Multicast Routing In Optical Access Networks

Miklós Molnár, Fen Zhou, Bernard Cousin

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Chapter 8

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Miklós Molnár
Irisa-Insa, France

Fen Zhou
Irisa-Insa, France

Bernard Cousin
Irisa-University of Rennes I, France

ABSTRACT

Widely available broadband services in the Internet require high capacity access networks. Only optical networking is able to efficiently provide the huge bandwidth required by multimedia applications. Distributed applications such as Video-Conferencing, HDTV, VOD and Distance Learning are increasingly common and produce a large amount of data traffic, typically between several terminals. Multicast is a bandwidth-efficient technique for one-to-many or many-to-many communications, and will be indispensable for serving multimedia applications in future optical access networks. These applications require robust and reliable connections as well as the satisfaction of QoS criteria. In this chapter, several access network architectures and related multicast routing methods are analyzed. Overall network performance and dependability are the focus of our analysis.

INTRODUCTION

Recent advances in communication technology have resulted in multicast applications playing an important part in everyday Internet traffic. Data transmission generated by multicast multimedia services as Video-On-Demand, High Definition TV diffusion, Video-Conferences, Distance Learning and Online-Games requires large bandwidth, while QoS (Quality of Service) parameters such as end-to-end delay and jitter must be tolerated. From the white paper of the European Information & Communications Technology Industry Association (EICTA) on Next Generation Networks and Next Generation Access, high speed network access is characterized as (a) the availability of symmetrical access (b) instant communication (no latency) and (c) simultaneous applications (EICTA, 2008). All-optical networks show promise as an infrastructure that can guarantee dependability, flexibility, high bandwidth and QoS

for users of multicast applications. All-optical networks have optical access network component directly connected to the mesh optical backbone. The huge capacity of fibers and light based routing in optical switches provide end-users with large bandwidth connections to the network. The most promising technology corresponds to wavelength division multiplexing (WDM). The transmission of data can be organized in either a connection based or a burst switched manner (Qiao & Yoo, 1999). Aggregation techniques and time division multiplexing can be applied to enhance overall network performance. In currently implemented solutions the optical switch configuration is performed via an independent control plane or a fixed-tuned wavelength channel for control messages. This control plane enables precise and thus efficient management of the optical network.

From the point of view of network operators and access providers, access network technology should offer a flexible solution at low cost. Low cost can be achieved with the use of passive equipment and a simple topology (for example a star). The huge capacity of an optical infrastructure currently allows wastage of network resources. However, in the long run a better utilization of network resources may be an important operator objective. The network should thus offer the possibility to manage resources and to balance network load. The dependability of the network is also a fundamental property for operators and users. Currently, optical access network technology is widely based on PONs (Passive Optical Networks), but Ethernet point-to-point and active Ethernet solutions are also present in the market. PONs contain passive elements. They are simple, easy to install and do not require an electrical power supply. A typical FTTx access network implemented with PONs is star based and contains splitters. The most significant drawback of star topologies is their vulnerability. Absolute dependability is a critical and fundamental requirement for modern communication networks. Dependable network services cannot be provided without redundancies

in the network topology. Thus, dependable access networks must contain, at least in their core part, redundant edges and nodes, thus producing cycle or mesh topologies.

Multicast routing is not specifically analyzed for current access networks. However, the coexistence of many multicast sessions raises some important problems. For instance, in a star topology the intelligent allocation of wavelengths among multicast sessions can optimize the use of network resources (Sheu & Huang, 1997; Sivalingam, Bogineni, & Dowd, 1992). In a mesh topology the light-tree structure can be introduced. Dependable multicasting is made possible using light-trees because they can be replaced entirely or partially when some network elements fail. In our analysis, we suppose that future optical access networks will be heterogeneous and meshed. This implies that the network topology has some active and configurable switches, and provides sufficient redundancy to offer dependable services with a high level of flexibility for efficient resource management. Moreover, precise configuration of the lightpaths and light-trees enhances the security of the network because data is not broadcast as in a star topology. Multicast routing in heterogeneous and mesh optical access networks (which contain active switches and passive elements) can play an important role in the all-optical networks of the future. Optical switch architectures and optical fiber characteristics introduce some specific constraints which must be taken into account by the routing algorithm. Moreover, the throughput of the network depends strongly on the efficiency of the routing algorithms. For these reasons, we propose a survey of multicast routing algorithms under the typical physical constraints of wavelength switched optical access networks.

This chapter presents the underlying problems as follows: following a description of typical access network architectures and routing (scheduling) methods, we describe the main constraints on optical switches and fibers. Since dependable network architectures correspond to mesh networks,

the constraints have a large impact on performance, restrain the routing algorithm, and influence the multicast structures. Multicast routes usually correspond to partial spanning trees, but due to optical constraints the light-tree structure must be adapted. Generally, light-trees and light-forests are proposed to support multicast communications. These two types of structures allow the various constraints in all-optical networks to be satisfied. Even when splitters are available in the network, splitting diminishes strongly (at least proportionally) the light power, thus several specific energy aware light-trees may be required to minimize splitting. Wavelength conversion capabilities can dramatically enhance the performance of multicast routing. In consequence, several multicast routing algorithms are presented which satisfy the various requirements of heterogeneous optical access networks.

OPTICAL ACCESS NETWORK ARCHITECTURES

To be competitive access network operators have to install cost-effective networks with a large enough bandwidth capacity to serve end-user requirements. For instance FTTH architectures and the deployment of physical fiber infrastructure in British Telecom experiments are discussed in (Mayhew, Page, Walker, & Fisher, 2002). This analysis illustrates very well the difficulties that an operator encounters when determining future network investments. On one hand the high bandwidth requirement of future services limits the choice of technology. Only optical fiber network offers the capability of cost-effective wide-scale provision of the full range of future broadband services. On the other hand, the cost and the profitability of the access network limit operator investment. The authors demonstrate that applying an FTTH network offers smaller potential revenue from a residential service than from a service in the business area. This leads to a need for cost

optimization of both the transmission system and the fiber infrastructure.

Star Topologies

The most frequently proposed topology is the passive star, where a PSC (Passive Star Coupler) links the access nodes. This configuration was developed to realize Ethernet-based PON (EPON) technology in access networks (Kramer, Mukherjee, & Pessavento, 2001). All communication in an EPON is performed between an optical line terminal (OLT) and optical network units (ONUs). The OLT connects the optical access network to the backbone. In the downstream direction (from OLT to ONUs), a PON corresponds to a point-to-multipoint network, and in the upstream direction it is a multipoint-to-point network (*Figure 1*).

Star based PONs are simple, easy to install in existing infrastructures and easy to maintain. In these access networks, each ONU has a dedicated short optical fiber and shares a long distribution trunk fiber to the OLT with the other ONUs. For downstream traffic the EPON implements a broadcast and select scheme using the splitting capacity of the central coupler. For upstream communication an appropriate Dynamic Bandwidth Allocation (DBA) algorithm is used to assign time slots to end-users.

Generally, multicast communication in the star can be realized easily, but as illustrated in the next section, the medium access control protocol can be very specific. The main disadvantage of star topologies is their vulnerability. If the coupler fails the entire access segment is hampered. The fiber connecting the core network to the PSC (Passive Star Coupler) via the optical line terminal (OLT) also represents a highly vulnerable joint of the access network. Moreover, it is difficult to resolve security and confidentiality issues. Last but not least, due to the fact that messages are broadcast in PONs, network capacity is wasted.

