♦ Comparison of Transport Network Technologies for IPTV Distribution

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The delivery of video services is generally considered a critical and perhaps the most difficult problem for telecommunications service providers to solve to achieve the "triple-play" of video, data, and voice. Transport of a mix of video, high-speed data, and voice—which is vital to maintain a competitive position against cable multiple systems operators (MSOs)—requires new solutions. Gigabit Ethernet interfaces can offer better network economics when combined with reliable synchronous optical network (SONET), wavelength division multiplexing (WDM), and/or fiber transport infrastructure. Here, we compare these transport technologies and present case study results. The case study includes broadcast as well as unicast traffic; SONET drop and continue or Ethernet multicast; a core network to connect super and regional headends/central offices, and an access network to connect regional headends/central offices to serving area locations. In this paper, we demonstrate that next-generation SONET can provide a balanced approach considering network economics and reliability.

Introduction

Internet Protocol television (IPTV) is becoming a common denominator for systems where television and/or video signals are distributed to residential subscribers via a broadband connection. Many of the world's major telecommunications providers are deploying IPTV as a new revenue opportunity in their local markets. IPTV is also a key element of the "triple play" where video, data and voice "services" are bundled together. IPTV is expected to grow at a brisk pace in the next few years, as broadband access is available to more than 100 million households [3] worldwide.

Much of the current broadband access service is aimed at residential customers accessing the Internet via an Internet service provider (ISP). Typically, the subscriber connection is via ADSL or ADSL2+ based copper interface (local loop). The subscriber data traffic, which tends to be bursty but with low average rates, is aggregated at a digital subscriber line access multiplexer (DSLAM) located at the central office (CO) or at a remote location. This traffic is routed to ISP(s) via an IP/asynchronous transfer mode (ATM) transport infrastructure. The local loop connection speeds vary with the condition of the copper loop, the distance of the subscriber from the CO, and the type of xDSL technology used.

Recent technology advances, such as VDSL and VDSL2 allow higher (tens of Mbps) downstream speeds

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Panel 1. Abbreviations, Acronyms, and Terms

ADM—Add/drop multiplexer
ADSL—Asynchronous digital subscriber line
ATM—Asynchronous transfer mode
CapEx—Capital expenditure
CIR—Committed information rate
CO—Central office
CPE—Customer premises equipment
CWDM—Coarse wavelength division multiplexing
D&C—Drop and continue
DSL—Digital subscriber line
DSLAM—DSL access multiplexer
EIR—Excess information rate
EoF—Ethernet over Fiber
EoF EM—EoF with Ethernet multicast
EoF w/LA—EoF with link aggregation
EoS—Ethernet over SONET/SDH
EPG—Electronic programming guide
ESCON—Enterprise systems connection
FICON—Fiber connectivity
GE—Gigabit Ethernet
GFP—Generic framing procedure
GFP-M—Frame mapped GFP
GFP-T—Transparent-mapped GFP
GMPLS—Generalized MPLS
GPR—Global packet ring
HDLC—High-level data link control
HDTV—High-definition TV
IOF—Inter-office facility
IP—Internet Protocol
ISP—Internet service provider
ITU—International Telecommunications Union
LAN—Local area network
LCAS—Link capacity adjustment scheme
MPEG—Motion picture experts group
MPLS—Multiprotocol label switching
MSO—Multiple systems operator
MSS—Multiservice provisioning platform
MSS—Multi-service switch
N-PVR—Network based personal video recorder
OAM&P—Operation, administration, management & provisioning
OPEX—Operational expense
OSS—Operations support systems
PEG—Public access, educational, or government sources
PPV—Pay per view
PVR—Personal video recorder
QoS—Quality of service
RPR—Resilient packet ring
RSTP—Rapid Spanning Tree Protocol
SDH—Synchronous digital hierarchy
SDTV—Standard-definition TV
SONET—Synchronous optical network
STB—Set-top box
STS—Synchronous transport signal
STS-1—SONET rate of 155 Mbps
TDM—Time division multiplexing
TV—Television
UPSR—Unidirectional path switched ring
VCAT—Virtual concatenation
VCG—Virtual concatenation groups
VDSL—Very high speed DSL
VHO—Video headend office
VLAN—Virtual LAN
VoD—Video on demand
VPLS—Virtual private LAN service
VPN—Virtual private network
VSO—Video serving office (local office)
WDM—Wavelength division multiplexing

over shorter distances from the DSLAM to the subscriber. At these speeds, local telecom service providers have the opportunity to introduce video services to augment their revenues and compete against cable multiple systems operators (MSOs). However, the digital video traffic tends to have a higher average rate per video stream (e.g., 2 Mbps for standard definition TV and 8 Mbps for high definition TV) which results in a higher average rate per subscriber with a video subscription. The inter-office facility (IOF) network capacity has to be augmented and engineered to support these higher average rates per subscriber when video services are offered over xDSL. In addition the fiber facilities have to be extended to additional DSLAMs which are now located in the outside plant (OSP) and closer to the residential subscriber.

The IOF/metro network capacity augmentation could follow two distinct paths:

- Evolve the existing synchronous optical network (SONET)/synchronous digital hierarchy

(SDH) based infrastructure to next-generation SONET/SDH (i.e., Ethernet over SONET (EoS)) to carry the Ethernet traffic to/from the newer DSLAMs that support higher speed subscriber traffic for IPTV video services, or,

- Build overlay Ethernet over fiber (EoF) infrastructure.

There are additional technology choices available within these two alternatives. Next-generation SONET/SDH equipment supports Ethernet over SONET/SDH using standards-based extensions such as virtual concatenation (VCAT), generic framing procedure (GFP) and link capacity adjustment scheme (LCAS), and integrates time division multiplexing (TDM) cross connect and switching functionality. In addition, the SONET/SDH drop and continue feature allows broadcast video traffic to be efficiently carried to the video drop nodes on the IOF rings. These features provide attractive network economics resulting from bandwidth efficiency, resiliency and simplified operations. In regions with fiber availability constraints, these alternatives can be combined with wavelength division multiplexing (xWDM) options to augment the fiber capacity and reduce the number of fibers required.

The equivalent SONET bandwidth required for Ethernet over SONET/SDH transport (e.g., 1 GE or approximately 21 STS-1s) is assumed to be available at a cost premium relative to Ethenet over fiber. However, by leveraging an existing infrastructure, the available capacity (e.g., STS-1s) can be used to offer video services early and at a lower risk. EoS also has the advanced performance and maintenance features of SONET/SDH that are part of the operations procedures in the embedded infrastructure. The reliability and fast restoration capabilities of SONET/SDH can improve the overall availability of IPTV video services. In addition, a range of current (TDM, private line) services can continue be maintained as these IOF networks evolve to support converged services.

In this paper, we consider the network economics for EoS versus EoF, including the options for hub, drop and continue, multicast and link aggregation. We start with the video services and bandwidth needs and outline a generic network for IPTV. Next, the optical transport network technologies and options in next-generation network equipment are described. We develop and analyze a simple transport network model that can be used for both core and access networks and for broadcast-only or mixed (broadcast video and unicast) traffic scenarios. We show the numerical results in terms of aggregate bandwidth requirements, fiber use and relative bandwidth costs. Similar results are computed for a case study based on fiber topologies in the existing network infrastructure and these results are then compared with the simplified model results. Overall, we believe that next-generation SONET/SDH can offer a balanced approach for service providers with existing infrastructure, considering the network economics and reliability.

