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INTERNATIONAL JOURNAL
OF CURRENT RESEARCH

International Journal of Current Research
Vol. 13, Issue, 11, pp.19417-19424, November, 2021

DOI: https://doi.org/10.24941/ijcr.42564.11.2021

ISSN: 0975-833X

RESEARCH ARTICLE

WDM BASED OPTICAL NETWORKS: ARCHITECTURAL ISSUES AND CHALLENGES

***Sunil P. Singh**

Department of Physics, Kamla Nehru Institute of Physical and Social Sciences, Sultanpur (UP)-228118, India

ARTICLE INFO

Article History:
Received 17th August, 2021
Received in revised form
10th September, 2021
Accepted 16th October, 2021
Published online 24th November, 2021

Keywords

Wavelength Division Multiplexing (WDM), Optical Time Division Multiplexing (OTDM) and Optical Code Division Multiplexing (OCDM).

Corresponding author:
Sunil P. Singh

ABSTRACT

The wavelength division multiplexing (WDM) technology has led to a tremendous amount of commercial and research interest in WDM-based networks. The emergence of WDM networking components led people to design and deploy WDM based networks. Such networks take advantage of the flexibility and configurability of components. In principle the optical time division multiplexing (OTDM) and Optical code division multiplexing (OCDM) can be exploiting to utilize the fiber bandwidth. But presently these technologies are in developing stage. In this paper the recent developments in WDM based optical networks are presented.

Citation: Sunil P. Singh. *"*WDM Based Optical Networks: Architectural Issues and Challenges*", 2021. International Journal of Current Research, 13, (11), 19417-19424.*

INTRODUCTION

The past few years have witnessed phenomenal developments in the field of fiber optic communications. The gradual amalgamation of computing and communication techniques, the enormous bandwidth (of the order of 25,000 GHz) and low loss of optical fibers has changed the concepts and means for realizing communication networks. It is expected that optical networks will be able to meet the need of tomorrow's bandwidth-hungry society by providing high-bandwidth data transport at all possible levels of networking infrastructures such as for local-area networks (LANs) and metropolitan-area networks (MANs), broadband access networks and wide-area networks (WANs) for national backbones. The wavelength division multiplexing (WDM) technology plays a very important role in optical networking development for bandwidth-hungry society. The Wavelength division multiplexing (WDM) networks is that, as more and more users start to use our data networks, and as their usage patterns evolve to include more and more bandwidth-intensive networking applications such as data browsing on the worldwide web (WWW), java applications, video conferencing, etc., there emerges an acute need for very high-bandwidth transport network facilities, whose capabilities are much beyond those that current high-speed networks can provide. A single-mode fiber's potential bandwidth is nearly 50 Tb/s, which is nearly four orders of magnitude higher than electronic data rates of a few gigabits per second (Gb/s). Every effort should be made to tap into this huge opto-electronic bandwidth mismatch. Realizing that the maximum rate at which an end-user— which can be a workstation or a gateway that interfaces with lower-speed sub networks—can access the network is limited by electronic speed (to a few Gb/s). It is the main limitation in designing optical communication networks in order to exploit the fiber's huge bandwidth and to introduce concurrency among multiple user transmissions into the network architectures and protocols. In an optical communication network, this concurrency may be provided according to wavelength or frequency (wavelength- division multiplexing (WDM)), time slots (time-division multiplexing (TDM)) and wave shape (code-division multiplexing (CDM)). Optical TDM and CDM are somewhat futuristic technologies today.

In TDM, each end-user should be able to synchronize within one time slot. The optical TDM bit rate is the aggregate rate over all TDM channels in the system, while the optical CDM chip rate may be much higher than each user's data rate. As a result, both the TDM bit rate and the CDM chip rate may be much higher than electronic processing speed, i.e., some part of an end user's network interface must operate at a rate higher than electronic speed. Thus, TDM and CDM are relatively less attractive than WDM. WDM is the current favorite multiplexing technology for long-haul optical communication networks (1-3).

Wavelength Division Multiplexed (WDM): Wavelength-division multiplexing (WDM) is an approach that can exploit the huge opto-electronic bandwidth mismatch by requiring that each end-user's equipment operate only at electronic rate, but multiple WDM channels from different end-users may be multiplexed on the same fiber. In WDM, the optical transmission spectrum (Fig.1) is carved up into a number of non overlapping wavelength (or frequency) bands with each wavelength supporting a single communication channel operating at whatever rate one desires, e.g., peak electronic speed. Thus, by allowing multiple WDM channels to coexist on a single fiber, one can tap into the huge fiber bandwidth, with the corresponding challenges being the design and development of appropriate network architectures, protocols, and algorithms. Also, WDM devices are easier to implement since, generally, all components in a WDM device need to operate only at electronic speed; as a result, several WDM devices are available in the marketplace today, and more are emerging. It is anticipated that the next generation of the Internet will employ WDM-based optical backbones.