Figure 1. Tree and ring based topologies
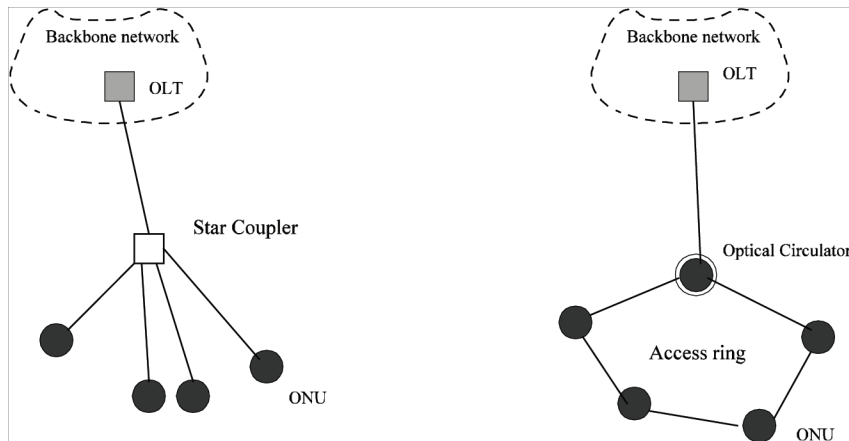
Ring Topologies

To improve private network capacity, a ring-based PON architecture is proposed to implement the LAN (Hossain, Dorsinville, Ali, Shami, & Assi, 2006). In this architecture, a long standard trunk fiber connects the OLT to the ONUs, which are interconnected within a short distribution fiber ring (*Figure 1*). The feeder fiber and the ring are connected using a 3-port optical circulator.

The links into the ring are unidirectional: both upstream and downstream communication use the same rotational direction. The ONUs apply the *Tap-and-Continue* (*TaC*) function to separate a part of the downstream flow for eventual local utilization. The downstream flow is then removed at the end of the ring to avoid its useless retransmission. The upstream transmission is based on a TDMA scheme and ONU-ONU communication is merged with the upstream traffic within the same pre-assigned time slot. To remove useless ONU-ONU and upstream communications from the upstream flow, a special removing, regenerating and retransmitting function is present in each ONU. This solution supports a fully distributed control plane among the ONUs as well as upstream communication to the OLT but does not ensure fault tolerance. This ring based architecture is improved in (Hossain, Erkan,

Hadjiantonis, Dorsinville, Ellinas, & Ali, 2008), where a two-fiber self-healing PON is proposed. This improved architecture provides simple and cost-effective fully distributed resilience capabilities against most kinds of networking failures. This solution also supports a truly shared LAN capability among end users. The control plane contains distributed fault detection and recovery mechanisms as well as a decentralized dynamic bandwidth allocation scheme. The proposed decentralized automatic protection switching technique is capable of protecting against both node (ONU) and fiber failures (distribution and trunk) through active participation of ONUs. Another simple, self-restoring and ring-based PON with two fiber-rings and TDMA option for bandwidth sharing can be found in (Yeh, Lee, & Chi, 2008). Optical line terminals and optical network units are used to protect against the occurrence of fiber failure in the optical access network; a protection technique is proposed for fast restoration of the access network in the case of failures.

New General Architectures

A project supported by DARPA has proposed a very flexible metropolitan and access network architecture (Kuznetsov, Froberg, Henion, Rao, Korn, Rauschenbach, Modiano, & Chan, 2000).

Figure 2. The hyper-channel concept in SMART
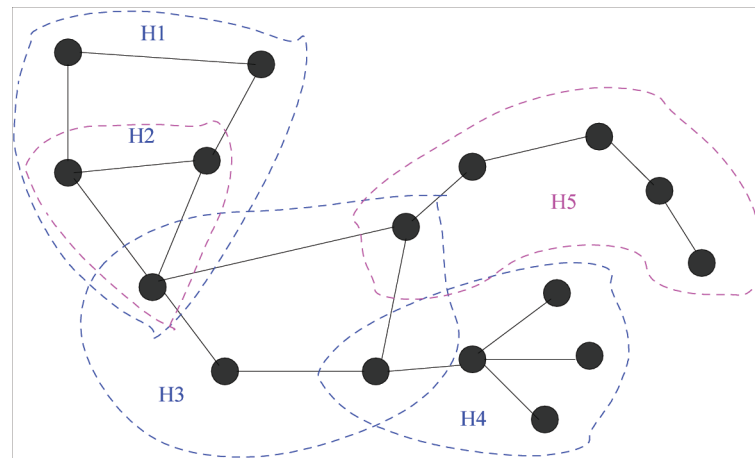
The proposition is based on the coexistence of WDM and IP routing, leveraging the advantages of both solutions. The different access networks are connected to the optical backbone using a (generally SONET based) double ring. The access network may correspond to an arbitrary topology (star, ring, bus or meshed). Electronic IP routing is combined with optical flow switching in the WDM domain using heterogeneous access node architecture in the OLTs. These OLTs allow IP routing and also to bypass it by optically switching the high capacity connections of some high-end users, while using electronic management for all other communication. Beyond its flexibility, an incontestable advantage of this network proposition resides in the dependability aspect of the access network design. The authors foresee protection switching and service restoration functions which are unavoidable elements of a dependable access networking.

A significantly different and new Internet architecture, called SMART (Scalable Multi-Access Reconfigurable Transport), for end-to-end optical networking is proposed in (Zheng & Gumaste, 2006). The suggested network organization can be applied in WAN, MAN, LAN and also access networks using the same basic idea. The proposition is based on light-trails which are extensions of lightpaths. A light-trail corresponds to an arbitrary optical bus connecting several nodes. The architecture requires a reconfigurable (active) node architecture. The abstract model of the network topology corresponds to a hyper graph (or "hyper-network"), where nodes are connected with hyper-edges (or hyper-channels). Using k wavelengths on a bus corresponds to k hyper-channels between the given set of nodes. A hyper-path connecting a pair of source and destination nodes is a sequence of hyper-channels. To connect hyper-channels, SMART also proposes O/E/O junctions containing electronic router or switch components. With the help of reconfigurable nodes, the hyper-channels can be configured statically or dynamically. On the base of a given reference physical topology, this configuration can produce arbitrary hyper-network topologies which can be used from WANs to access networks anywhere (cf. *Figure 2*).

Hyper-channels are considered as shared medium, single-hop optical subnets. For a hyper-channel to be efficient, bandwidth allocation among traffic components using the channel must be provided. Fixed scheduling coordination (such as TDMA) or dynamic scheduling mechanisms can be used to ensure channel efficiency. The proposed mixed (optical-electrical) node architec-

ture allows expensive optical components such as wavelength converters and splitters to be replaced by the cheapest electronic routers. The authors state that the solution is universal and scalable. So, a hyper-channel can be seen as a linearly arranged PON which is more scalable than a star-coupler based PON (Zheng & Gumaste, 2006).

In conclusion, cheap solutions are based on broadcast and select networks. However user-friendly and efficient these optical network architectures are, they should offer dependability and the possibility of dynamic reconfiguration. To provide dependable services, robust, general and efficient solutions should be used. This is increasingly true for new and forthcoming multicast-based multimedia services.

MULTICASTING IN SIMPLE ACCESS NETWORKS

To demonstrate the capacities and limits of star topologies we first present a brief introduction to the most important communication scheduling and multicast routing methods used in them. Because dependable multicasting needs route redundancies, the mesh topology appears to be the best solution. Due to its importance the problem of multicast routing in mesh networks is presented in the last section.