IPTV Services and Bandwidth Needs

Current residential broadband access via xDSL is aimed at supporting Internet access and web-based services. The newer xDSL platform can support higher bandwidths to individual residential subscribers. This opens up the possibility of new revenue streams for local service providers who can leverage their existing copper loop infrastructure. Combined with the middleware, electronic program guides (EPG) and other client software features, a range of new revenue services can be offered to a video subscriber via an xDSL modem, home gateway and subscriber's television receivers. The following is a sample list of service features that the middleware allows the service provider to deliver to a subscriber: Digital TV (DTV), pay-per-view (PPV), video on demand (VoD), integrated TV services (caller ID, web portal, favorites/reminders, pause live TV, digital music, parental controls/settings), IP-based emergency alert system (EAS), and network personal video recorder (N-PVR).

The television video transmission, in its uncompressed form, requires very high bandwidth connections that are beyond the rates supported by current very high speed digital subscriber line (VDSL) technologies. However, there has been significant progress (more than 50:1 video compression ratio) in the past decade in the development and implementation of commercial video compression technologies. Currently, the video compression technology based on the motion picture experts group (MPEG-2) standard is being used in cable, digital satellite and most desktop video transmission. An enhanced video compression, MPEG-4 is being implemented and is expected to be available shortly. MPEG-4 offers additional video compression that enables higher definition television to be delivered over the xDSL copper loops. **Table I** shows the compressed television video transmission rates, based on the MPEG standards. The Windows Media* 9 Advanced Profile (VC-1) offers video compression comparable to MPEG-4. The video headend infrastructure, middleware and home gateway/set-top box client software are being developed by major software vendors and are being trialed by major telecommunications service providers.

Television video distribution is highly asymmetric, with most of the traffic originating at the video headend located in a metropolitan area. xDSL also supports asymmetric data rates, with higher downstream capacity from the CO to the subscriber. Internet access and web-based services also tend to have higher downstream traffic for the residential subscriber applications. Total downstream traffic can be computed based on certain assumptions about the subscriber television viewing patterns [10, 11] and Internet access usage since there is limited data available on these emerging video and web-based applications. Besides, high speed, bursty data services tend to be highly variable based on time of day, as well as local subscriber market conditions. For planning purposes, downstream xDSL traffic to the subscriber home in the range of 15 to 25 Mbps will be considered. This is based on two to five SDTV channels and one or two HDTV channels with the remainder for high-speed data. Upstream traffic from the subscriber home consists of, primarily, the program selection and control traffic, which is a small fraction of the compressed video bandwidth (not counting other data applications). Therefore, we use downstream traffic requirements for the bandwidth analysis and cost comparison of the optical transport technologies.

Table I. IPTV video sources and rates.

Video Compression Standard	TV Video Definition	Compressed Video Rates
MPEG-2	SDTV	2.5–3.5 Mbps
	HDTV	16–19 Mbps
MPEG-4 AVC (ITU-T H.264)	SDTV	1.5–2 Mbps
	HDTV	6–8 Mbps

AVC—Advanced video coding
HDTV—High-definition TV
IP—Internet Protocol
ITU—International Telecommunication Union
ITU-T—ITU-Telecommunications Standardization Sector
MPEG—Motion picture experts group
SDTV—Standard-definition TV
TV—Television

Assuming, tens of subscribers per DSLAM and that the popular broadcast television channels are chosen simultaneously by many subscribers, the video bandwidth requirements for the Gigabit Ethernet connection from the CO to the DSLAM can be estimated. We provide the model analysis results for broadcast traffic up to 3 Gbps. The unicast traffic will vary significantly with the business model of the service provider. Some providers may choose to provide, primarily, broadcast television channels while others may opt for more personalized video services (e.g., VoD, N-PVR.). Therefore, we analyze the network economics for a mix of broadcast plus unicast video services in the simplified transport network model. In addition, for a more complex network based on actual fiber topology, we compute the network economics assuming a 1 Gbps Ethernet connection between the CO and DSLAM, with a mix of broadcast and unicast cast video transmission.

Generic IPTV Network

A high-level view of an IPTV generic system is shown in **Figure 1**. Various video content comes into the video headend. The video streams are then assembled, using the associated middleware control, for distribution to the subscribers. These video streams are transmitted to various central offices via the IOF metro core optical transport network. From the COs, the video streams are in turn distributed to DSLAM locations in the outside plant through the optical access network infrastructure. The functional elements of a generic IPTV network are described below.

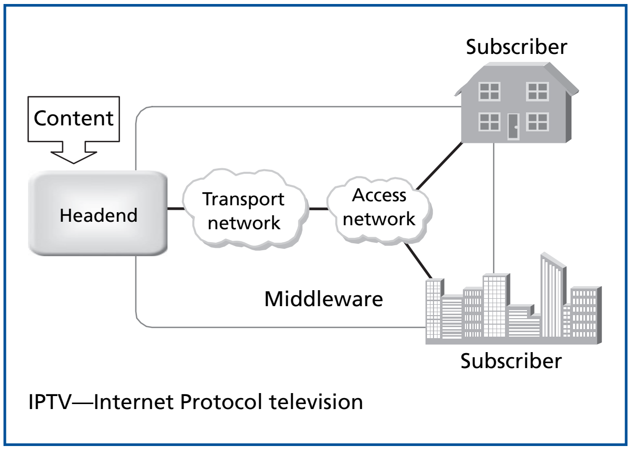


Figure 1.
IPTV generic network—high level view.

Content and Sources. Video content can come from multiple sources: (a) pre-compressed video content is delivered via satellite for network distribution; (b) analog off-air or direct feeds come from broadcasters; (c) MPEG-formatted movie files may be copied onto a local VoD server; and (d) videotapes or live feeds arrive from local public access, educational or government (PEG) sources. Pre-formatted content may also come from another headend (for example, from a regional headend to a local headend), especially for local advertisement insertion into the video stream before transmission to local subscribers.

Headend. The headend receives signals from content sources, implements the channel line-up, inserts commercials and encodes signals feeding the downstream transport network. The headend may house VoD servers, middleware servers, EPG servers and the service provider's operations support systems (OSS).

Middleware. Middleware deals with presentation and experience management—it is employed to provide a consistent user experience across the network. It may include packaging, provisioning and product definition; securing, tracking and alerting services; settlement and billing management for content; and interfaces with other network elements and the service provider's OSS infrastructure.

IP Video CPE. The customer premises equipment (CPE) typically includes an xDSL modem and provides the Ethernet interface for connection to a set-top box (STB). The STB connects to a TV receiver set running video middleware client software. An integrated home gateway could combine the DSL modem and STB functionality.

Transport Network Technologies

The optical transport network technologies for core and access networks are considered below.

Ethernet Over SONET/SDH

Many next-generation technologies exist for optical transport yet SONET/SDH dominates the public and to a large extent, the private telecommunications networks. The optical fibers already deployed allow systems to be built with ring-based topology and resiliency. The new Ethernet mapping, switching, and interface standards give service providers an opportunity to offer emerging digital video services by leveraging metro SONET/SDH networks. The VCAT, LCAS, and GFP standards allow an efficient transport solution for digital video by leveraging the existing optical transport infrastructure. These standards based on non-proprietary technologies are implemented in the next-generation SONET/SDH equipment available now.

SONET/SDH virtual concatenation (VCAT) [1, 8], allows the network operator to bundle containers (such as low order VC-12s and VT1.5s or higher order STS-1/STS-3c and VC-3/VC-4s) into aggregates that need not fall on predetermined boundaries in the SONET/SDH frame, or be contiguous, or even be routed on the same optical line. The components of a VCAT group can be switched on any SONET/SDH infrastructure supporting their transport, whether it is the new or the legacy [2] network infrastructure. VCAT gives the network operator the flexibility to create containers of bandwidth, called virtual concatenation Groups (VCGs), such as an STS-1-Xv where $X = 1 \ldots 64$, of effective payload size X multiplied by 49.536 Mbps. The benefit of this approach is that carriers can closely align the size of their payload requirements to container size as compared with the wasted bandwidth in contiguously concatenated SONET/SDH containers (e.g., STS-1, STS-3c/VC-4, STS-12s/VC-4-4c . . .) when used to carry a non-standard rate.

