection by means of an optical fiber*** (which could carry both a single channel as well as a wavelength multiplex). WDM may be used to create multiple links on a given fiber, to increase network capapubs/freety, to control congestion, and to carry signaling and control information. Nevertheless, no semantic meaning regarding the network destination is carried by the wavelengths of a fiber, which are equivalent as far as the data path is concerned.
- ***Connection by means of a WDM transport network***. Here the wavelength domain is used for switching and the routing information is encoded in the wavelength. Therefore, data flows must be encoded on the proper wavelength with respect to their destination.

The former option is more likely to be suitable for the implementation of metropolitan or regional networks based on OTP technology, in which case the distances between the network nodes are relatively small, and an ad hoc infrastructure can be put in place. The latter is more suitable for the case of a geographical network. The distance between the switches is much greater, and it is possible to take advantage of already deployed technologies such as WDM transport networks.

For instance, in Figure 1 two OTP islands are shown with direct interconnection of switches within the islands and with a WDM transport layer for interisland communication. According to what was just explained, the figure shows that wavelength conversion is necessary at the edges of the OTP islands only, whereas within the islands wavelength management is up to the network administrator.
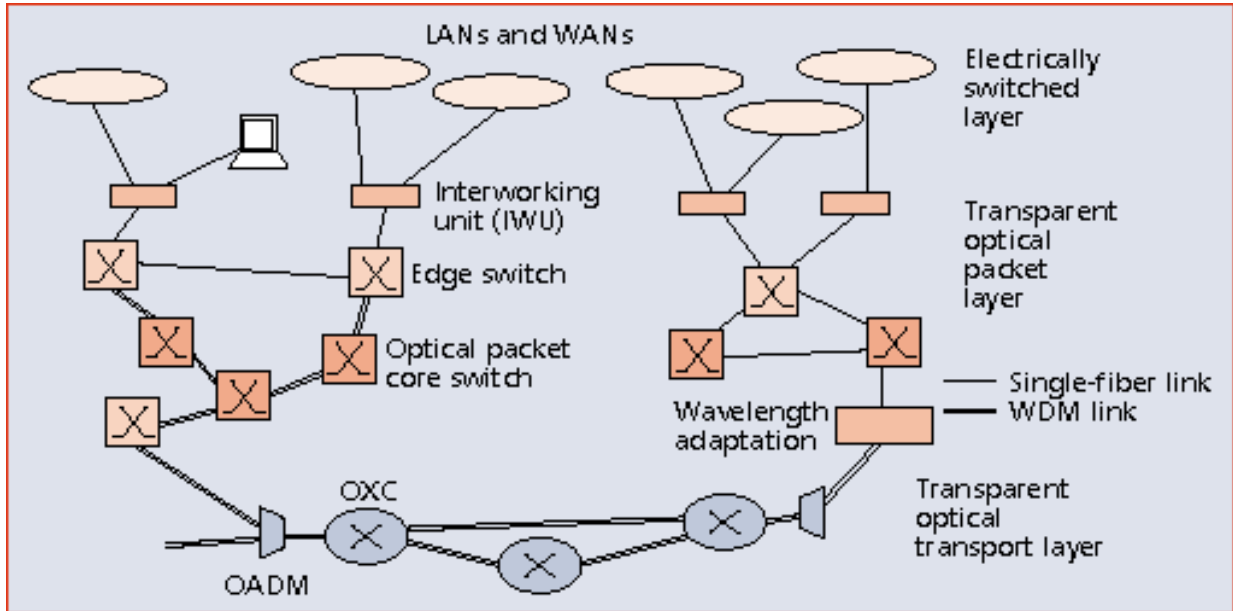

Figure 1

The OTP-N Reference Model

The OTP-N reference model is represented in Figure 2. Four logical sublayers are identified:

- The data convergence sublayer (D-CSL) is a convergence layer that adapts the higher-layer data flow to that of the optical packet layer.
- The network sublayer (NSL) performs header processing functions (header generation and header rewriting) and takes care of proper packet routing.
- The link sublayer (LSL) transmits the optical packet flow on the optical link, hence supporting the optical multiplexing-demultiplexing functionality. Note that optical idle packets may be inserted prior to multiplexing to keep the transmitted optical power constant.

- The wavelength convergence sublayer (W-CSL) adapts the optical packet flow for delivery to the WDM transport layer, by means of wavelength reallocation and/or conversion.

