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EVOLUTION OF WDM OPTICAL NETWORKS

This paper is dedicated to Professor Jovan Surutka on the occasion of his 80th birthday

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Abstract: Implementation of wavelength division multiplexing (WDM) in optical networks increased the fiber bandwidth utilization and emerged from the use in point-to-point applications to its current position as the next optical networking technology. There are, as well, other competing network approach, such as optical time division multiplexing (OTDM) and code division multiplexing (CDM), both suffering from severe limitations and still immature technology. This paper reviews some mayor technological developments in architectures, devices and systems involved in WDM optical network evolution and discusses issues dealing with optimal exploitation of fiber bandwidth for information transmission and processing. Keywords - Optical communications networks, wavelength division multiplexing.

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1. Introduction

Optical communication networks based on wavelength division multiplexing (WDM) offer enormous transmission capacity which is expected to solve many problems in the next-generation Internet network infrastructure. WDM line systems are already used around the globe, and attention is now turning towards practical issues of the WDM-based local and metropolitan networks. At the moment there are many physical devices enabling

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WDM implementation that are operational [1], [2]. Also, there are several fundamental researching programs addressed to problems connected with switching, routing, protection and survivability mechanisms, quality of service support and scheduling algorithms, efficient wavelength assignment and routing algorithms.

We are moving toward a society which will require fast access to information that is provided through a global networks, whose today's Internet and asynchronous transfer mode (ATM) networks, do not have the capacity to support the future bandwidth demands. Fig. 1 illustrates the past and projected traffic growth reported by many telecom carriers. Although voice traffic continues its growth at about 7% per year, the data traffic is growing much faster and it has already exceeded the voice traffic [1], [3], [4].

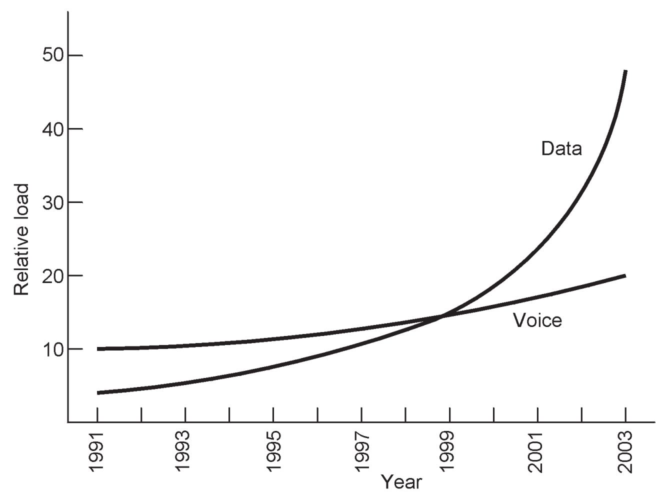

Fig. 1. Past and projected future growth of data and voice.

Single-mode fiber's potential capacity is nearly 50 Tb/s, which is several order of magnitude greater that electronic data rates of few Gb/s, and it is a fact that must be taken into account. Having in mind that the maximum rate at which an end-user can access the network is few Gb/s, the key in designing optical communication networks, which could potentially exploit much higher fiber's bandwidth, is to introduce concurrency among multiple user transmission into the network architecture and protocols. In an optical communication network, the concurrency may be provided according to either wavelength or frequency, (wavelength division multiplexing WDM), time slots (time-division multiplexing, TMD), or wave shape (spread spectrum, code- division multiplexing, CDM) [5], [6].

Optical TDM, and CDM are difficult technologies to be exploited in the near future [1], [7], [8]. OTDM has been a subject of profound research lately. It would involve all- optical interleaving and regeneration of many lower bit-rate channels, each at a high bit rate (10 Gb/s or more) and all at the same wavelength, optically multiplexed at much higher bit rate (100 Gb/s or even more). Each stream of very narrow pulses would be separately generated and delayed by extremely precise optical delay with reference to the initial bit stream and than combined into a single fiber. The order of magnitude of pulse is to be of several picoseconds, the bit period 100 ps or less and the delay between streams of a 10 ps. Short time slots in TDM makes extremely difficult for an end-user to be able to synchronize to within one slot. Similar, or even more critical, is the optical CDM in which the required speed of an end-user equipment is even higher, and in both types of multiplexing requirements by far exceed that of the present day end-user technologies. No matter which transmission technology is involved for increasing the amount of data transported from point to point the electronic bottleneck problem, the limitation of electronic switches and routers to process the very high bit-rate signals terminated on their ports, exists.