The generic framing procedure (GFP) [7] allows for predictive encapsulation (e.g., without byte-stuffing) of multiple protocols for transport [5]. GFP does not rely on embedded data or control bits as in 8B/10B or 64B/66B encoding, nor does it rely on delineation flags as in high-level data link control (HDLC). Instead, as in ATM, GFP relies on a header error check for initial determination of frame delineation. Unlike ATM, a length field can be used by framer logic to read the size of the frame and hence identify the beginning of the next one. The use of the length field in the packet eliminates the need for the segmentation and reassembly function of ATM since variable length client level packets can be accommodated. A byproduct of this GFP protocol design decision is a much smaller "overhead tax" when compared with the ATM "cell tax."

GFP comes in two modes of operation. Frame-mapped GFP (GFP-F) is optimized for packet switching environments. Frame-mapped GFP is used for point-to-point protocol as a layer 2 for MPLS, IP, and Ethernet. The client layer packet is buffered and then mapped into GFP. Transparent-mapped GFP (GFP-T) is intended for delay-sensitive applications such as storage area networking. This transport mode is used for fiber connectivity (FICON) and enterprise systems connection (ESCON) traffic. Individual characters of a client signal are de-mapped from the client block codes and then mapped onto periodic, fixed-length GFP frames. By pipelining the data without buffering, latency can be reduced compared to a scheme that requires buffering a client packet before its encapsulation can be constructed (GFP-F).

In practical applications, GFP-T is used for low-latency scenarios, the most common of which is synchronous database back-up. It requires the allocation of at least the bandwidth of the client signals. By contrast, GFP-F can use fractional bandwidth (e.g., a Gigabit Ethernet circuit can be allocated a number of STS-1s which add up to less than 1.25 Gbps).

The link capacity adjustment scheme (LCAS) [6] will be a valuable tool in ensuring the management and high availability of packet bandwidth transported over SONET/SDH. It allows for the hitless removal/addition of bandwidth in a SONET/SDH VCG. It also provides its own signaling protocol, carried in-band over SONET/SDH, and used to support dynamic management of VCGs. But perhaps the most compelling near-term application of LCAS is as a load balancing methodology for protecting packet traffic carried over SONET/SDH. For example, two diversely routed components of the same VCG will protect each other: if one fails, the layer failure will trigger LCAS commands to dynamically re-size the transport pipe, removing the failed components from the VCG, and allowing the remaining components of the group to pick-up the traffic.

In addition to point-to-point applications, broadcast applications for video distribution via SONET/SDH can be efficiently supported using the "drop and continue" feature. Due to this robust broadcast capability, the SONET/SDH network can be used to broadcast video signals from a TV service provider's headend location to the remote distribution hubs. In this application, incoming video signals are duplicated to multiple output ports and sent to several distribution hubs. As shown in **Figure 2**, the drop and continue feature of SONET/SDH is used to extract the video signal from the main ring and direct it to other feeder rings/distribution hubs while keeping a copy of the video signal traversing the main transport ring. In the case of an IOF, the broadcast video input from the video hub office is carried around the ring and dropped at each of the central offices or video serving offices. This is illustrated in the OC-48 ring. At the headend, the digital video is fed into the unidirectional path switched ring (UPSR) in both directions (i.e., clockwise and counter-clockwise direction) to deliver to both the west and east neighbor VSOs. In the intermediate nodes, the video is dropped as well as passed through in both directions until the east and the west neighbors, respectively, are reached. Then, the video is dropped at these neighbors and not passed back to the headend.

Ethernet Over Fiber (EoF)

The foundation of an EoF network is a point-to-point Ethernet connection between a pair of carrier-grade Ethernet switches and extending into a mesh network of Ethernet switches. In EoF solutions, traffic

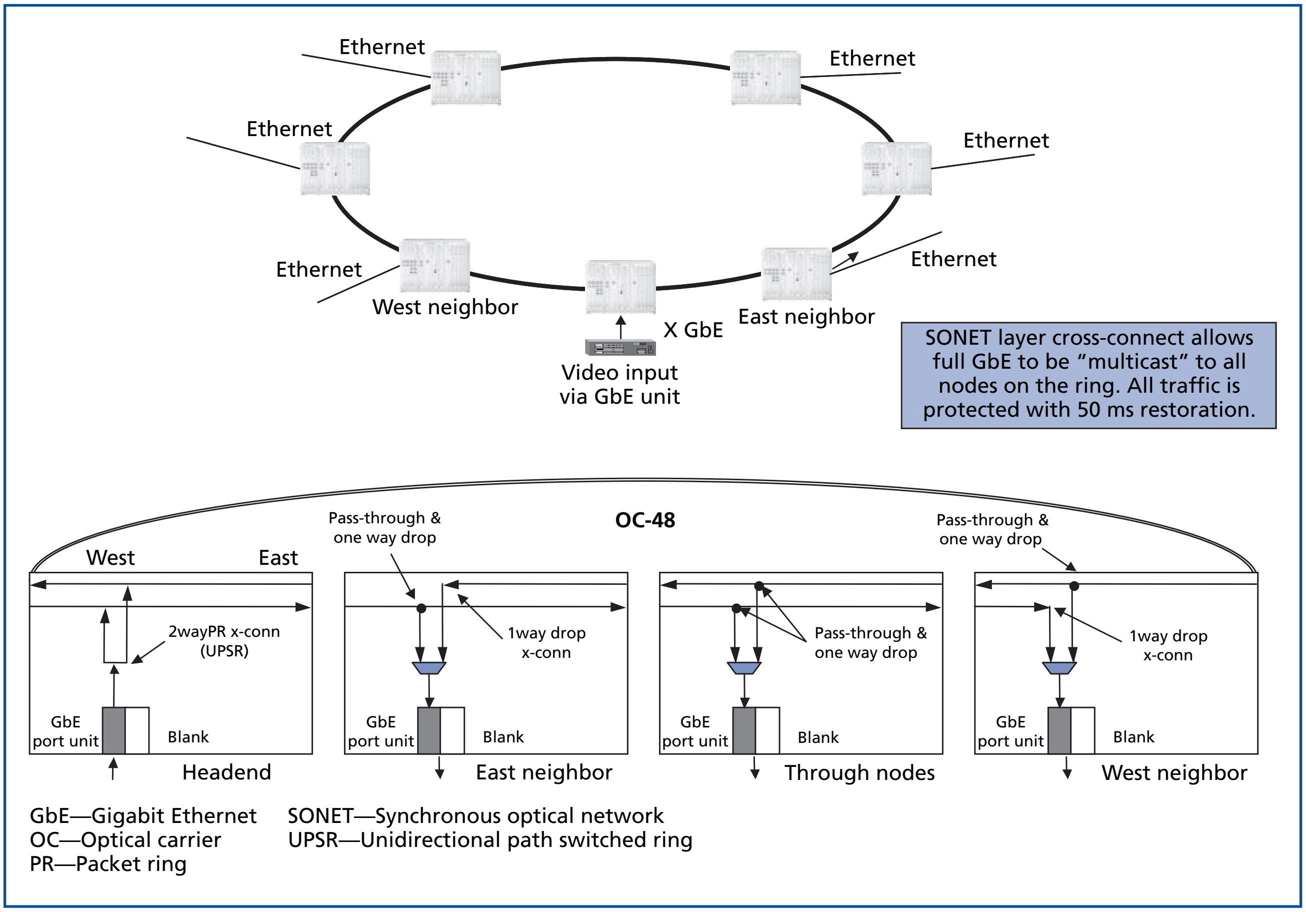


Figure 2.
Ethernet over SONET drop and continue.