Channel Sharing in Passive Star Networks

Access nodes in optical access networks can have a number of tunable or tuned transmitters and receivers. Frequently there is only one transmitter and receiver in the access nodes and different configurations may exist depending on the tuning situation. For example, an FT-TR configuration indicates a fixed-tuned transmitter and a tunable receiver in the node. The optical channels of the fibers are distributed according to static or dynamic (tuned) wavelength allocation. Moreover,

time or code division based multiplexing can be used to improve channel sharing. In the following, we assume that the network operates in a slotted mode. Generally, messages should be *queued* at the source nodes for scheduling. To manage message transmissions, two main approaches have been proposed: single-hop and multi-hop.

Single Hop Networks

In the single-hop approach, each communication uses only one lightpath (or light-tree) from the source node to the destination(s) (Mukherjee, 1992a). The passive star coupler based architectures suppose tunable receivers and/or transmitters in the nodes. In some cases a reserved bidirectional control channel between a central scheduler and each node is required.

To transmit the queued messages, the network resources (transmitter of the source, receivers of the destinations and the wavelengths) should be allocated and configured in conformance with the communication requests. Numerous channel access methods are proposed. These access methods are often classified as random access based, reservation based and pre-allocation based methods.

Random scheduling implements a simple but efficient scheduling scheme. In random methods, when a channel becomes available, the scheduler randomly selects a source node that is waiting to send data. A given node may correspond to the destination of several messages at the same time. If the destination has only one tunable receiver, then a collision will occur and some transmissions will fail. Generally, in the case of failure the messages are retransmitted. In the case of multicast messages, all destinations should receive the messages. An analysis of two random scheduling of multicast requests can be found in (Modiano, 1999). In the proposed model, at each time slot, the W channels of the star network can simultaneously be used to transmit multicast messages, each channel intended for k randomly

chosen nodes.

The optimum case is when the receivers of the destinations are tuned to the chosen wavelength, in other cases they are tuned to other wavelengths. In the first proposed strategy, a selected message is continuously retransmitted until it is received by all of its intended destinations. A second strategy consists of the introduction of a random delay before the retransmission of a message that was not received by all recipients. Performance evaluations show that this second strategy is more advantageous for overall network throughput (Modiano, 1999). Performance can be improved when several messages arrive at a node by tuning the receiver to receive the multicast message having the least number of destinations. Network utilization can also be significantly enhanced with multiple receivers in the nodes.

Reservation based scheduling dedicates channels exclusively for data transmission. For example, in (Wu, Ke, & Huang, 2007) potential senders use an ALOHA based random MAC scheme to send reservation requests to the central node. As reservation requests may collide and be lost, the reservation process needs an explicit confirmation. The scheduler (using its knowledge of the tuning time and delays) organizes asynchronous data transmissions between senders and destinations. A multicast scheduling algorithm called LBQA (Look Back Queue Access) is proposed. This algorithm favors multicast messages which can be sent immediately to all destinations. When there are no more all-receiver messages to transmit and while there are available data channels, the algorithm schedules also partitioned multicast messages (for an available subset of the destinations). The authors state that this scheduling algorithm can also be applied in PONs. The proposed architecture and the scheduling have some drawbacks. The scheduled time slot must allow sufficient time to tune the concerned transmitter and the receivers before data communication can start. This delay limits network performance. A large number of nodes in the domain can lead to heavy collisions

on reservation control channels. To diminish the number of collisions an architecture with two star coupler subnets bridged by two tunable pass band filters is proposed. The separation of the nodes into two sub-networks reduces the control load on each of them and improves the wavelength reuse possibilities in both sub-networks.

In *pre-allocation based channel access methods* the data channels (*i.e.* wavelengths) for transmission and reception are assigned to the nodes in advance. Thus, a control channel is not needed for resource allocation. Different communication flows using the same channel may share it via TDM-like multiplexing. The objective of the channel access method is to assign time slots of the different channels to the communication flows. If the bandwidth demand is uniformly distributed between flows, the simplest solution, a simple round-robin algorithm (each communication has a slot in a frame) results in very good performance (cf. the scheduling of *unicast* requests in (Bogineni, Sivalingam, & Dowd, 1993)). When the various communication flows need different bandwidths, the problem is finding an optimal scheduling which satisfies communication flow QoS requirements by minimizing the overall network mean packet delay. This optimization corresponds to an *NP*-hard load balancing problem. A typical scheduling algorithm for the pre-allocation method is presented in (Borella & Mukherjee, 1996). An efficient approximated algorithm is proposed for an arbitrary traffic pattern on any number of channels assuming an arbitrarily large transmitter tuning time.

The allocation problem for *multicast* traffic in WDM/TDM based star networks is presented in (Bianco, Galante, Leonardi, Neri, & Nucci, 2003). In the proposed broadcast and select network, transmitters operate on fixed wavelengths, while receivers can be tuned to any available wavelength. If there are more source nodes than available wavelengths, several communication flows share a wavelength. Wavelengths are slotted and synchronized; each slot on a wavelength can

transmit one packet. By dynamically allocating the available slots (wavelengths are assigned to the sources), full connectivity can be achieved among nodes. The tuning times are assumed to be non-negligible with respect to the fixed size slot time. The problem is formulated as follows. The traffic pattern is given by a slot allocation request matrix R. An element $r_{s,D}$ corresponds to the number of packets which should be transmitted from the source s to the destination set D. The scheduling algorithm aims to find a time/wavelength assignment that satisfies the requests while minimizing the requested frame length. This latter corresponds to the total time necessary for the requested data transmission. It is immediately apparent that the tuning time of receivers has an impact on the optimal solution. The overall network throughput can be improved by minimizing the number of times each receiver must be tuned within a frame. Since the scheduling problem is *NP*-hard, the author proposes a heuristic algorithm based on the Tabu Search. Of course, the algorithm solves the off-line scheduling problem but cannot react quickly enough to assure the allocation on a packet-by-packet basis; only a slow variation of bandwidth can be tolerated in this solution.

Thus multicasting in star networks with passive couplers corresponds to a particular scheduling problem. The main difficulty with multicast is that the receivers of the destinations should be available (together or separately) to transmit multicast messages successfully. Large multicast trees can overload the network: reservations and/or retransmissions can block other requests. Moreover, dynamic tuning for every time-slot and the resultant latencies decrease overall network performance. Let us also notice that the messages have to be queued for scheduling purposes at the nodes of the PON. At the end users, this is not problematic: messages can be buffered electronically. At the OLT side, storage requires O/E/O conversion and as a result the communication between end points becomes opaque.

Multi-Hop Networks

Based on a physical star topology, virtual multi-hop topologies for optical access networks are proposed in (Mukherjee, 1992b). In these networks, the transmitters and the receivers of the access nodes are tuned in a fixed manner. Since the transmitter of the source node of a given communication flow can be tuned to a different wavelength from that used by the receiver of the destination(s), a route may contain different hops (lightpaths). In a multi-hop path, the wavelength of a (first) segment should be converted according to the tuning of the receiver(s). This wavelength conversion can be performed using O/E/O conversions of ONUs. The retransmission of the incoming light after conversions uses the transmitter of the ONU which is tuned for a different wavelength. So, the route from an arbitrary source to a destination may correspond to a multi-hop route and the virtual topology is a meshed graph. The diameter of this graph is limited. To perform multicast, multi-hop trees can be built by assembling the concerned hops in the directed virtual topology.

Figure 3 shows a physical star topology of seven nodes. Using two wavelengths in each direction and in each fiber, the regular virtual topology illustrated in *Figure 3(b)* can be configured using only fixed tuned receivers and transmitters. The used wavelengths are indicated with numbers between 1 and 14. A two-hop path from the node *a* to the node *g* is indicated with dotted lines.