WDM technique requires attainable speed of an end-user equipment, which can be chosen arbitrarily according to the peak electronic processing speed. The bit rate that can be easily converted from electrical to optical domain is currently still ca. 10 Gb/s, although 40 Gb/s have been demonstrated using InGaAs-Ga as photo-receivers. The modulation rate per channel will increase with developments in laser and detectors solutions. To achieve very high rates a careful optimization of fiber dispersion to control pulse spreading must also be performed. For this reason, most today's carriers devote significant effort to developing and applying WDM technologies in their networks [2], [4].

The penetration of optical technologies into the various network levels is schematically illustrated in Fig. 2. Optical fibers have been extensively used since 1980 in the trunk transmission, because early optical technology was best suited for this application which requires wide bandwidth long distance transmission. The cost per bit in optical system was considerably lower than that for wire systems. This was economically interesting for end-user in the period when they required relatively small data rate. At about 1990s, when the need for end-used higher data rate became a need, it was essential to reduce not only transmission cost but also transport node (cross-connect and ADM nodes) cost. The optical path technologies will play a key role in reducing both transmission and transport node costs [5].

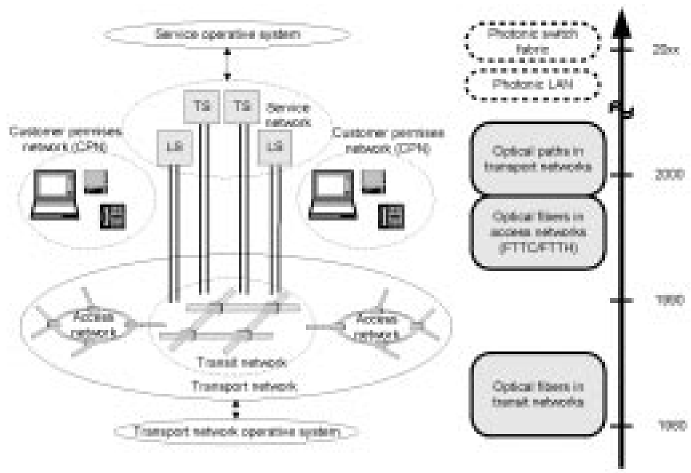

Fig. 2. Penetration of photonic technologies.

The application of optical transmission into local area networks (LAN) started in 1980s. Among the first in this field were fiber-optic Ethernet, fiber data interface (FDDI) and fiber channel. The maximum data rate of FDDI is 100 Mb/s. The fiber channel offers point-to-point data transmission rates between 100 Mb/s and 800 Mb/s. The transmission medium can be single mode (up to 10 km) or multimode fiber (up to 2 km), or coaxial cable (up to 50 m). Photonic LAN which utilize in addition to fiber transmission also optical routing and other optical processing, can be introduced only after optical processing technologies develop further and their cost is reduced to be competitive with that of electronic technologies.

2. WDM Techniques

2.1 Point-to-point networks

WDM is technique which can exploit enormous optical bandwidth of a fiber in spite of a relatively much smaller electronic bandwidth of an end-user. On the fiber one can transmit a great number of optical carriers used by different end-user. In this way, the low attenuation region of a standard silica fiber, extending over 50 THz, is "divided" into many channels operating at the peak electronic data rate. What is required is to develop appropriate network architecture, protocols and algorithms and to achieve high spectral efficiency which defines how many channels can be slotted within the available spectrum. It is determined by the usefulness of stable single-frequency sources and demultiplexers or routers able to select individual wave- length channels out of the entire spectral comb [2], [4].