The WDM network will be deployed mainly as a backbone network for large regions, e.g., for national or global coverage. Optical WDM networks for local and metropolitan applications are also being developed and prototyped. End-users, to whom the architecture and operation of the backbone will be transparent except for significantly improved response times, will attach to the network through a wavelength-sensitive switching/routing node. An end-user in this context need not necessarily be a terminal equipment, but the aggregate activity from a collection of terminals including those that may possibly be feeding in from other regional and/or local sub networks. So that the end-user's aggregate activity on any of its transmitters is close to the peak electronic transmission rate.

Basic configuration of a WDM system: A typical configuration of a WDM system is shown in Fig.2. It mainly consists of transmitters of different channels, multiplexer (MUX), amplifier/s, communication link, i.e., optical fiber, demultiplexer (DEMUX)/tunable filters, and receivers. In WDM system outputs from several channels are multiplexed together, and then transmitted after amplification. Each channel is operated at distinct wavelength and consists of an optical source, pseudo random bit sequence generator, pulse generator and optical modulator. Output of the light source of each channel is modulated according to the individual data stream and combined together. A post-amplifier is used to boost the multiplexed output. Various optical amplifiers (particularly erbium-doped fiber amplifier) are placed in the line to compensate the loss in the power that occurs as the light propagates down the fiber. These amplifiers have the characteristic that they can amplify several channels simultaneously. Dispersion compensated units (not shown here) are also used to compensate the dispersion. At the receiver end each wavelength is first separated by demultiplexers or tunable optical filter and then processed individually.

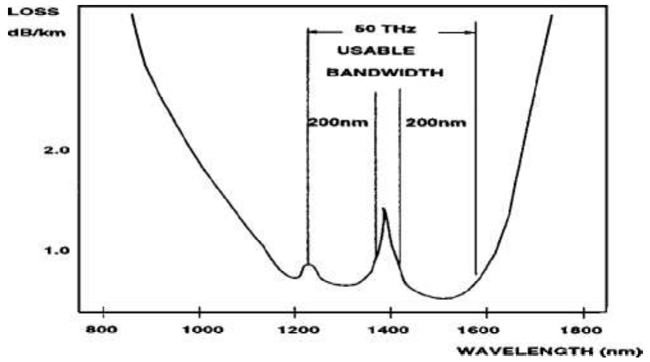

Figure 1. The low-attenuation regions of an optical fiber

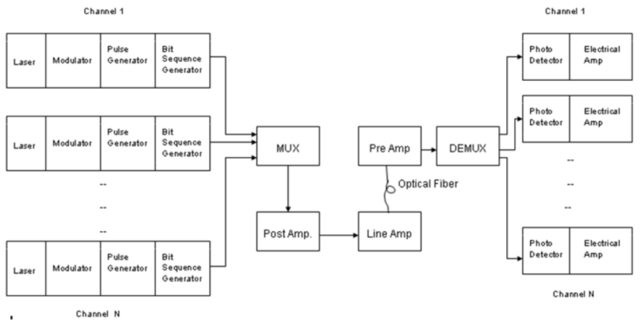

Figure 2. Block Diagram of WDM System

Evolution of WDM networks: The evolution of WDM networking in deferent stages is discussed here briefly (1,6,7).

Point-to-Point WDM Systems*:* WDM technology is being deployed by several telecommunication companies for point-to-point communications. This deployment is being driven by the increasing demands on communication bandwidth. When the demand exceeds the capacity in existing fibers the WDM is turning out to be a more cost-effective alternative compared to laying more fibers. A study (4) compared the relative costs of upgrading the transmission capacity of a point-to-point transmission link from OC-48 (2.5 Gb/s) to OC-192 (10 Gb/s) via the following three possible solutions is carried out.

- Installation/burial of additional fibers and terminating equipment (the multi fiber solution).
- A four-channel WDM solution (Fig. 3) where a WDM multiplexer (mux) combines four independent data streams, each on a unique wavelength, and sends them on a fiber. A demultiplexer (demux) at the fiber's receiving end separates out these data streams.
- OC-192, a higher-electronic-speed solution.