At the current stage of development of this proposal, it is assumed that the matching between the routing functions at the electrical layer (e.g., the IP routing table) and OTP addresses is made at the D-CSL. Each D-CSL block represents one endpoint of a given connection between remote subnetworks, and the data stream crossing one D-CSL will be forwarded to one destination subnetwork through the OTP-N. Also, it is assumed that the OTP-N is connection-oriented; therefore, packets belonging to the same virtual path (i.e., with the same D-CSLs as source and destination) will follow the same path within the network.
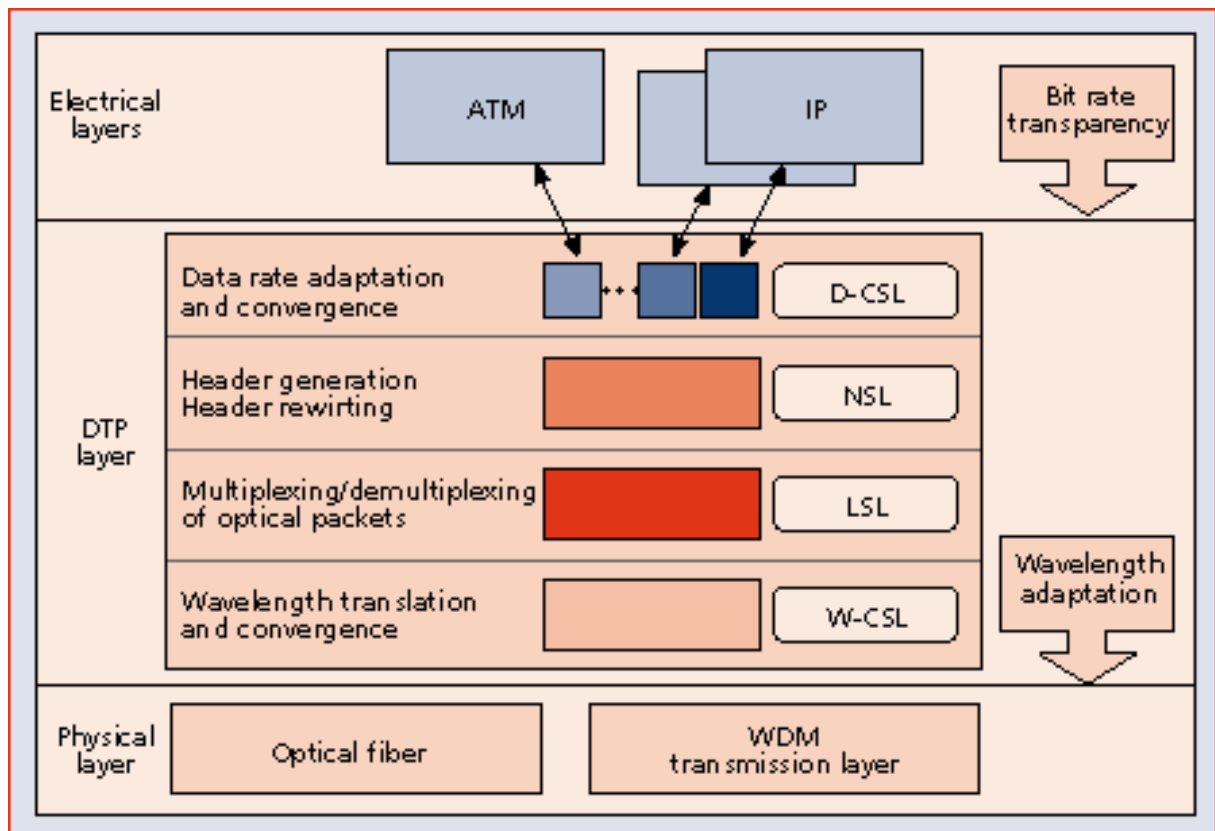

Figure 2

IP over OTP

It is believed that the growth rate of the Internet will lead to a huge bandwidth requirement the present infrastructures for data transport will no longer be able to support. New techniques for the transport, routing, and switching of IP packets are actually a matter of study to face this demand. In this section we describe possible solutions to support IP over OTP.

At the beginning, we stick to the case in which the OTP-N is seen as a path-routed network, providing virtual paths between network access points (namely D-CSLs). This service is suitable to link electrical networks or subnetworks at very high speeds, and is considered the first possible medium-term commerpubs/freeal application of the OTP-N. The IP layer sees the OTP-N as a sort of dedicated point-to-point link between access points, very similar to the case, for instance, of an extended LAN built over frame relay or switched multimegabit data service (SMDS). In the last part of this section we also briefly discuss how optical switches can fit into new emerging high-performance routing architectures.

TCP/IP over Point-to-Point Links

TCP/IP protocols provide a universal network-level interconnection. The Internet bases its organization on a hierarchy. At the center of the hierarchy lie the *Internet service providers,* which connect their networks to form the worldwide backbone for the Internet. Collections of networks (i.e., LANs) controlled by independent administrators are at the edges of the Internet.