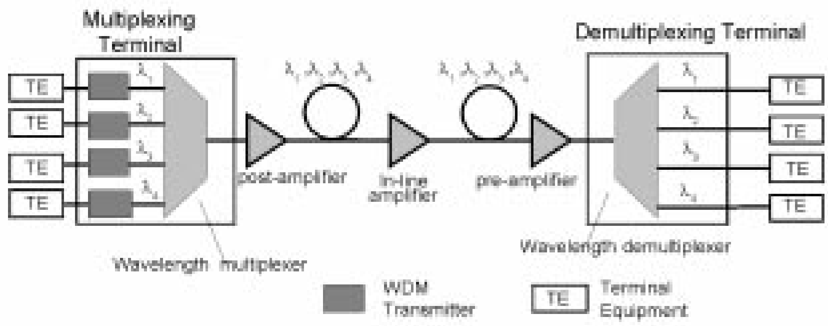

Fig. 3. A four-channel point-to-point WDM transmission system with amplifiers.

Research and production of comp onents for WDM have been accelerated last years. A number of experimental prototypes have been and are under development and tested by telecommunication providers. It is expected that the next generation of the Internet will employ WDM optical backbones. An example of modern four-channel point-to- point WDM transmission system using optical line amplifiers, multiplexer and demultiplexer, as well as four transmitters is shown in Fig. 3. Such systems can be used when the demand exceeds the capacity of the existing fibers carrying only one modulated carrier. Of course, one can increase the point-to-point capacity from 2.5 Gb/s to 10 Gb/s (in the future to 40 Gb/s), or employ a new cable, or use the four channel WDM. A study of the three possible solutions for upgrading point-to-point links indicated that for distances shorter than 50 km new cable is preferred solution; for longer distances the other two solutions are nearly the same. WDM multiplex/demultiplex is the product of several vendors (IBM, Pirelli, AT& T, etc.). Maximum number of channels is 64 but in experimental tests the number of channels exceeded 100. Evolution of high-speed and large capacity transmission systems using

WDM and TDM is illustrated in Fig. 4. These data are published by NTT Photonic Transport Network Laboratory of Japan. Naturally, these data quickly become obsolete as many experimental system in a relatively short time become commercial systems. As it can be seen from the graph, NTT results for a single carrier system based on the time division multiplexing reach fantastic 640 Gb/s but it is not known to what distance. Anyhow, it seems that 40 Gb/s per carrier is firmly on the way to be applied soon [6].

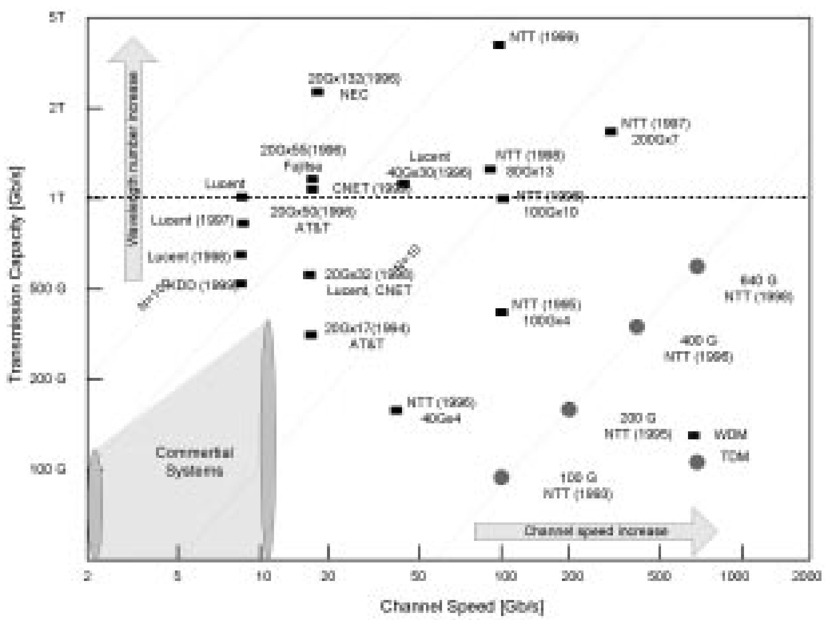

Fig. 4. Evolution of high-speed and large capacity transmission.