engineering is achieved through an over-provisioning of connections between Ethernet switches, with per-customer traffic segmented using VLAN tags. Each VLAN connection has a committed information rate (CIR) for guaranteed bandwidth and an excess information rate (EIR) for traffic bursts. In case of a link failure, connections are restored through the Rapid Spanning Tree Protocol (RSTP), which generally provides restoration at times greater than 300 ms for a large network with many nodes. Some EoF networks, however, offer best-effort services only, where the level of oversubscription limits packet transport performance. When these networks are oversubscribed, latency and jitter across paths increase. These networks can be identified by their lack of service level agreements from the operator. The key advantages of EoF are lower cost, and bandwidth ranging from 10 Mbps to 1 Gbps. The key disadvantages of EoF are its longer restoration times and higher latency and jitter caused by buffering of traffic as it traverses multiple Ethernet switches.

Newer generation EoF networks are addressing the latency, jitter and resiliency (e.g., restoration time) issues. Carriers are increasingly interested in using multiprotocol label switching (MPLS) traffic engineering capability inside the core of an EoF network to offer point-to-point and multipoint-to-multipoint service through virtual private LAN service (VPLS). These approaches have the potential to provide reduced latency and decreased restoration times. In addition to MPLS, resilient packet ring (RPR) is a recently ratified IEEE standard which provides a ring-based packet network with resiliency and latency levels approaching that of SONET/SDH. Another potential solution uses Ethernet over SONET at the core with

Ethernet over fiber in the access rings to take advantage of SONET's proven reliability. This has the important added advantage of facilitating handoffs to the installed base of optical infrastructure in carrier networks. As EoF adds MPLS, RPR or SONET at its core, it will become more attractive to business users who may move away from their existing lower-speed frame relay and ATM services. However, despite these improvements, EoF still does not offer the low jitter and guaranteed bandwidth of EoS and private line services from N × DS1 to OC-48.

Ethernet Over Fiber with Link Aggregation

Link aggregation allows a set of Ethernet links between a pair of node equipment to be grouped together in order to carry a higher volume of total traffic. The RSTP will treat this set of links together as one connection and not consider the links as forming loops. In addition, if any one link in this set fails (e.g., port failure), the remaining links can carry the traffic that was on the failed link, provided the set of links are engineered accordingly. For video distribution via EoF, we have the option of employing link aggregation between each pair of adjacent nodes, as shown in **Figure 3**. By adding an extra link between adjacent nodes, traffic between the nodes is shared among all links between each pair of nodes. This solution allows for faster restoration in the case of port failure on a link between a pair of adjacent nodes. As in EoF, RSTP will be used for restoration if there is a fiber cut between a pair of adjacent nodes that affects all the fibers in the set of links between a pair of nodes.

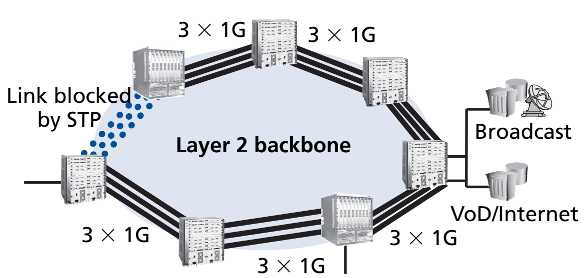


Figure 3.
Ethernet over fiber with link aggregation.

Comparison of Transport Network Technologies

We will now compare the transport network technologies EoS, EoF and Ethernet over fiber with link aggregation (EoF w/LA), in qualitative (general) terms such as protection/restoration. Later, the transport model analysis and case study results will quantify the differences among these technology options and their variations. Video transport in best-effort networks, such as today's Internet, can result in packet losses that degrade video playback quality. In a streaming video application, a movie is played as it is received and there is no possibility of retransmitting the lost packets in time for video playback. Therefore, video transport over the carrier network must proceed at a specified and guaranteed traffic rate to prevent buffer overflow or underflow at the end user display. Also, in the case of network failure, rapid restoration should be employed so that playback can resume quickly (e.g., within 125 to 150 ms). In the EoS solution, the video broadcast is carried through SONET/SDH with drop and continue cross-connections in order to drop the traffic at each of the central office locations. The video on demand traffic is carried as point-to-point dedicated connections to guarantee the bandwidth between the hub and the central offices. This video traffic uses UPSR protection at the SONET/SDH layer. The following transport options exist for the Ethernet over fiber solution: unprotected traffic, traffic protected via link aggregation (link failure protection), or traffic protected through RSTP (link and node failure protection).

The fiber use is higher for EoF since the capacity of a Gigabit Ethernet (GE) link is equivalent to 21 STS-1s (less than half the capacity of an OC-48). The evolution for growth is listed in the "scalability" column.

A qualitative comparison of optical transport technologies is summarized in **Table II**.

Transport Network Model and Analysis

We begin with a simplified transport model consisting of a video head office (VHO) and four video serving offices (VSO) on the same fiber ring. The VHO could be the video headend or video content location from which video traffic is transmitted to the local COs (same as the VSOs), which then distribute the video

Table II. Optical transport technology—qualitative comparison.

Solution	Reliability	Fiber Utilization	Scalability
Ethernet over SONET (EoS)	Protection against port failure and fiber cut; Ring restoration ~ 50 ms	Low with broadcast video only traffic; Low for video on demand with OC-48 ring capacity	Upgrade to OC-192 or add more OC-48 rings
Ethernet over fiber (EoF)	For point to point link, no protection; For loop, protection against node failure and fiber duct cut with RSTP restoration ~ 50 ms	Low with broadcast video only traffic; Higher than EoS for video on demand traffic exceeding 1 GE	Upgrade to 10 GE or add more GE
Ethernet over fiber with link aggregation (EoF w/LA)	For point to point connection, N:1 protection against port failure and fiber cut with restoration time ~ 50 ms; For loop, protection against node failure and fiber duct cut with RSTP restoration ~100 to 300 ms	Low with broadcast video only traffic; Higher than EoS and EoF	Upgrade to 10 GE or add more GE

EoF—Ethernet over fiber
EoF w/LA—EoF with link aggregation
EoS—Ethernet over SONET
GE—Gigabit Ethernet
OC—Optical carrier
RSTP—Rapid Spanning Tree Protocol

traffic to the subscribers in the local VSO serving area. Intra-office video add/drop for the VHO and VSOS is provided via Gigabit Ethernet links. The VHO and VSOs are assumed to be on the same fiber loop. For EoS, UPSR is used for restoration in the event of a fiber cut or node failure. For EoF, Rapid Spanning Tree Protocol-based restoration and loop prevention is used. This can be augmented using link aggregation [4, 9] on the links between adjacent VSOs. The broadcast video bandwidth assignment is shown in **Table III** for one (counter-clockwise) fiber. Similar assignment is made in the clock-wise direction on the other fiber of the (UPSR) fiber ring. The following descriptions use the SONET terminology but similar concepts with comparable rates apply to the SDH network as well. We consider the following transport options in **Figure 4**.