The connection among different networks is provided by *routers*, which manage routing protocols to forward IP packets. Routers can be interconnected through a meshed network topology based on point-to-point links that carry flows of aggregated IP traffic potentially reaching several gigabits per second. This solution shows drawbacks over a wide area since complexity increases as the number of routers grows. Therefore, a solution for router interconnection, flexible in terms of bandwidth management, scalability, and path reconfiguration, is recommended.

Current approaches to fapubs/freeng these issues are based on the implementation of high-performance routers, using existing high-speed switching technology and links for packet delivery; for instance, gigabit IP routers with output ports toward synchronous digital hierarchy (SDH) or ATM. These solutions, although based on fairly mature technologies, lack

flexibility and/or scalability. In particular ATM, due to its very short cells, does not seem to be able to follow through to the huge increase of bandwidth made available by optical technology. This means that for link speeds up to 40 Gb/s and beyond, the cell duration is so short that cell processing in the switches becomes difficult, even with very advanced electronics. On the other hand, SDH is well suited to high speeds, but since it is based on a pubs/freercuit transfer mode, it lacks flexibility in bandwidth management. In practice, the considerations mentioned earlier for WDM pubs/freercuits still hold in this case.

Thus, the proposal described in the next subsection is to provide interconnection among remote IP islands by means of the OTP-N.

The OTP-N as an IP Interconnection Fapubs/freelity

Figure 3 shows the use of the OTP-N to transport IP packets providing point-to-point connection between the routers that interface two separate subnetworks. The interfapubs/freeng between LAN subnetworks and OTP-N is provided by routers, which have to include the interworking units for OTP (OTP-IWUs).

Endpoints are connected by means of connection-oriented virtual paths. These paths can be permanent or switched, depending on the level of development of the OTP switches and of the whole network architecture, as well as on user demand.
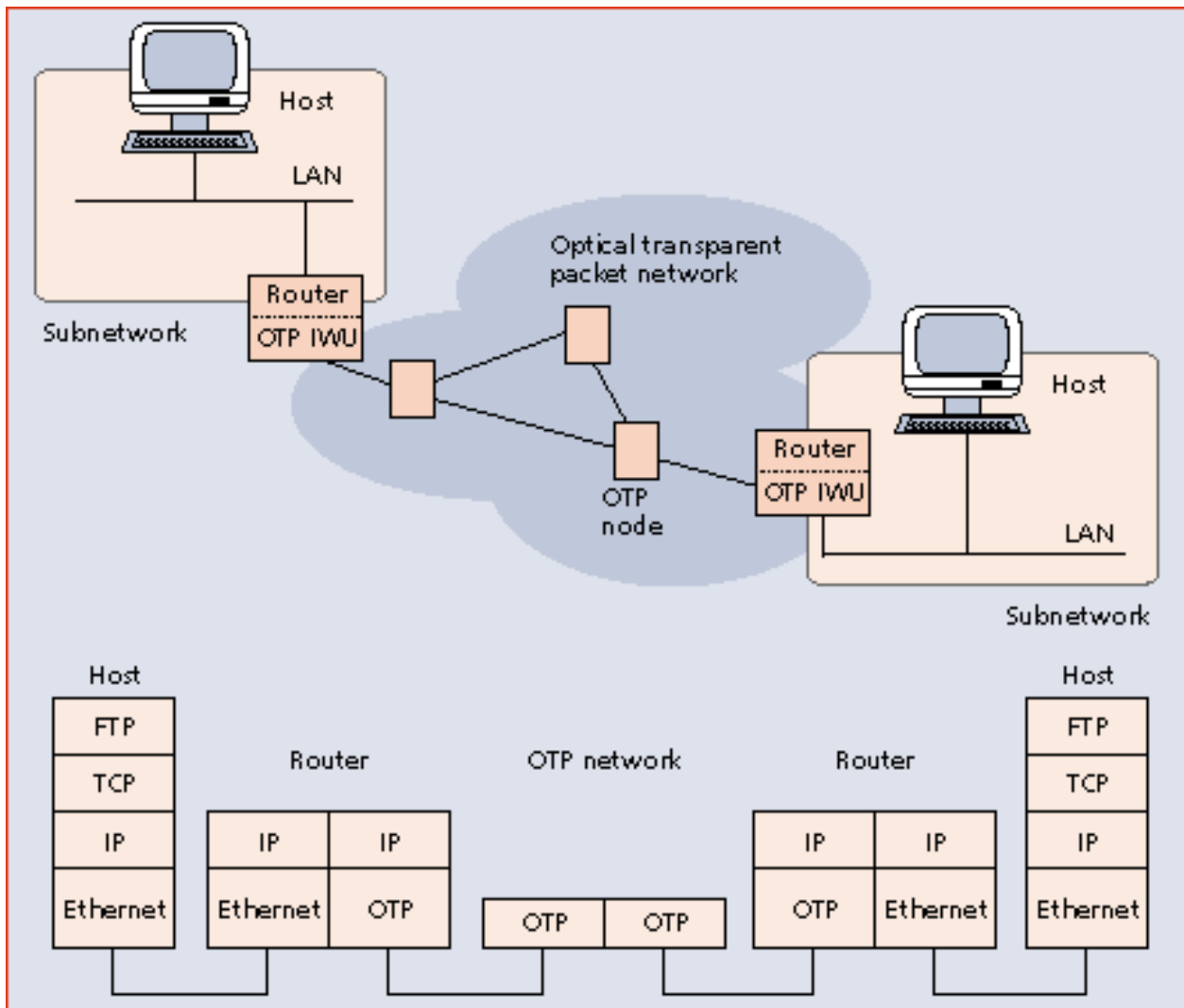
Figure 3