2.2 All-optical networks

Extensive research in a large number of laboratories has been performed not only for using the available spectrum of optical fibers for transmission in point-to-point (mainly SONET/SDH based long haul terrestrial and transoceanic) networks, but also for wavelength routing in all-optical networks. A wavelength routed optical network is an extension of point-to-point WDM, since the number of wavelengths that is required is determined not only by transmission impairments but also by the traffic demands and physical connectivity of the network. It consists of the interconnections of a large number of point-to-point WDM systems by optical routers or cross-connects, able to route channels according to their wavelength [1], [4], [6], [9], [10]. As pointed out, wavelengths can be used to denote routing destinations, directing high-capacity optical signals, transparently for all bit-rates and formats, between source and destination network nodes with no electronic processing in any intermediate node. In such networks the routing and wavelength allocation (RWA problem) are predominant and they introduce at least four groups of problems. First, determination of the number of wavelengths required to provide binding connectivity - the ligthpath without intermediate opto-electronic conversion or switching (Fig. 12). It directly affects the density of the channel spacing, the necessary stability of laser sources and the accuracy of wavelength selective components such as lasers, multiplexers/ demultiplexers filters or cross-connects. Second, the determination of the number of wavelengths and the distance without incurable errors caused by channel interactions as a result of combined dispersion (uncompensated chromatic and polarization mode dispersion PMD) and different nonlinear effects in fiber (Raman and Brillouin scattering, four-wave mixing FWM, cross-phase modulation XPM, self-phase modulation SPM) and accumulated cross-talk from imperfect selectivity of filters. Third, some form of all-optical wavelength conversion is required to avoid wavelength contention. Fourth, it is necessary to define how to manage the all-optical networks [1], [4], [11].

2.3 Key optical components for WDM networks

Evolution of WDM, lasting some two decades, from concept to real implementation in optical communication networks posed several technology problems to be solved. The key role played the developments of stable lasers, erbium doped fiber amplifiers that could replace electrical regenerators to amplify the entire spectrum of interest around 1550 nm with a single optically pumped amplifier, and optical low cross-talk, stable and compact filters.

A dense WDM network requires stable, precisely defined wavelength sources, either capable of high-speed direct modulation for NRZ transmission or of generating very short pulses for RZ/OTDM transmission. The tuning bandwidth and speed, and temperature stability are essential characteristics of lasers suitable for WDM systems.

In WDM systems several types of rare-earth-doped- fiber amplifiers are used in different sub-bands, depending on required characteristics (gain, gain efficiency, gain bandwidth, gain saturation, polarization sensitivity, noise which arises predominantly from amplified spontaneous emission, etc. [4], [11]) as illustrated in Fig. 5 [6]. Semiconductor laser amplifiers, such as Fabry-Perot amplifiers or traveling-wave amplifiers have not been largely used in WDM networks.

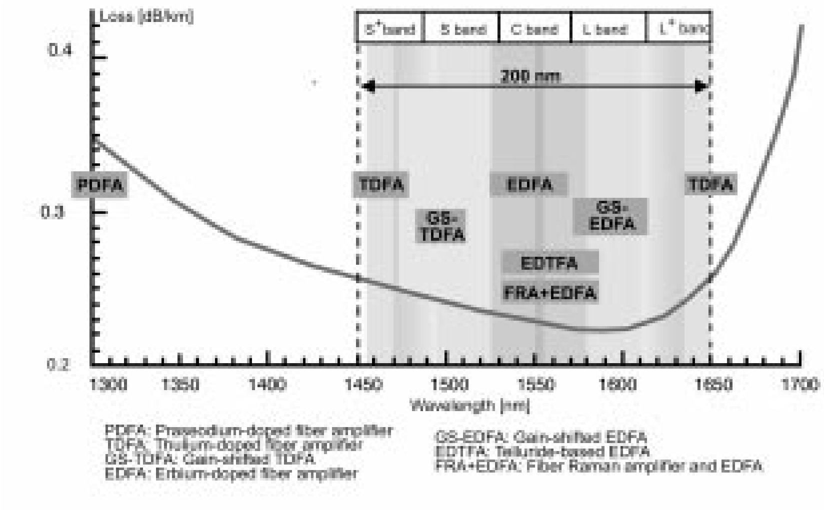

Fig. 5. Optical amplifiers used in various bands for WDM system.