Improvement of Access Network Performance

The optimal scheduling for heterogeneous unicast and multicast communications is a *NP*-hard problem. Moreover, the tuning time of transmitters/receivers and the synchronization requirement for multicast communication (*i.e.* all destinations should be available and tuned at the moment of data transmission) create scheduling difficulties. Some important propositions have been formu-

Figure 3. Physical (a) and virtual (b) topology of a multi-hop network
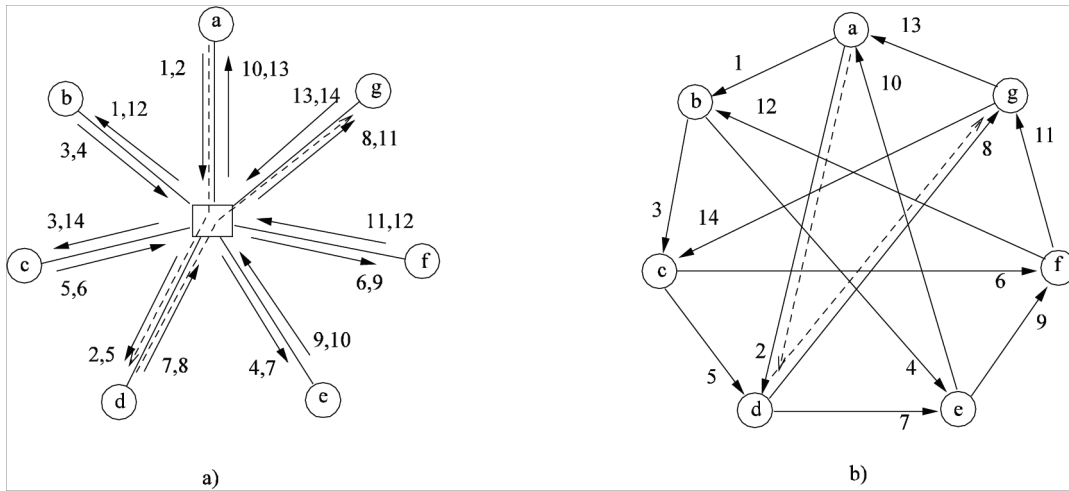
lated to resolve these problems.

To enhance the throughput of the network, the technique of *wormhole scheduling* can be applied. With this scheduling approach, several packets (and not only one) can be scheduled in order to minimize the overall tuning time. This technique can be applied both for unicast and multicast communications. Another idea to improve network performance is *pipelining of the tuning latency* by permitting data transmission for some nodes and transmitter/receiver tuning for others (Borella & Mukherjee, 1996; Tridandapani, Meditch, & Somani, 1994). The synchronization of all receivers belonging to a given multicast group can also have a significant affect on latency. Partitioning multicast communication (Jue & Mukherjee, 1997) aims to reduce this latency. In this solution, the multicast message is sent even if all the destinations are not ready. To cover the entire group, the same message is transmitted several times until all destinations have received the message.

Traffic is frequently burst transmitted which occasionally leads to some idle wavelengths, while other wavelengths are overloaded. This results in an inefficient use of network capacity. In (Papadimitriou & Pomportsis, 1999), the authors propose the application of tunable wavelength

converters placed at the network hub and a new MAC protocol which is capable of scheduling the incoming packets to the available wavelengths. With the help of wavelength conversions, the packet load is balanced between the wavelengths and consequently network performance is improved.

Multicast Routing in Ring Topologies

To perform multicast communications in ring topologies, splitters are not needed as long as *Tap-and-Continue* capability (*TaC*) (Ali & Deogun, 2000) exists in all ONUs. Generally, with the *TaC* capability of ONUs, one lightpath per multicast group is sufficient to cover any destination of ONUs. Using the TDMA scheme, several multicast groups can share the same lightpath to exploit its capacity. Let us notice that routes in a ring topology can be easily protected if the ring can be used in both directions.

Figure 4 illustrates a ring access network topology. Let us suppose that nodes *d, f* and *g* belong to a given multicast group. Taking advantage of the *TaC* capabilities of the traversed member nodes, the lightpath indicated with arrows is sufficient to supply all members in the ring.

Figure 4. Multicasting in a Ring Topology
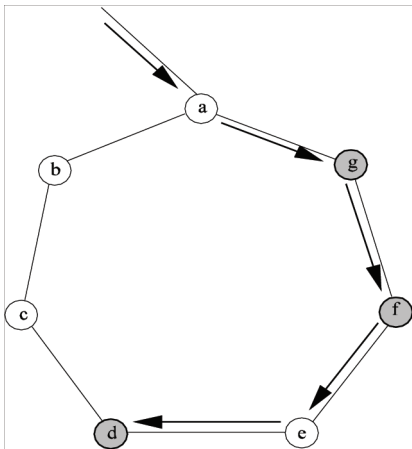
Multicast Using Active Elements

Active components in the last segment of optical networks can improve overall network performance. PON developers focus on integrating high performance active components into OLTs and ONUs that are located at both ends of the access network. For example in (Han, Kim, & Chung, 2001) the authors state that the scalability of multi-purpose fiber-optic access network can be improved significantly by using active components at the remote nodes. Unlike passive access networks, an architecture which includes active end nodes can support a large number of optical network units.

The authors in (Kim, Choi, Im, Kang, & Kevin Rhee, 2007) propose a switching system using fast time-slotted passive switching with O/E/O conversion and shared buffers. This system provides more flexible routing and significantly reduces the blocking probability by using electrical buffers. This optical access network facilitates multicast routing because the electrical buffer equipped switches can split the messages arbitrarily and any of these nodes may correspond to a branching node of multicast trees. Moreover optical amplification is not needed in this kind of node. The proposed switching system is believed to be a

techno-economically feasible and implementable solution for both optical packet and burst switching with current optical technologies.

Multicast routing in redundant (ring and mesh) networks provides a dependable solution for multicasting even in access networks. In these kinds of topology, efficient multicast routing is a challenging task which must also take into account the physical constraints of the optical network. The most important and specific constraints in optical routing and the most common algorithms are presented in the following sections.

CONSTRAINTS OF MULTICAST ROUTING IN ALL OPTICAL NETWORKS

Impact of Multi-Optical Channels

Wavelength-rooted networks operate based on the concept of lightpath and light-tree (He, Chan & Tsang, 2002). A lightpath is an all-optical communication channel between two end nodes, established by allocating the same wavelength throughout the route of the transmitted data. The light-tree is an extension of the lightpath which consists of multiple lightpaths on the same wavelength from the source to several destinations. The use of multiple wavelength channels on mesh topology precludes the use of several conventional multicasting techniques in IP networks (Hamad, Wu, Kamal, & Somani, 2006). Firstly, in the absence of a wavelength conversion device, it is required that the same wavelength be employed over the entire route (*i.e.* on the lightpath and light-tree). This is known as the wavelength continuity constraint (Mukherjee, 2000). Notice here that wavelength continuity must be satisfied both in depth due to signal propagation on the lightpath, and in breadth due to multicasting and signal branching in the light-tree. Channels on different fibers therefore cannot be treated independently, as is the case for multicasting in conventional IP

networks. Secondly, two or more lightpaths and light-trees traversing the same fiber link cannot be assigned the same wavelength; otherwise they will interfere with one another. This requirement is known as the distinct wavelength constraint (Mukherjee, 2000). However, two lightpaths can share the same wavelength if they use disjoint sets of fiber links. This property is known as wavelength reuse (Murthy & Gurusamy, 2002).