The router at the boundary of the OTP-N is responsible for forwarding IP datagrams to the proper D- CSL in the OTP-N access interface, depending on their final destination (i.e., IP destination address) as shown in Figure 4.

The IP datagrams originated by the host application must be adapted to the length of the OTP payload. This may lead to fragmentation in the case of long IP packets. At the same time, short IP packets, addressed to the same OTP endpoint, can be multiplexed in the same OTP in order to achieve maximum payload usage. Therefore, framing and multiplexing / demultiplexing are managed by the OTP layer in the D-CSL, and no ad hoc link control protocol is strictly required.
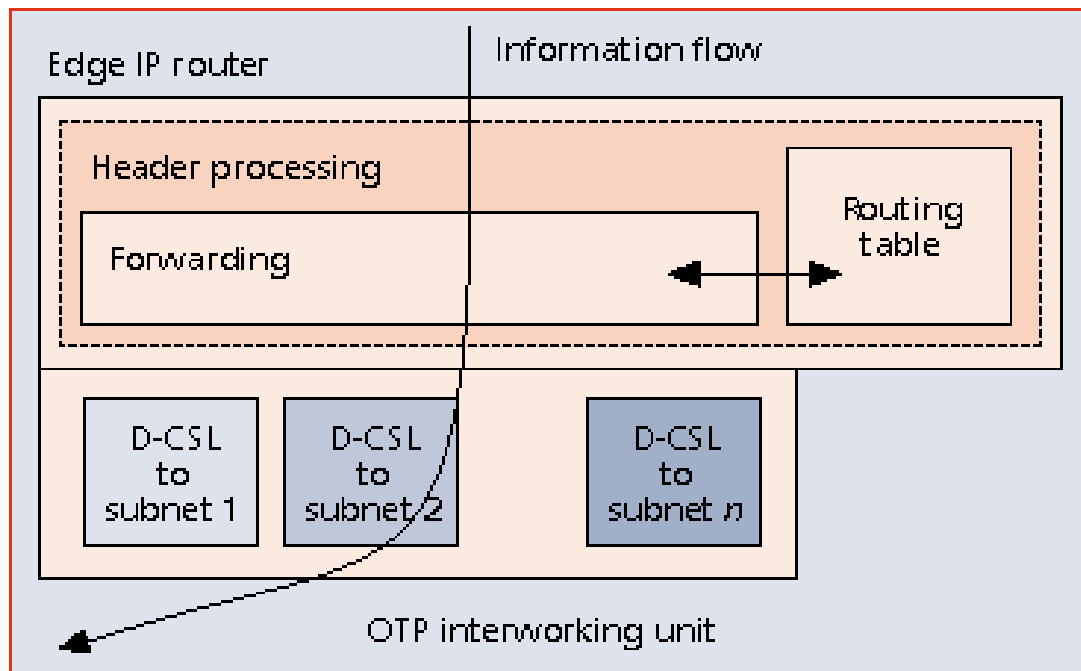
Figure 4

However, if some link layer protocol is added for further link control purposes, the Point-to-Point Protocol (PPP) can be used between the IP and the OTP layers in the edge routers. As is already done for SDH (RFC1619), PPP can easily be adapted to this task, as long as the PPP maximum receive unit (MRU) size is spepubs/freefied according to the OTP definition.