The demultiplexers must be able of separating high- capacity multiple-wavelength signals to enable each wavelength channel processed, i.e. detected, switched or routed to its final destination with a low cross-talk and transparently to any modulation format. Among several proposed approaches the most attention is given to an arrayed waveguide grating (AWG), known also as a waveguide grating router and phased array, shown in Fig. 6. It is a planar waveguide device fabricated on Si or InP substrate consisting of an array of waveguides of different lengths with a linear length difference. A multi-wavelength signal will experience a wavelength dependent tilt of the wave front resulting in a shift of each wavelength into a different output waveguide. If there is single wavelength input, the device acts as a $1 \times N$ demultiplexer but with M inputs it can be used as a $M \times N$ router or cross-connect. The slight inaccuracies in the defined path lengths result in a considerable cross-talk and cause problems especially in cases when a number of such devices is cascaded within the source - destination path. An alternative approach, particularly for much larger routers, is the use of a free-space aberration-corrected grating-based device with concave substrates that allow both focusing and dispersion in a single element [4], [11].

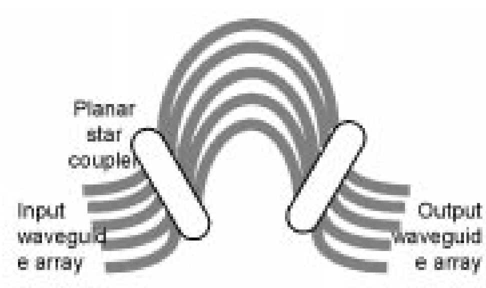

Fig. 6. AWG acting as a $1 \times N$ demultiplexer or $M \times N$ router.

In developing WDM networks one has to add or drop signals from the fiber carrying a multiplexed carriers. One form of wavelength add/drop multiplexer (WADM) is shown in Fig. 7. Demultiplexer separates carriers and with the use of 2×2 switch for each wavelength, signals can be separated or added. The switches are connected to multiplexer and the multiwavelength signals are sent to the fiber. The WADM can be "inserted" on a physical fiber link.

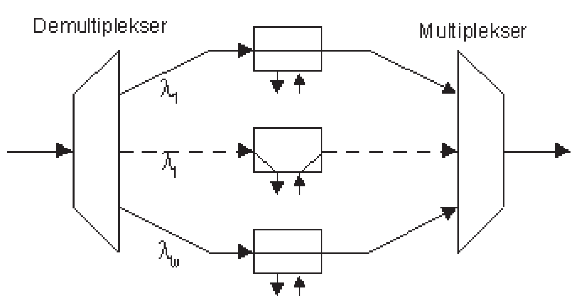

Fig. 7. A wavelength add/drop multiplexer.

If all switches in Fig. 7 are in the "bar" state then all signals pass undisturbed. If the switch is in the "cross" state, as for the wavelength λ_i in Fig. 7, then the signal at that wavelength can be dropped and modified signal at that wavelength added. For the time being the switches are operated electrically.

The passive star is a device that signals of various wavelengths, incident from the input fiber ports, delivers equally to all output fibers ports, as shown in Fig. 8.

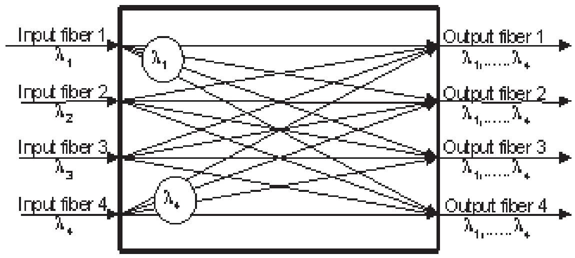

Fig. 8. Pasive star 4×4.

With configuration shown in Fig. 8, "collision" will occur when two or more signals from the input fibers are simultaneously launched into the star at the same wavelength. With as many wavelengths as there are ports, an $N \times N$ passive star can route N simultaneous connections through itself.

A passive router operating at four wavelengths, as shown in Fig. 9, can separately route each of the four wavelengths on separate output fibers [1], [4], [11].