Ethernet Over SONET Hubbed Transport. Video traffic is handed to/from the next-generation SONET add/drop multiplexer via intra-office GE links. The traffic destined to each VSO (from the VHO) is mapped on to a separate group (VCG) of STS-1s and transported over OC-48 or OC-192 rings as point-to-point traffic. Note that the broadcast video traffic in the EoS hub model has to be transported as separate streams destined for individual VSOs, just as in the case of unicast traffic. This is applicable to a situation where the add/drop multiplexer (ADM) does not have the SONET drop and continue functionality.

Ethernet Over SONET Drop and Continue. As in the EoS hub option, video traffic is handed to/from the next-generation SONET add/drop multiplexer via intra-office GE links. The ADMs in each VSO are assumed to support SONET drop and continue functionality. Then, the broadcast traffic is mapped on to one group (VCG) of STS-1s and transported over OC-48 or OC-192 rings. This group of STS-1s is dropped at each VSO and continues via SONET cross-connect functionality in next-generation SONET ADMs on to the next VSO. Therefore, only one group of STS-1s is needed to carry broadcast video traffic from the VHO to all the VSOs on the ring. The unicast traffic to each VSO is mapped on to separate groups (VCGs) of STS-1s and carried as point-to-point traffic.

Ethernet Over Fiber Hubbed Transport. As in the EoS hub option, broadcast traffic is transported as separate streams to individual VSOs. Both the broadcast and unicast traffic are carried over point-to-point Gigabit Ethernet over fiber connections.

Table III. Transport model analysis for broadcast and unicast traffic.

Transport Model Analysis for Broadcast Video Traffic		
Transport Option	**Aggregate Network Bandwidth**	**Aggregate Network Fiber Pairs**
EoS Hub	Number of VSOs * [Video bandwidth per VSO drop in STS-1s]	[Number of OC-48 rings to carry aggregate network bandwidth]
EoS D&C	[Video bandwidth per VSO drop in STS-1s]	[Number of OC-48 rings to carry aggregate network bandwidth]
EoF Hub	Number of VSOs * [Video bandwidth per VSO drop in GEs]	[Number of GE links to carry aggregate network bandwidth]
EoF EM	[Video bandwidth per VSO drop in GEs]	[Number of GE links to carry aggregate network bandwidth]
EoF w/LA EM	[Video bandwidth per VSO drop in GEs] + 1	[Number of GE links to carry aggregate network bandwidth] +1
Transport Model Analysis for Unicast Video Traffic		
EoS Hub	Number of VSOs * [Video bandwidth per VSO drop in STS-1s]	[Number of OC-48 rings to carry aggregate network bandwidth]
EoS D&C	Number of VSOs * [Video bandwidth per VSO drop in STS-1s]	[Number of OC-48 rings to carry aggregate network bandwidth]
EoF Hub	Number of VSOs * [Video bandwidth per VSO drop in GEs]	[Number of GE links to carry aggregate network bandwidth]
EoF EM	Number of VSOs * [Video bandwidth per VSO drop in GEs]	[Number of GE links to carry aggregate network bandwidth]
Eof w/LA EM	Number of VSOs * [Video bandwidth per VSO drop in GEs] + 1	[Number of GE links to carry aggregate network bandwidth] + 1

EoF—Ethernet over fiber
EoF EM—EoF with Ethernet Multicast
EoF w/LA EM—EoF with link aggregation
EoS—Ethernet over SONET/SDH
EoS D&C—EoS drop and continue
GE—Gigabit Ethernet
OC—Optical carrier
SDH—Synchronous digital hierarchy
SONET—Synchronous optical network
STS—Synchronous transport signal
STS-1v—SONET rate of 155 Mbps
VSO—Video serving office (local office)

Ethernet Over Fiber Ethernet Multicast. As in the EoS D&C option, broadcast video traffic is replicated at the Ethernet multicast functionality assumed to be available at each VSO for transmission to the next VSO on the fiber loop. Again, only one video broadcast traffic stream is carried around the fiber loop for delivery to all VSOs on that fiber loop. The unicast traffic is carried via point-to-point Gigabit Ethernet over fiber connections. The unicast traffic may be combined with the broadcast traffic before being dropped at each VSO.

Ethernet Over Fiber with Link Aggregation and Ethernet Multicast. Broadcast and unicast traffic in this option are handled the same way as in EoF EM. However, the Gigabit Ethernet traffic links between adjacent VSOs is augmented by one additional link and Ethernet link aggregation is assumed to be supported on this group of GE links between adjacent VSOs. This allows for faster recovery (compared to EoF EM) in the case of equipment port failure on a given link between adjacent VSOs.

Table III shows the summary results of transport model analysis for broadcast and unicast traffic. The video bandwidth assigned is similar for unicast traffic, i.e., the assigned bandwidth is rounded-up to the granularity provided in STS-1s or Gigabit Ethernet. However, the hub model transports broadcast traffic in separate streams to each VSO and the assigned bandwidth increases with the number of VSOs in the fiber loop. The D&C and EM options require only the bandwidth corresponding to a single video broadcast

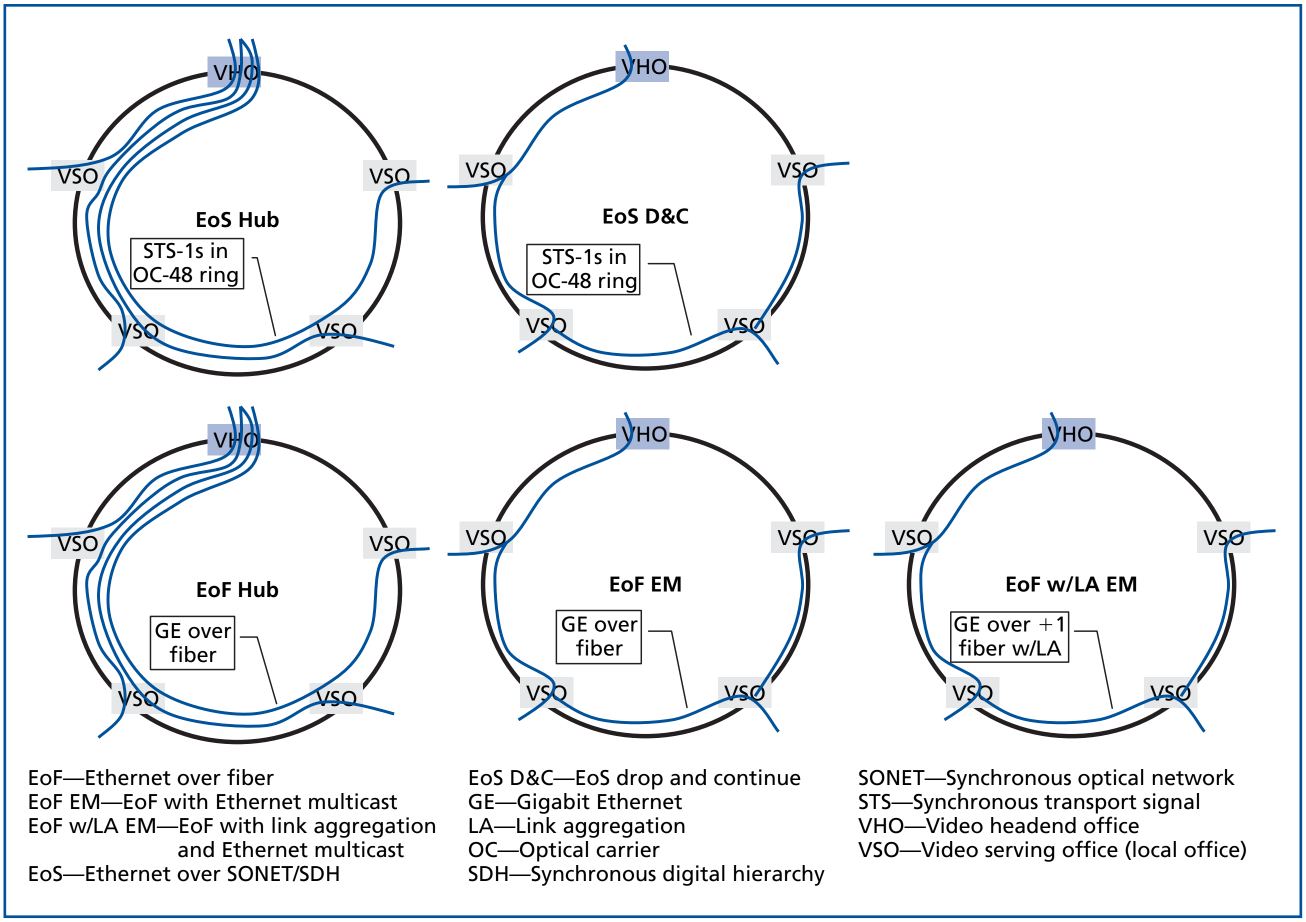


Figure 4.
Optical transport options.