For distances lower than 50 km for the transmission link, the multifiber solution is the least expensive; but for distances longer than 50 km, the WDM solution's cost is the least with the cost of the higher-electronic-speed solution not that far behind. WDM mux/demux in point-to-point links is now available in product form from several vendors such as IBM, Pirelli, and AT&T (12).

Wavelength Add/Drop Multiplexer (WADM): One form of a wavelength add/drop multiplexer (WADM) is shown in Fig. 4. It consists of a demux, followed by a set of 2×2 switches one switch per wavelength followed by a mux. The WADM can be essentially inserted on a physical fiber link. If all of the 2×2 switches are in the bar state, then all of the wavelengths flow through the WADM undisturbed. However, if one of the 2×2 switches is configured into the cross state (as is the case for the switch in Fig.4) via electronic control (not shown in Fig.4), then the signal on the corresponding wavelength is dropped locally, and a new data stream can be added on to the same wavelength at this WADM location. More than one wavelength can be dropped and added if the WADM interface has the necessary hardware and processing capability. The functionality of add/drop multiplexing can be enhanced for practical implementation of an optical add/drop multiplexer (OADM). For example, an OADM may drop part of the traffic on a wavelength or it may drop a band of wavelengths.

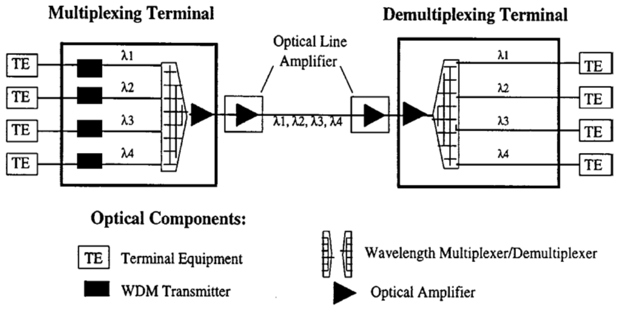

Figure 3. A four-channel point-to-point WDM transmission system with amplifiers

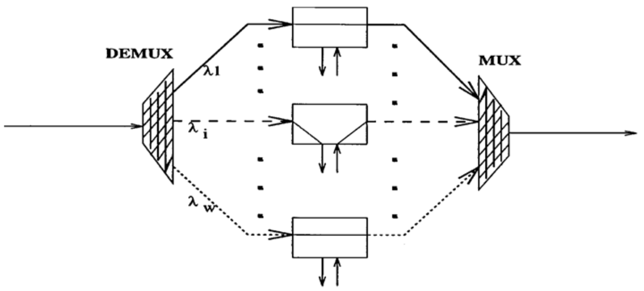

Figure 4. A wavelength add/drop multiplexer (WADM)

***Fiber and Wavelength Cross connects – Passive Star, Passive Router, and Active Switch*:** In order to have a network of multi wavelength fiber links, we need appropriate fiber interconnection devices. These devices fall under the following three broad categories:

- Passive star
- Passive router
- Active switch

The passive star is a broadcast device, so a signal that is inserted on a given wavelength from an input fiber port will have its power equally divided among (and appear on the same wavelength on) all output ports. As shown in Fig. 5. A signal on wavelength λ_1 from Input Fiber 1 and another on wavelength λ_4 from Input Fiber 4 are broadcast to all output ports. A collision will occur when two or more signals from the input fibers are simultaneously launched into the star on the same wavelength. Assuming as many wavelengths as there are fiber ports, an $N \times N$ passive star can route N simultaneous connections through itself. A passive router can separately route each of several wavelengths incident on an input fiber to the same wavelength on separate output fibers, e.g., wavelengths λ_1 , λ_2 , λ_3 , and λ_4 incident on Input Fiber 1 are routed to the same corresponding wavelengths to Output Fibers 1, 2, 3, and 4, respectively as shown in Fig.6. Observe that this device allows wavelength reuse, i.e., the same wavelength may be spatially reused to carry multiple connections through the router. The wavelength on which an input port gets routed to an output port depends on a routing matrix characterizing the router. This matrix is determined by the internal connections between the demux and mux stages inside the router (Fig. 6). The routing matrix in a passive router is fixed and cannot be changed. Such routers are commercially available, and are also known as Latin routers, waveguide grating routers (WGRs), wavelength routers (WRs), etc. Again, assuming as many wavelengths as there are fiber ports, a $N \times N$ passive router can route N^2simultaneous connections through itself (compared to the passive star); however, it lacks the broadcast capability of the star. The active switch also allows wavelength reuse, and it can support N^2 simultaneous connections through itself (like the passive router). But the active star has a further enhancement over the passive router in that its routing matrix can be reconfigured on demand, under electronic control. However the active switch needs to be powered and is not as fault-tolerant as the passive star and the passive router which don't need to be powered. The active switch is also referred to as a wavelength- routing switch (WRS), wavelength selective cross connect (WSXC), or just cross connect for short. The active switch can be enhanced with an additional capability, viz., a wavelength may be converted to another wavelength just before it enters the mux stage before the output fiber (Fig. 7). A switch equipped with such a wavelength-conversion facility is more capable than a WRS, and it is referred to as a wavelength-convertible switch, wavelength interchanging cross connect (WIXC) etc. Although the active switch in Fig. 7 is assumed to include the wavelength demux/mux devices, note that the mux/demux devices could be part of the multiwavelength fiber transmission system. Thus, the mux/demux devices are not included in the optical cross connect products being developed by most vendors today. The passive star is used to build local WDM networks, while the active switch is used for constructing wide-area wavelength-routed networks. The passive router has mainly found application as a mux/demux device. The WADM device and its variants are mainly used to build optical WDM ring networks which are expected to deploy mainly in the metropolitan area market.