Multicasting over the OTP-N

Multicasting is a common feature of several emerging Internet applications, and support for multicast is now available built into the majority of routers. Therefore, a new network aimed at carrying IP traffic must provide support for multicast service.

The OTP-N can natively support multicast traffic. The architecture of the optical switches is such that packet multicasting can be achieved with little effort, by exploiting the use of WDM within the nodes. A packet can be

replicated and sent to different destinations at the same time, with minimal effort at the level of the switch control logic.

Therefore, it is possible to say that multicast is a built-in network service in the OTP-N. Delivery of messages to multiple destinations can be achieved without requiring replication in the end routers with additional point-to-point virtual links.

Evolution Toward Gigabit Routers

To better exploit the high bandwidth and fast switching capability of new networking technologies, these days proposals are emerging to make the Internet protocols evolve toward simpler and faster routing techniques. Several implementations are proposed, but the underlying idea is common: speed up the routing process. For instance, in label switching the approach is to cache information regarding the routing of streams of packets, which can then take a shortcut on the basis of a simple label without whole IP header processing Callon (1997) The goal is to perform routing processing at the IP level only periodically, rather than per packet.

The OTP proposal can suit this kind of architecture as well. OTP switches can be one of the underlying technologies for IP gigabit routers. The label could be mapped on the OTP header, and flows of packets switched at high speed in the OTP nodes. Path reconfiguration and update of packet flows can be managed by means of proper information exchange between the IP router and the OTP node control logic, with minimal setup time required.

WDM: FUTURE

Optical fiber communications owes much of its success to two complementary conditions: one, a staggering increase in demand for bandwidth between distant points, and two, an inherent capability within fiber optics to provide such bandwidth. Two ubiquitous applications of optical fiber communications, undersea systems and long haul networks, directly leverage this relationship. Both highly developed applications realize tremendous gains by partnering with optical communications. However, the insatiable demand for bandwidth extends beyond long haul networks-access and aggregation networks must scale to meet demand as well. Metropolitan Area Networks (MANs), which bridge the gap between

long haul networks and access networks, have enjoyed much attention as optical technologies enable novel MAN designs.

- *More capacity*

Driven by increasing demands for Internet bandwidth.

- *More functionality*

Driven by the need to build highly flexible networks that can respond to rapidly changing business and consumer needs.

- *More speed*

Driven not only by the need for higher capacity but also by the inherent advantages of time-division multiplexing (TDM), that when coupled with the advantages of WDM make possible many new kinds of communications systems.

- *More penetration*

Driven by the need to deliver higher capacity services closer to the customer, be it big business, small business or even individual consumer.

- *More cost-cutting*

Before any of these technologies can make their way to the consumer, new ways to manufacture WDM components at low cost have to be developed.

- *Definition*

In practice, WDM is simply the simultaneous transmission of a number of independent optical data channels through the same optical system, either fiber or free-space.

Challenges

Researchers still face a number of important challenges in MAN development. Perhaps the most apparent is the need to achieve greater capacity, i.e. 10-100 Tbit/s, while maintaining competitive costs. Achievement of this goal will depend on efficient MAN design. The need to support a diverse mix of traffic must not be overlooked. Networks need to be bandwidth efficient, flexible enough to adjust to customer requirements and designed so as to reduce the hardware requirements of the service providers.

The needs of providers should be considered when designing MANs. Ease of migration/integration, operation, administration, maintenance, and provisioning represent critical issues. Important considerations include: what types of fiber are already deployed, what topologies providers already use and plan to use in the near future, and what supporting components, such as optical amplifiers and high speed electronics, are commercially available or will become available in the future. MANs must preserve the resiliency and survivability of SONET while eliminating its in-efficiencies. Lastly, dynamic reconfiguration of network bandwidth will be extremely important to providers, considering the diversity in traffic patterns within MANs.