Impact of Light Splitting

The capability to split light is a key enabling technology for multicast communication in wavelength-routed networks (Hamad et al., 2006). Light splitting can be realized with a passive optical device called an optical power splitter (Mukherjee, 1997) which is able to replicate the incoming light signal in the optical domain and thus transmit it to several outgoing ports simultaneously without any O/E/O conversion. Splitters maintain optical signal transparency and also eliminate the need for the buffers usually required for data duplication in the electronic domain. However, the power splitter degrades signal power and causes crosstalk. Furthermore, due to the complicated architecture and expensive components, optical switches with power splitters are always more costly to build than those without. Hence, typically only a subset of optical switches support light splitting and such a network is characterized as a *sparse splitting* network (Malli, Zhang, & Qiao, 1998). Usually, an optical node with a light splitting capability is called a *Multicast Capable* (*MC* node), otherwise it is called a *Multicast Incapable* node (*MI* node) (Malli et al., 1998). In addition, the *TaC* capacity is assumed to be available at all *MI* nodes. This refers to tapping a small amount of the power for signal detection from the incoming light signal, and forwarding the light signal to only one outgoing port.

Moreover, the splitting fanout also influences multicast routing in wavelength-routed optical access networks. The splitting fanout is the maximum number of light branches supported per node. It is an important parameter in the design of multicast trees and it also impacts the choice of the number of amplifiers, their placement, and also the value of the signal-to-noise ratio (*SNR*) (Hamad et al., 2006).

Impact of Wavelength Conversion

Wavelength conversion also has a significant influence on multicast routing in wavelength-routed optical access networks. Wavelength converters enable the optical switch nodes to shift the incoming optical signal from one wavelength to another. Wavelength conversion functionality provides flexibility in network operation and simplifies multicast routing, since wavelength continuity is no longer a strict requirement if converters are used. All-optical wavelength converters (Elmirghani & Mouftah, 2000), however, are still very expensive and immature. As is the case with the power splitter, the architectures of optical switches equipped with all-optical wavelength converters are very complicated to design and therefore costly. This hinders the full deployment of wavelength converters. Hence, an optical access network where only some nodes are equipped with full wavelength conversion capability is more practical, and is referred to as a *sparse wavelength conversion* network. As a result, the limited availability of wavelength conversion restricts the construction of multicast trees.

Impact of Optical Amplification

When a light signal passes through a k-out power splitter, it is equally divided into k light beams and forwarded to different outgoing ports. The power of the light signal at each output port is only $1/k$ of the incoming light signal and thus is significantly degraded. In addition, power loss is also caused by power attenuation during light propagation. For a multicast light signal to be detected by all session members its transmission power must be carefully

designed to guarantee a satisfactory *SNR* at the end users. Otherwise the maximum distance from the source to the destinations, namely the diameter of the multicast trees, will be affected and bounded due to light power loss. To minimize the impact of power loss when constructing multicast trees, active optical amplification devices such as the erbium-doped fiber amplifier (*EDFA*) (Desurvire, 1991) are required. However, optical amplifiers are expensive to fabricate and introduce many problems which complicate network management such as *Gain Dispersion*, *Gain Saturation* and *Noise* (Yan, Deogun, & Ali, 2003). Moreover, placing amplifiers on fiber links will increase the possible number of potential multicast receivers. However, the total number of amplifiers in the network can be reduced by an optimal placement strategy. To solve the optimal amplifier placement problem, at least two parameters, namely signal power and source-destination distance, should be given.

Due to the optical constraints discussed above, multicast routing algorithms in all-optical mesh access networks are different from those in traditional data networks; thus a great deal of research has been done to solve this challenging problem.

MULTICAST ROUTING IN OPTICAL MESH CORE AND ACCESS NETWORKS

Wavelength-division multiplexing (WDM) is an effective technique to exploit the large bandwidth of optical fibers and to meet the explosive growth of bandwidth demand in networks (He, Chan, & Tsang, 2002). Furthermore, the light signal in all-optical networks is optically switched without any O/E/O transition, thus optical routing results in very low latency. WDM networks therefore have the capability to support bandwidth-driven and time sensitive multicast multimedia services with a high level of QoS. The light-tree concept was first proposed in (Sahasrabuddhe & Mukherjee, 1999). However, due to the physical constraints discussed in the previous section it is very hard to build such an all-optical light-tree. Then, in (Zhang, Wei, & Qiao, 2000), the light-forest is employed to solve the multicast problem in sparse splitting WDM networks. However, a recent work shows that more advantageous routing structures can be obtained using *light-hierarchies* (Molnár, 2008).

It is proved that the computation of the optimal multicast tree under optical constraints is *NP*-hard. Therefore, many heuristics have been proposed for the formation of light-trees to satisfy specific requirements. Typically, the network resource utilization and the power budget are taken into account.

Costs & Delay Sensitive Multicast Routing

Many existing routing algorithms focus on network costs and delay. For simplicity, the same cost is assumed for different wavelengths on different links, and hence hop count is used to calculate the wavelength channels and the delay, etc. Generally, these algorithms are evaluated in terms of link stress (the number of wavelengths required), wavelength channel cost (the number of wavelength channels used), average delay (the average hop counts from the source to the destinations) and the diameter of the multicast light-trees (the maximum number of hop counts from the source to the destinations). Existing multicast algorithms can be classified into two categories according to the technique used to construct the multicast tree. The first technique could be called the post processing or adaptation method. Firstly, it constructs a multicast tree for the multicast members without considering any constraints. It is always a shortest path tree or a tree approximated to the Steiner tree. Then, some adaptations will be made to this tree in order to satisfy the optical constraints. The second technique could be called the direct method, which takes into account optical constraints when building the multicast tree.

This kind of routing algorithm directly produces a light-tree or a light-forest.

Adaptation Methods

The post processing method always divides the construction of the multicast tree into three stages: (*i*) construct a multicast tree without considering any constraint, (*ii*) check the splitting capability of the nodes on the tree and (*iii*) reconnect the multicast forest. Three typical post processing methods namely Re-route-to-Source, Re-route-to-Any (Zhang, Wei, & Qiao, 2000) and Avoidance-of-MIB-Nodes (Zhou, Molnár & Cousin, 2008a) will be discussed in the following with some illustrative examples.

Re-route-to-Source & Re-route-to-Any
Initially, a multicast tree is constructed using any existing algorithm (*e.g.* a shortest path tree formed by Dijkstra's algorithm). Then, its nodes are checked one by one in the breadth-first or the depth-first order. If node *v* is an *MI* node and it has at least two children in the tree, then only one of them is kept (no heuristic is specified to choose which branch to keep in the algorithm (Zhang et al., 2000)) while all the other downstream branches are cut from *v*. The affected children of *v* re-join the forest either via the nearest *Virtual Source* node (*VS*, a Virtual Source node is capable of both splitting and wavelength conversion) along the reverse shortest path to the source (Re-route-to-Source), or via any other path leading to a *MC* node or a leaf *MI* node already in the cut tree (Re-route-to-Any).