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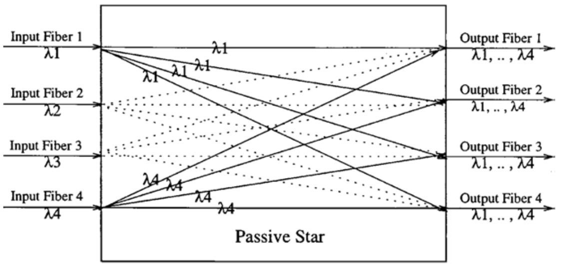

Figure 5. A 4 × 4 passive star

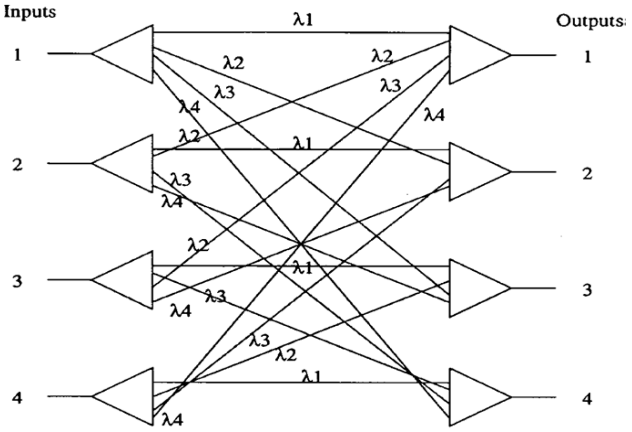

Figure 6. A 4 × 4 passive router (four wavelengths)

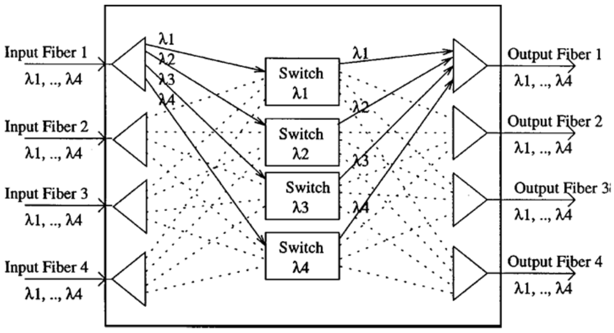

Figure 7. A 4 × 4 active switch (four wavelengths)

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WDM NETWORK CONSTRUCTIONS: Today's WDM-based optical networks can be categorized broadly in two types-Broadcast and select networks (BSNs) and wavelength routed networks (WRNs).

Broadcast and select networks (BSNs): A WDM optical network may be constructed by connecting network nodes via two-way fibers to a passive star topology. A node sends its transmission to the star on one available wavelength, using a laser which produces an optical information stream. The information streams from multiple sources are optically combined by the star and the signal power of each stream is equally split and forwarded to all of the nodes on their receive fibers. A node's receiver, using an optical filter, is tuned to only one of the wavelengths; hence it can receive the information stream. Communication between sources and receivers may follow one of two methods: (1) single-hop or (2) multihop (8-9). When a source transmits on a particular wavelength λ_1, more than one receiver can be tuned to wavelength λ_1, and all such receivers may pick up the information stream. Thus, the passive-star can support multicast services.