stream, around the fiber loop. Additional options such as global packet ring (GPR) and resilient packet ring (RPR) over SONET, have comparable bandwidth requirements. Multiprotocol label switching (MPLS) allows additional technology options to assign bandwidth to the video streams to each VSO but these options tend to be in addition to the transport options listed here.

In the numerical results, a Gigabit Ethernet channel is equivalent to 21 STS-1s. This results in truncation or rounding when we plot the equivalent bandwidth for EoS and EoF scenarios. The fiber pairs are computed assuming OC-48 rings or GE over fiber. This leads to increased fiber use for EoF, as an OC-48 can accommodate twice the traffic carried over a GE link. Besides, the unused STS-1 capacity in an OC-48 could be assigned to other traffic types. If OC-192 and 10 GE links are deployed, their capacities are similar and these will result in decreased fiber count.

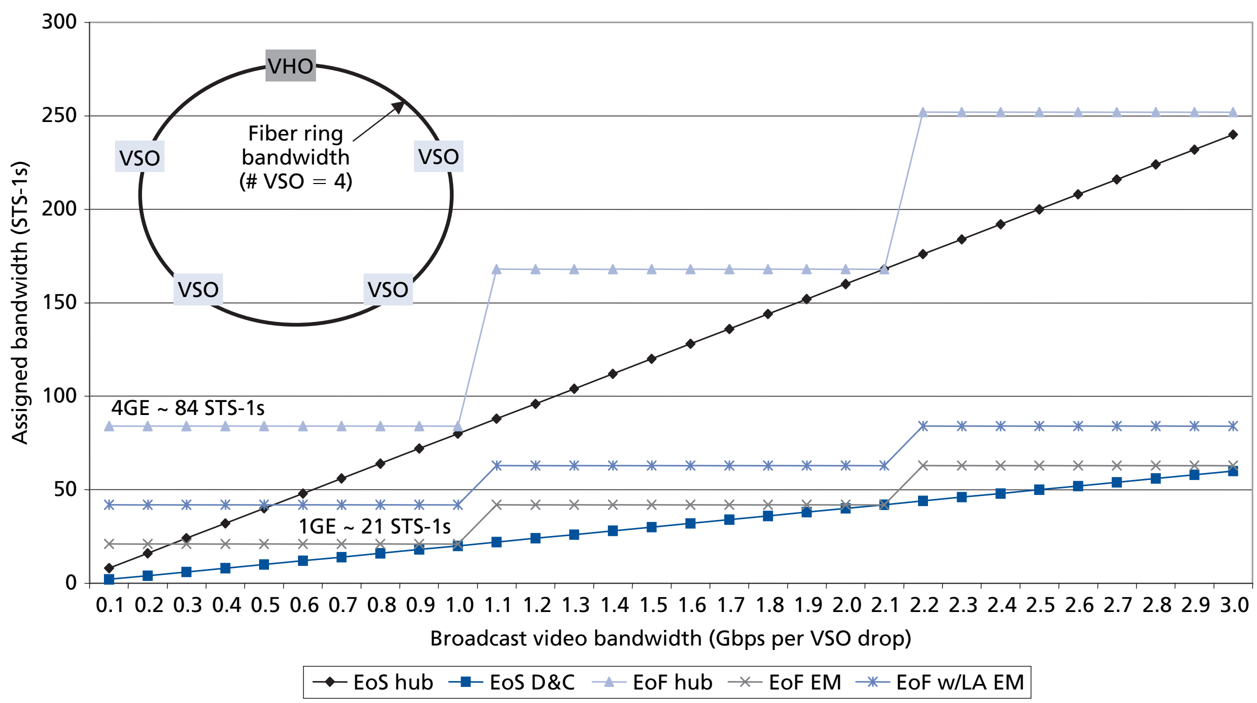
In the cost computations, we assume that STS-1 bandwidth is at a premium compared to the equivalent bandwidth over GE links. Here, these costs include the CapEx for fiber installation and for the terminating equipment. Equipment costs are driven by network equipment functionality and by market volumes, both of which are very different for the two technologies. The fiber pairs are typically deployed as a bundle and the material cost of an additional fiber pair within the fiber bundle is a small fraction of the overall deployment costs, which include trenching, for buried fibers.

It is important to note that the EoS and EoF transport options have different resiliency. A service provider is expected to select a subset of options that meet their requirements for reliability in a given segment of their network. Once the reliability threshold is met, this subset of options can be compared using metrics such as assigned network bandwidth, fiber use and/or their equivalent costs.

Transport Network Model Results—Broadcast Video Only

A transport model, consisting of one VHO and four to six VSOs on a fiber loop was used to derive the numerical results for aggregate bandwidth assignment and the aggregate fiber use. Aggregate bandwidth assignment for EoS is the number of STS-1 frames that are used to map VHO Gigabit Ethernet traffic in order to carry the VHO-to-VSO video traffic over the OC-48 UPSR rings. The remaining OC-48 ring capacity is available for mapping other (e.g., TDM) traffic. For each Gigabit Ethernet over fiber connection, the equivalent bandwidth assignment is 21 STS-1s. EoS bandwidth mapping has finer granularity (e.g., STS-1s) compared to the coarse granularity of EoF (1 GE ~ 21 STS-1s). This coarse granularity results in an increased aggregate bandwidth assignment for EoF compared to the aggregate bandwidth assignment needed for EoS, given comparable video traffic. For EoF with link aggregation, each span between adjacent nodes uses an extra link and the traffic is balanced among all the EoF links between the two adjacent nodes. The fiber assignment is computed based on OC-48 rings or Gigabit over Ethernet fiber connections. As noted before, since the capacity of each GE link is equivalent to 21 STS-1s, the OC-48 provides more than twice this capacity and therefore requires fewer fibers. Numerical results for broadcast video traffic for various optical transport options, namely, EoS hub; EoS D&C, EoF hub, EoF EM, and EoF w/LA EM are detailed in Figures 5, 6, 7, 8, and 9.

Aggregate network bandwidth versus broadcast video drop bandwidth per VSO is shown in **Figure 5**.