Avoidance-of-MIB-Nodes
The adaptation algorithm proposed in (Zhou et al., 2008a) has three important advantages:

i.	It results in a shortest path tree with fewer Multicast Incapable Branching (MIB) nodes (decreasing up to 38% in some networks). This gain is obtained with the help of an enhanced version of Dijkstra's algorithm where *MC* nodes have a higher priority to compute shortest path than the other candidate nodes at the same *level* (*i.e. Candidate* nodes are at the same level when they are at the same shortest distance to the source), and with the help of a special *Node Adoption* procedure. In the adoption procedure, when all *Candidate* nodes at the same *level* are permanently labeled, a child is adopted from an *MI Candidate* node with several children to another leaf *MI Candidate* node without children at the same level if possible (cf. our example).

ii.	It aims to reduce link stress. In the second phase, when *MIB* nodes are processed, some branches of the tree are kept even if their root is an MIB node. If an *MIB* node is a critical articulation node of a branch (this can be very important when some nodes in the network fail), then this branch is kept, otherwise the deepest downstream branch will be kept. So, critical branches are left untouched.

iii.	In the reconstruction phase, distance priority mechanisms are employed to reduce delay and diameter. An example in the well known NSF network is now considered (*Figure 5*). Let

m={*source*: 10|*members*: 1-14} be a multicast session, where nodes 1, 8 and 10 are *MC* nodes. The traditional Dijkstra algorithm may produce a shortest path tree like that in *Figure 6*(a). There are 2 *MIB* nodes (node 6 and 12) in this shortest path tree. They are only able to feed one branch and the other branches must be cut. According to Re-route-to-Source, the affected nodes 3 and 13 should be connected to the source using the shortest path on another wavelength, thus two light-trees respectively using wavelengths w_1 (dash and dot line) and w_2 (dot line) can be obtained in *Figure 6(a)*. Meanwhile, with the Re-route-to-Any algorithm, the light-tree shown in *Figure 6(b)* may

Figure 5. NSF network
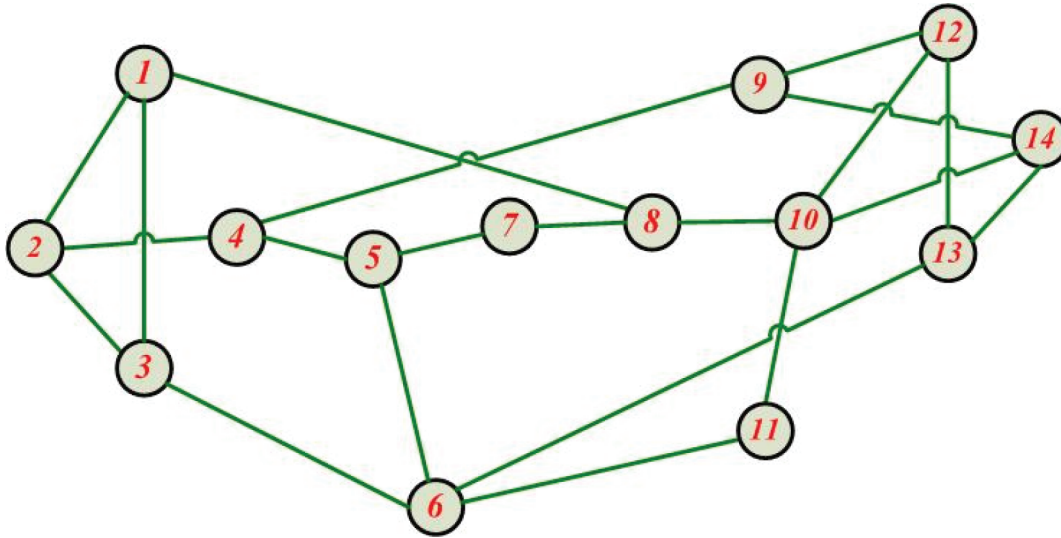
be constructed (for instance, node 2 is the closest connect node to node 3 and node 14 is the closest connect node to node 13). The Avoidance-of-*MIB*-Nodes algorithm can produce an even better result. In the shortest path tree shown in *Figure 6(a)*, we can see that nodes 1, 6, 7, 9 and 13 have the same shortest distance to source node 10. So, they can be viewed as *candidate* nodes. And, if node 1 (*MC* node) is raised to a higher priority and is chosen to be permanently labeled first, followed by 7, 9, 13 and 6, then the new shortest path tree of *Figure 7(a)* is produced which has only one *MIB* node. It is obvious that nodes 11, 12 and 14 have the same shortest distance to source node 10. Hence, they can be viewed as candidate nodes. When all of them have been permanently labeled, we can see that node 12 is an *MIB* node and node 14 is a leaf *MI* node. Note that nodes 13 or 9 can reach source node 10 by the shortest path through both nodes 12 and 14. One of them can be adopted by node 14, and a new shortest path tree without an *MIB* node is obtained in *Figure 7(b)*. Its link stress is 1 and cost is 13, while it is 2 and 16 respectively for Re-route-to-Source (in *Figure 6(a)*). Its average delay and the diameter of tree (2.0 and 3 respectively) are also better than

those of Re-route-to-Any (2.1 and 4 respectively, in *Figure 6(b)*).

Among these three adaptation algorithms, the Re-route-to-Source algorithm is able to produce the optimal average delay and the minimal diameter for the multicast tree. However, its total cost and the link stress are the worst. The Avoidance-of-*MIB*-Nodes algorithm outperforms the Re-route-to-Any algorithm in terms of link stress, average delay and multicast tree diameter.

Direct Methods

In the direct method, the light splitting and wavelength conversion capabilities of nodes are considered while spanning the multicast tree. The resulting trees already satisfy the optical constraints, thus no adaptation processing is required. However, while respecting the optical constraints, it is possible that a single light tree may not always be able to span all the destinations. As a result, several light-trees may be required to accommodate a multicast session. Here, we present three direct light-forest constructions, where the light-trees are constructed one by one: the Member-Only algorithm (Zhang et *al*., 2000)),

Figure 6. (a) Shortest path tree, and the multicast tree constructed by Re-route-to-Source. (b) The multicast tree built by Re-route-to-Any. (Zhou et al., 2008a).)
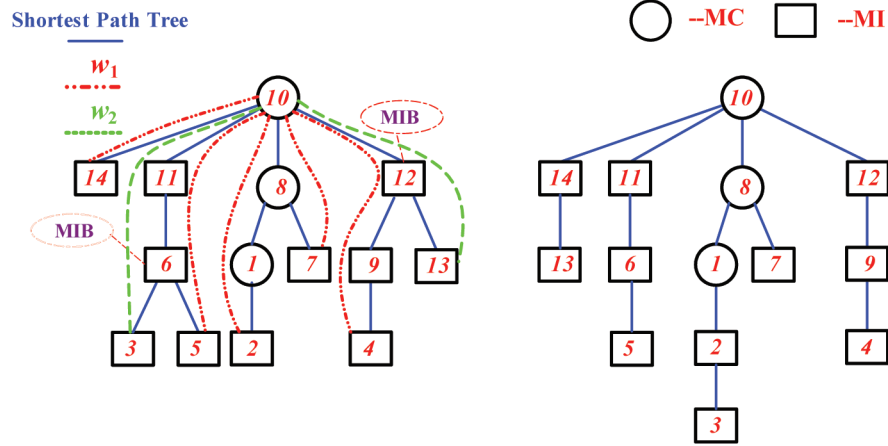

the Distance-Priority-Based algorithm (Zhou, Molnár & Cousin, 2008b) and the Virtual-Source-Capacity-Based algorithm (Sreenath, Satheesh, Mohan & Siva Ram Murthy, 2001). In order to facilitate the description of the algorithms, a number of notations should be introduced first. Let *MC_SET* denote the set of *MC* nodes and leaf *MI* nodes that are currently on the multicast tree under construction. The nodes in *MC_SET* may be used to connect unvisited (not yet spanned) destinations to the tree, because their splitting capability has not been exhausted. Let *MI_SET* be the set of non-leaf *MI* nodes on the current

multicast subtree. They are not capable of connecting any other node to the current subtree due to their splitting limitation. *VS_SET* consists of the virtual source nodes on the current multicast subtree. These nodes have both light splitting and wavelength conversion capacities. Finally, *UD* consists of the unvisited destination nodes of the multicast session.