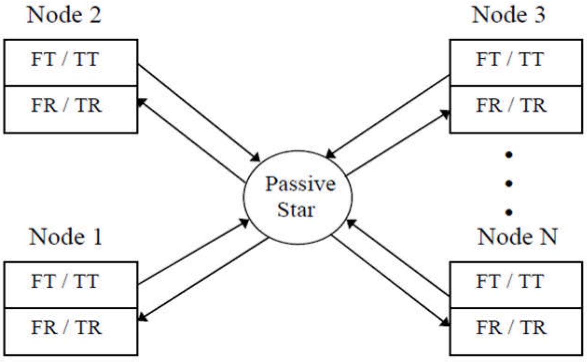

Figure 8. A WDM-based broadcast and select network

Here FT, TT, FR, FR are fixed-tuned transmitter, tunable transmitter, fixed-tuned receiver and tunable receiver respectively. A passive star broadcast and select network is shown in Fig.8. Wherein a packet from a transmitting node is broadcast to all nodes of the network at a specific wavelength, and the destined receiver selects (tuned) the desired wavelength to receive the packet. Each node, in general, can employ either a tunable or a fixed tuned transmitter/receiver, thus leading to four possible network architectures. Such networking setup usually employs appropriate MAC protocol for multiple-access-based transmission over WDM channels, and thus find themselves useful for implementation of LANs/MANs and broadband access networks. The broadband access networks are thus expected to employ two level hierarchical topology, wherein the higher level would assume the form of a WDM ring employing wavelength routing, while the lower level clusters would employ passive- star based BSN architecture.

Broadcast-and-Select Single-Hop Networks: Two alternate physical architectures for a WDM- based local network as shown in Fig. 9. Here, N sets of transmitters and receivers are attached to either a star coupler or a passive bus. Each transmitter sends its information at different fixed wavelength. All the transmissions from the various nodes are combined in a passive star coupler or coupled onto a bus and result is sent out to all receivers. Each receiver sees all wavelengths and uses a tunable filter to select the one wavelength addressed to it. In addition to point-to-point links, this configuration can also support multicast or broadcast services, where one transmitter sends the same information to several nodes.This concept for a star networks is shown in Fig. 10. Workstation at nodes 4 and 2 communicate using λ_2, whereas a user at node 1 broadcast information to workstations at nodes 3 and 5 using λ_1. The same concepts are applicable to bus structure. The losses encountered in the star and bus architectures are different. The WDM setup in Fig. 10 is protocol transparent. This means that different sets of communicating nodes can use different information- exchange rules (protocols) without affecting the other nodes in the network. This analogous to standard time-division-multiplexing telephone lines in which voice, data, or facsimile services are sent in different time slots without interfering with each other. However, here the rates differ widely. The architectures of single-hop broadcast-and-select networks are fairly simple, there needs to be careful dynamic coordination between the nodes.

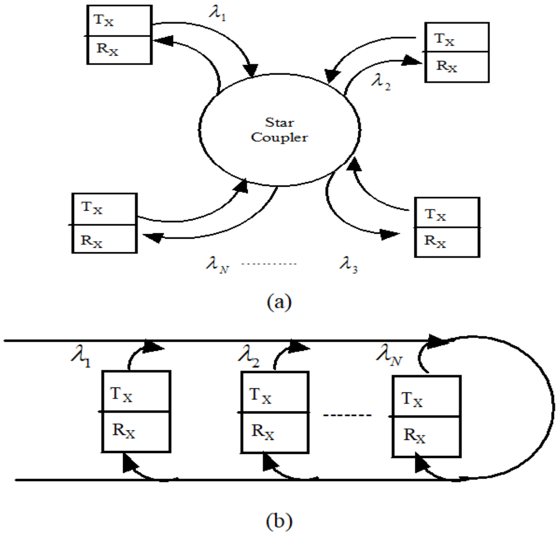

Figure 9. Two alternate physical architecture for a WDM based local networks: (a) star (b) bus