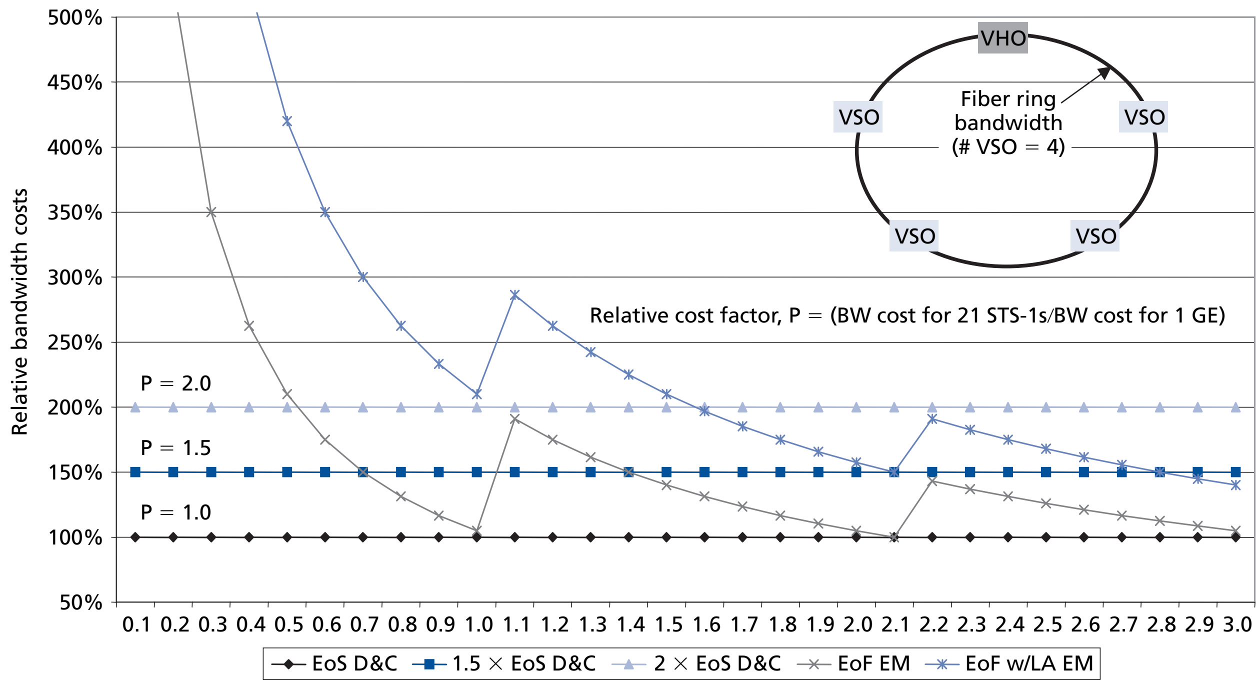


EoF—Ethernet over fiber
EoF EM—EoF with Ethernet multicast
EoF w/LA EM—EoF with link aggregation and Ethernet multicast
EoS—Ethernet over SONET/SDH
EoS D&C—EoS drop and continue
GE—Gigabit Ethernet
SDH—Synchronous digital hierarchy
SONET—Synchronous optical network
STS—Synchronous transport signal
VHO—Video headend office
VSO—Video serving office (local office)

Figure 5.
Aggregate assigned network bandwidth for broadcast video transport options.

The EoS Hub option requires four times the bandwidth required for the EoS drop and continue (EoS D&C) option since the number of VSOs is four. Similarly, the EoF Hub option requires four times the bandwidth required for the EoF EM option. The EoF LA requires an extra link between adjacent nodes (e.g., VHO-VSO or VSO-VSO) and the equivalent bandwidth assignment is computed to be correspondingly higher. The difference between the EoS and EoF (for both the hub and D&C options) depends on the operating point (i.e., the broadcast video drop per VSO). As the broadcast drop bandwidth approaches the GE link capacities (e.g., 1, 2 or 3 Gbps), the difference in aggregate bandwidth assignment between EoS and EoF narrows for both hub and D&C options. For other (intermediate) values (e.g., 1.2 Mbps to 1.5 Mbps) EoF aggregate bandwidth assignment is over 20% higher than for EoS, due to the finer granularity of STS-1 mapping/bandwidth assignments in EoS.

For a comparable transport (ring network) bandwidth, the cost of EoS and EoF provisioning are different as the network equipment is based on fundamentally different switching technologies. SONET and Ethernet technologies have very different technology origins, functionality, protocol complexity and implementation maturity, as well as total addressable market (TAM), market volume, and volume price reduction over time. A network cost model must include detailed equipment configuration and pricing, taking into account the specific network topology and traffic. However, a simple cost model for aggregate assigned bandwidth can provide insight into the trends and trade-offs among transport options, as traffic volumes change over time. Assuming that SONET transport is at a premium for comparable bandwidth (1 GE ~ 21 STS-1s), we plot the relative bandwidth costs at 100%, 150%, and 200% for EOS D&C and present that in **Figure 6**. The corresponding costs for



BW—Bandwidth
EoF—Ethernet over fiber
EoF EM—EoF with Ethernet multicast
EoF w/LA EM—EoF with link aggregation and Ethernet multicast
EoS—Ethernet over SONET/SDH
EoS D&C—EoS drop and continue
GE—Gigabit Ethernet
SDH—Synchronous digital hierarchy
SONET—Synchronous optical network
STS—Synchronous transport signal
VHO—Video headend office
VSO—Video serving office (local office)

Figure 6.
Aggregate network bandwidth costs for broadcast video transport options.

the EoF EM and EoF w/LA EM options are also included here. The EoS D&C provides lower costs (compared to EoF) for early deployment when the broadcast video traffic volume is relatively low (e.g., 0.5 Gbps). This can also apply to the broadcast video channel lineup in smaller markets since this transport bandwidth will allow a service provider to offer over 250 standard television video channels. As broadcast traffic increases (e.g., as the number of broadcast channels increases and/or high definition television channels are introduced), EoF becomes cost competitive, particularly if the SONET bandwidth is at a 200% premium (p = 2). EoS D&C provides fast (50 ms UPSR based) restoration whereas EoF w/LA EM adds to the EoF bandwidth costs. However, fiber costs are considered to be similar for these transport options (per meter cost of $75 for trenching in urban areas to $3 for trenching in rural areas versus $0.04 for material cost of a fiber pair [11]) for a given topology, assuming that the fiber bundle has adequate fiber pairs and the material cost per fiber pair is a small fraction of the overall fiber deployment CapEx.

If the network elements do not have EoS D&C functionality, a service provider can implement EoS and EoF using a hubbed transport option. However, this will require assignment of additional transport bandwidth compared to the EoS D&C or EoF EM options. Bandwidth assignment increases with the number of VSOs in the ring as **Figure 7** shows. The difference in transport bandwidth between hubbed and non-hubbed options doubles as the broadcast video bandwidth VSO drop is doubled.

The number of fibers used for each transport option depends on the aggregate assigned bandwidth, the granularity (e.g., STS-1 or GE) of the bandwidth assignment, and the overall transport capacity per fiber (e.g., OC-48 or GE). While the fiber deployment