There are some technical challenges to building these kinds of systems. Currently, there is over 200 numbers of wavelengths available in commercial WDM systems as shown in the following Figure 5. Clearly, there has been major progress in this field.
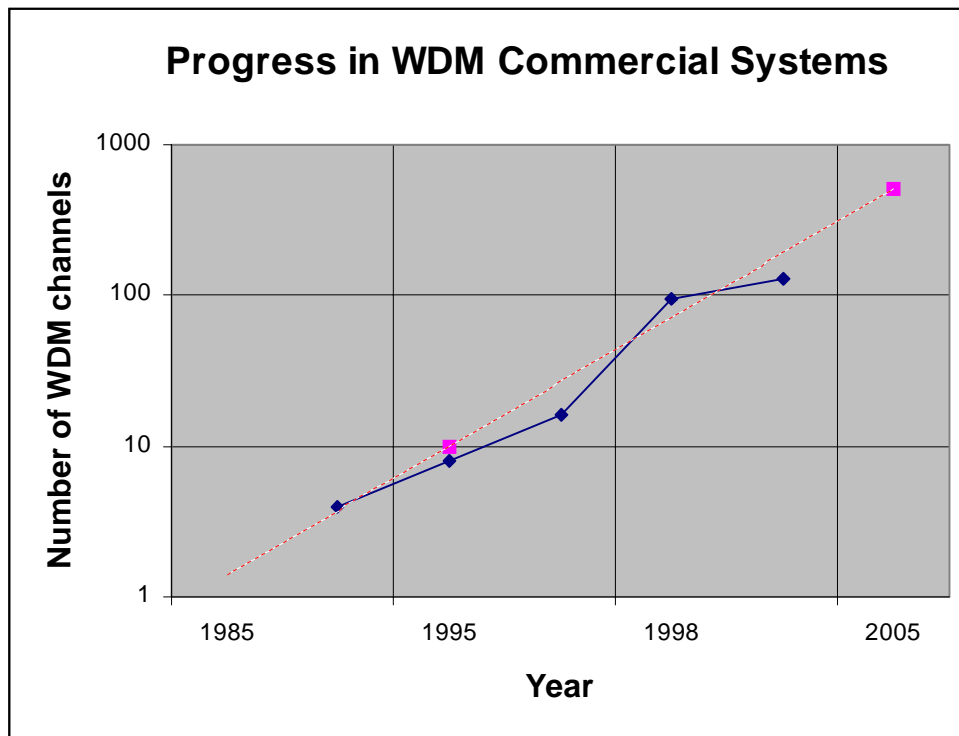

Figure 5

Conventional systems these days generate individual WDM signals with one laser per wavelength. Distributed feedback laser diodes (DFBs) are typically

used for this purpose. To achieve a record capacity of 7 Tbit/s in a single fiber, as many as 175 separate DFB lasers have been used with 40Gbit/s modulation Farbert (2000).

Using chirped-pulse WDM, a new approach to WDM signal generation has been demonstrated at the Bell Laboratories in 2001. Using this technique, 1,021 individual wavelength channels can be generated, 554 channels in the C band, or conventional band, and other 468 channels in the L band, or long wavelength band, with a channel spacing of 9.5 GHz. Conventional tunable filters have enough resolution to demultiplex a single channel with adequate rejection of adjacent channels even at this channel spacing. To achieve this resolution, a combination of chirp, modulation, and spectral slicing can be used.

Up to 15,000 WDM channels can be obtained by using a single broadband laser covering ~50THz optical bandwidth. Such a system would require a fiber that has clear transmission with low loss continuously from 1.3 to 1.6 µm. Fortunately, such a fiber-in which the loss peak due to water vapor at 1.4 µm has been eliminated-is now available. This fiber, dubbed 'AllWave' as shown in the figure below *[Lucent Technologies, www.lucent.com]*, challenges researchers to think of new ways to fill its generous bandwidth.
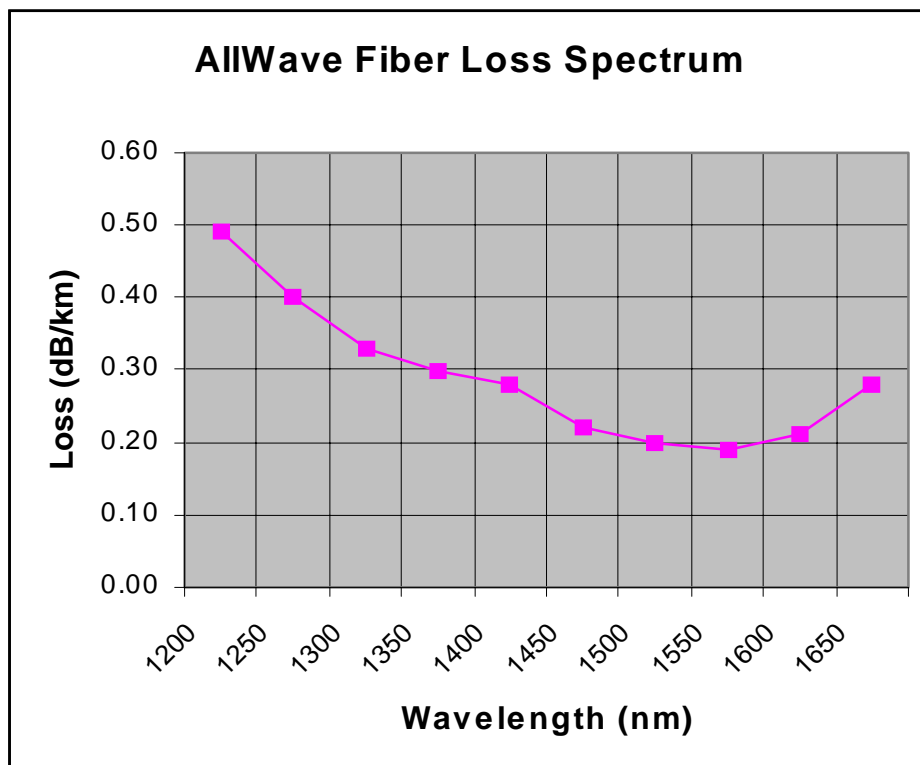
A single fiber can support about 50 THz of optical bandwidth. There are about five billion people on the planet. Therefore, in principle at least, we could give every person on the planet an individual wavelength. So instead of an IP address like 255.23.43.122, the user address would be 1552.2364510174 nm. In each channel there would be 10 kHz of optical bandwidth, still enough to carry 128 kbyte/sec, comparable to an ISDN line rate Knox (2001).