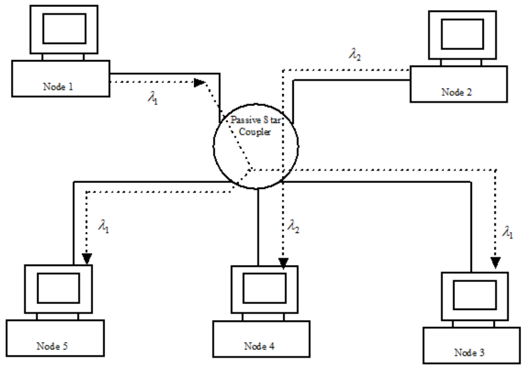

Figure 10. Architecture of a single-hop broadcast-and-select network

Broadcast-and-Select multihop Networks: A drawback of single- hop networks is the need for rapidly tunable lasers or receiver optical filters. The designs of multihop networks avoid this need. Multihop networks generally do not have direct paths between each node pair. Each node has a small number of fixed-tuned optical transmitters and receivers. Fig.11 shows an example of a four node broadcast-and select multihop network. Where each node transmits on one set of two fixed wavelengths and receivers on another set of two fixed wavelengths. Stations can send information directly only to those nodes that have a receiver tuned to one of the two transmit wavelengths. Information destined for other nodes will have to be routed through intermediate stations. To consider a very simplified transmission scheme in which message are sent as packet with a data field and an address header containing source and destination identifies (i.e. routing information) together with other control bits as shown in Fig.12.

At each intermediate node, the optical signal is converted to an electrical format, and the address header is decoded to examine the routing information field, which will indicate where the packet should go. Using this routing information, the packet is then switched electronically to the specific optical transmitter that will appropriately direct the packet to the next node in the logical path toward its final destination. The flow of traffic can be seen from Fig. 11. If node 1 wants to send a message to node 2, it first transmits the massage to node 3 using λ_1. Then node 3 forwards the message to node 2 using λ_6. In contrast to single hop networks, with this scheme there are no destination conflicts or packet collisions in the network, since each wavelength channel is dedicated to a particular source-destination link. However, for H hops between nodes, there is a network throughput penalty of at least 1/H.

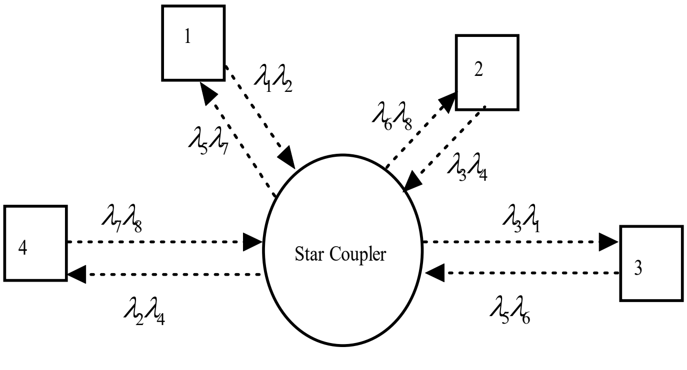

Figure 11. Architecture and traffic flow of multihop broadcast-and-select network

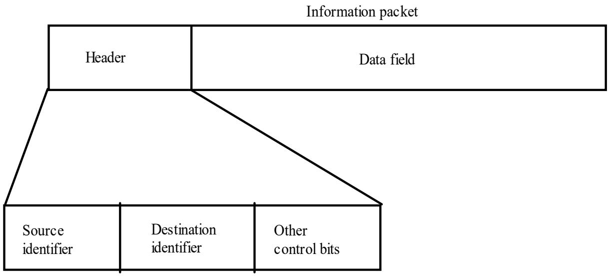

Figure 12. Simple representation of the fields contained in a data packet

Wavelength-Routed Optical Network: A wavelength-routed (wide-area) optical WDM network is shown in Fig.13. The network consists of a photonic switching fabric, comprising active switches connected by fiber links to form an arbitrary physical topology. Each end-user is connected to an active switch via a fiber link. The combination of an end-user and its corresponding switch is referred to as a network node (1, 10). Each node (at its access station) is equipped with a set of transmitters and receivers, both of which may be wavelength tunable. A transmitter at a node sends data into the network and a receiver receives data from the network. The basic mechanism of communication in a wavelength routed network is a lightpath. A lightpath is an all-optical communication channel between two nodes in the network, and it may span more than one fiber link. The intermediate nodes in the fiber path route the lightpath in the optical domain using their active switches. The end-nodes of the lightpath access the lightpath with transmitters and receivers that are tuned to the wavelength on which the lightpath operates. For example, in Fig.13, lightpaths are established between nodes A and C on wavelength channel λ1, between B and F on wavelength channel λ_2, and between H and G on wavelength channel λ_1. The lightpath between nodes A and C is routed via active switches 1, 6, and 7. (Note the wavelength reuse for λ_1).

In the absence of any wavelength-conversion device, a light path is required to be on the same wavelength channel throughout its path in the network; this requirement is referred to as the wavelength-continuity property of the light path. This requirement may not be necessary if we also have wavelength converters in the network. For example, in Fig.13, the light path between nodes D and E traverses the fiber link from node D to switch 10 on wavelength λ_1, gets converted to wavelength λ_2 at switch 10, traverses the fiber link between switch 10 and switch 9 on wavelength λ_2, gets converted back to wavelength λ_1 at switch 9, and traverses the fiber link from switch 9 to E node on wavelength λ_1.