Member-Only

The Member-Only algorithm is an adaptation of the famous *Minimum Path Heuristic* (Takahashi & Matsuyama, 1980) that respects the splitting

Figure 7. (a) Priority assignment. (b) Node adoption. (Zhou et al., 2008a)
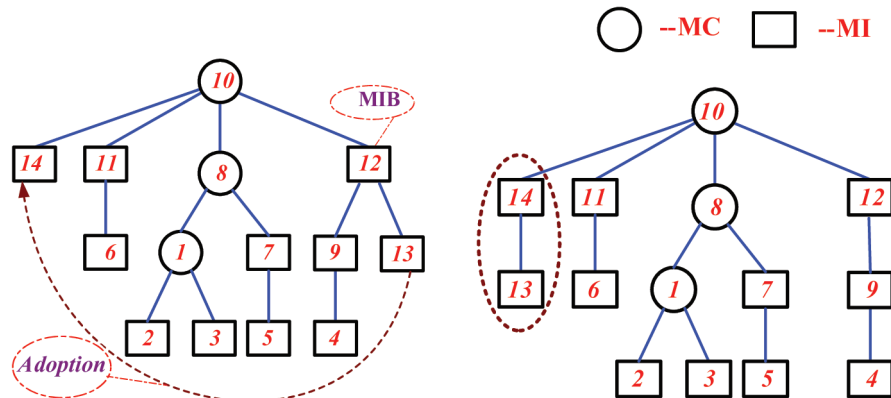
capability constraint on the optical nodes. It begins to build the multicast tree from the source and includes the destination nodes one by one. At each step, the nearest destination to the tree under construction is selected and joined to the tree through the shortest path as long as this path does not pass through any node in *MI_SET*. Since the nodes in *MI_SET* have no capacity to connect other nodes to the current tree, the algorithm only needs to try to find the shortest path $SP(c,d)$, where $c \in MC\_SET$, $d \in UD$, which does not involve any node in *MI_SET*. If such a shortest path is found, it is added to the subtree and the node sets are updated along the path; all *MC* nodes are added to *MC_SET* and the formerly leaf *MI* node is removed from it; all non-leaf *MI* nodes are added to *MI_SET*, and the newly added destination is removed from *UD*. When no shortest path satisfying the constraints can be found the current multicast tree is finished, and another multicast tree is started using the same procedure until no destination remains in *UD*.

Distance-Priority-Based Algorithm
This algorithm improves the Member-Only algorithm by attempting to diminish the average delay and diameter of the multicast trees while keeping almost the same link stress. It introduces two distance priority mechanisms in the construction of multicast light-trees. At each step of the Member-Only algorithm there can be several constraints-satisfied shortest paths found, say $SP_i(c_i,d_i)$ and $SP_j(c_j,d_j)$, where $c_i,c_j \in M\_SET$, $d_i,d_j \in UD$ and $dist(SP_i)=dist(SP_j)$. The choice of the path to be joined to the multicast tree will in fact greatly affect the final tree. Unlike Member-Only, where the nearest destination is selected randomly when several nearest destinations are found, this algorithm preferentially connects the candidate destination, say $d_{nearest}$, to *T* earlier, which is the nearest to the source (*destination priority*). Furthermore, at each step, there may exist several connector nodes in *MC_SET* at an equal distance to the selected candidate destination $d_{nearest}$. It is

advantageous to connect the destination $d_{nearest}$ via the connector node closest to the source in the tree (*connect node priority*). The algorithm results in a great reduction of the average delay and the diameter of light-trees, for instance up to 50% and 51% respectively in the USA Longhaul network (Zhou et *al.*, 2008b).

Here, we use a simple example to show the difference between the Member-Only and the Distance-Priority-Based algorithm. A multicast session *m*= {*source*: 2 | *members*: 2~6} is required. Initially, source node 2 is in the subtree *T*. At each step, the nearest destination is added. With the Member-Only algorithm the light-tree in *Figure 8(a)* can be produced. It is interesting to note that when adding node 4, it could be connected via either the source 2 or node 5. If we use *destination priority*, it should be connected to the source as shown in *Figure 8(b)*. Still with regard to this graph, if node 4 (1 hop to the source in NSFNET) is added to *T* earlier than node 5 (2 hops to the source in NSFNET), then node 5 could be connected to node 4 as shown in *Figure 8(c)*, which corresponds to *connect node priority*. We compare the average delay and the diameter of the light-tree resulting from these three results in *Table 1*. It is apparent that the reduction in the delay and the diameter is significant while the link stress remains the same.

Virtual-Source-Capability-Based Algorithm
This algorithm can be viewed as an enhancement of the Member-Only algorithm. The enhancement derives from two heuristics, namely Spawn-from-VS and Capability-based-Priority. The network is assumed to have nodes with different capabilities, namely splitting (*MC*), wavelength conversion (*WC*), Tap-and-continue (*TaC*) and splitting plus wavelength conversion (*VS*) nodes. A priority is assigned to the nodes depending on their capabilities in the following descending order: *VS*, *MC*, *WC* and *TaC*. The node with the highest priority is used when a destination needs to be included in the tree and is equally distant to more than

Figure 8. (a) Member-Only. (b) Destination Prior-ity. (c)Connect Node & Destination Priority

(a)   (b)   (c)
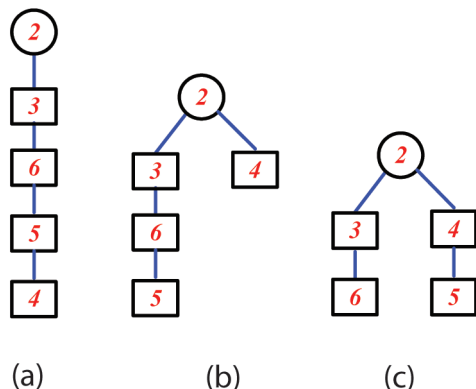
one node in the *MC_SET* for the current tree. In addition, if no constraints-satisfied shortest path from a destination *d* to the members in *MC_SET* could be found, the algorithm tries to find the nearest *VS* node $z \in VS\_SET$ for the current tree. If $dist(d,z) < dist(d,s)$, then *d* is joined to the current tree on another wavelength via *z*. Otherwise, a new tree is needed. This algorithm reduces the number of wavelength channels required and improves network resource utilization by using wavelength converters.

Power Aware Multicast Routing

As mentioned in the previous section, a light signal suffers power loss due to light splitting. Moreover, light attenuation along the long route from the source to the multicast members may not be negligible. Consequently, routing schemes should be carefully designed to guarantee signal delivery to multicast members, thus the multicast routing problem in a sparse splitting network with power considerations is an important topic. Next, we present two power aware multicast routing algorithms: Centralized-Splitting algorithm (Wu, Wu, & Yang, 2001) and Balanced-Light-Tree (Xin & Rouskas, 2004).

Centralized-Splitting Algorithm
This algorithm aims to build a Steiner-based tree that achieves an efficient utilization of network resources while producing low power loss in order that the transmitted light signal is maintained above the signal sensitivity threshold. Initially, a multicast diffusion tree is constructed by applying the Member-Only algorithm without any consideration of the power-level impairment. Then some adjustments are made in the tree produced according to the following guidelines. Firstly, if there are more than two successive *MC* nodes in a subtree, they will produce a cascade effect on power loss (as indicated in *Figure 9(a)*). Hence, it is better to replace the successive *MC* nodes by a single *MC* node. Secondly, although a power splitter located near to the source can balance the power loss on each subtree, the effect of the power loss will be propagated to all children nodes located within its subtree. In order to reduce power loss, the algorithm assigns the splitting capability to the node furthest from the source node whenever possible. For instance in *Figure 9(b)*, the light splitting happens in the last level of the tree; hence the power loss decreases to $2e_0/3$ compared to the cascade splitter situation with $3e_0/4$ in *Figure 9(a)*. Thirdly, when the number of splittings at a node increases, the incremental power loss caused by each additional splitting decreases. As a result,

Table 1. Comparison of Light-trees in Figure 8

	Member-Only	Destination Priority	Two Priorities
Link Stress	1	1	1
Diameter	4	3	2
Average Delay	2.5	1.75	1.5

Figure 9. (a) Cascade Power Loss. (b) Splitting far from the Source
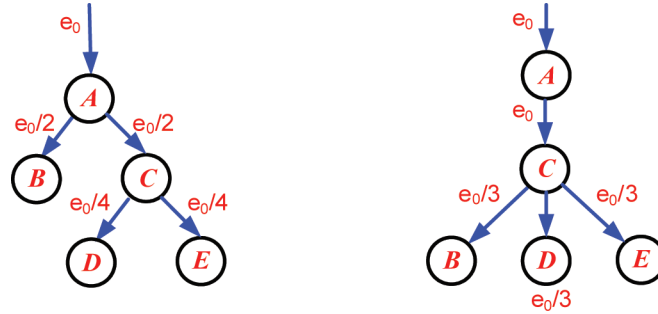
if a node is chosen to be a branching node in the multicast tree it is desirable to assign as many splittings as possible to this node.