3.<u>The Economics of R&D and Innovation</u>[1]: WDM and OTDM

The economics of WDM and OTDM can not be discussed properly without understanding the economics of R & D and innovation in the ICT and knowledge sectors in general.

The key to understanding the economics of ICT and knowledge sectors is to realize that a disequilibrium process has set in within the world economy and the advanced countries of the world that is leading to rapid economic changes. These changes include intersectoral shifts toward the ICT and knowledge sectors, changing skill requirements, high volatility of wages, profits and financial variables and consequent increase in uncertainty about the future states of the economy. The dynamics of this disequilibrium process must be studied through methods of understanding complexity. Clearly, our knowledge of such dynamic systems is still in its infancy; but much can be learned by studying some known features.

In the last twenty years, the frontiers of economics have moved far beyond the standard models of decreasing or constant returns where costs can not be decreased beyond a certain point, unless factor markets behave in a peculiarly decreasing marginal cost fashion. Leaving the perfectly competitive world behind, economists at the frontiers have been focusing on increasing returns to scale, economies of scope and network externalities. The world of high technology in general and the ICT and knowledge sectors in particular, are characterized much better through these approaches than the old perfectly competitive models. Many models of imperfect competition have also been developed to study interesting and relevant phenomena such as R&D rivalry and R&D expenditures. The upshot of these developments is that economists at the frontiers of their discipline are much closer to understanding many aspects of the digital economy than they were ten years

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[1] This section draws upon, Khan, H. A., "Digital Development", Unpublished paper, University of Denver, 2001.

ago. In this paper I want to illustrate this point by discussing informally a recently developed theoretical and modeling approach. The policy implications for the development of new technologies such as WDM and OTDM are quite striking.

Positive Feedback Loops, Innovation and Intellectual Property Rights--- Firm-based Innovation of WDM and OTDM:

Our discussion of the requirements of technical progress shows that we need both a deeper understanding of the diseqilibrium processes at work leading towards multiple equilibria, and the economic implications of the complexities of **the production and distribution** aspects of WDM and OTDM. It is with a view towards capturing these complexities leading towards multiple equilibria that an alternative conceptualization of technology systems transition has been formulated by some economists (Khan 1993; James and Khan 1997; Khan 1998, 2001a,b). In addition to capturing both equilibrium and disequilibrium features of technological transitions, this broad approach can illuminate distributional issues as well. Since poverty alleviation remains on the agenda of the national governments of developing countries and the international development agencies, it can be argued that from this perspective at least the new approach has obvious relevance for the developing countries. But clearly, such distributional considerations are of importance in the advanced countries where WDM and OTDM are being developed, as well.

Khan (1998, 2001a) has formalized this approach and has coined the abbreviation POLIS to emphasize both the disequilibrium positive feedback loop features and the other economic, political and social dimensions of the technological transitions. For the current ICT transitions in developing countries this model has been applied to South Korea, Taiwan, China and India, with work underway for Indonesia. The key results for policy purposes will be described shortly; but first let us take a closer look at the concept itself and see how it can be applied to specific technologies and sub-systems such as WDM and OTDM.

Models of POLIS: A Study in Technological Complexity with Application to WDM and OTDM

.   In this section we discuss positive feedback loop innovation systems and their significance for both economies and their constituent firms. As the debate on the "East Asian miracle" underlines and the histories of technologies in advanced countries confirm, the key strategic question for a country that has made a technological transition from a traditional to a modern system concerns the prospects for long-term economic growth. Ultimately, it is the sustainable long-term rate of growth that will determine the wealth that can be distributed among personal consumption, investment, government spending on infrastructure and public services, etc.