A fundamental requirement in a wavelength-routed optical network is that two or more light paths traversing the same fiber link must be on different wavelength channels so that they do not interfere with one another.

NATION-WIDE WDM NETWORKING INFRASTRUCTURE: A possible realization of a nation-wide WDM networking infrastructure with WRN-based optical WAN interconnecting regional access networks is shown in Fig.14, wherein the access networks are comprised of two levels of hierarchy. The higher level of access networks (connected to the WAN) employ wavelength-routed feeder ring (with WXCs) and each node on the feeder ring is connected to the corresponding WDM-based BSN. In a realistic situation depending on the size and population densities, the regional access networks may be further divided to form a three-level hierarchical topology. It may be noted that in such WDM networks optical signals need to propagate through passive devices (such as, WXCs and passive stars) and long fiber spans, at times incurring significant power loss. In such situation, when the signal loss causes unacceptable transmission errors, one needs to employ optical amplifiers to compensate for the signal losses for all the wavelengths at a time.

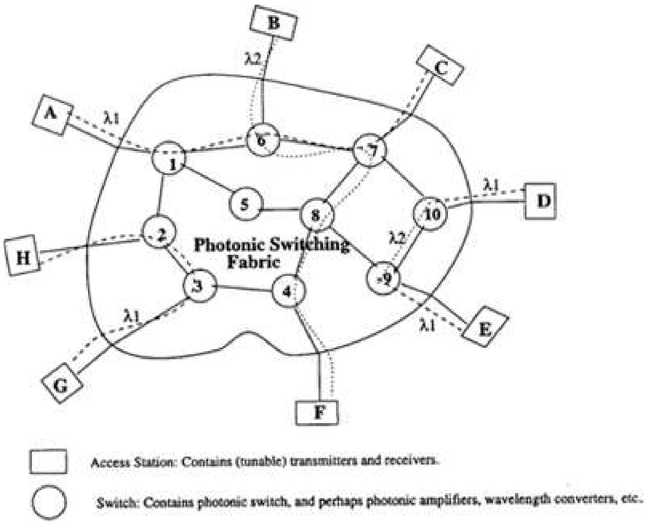

Figure 13. A wavelength-routed optical WDM network

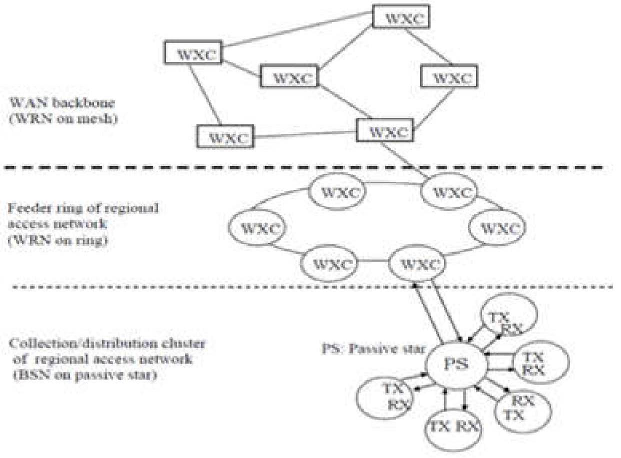

Figure 14. A possible realization of a national-wide WDM networking infrastructure

ARCHITECTURAL ISSUES AND CHALLENGES IN WDM NETWORKS: Besides the technological innovations of WDM devices (i.e., at the physical-layer level), tomorrow's optical network needs to provide an efficient and reliable framework for supporting wide range of services in both BSN as well as WRN settings. In broadband access networks, the higher level may employ wavelength-routing-based feeder rings with appropriate traffic grooming, which will in turn be feeding into the lower-level clusters employing BSN-based PONs with appropriate MAC protocols (supporting wide range of services). On the other hand, for WRN-based WANs (usually, with mesh topologies) one needs to design appropriate virtual topology and use optimum routing and wavelength assignment schemes for the establishment of light paths conceived in the virtual topology, effective bandwidth management scheme by dynamic setting up/ tearing-down of light paths in a circuit-switching based network setting, etc.