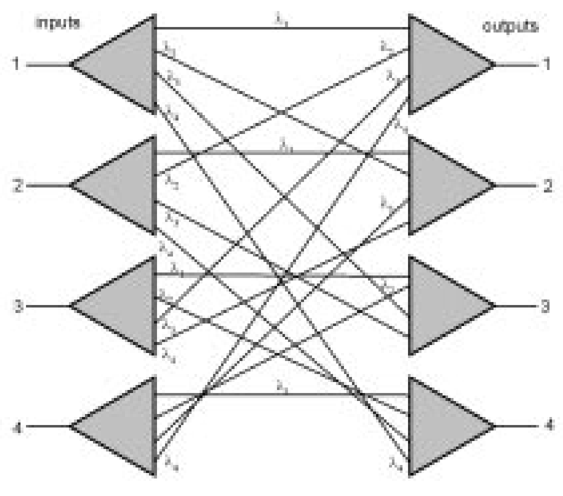

Fig. 9. Passive nonreconfigurable router for four wavelengths.

This device allows wavelength reuse. The wavelength on an input get routed as determined by "routing matrix". This matrix is determined by internal connections between the demultiplexer and multiplexer stages inside the router. The routing matrix in a passive router cannot be changed. Such routers can be obtained commercially known as Latin router, waveguide grating routers or wavelength routers. For N ports the passive router can route N^2 simultaneous connections.

Active switch can support N^2 simultaneous connections, similar to passive router but its "routing matrix" can be reconfigured on demand, under electronic control. The schematic view of active switch is shown in Fig. 10.

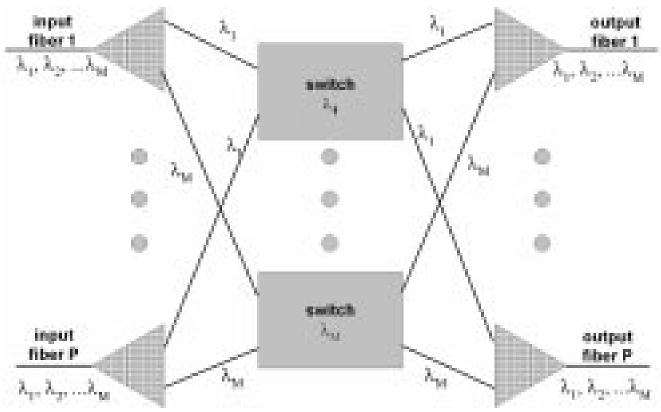

Fig.10. An active reconfigurable routing switch.

An active switch needs to be powered. It is also called cross-connect. This switch can also be used to convert the wavelengths [1], [4], [11].

The passive star is used in local WDM networks, while active switch is used for wide-area wavelength networks.

To establish a lightpath in a wavelength routed network it is necessary to have the same wavelength allocated on all the links in the path. This requirement is known as the wavelength-continuity constraint and it distinguishes the wave-routed networks from the circuit-switched networks and can cause a high blocking probability. It is possible to eliminate the wavelength-continuity constraint if the wavelength conversion into another wavelength is enabled in intermediate nodes between source and destination. An ideal wavelength converter should perform transparency for all bit rates and signal formats, conversion to both shorter and longer wavelengths and be able to setup fast to output wavelength. There are several wavelength conversion technologies proposed. Besides the use of active reconfigurable switches, as already mentioned above, for wavelength conversion can be performed as optoelectronic conversion and all-optical conversion (employing coherent effects or techniques using cross modulation) [4], [11]. Fig. 11 illustrates the wavelength conversion based on nonlinear wave-mixing, which is typical coherent effect used in this type of converters. Wave-mixing is caused by nonlinear optical response of medium when more than one wave is present. As a result another wave is generated with intensity proportional to the product of the interacting wave intensities. In this way both the phase and amplitude information are preserved. This is the only technique that allows simultaneous conversion of a set of multiple input wavelengths to another set of multiple output wavelengths. It is transparent for bit rates and signal formats and can be used for signals with bit rates that exceed 100 Gb/s.

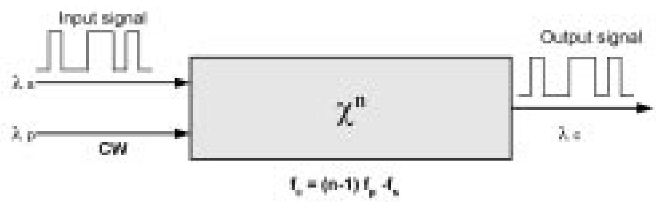

Fig. 11. A wavelength converter based on nonlinear wave-mixing effects.