Therefore, it is the creation of an innovation system that will determine the viability of a technology-based growth process. This process of building an innovation system is very much an evolutionary and path-dependent process.(Nelson 1981, 1989, 1993, 1994; Nelson and Winter 1974, 1977, 1982) The central idea is that the provision of appropriate types of capital, labor and forms of organization for high value-added industries will lead to rapid productivity increases. However, to sustain such an increase, a domestic innovation system must be set up. There is a further requirement that this innovation system must fulfill. This is the requirement of a positive feedback loop or a virtuous cycle of innovations.

This problem, as we have emphasized, is intimately connected with the existence of multiple equilibria in complex economies. A positive feedback loop leading to a virtuous cycle of growth and technology development is one particular sequence of equilibria in this context.[2] In general, such a sequence also involves increasing returns. In the remainder of this section a theoretical exploration of innovation with increasing returns and multiple equilibria will be undertaken.

In a market economy, 'success' is often cumulative or self-reinforcing. Typically outcomes are not predictable in advance. However, once an equilibrium gets selected out of a number of long-run equilibria, there is a tendency to be locked in. Technically, economic processes exhibit non-

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[2] If there is more than one such sequence, we may be tempted to choose from among them, the "optimal" sequence, according to some well-defined criterion, e.g., present value maximization.

convexities -- violating the generic assumption of competitive equilibrium economics. The presence of self-reinforcing mechanisms sharing common features found in fields as far apart as enzyme reactions and the economics of technical change underlines the importance of such mechanisms in governing the dynamics of self-reinforcing processes regardless of the field in which they occur.[3]

In order to give the reader some informal idea of the problem of formalizing complex technological systems we summarize here the basic structure of a 'simple' non-linear model embodying distinct technological systems. At any single point in time, the model can be presented as a Social Accounting Matrix (SAM) representation of the socio-economic system. The key distinction here is the explicitly non-linear nature of the economy-wide functional relationships. The key theorem shows the existence of multiple equilibria (Khan 1998;2001a and b). Some further considerations lead to the specification of definite technology sectors such as the ICT sectors, productivity enhancement and income distribution. Thus a closed loop feedback system including all the production and distribution mechanisms can be set to work. The attractiveness of such an approach to the proponents of a holistic perspective should be readily apparent. What is even more intriguing is that apparently a way has been found to move beyond the annoying vagueness of the proponents of the systems approach to a precise and even mathematically and statistically formal way of describing complex technology systems. Some of the key results obtained so far for the ICT sectors can be applied specifically to WDM and OTDM.

In particular, the key engineering characteristics described in the previous section suggest that WDM and OTDM have considerable economies of scale. The increase in speed in the near future will involve economic costs, but exploiting these economies of scale, both the average and marginal costs of production can be brought down.

The second interesting aspect of WDM and OTDM emerging from the engineering analysis is the nature of possible positive feedback loops in production. In almost all aspects these innovations can lead to rapidly accumulating advantages for the first mover. However, to keep abreast of competitors, an almost continuous chain of subsequent innovations will be necessary. This underlines the need for both economic understanding of

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[3] See the essays in Arthur (1994) for some illuminating discussions.

production and marketing, and the engineering research and development aspects. Thus the synergy between good economics and good engineering can create a virtuous positive feedback loop. Contrariwise, a combination of bad economic and engineering practices will create a vicious positive feedback loop where instabilities of firms and markets will lead to a decline in innovation, production and consumer welfare.

4. Conclusions:

In conclusion we note that the technological pace of innovation with regards to WDM and OTDM is quite rapid; but in the advanced countries this pace is driven by expected profit outlook, which may vary over time. This is why strategic alliances between companies at the research and development phases may be beneficial. At the same time, given the need for competition to enhance both productive efficiency and consumer welfare, there has to be a clear distinction between pre-competitive R & D phase and a more competitive production and marketing phase.

With the existence of increasing returns to scale and stable input prices come the real possibility of lowering price progressively by serving ever larger markets. Thus the diffusion of WDM and similar technologies can occur quite rapidly if the firms produce with economies of scale. This implies that the optimal competition will occur with a few large-scale firms under strict enforcement of anti-monopoly laws. Under such circumstances prices will match closely social marginal cost of production. Smooth production and marketing schedules will mean that the logistic curve for diffusion will display a high rate. This leads us to predict that under such market conditions, which are approximated in the US, both WDM and OTDM will diffuse quickly. Consequently, social welfare from the diffusion of technologies can be expected to increase quite rapidly.

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