Appropriate architectures and protocols for these networks to make the devices work together for next-generation networks are now the major issues and are under vigorous Investigation all over the world. It may be worthwhile, to deliberate further on some of these issues in respect of upgrading today's IP-based Internet by employing WRN-based optical backbone. In particular, while upgrading the IP-centric network backbones, one will have to work out the means to bring together the intrinsically circuit-switching lightpaths of WRNs with packet-switching nature of existing IP. Establishing a lightpath between a node pair (i.e., a router pair) would be equivalent to setting up a circuit-switched connection, while above such optical layer there would exist the packet-switching-based IP layer. However, considering that the traffic therein would consist of a large share of bursty data, such circuit-switched connections can not offer optimum utilization of the bandwidth of each lightpath (of the order of a few Gbps). The other option would be to use additional electronic layers (SONET/SDH/ATM/frame relay) between IP and WDM layers to provide flexible and granular access to the bandwidth of each lightpath. But this option would suffer from additional overheads and need electro-optic regeneration at every intermediate node, defeating thereby the basic advantage of transparent networking.

However, one can attempt to implement optical packet-switching (OPS) in WDM networks (i.e., mimic the packet switching employed by IP-based networks), thus providing the best possible utilization of the entire fiber bandwidth in the optical domain itself. Unfortunately, in spite of the ongoing research effort, this technology is yet to mature, more particularly due to limited buffering capability in optical domain and the sluggish reconfiguration capability of optical switches. Consequently, a new switching paradigm, called optical burst switching (OBS) (14), basically an improvisation OPS to get around the problems of buffering and slow-speed optical switches, has started gathering research interest, but will indeed take several years to be available in the form of finished product. It therefore appears that, notwithstanding the fact that the wavelength-routing based circuit-switching-centric WRNs are not the most optimum solution to exploit the bandwidth-resource of optical fibers, one needs to harness them in their present form to meet the fast-growing bandwidth demand of our society. More so, because OBS and OPS may not be available in the near future in the form of commercial products, while varieties of wavelength-routing WXCs have already started arriving in the market, having their feasibility been demonstrated in experimental tested. One therefore needs to accept the reality and make use of these products to make a reliable networking infrastructure for near future. Having accepted this limitation of circuit-switched light paths (i.e., the suboptimum utilization of fiber capacity in WRNs), the issue of survivability of such optical WDM backbones against failures would need special attention. In general, a network is referred to as survivable if it provides some ability to recover ongoing connections disrupted by sudden failure of a network component, such as a line cut or a node failure. It may be noted that, while WDM provides large bandwidth, it has additional problem and complexity in the event of network failures, such as, fiber cuts or node failures. Because of large amount of traffic a fiber carries, even a single failure in a WDM link or in a WXC would inflict severe service interruption. In general, survivable network can be designed by employing restoration and/or protection schemes. Following a network failure, a restoration scheme in a WRN should dynamically look for backup light paths of spare capacity in the network. A protection scheme in a WRN should reserve in advance dedicated backup light paths in the network. The former scheme can be made available in the higher layers of the network (such as, IP layer), while the latter scheme would be employed at the lower layer (such as, optical layer). In practice, it is expected that both layers will jointly cooperate to provide the necessary resilient schemes to protect ongoing connections from disruptions (15). Finally, it may be worthwhile to indicate that providing an appropriate network management and control (NM&C) framework is a quintessential step towards commercialization of such networks. The major functionalities of this framework would include the management of network configuration (resource configuration & connection) faults, performance, security and accounting (16). These management functionalities need to be implemented by adopting a telecommunication management network within the architectural framework which in turn can employ the necessary management functions through a number of management layers, e.g., network management layer, element management layer and network element layer. The NM&C system is expected to operate with a user-friendly graphical user interface for network/site maps, alarms and performance-monitoring information displays, and thus enable a network administrator to dynamically discover information about the network, provision connections across the network, and monitor and react to network failures and connection problems.

CONCLUSION

An overview of the recent trends in the evolving fields of optical networking and examined the challenges ahead towards commercial realization of tomorrow's optical networks. We have discussed, the networking concepts and technologies have gradually changed with the advent of optical communication systems, more significantly after the emergence of mature WDM technologies. In smaller geographical areas served by LANs or lower –level clusters of access networks. WDM is found to be an attractive means in providing broadcast-based networking architectures. On the other hand, for national backbones (with mash topology) as well as for feeder rings in regional access networks, light path-based wavelength routing would offer the best possible utilization of fiber band for today.

ACKNOWLEDGEMENT

Author is thankful to higher education department, Government of Uttar Pradesh, India for financial support vide letter no. 46/2021/603/70-4-2021-4 (56)/2020. Author is also thankful to Prof. N Singh, University of Allahabad for providing computational facilities.

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