3. Realized WDM Networks

Optical routers, switching elements or wavelength converters are needed in WDM networks for establishing the lightpaths from a source node to a destination node thus bypassing electronic bottlenecks at intermediate switching nodes. This concept, illustrated in Fig. 12, allows multiple lightpaths to share each fiber link. Also, since each wavelength may be used on each fiber link in the network, multiple lightpaths that do not share any links may use the same wavelength - wavelength reuse is enabled.

A number of research programs, dealing with transport, metropolitan and access networks have been established, but here we are going to mention only the main results in Europe and United States [2], [3], [4].

In Europe several research projects, first RACE-MWTN and afterwards ACTS, dealt with WDM technologies from concept to realization of all necessary components and field trials. The network functionality and over an

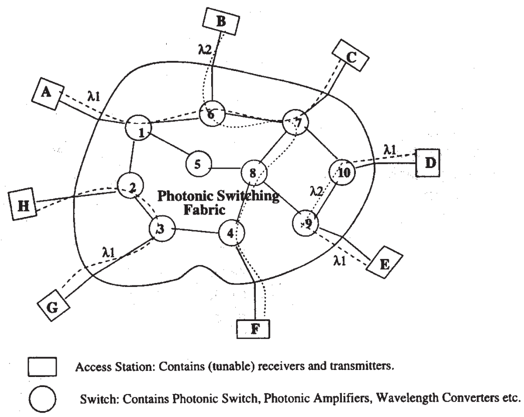

Fig. 12. Lightpaths in all-optical networks.

all-optical WDM network infrastructure has been demonstrated of in PELICAN project shown in Fig. 13.

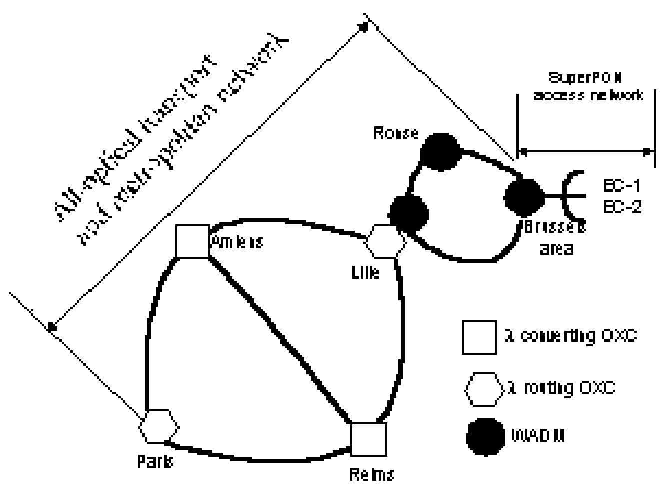

Fig. 13. PELICAN project.

This project trail is the first representative of an advanced global optical network infrastructure including core, metropolitan and access networks, supporting end-to- end multimedia services. The core network is a transparent all-optical meshed network with optical crossconnects and 2R-regeneration on same links operating at 2.5 and 10 Gb/s. The metropolitan network is a ring with optical add/drop multiplexers. The SuperPON access network is connected through an ATM switch. Different protection schemes and different signaling methods are used with an aim to test the integration and operation of a large optical network covering transport and access parts.

In United States the most important are AON project and afterwards MONET and ONTC projects. The main goals of these projects was to develop national information infrastructure with architecture enabling scalability in geographic area, number of access nodes and services, flexible to incorporate all technological developments. The reported results had proven the viability of WDM all-optical networking.

4. Optical Packed Switched Networks and IP over WDM

Wavelength routed optical networks and high-capacity WDM transmission are the solution for electronic bottleneck in transport network which are primarily designed for circuit switching. At the access network level the provision of huge bandwidth to the individual user, capable of supporting all today's and future services, would be rather costly. On the other hand, all future communications studies predict that data traffic will continue to grow much more rapidly than voice (as shown in Fig. 1). Therefore future transport infrastructure must be optimized for data, precisely to carry IP traffic that involves packed switching. Existing circuit switched networks will need to be upgraded to support packed switched data traffic [1], [4], [19]. Utilization of available resources through packet network can solve the existing access-transport mismatch at a relatively modest cost [12], [13], [14], [15].