Balanced-Light-Tree Algorithm

In the Balanced-Light-Tree (*BLT*) algorithm, it is assumed that signal attenuation is negligible while power loss due to light splitting is the dominant factor. Hence, the power loss imposes an upper bound on the splitting ratio on the path to each destination node. Furthermore, the splitting ratios of any two paths from the source to two destination nodes of the same multicast group should be within a tight range of each other. In other words, the multicast trees must be as balanced as possible. This is because an unbalanced tree results in two important disadvantages. Firstly, it is unfair for certain destination nodes, since the destination node at a smaller depth receives a better quality signal than the one at a large depth. Secondly, it is not scalable, since it may introduce excessive losses that make it impossible to deliver a light signal to a large destination set. Similarly to the Centralized-Splitting algorithm, an initial multicast tree spanning all multicast members is built by any existing algorithm such as Member-Only. Then, the balancing procedure is performed on the tree to check the splitting ratio of the nodes. Consider an intermediate multicast tree *T*, and let *u* (respectively *v*) denote the leaf node with maximum (respectively minimum) splitting ratio. The main idea behind the *BLT* algorithm is to delete

node *u* from *T* and then add it back to the tree by connecting it to some node *y* in the path from source *s* to *v*. This procedure reduces the splitting ratio of *v*, though it increases the splitting ratio of all nodes below *y* in the tree. Thus, it is desirable to perform this pair of delete/add operations as long as it does not increase the splitting ratio of any node beyond node *u*. It is worth noting that the difference between the maximum and minimum splitting ratio values decreases after the balancing operation.

On the Optimality of Multicast Routes in WDM Networks

In this section, we examine optimal routing structures for multicast communications under splitting constraints in meshed WDM networks. For source based multicast routing current practice is to propose light-trees. We shall see next that optimal multicast routing structures do not always correspond to trees. Let us suppose that the links can be used in both directions and the topology of the optical network is given by an undirected graph $G=(V, E)$. The multicast group is given by a source node *s* and a set *D* of destination nodes. A multicast route, a directed sub graph spanning the source and the set of the destinations is required. Remember that *MC_SET* contains the splitting capable nodes (accordingly, the nodes in $MI\_SET = V \backslash MC\_SET$ cannot duplicate the light). So, only the nodes in *MC_SET* can have a degree

Figure 10. Light-Tree and Light-Hierarchies
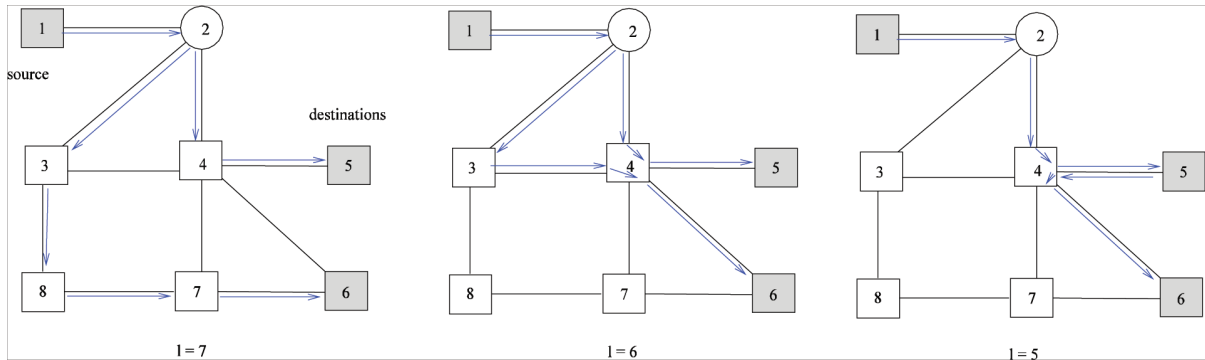
greater than two in the multicast routing structure. Wavelength constraint in the fiber implies that two arcs of the minimal length structure cannot use the same edge of the topology graph in the same direction. But in general the same switch can be used twice (or more) because the switch architecture offers several disjoint lightpaths between its interfaces. The optimal solution must have the minimal length of all sub graphs spanning $s \cup D$ and must satisfy the constraints. This connected and minimal length solution is not always a tree or a forest: the same switch can belong several times to the optimum structure which is called a hierarchy (Molnár, 2008). To illustrate this, let us consider the example in *Figure 10*. In this example the source node is node 1 and the destinations are the nodes 5 and 6. In the given network only node 2 can duplicate light and can be selected as a branching node. The light-tree with minimal length is shown in *Figure 10(a)*. The length of this tree is equal to *7*. More advantageous spanning structures can be obtained by relaxing the tree construction constraint. *Figure 10(b)* illustrates an optimal hierarchy which uses node 4 twice when the wavelength is unique in each link. If the links can be used in both directions (there is bi-directional fiber or two fibers between the switches), the minimal length hierarchy corresponds to a light-trail illustrated in *Figure 10(c)*.

CONCLUSION

This chapter focused on multicast routing over an optical access network. Our first point was intended to demonstrate that in the future many optical access networks will have meshed topology, and will require automatic and smart management. Indeed, mesh topologies have inherently good properties: flexibility and dependability. A mesh topology can freely evolve with technology and with users' requirements and may be as redundant as required. Dependability becomes a very important factor in access networks because of the increasing variety of services which must be reliable.

Our second point was that data broadcasting to a specific set of end users over a certain network domain will increase with the development of new multimedia distributed applications, and the use of multicasting can lead to huge savings in network resources. However, due to the specific physical constraints which can be found in optical networks, the computation of efficient light trees is not a trivial task. For instance, some optical switches have to be selected as branching nodes and have to split the light and the power of the transmitted light has to be intelligently controlled to ensure sufficient signal level at the final receivers. Thus the relevant multicast routing algorithms which can be applied to meshed optical access networks under the physical constraints presented by the

network were described.

One surprising concluding point is that the optimal multicast structure is not always a tree or a forest. Indeed the analysis shows that if you try to find the most efficient multicast structure which spans all desired destinations, taking into account the numerous optical constraints, it will lead to a hierarchical structure. In this hierarchy some switches may be used several times to transmit light to the destinations. So, the tree search constraint in the different route computation algorithms can be relaxed and more efficient hierarchies can be found for multicast routing.

Our last concluding remark is the following. To provide strong dependability, a high level of flexibility and to be as efficient as possible in network resource utilization, we forecast that some integration between access and core optical networks will be required. That will necessitate some network management and control coordination. For instance, some of the solutions developed for burst or packet optical networks could be reused in optical access networks.

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