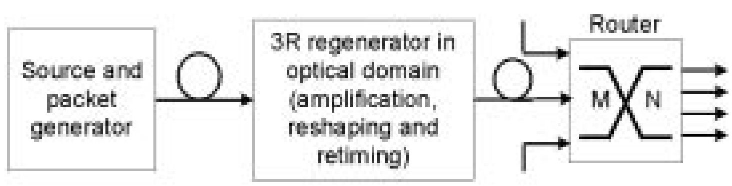

Fig. 14. Key functions needed for optical packet networks.

Packed switched networks have been seen as a good alternative to conventional circuit switched at the end user level since, over the last couple of years, a huge progress in packetizing voice signals, using compression and speech encoding techniques, and improved router design reducing delays through the network have been achieved. Key functions for digital optical packet networks, independent of exact implementation technology (WDM/OTDM) are shown in Fig. 14. The buffering in routers is needed to delay packets during header recognition and processing and in the process of switching to avoid packet contention. There is no available optical random access memory and the only way to introduce buffering is through precisely set optical delays. It is clear that the higher the channel rate is, the shorter the buffers need to be, and the issue is yet to be researched. Another problem to be researched is address recognition for which the synchronization is the key since each node must be able to recognize the start of a packet and it is almost impossible to implement a network-wide clock. Some alternative approaches to avoid optical buffering, such as deflection or "hot potato" routing, have been proposed but it is unclear if it is really implementable [1], [2], [16].

The running of IP network over a WDM physical infrastructure, which is considered to be the future network solution as illustrated in Fig. 15, needs a very careful planning. The multilayer architecture, with layers unaware of each other, used in today's Sonet/SDH WDM networks is not ideal for data. Network management and flow control mechanisms can even work against each other. Also, some functions will be unnecessary, but some new functions must be introduced [17], [18]. Two main issues will affect the success of IP over WDM: the capability of IP to support the required quality of services (QoS) grade, and the capability of WDM to provide robustness and survivability of network. Different protection schemes and network management platforms were widely tested in different field trials and WDM network implementations (MONET, ONTC, ACTS- PELICAN, MEPHISTO, PLANET, etc.) exhibiting excellent features. Internet standardization group IETF proposed a connection-oriented multiprotocol label switching (MPLS) to meet the QoS requirements particularly for delay sensitive services. With MPLS all packets, associated with same label in a particular session, are sent along the pre-established path between source and destination node. Although there is no physical connection it is similar to establishing a circuit which take place in initial stage of a call in circuit switched networks. At the WDM layer the MPLS concept is simplified to multiprotocol lambda switching (MPΛS) since the signal wavelength can be used as a label enabling the wavelength routing and lightpath switching [13], [15], [19], [20].

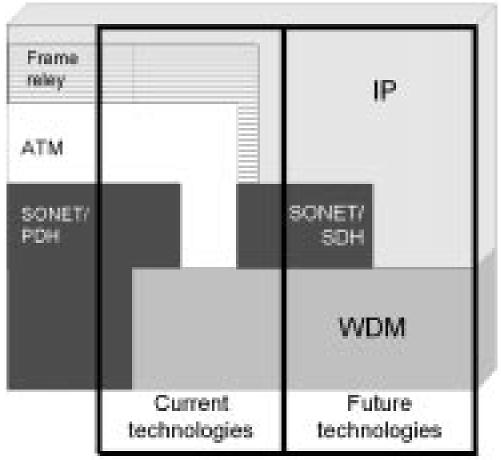

Fig. 15. Evolution of WDM telecommunication.

5. Conclusion

This paper gives an overview of WDM networks evolution since its first implementation in 1993. WDM achieves the use of excess fiber bandwith by dividing the optical transmission spectrum into a number of discrete wavelength bands, each supporting a single communication channel operating at peak electronic rate. The system with unidirectional transmission of 128 channels at 40 Gb/s (total throughput of 5.12 Tb/s) over 300 km is reported. Also the designed all-optical wavelength routed networks with lightpath switching and no need for electrooptical conversion at intermediate nodes between source and destination nodes have proven their viability through realization of different projects. The next goal is to optimize network structure for end user level. IP over WDM togather with optical packet switched networks (WDM/ OTDM/ CDM) are the main target of contemporary research efforts.

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