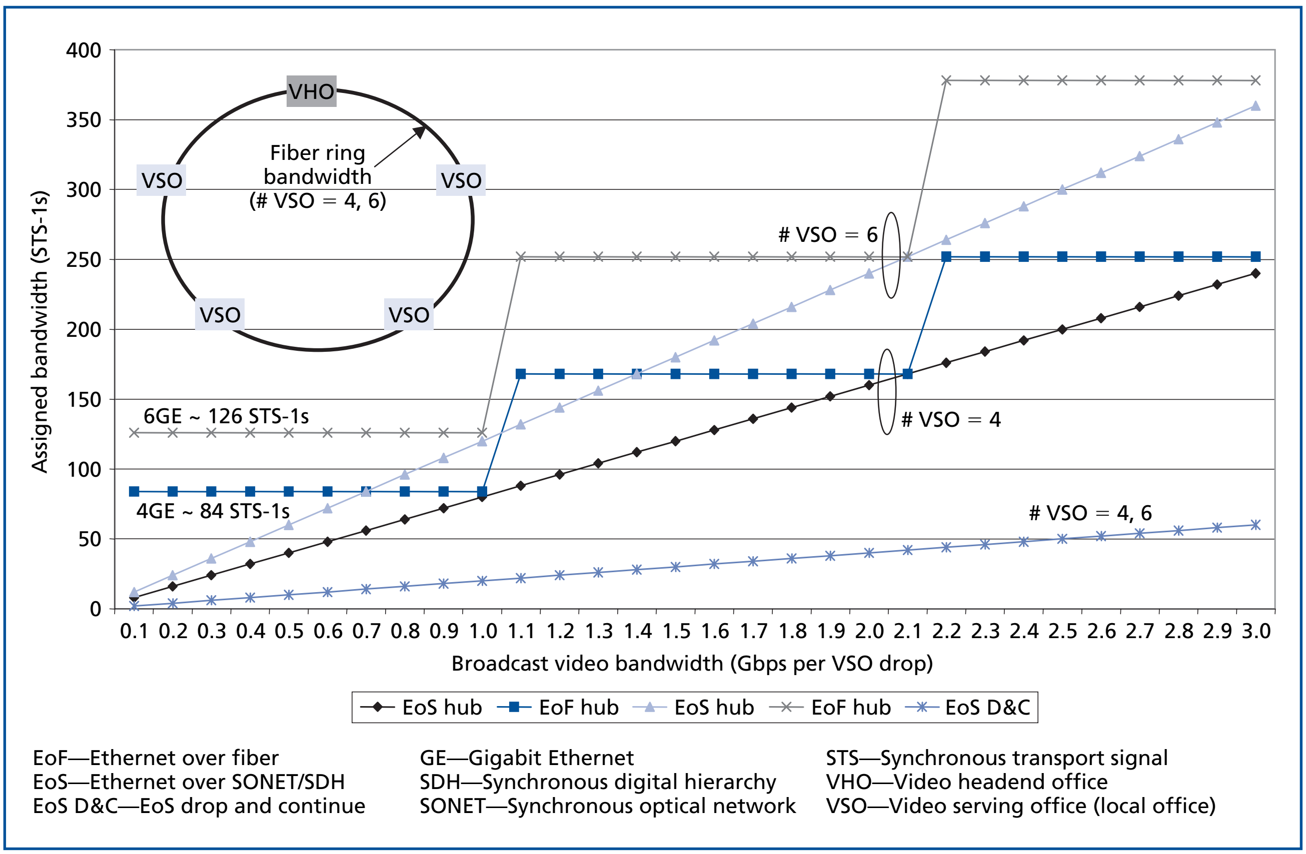
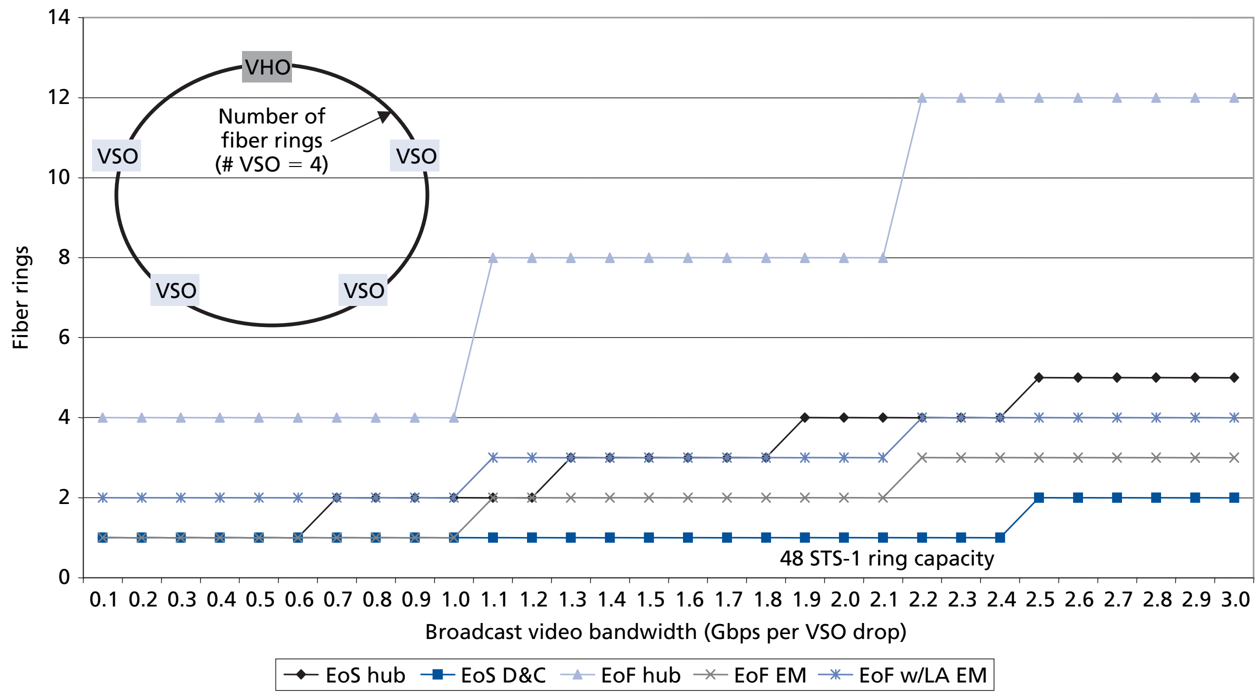


Figure 7.
Aggregate network assigned bandwidth for broadcast video hubbed transport options.



EoF—Ethernet over fiber
EoF EM—EoF with Ethernet multicast
EoF w/LA EM—Ethernet over fiber with link aggregation and Ethernet multicast
EoS—Ethernet over SONET/SDH
EoS D&C—EoS drop and continue
SDH—Synchronous digital hierarchy
SONET—Synchronous optical network
STS—Synchronous transport signal
VHO—Video headend office
VSO—Video serving office (local office)

Figure 8.
Aggregate network fiber usage for broadcast video transport options.

CapEx is similar (as noted earlier, the material cost of an additional fiber pair in the same installed cable is marginal), a higher fiber consumption will result in higher opportunity costs for that particular transport option. As **Figure 8** shows, aggregate network fiber usage is low for EoS D&C, since it has finer (e.g., STS-1) bandwidth assignment granularity, as well as higher (e.g., OC-48) traffic capacity per UPSR ring. A second ring is needed when the broadcast video traffic reaches 2.5 Gbps. In comparison to EoS D&C, EoF EM requires additional fiber beyond its initial fiber capacity of 1 Gbps; EoF w/LA EM uses an extra fiber pair between adjacent nodes compared to EoF EM. While the EoF Hub option requires four times the fibers for EoF EM since the number of VSOS is four, the EoS hub option exhibits a more gradual increase in the use of fiber due to its finer (STS-1) granularity bandwidth assignment and higher capacity (OC-48) UPSR ring. As shown in **Figure 9**, where the number of VSOs is six, fiber requirements for a larger ring show a large incremental increase for the EoF hub compared to a gradual increase in fiber use for the EoS hub option. Again, EoS D&C uses less fiber for VSO = 4, 6 compared to the hub options. If the fiber capacity is increased (e.g., to OC-192 or 10 GE), the number of fibers used will be lower and the difference in fiber use between EoS and EoF will also tend to be lower.

Overall, when we consider broadcast video traffic only, the EoS D&C option provides a balance between the network economics (bandwidth and fiber use and their costs) and the fast restoration (UPSR) capability. EoF EM can implement fast restoration using link aggregation in areas where additional fiber is available.

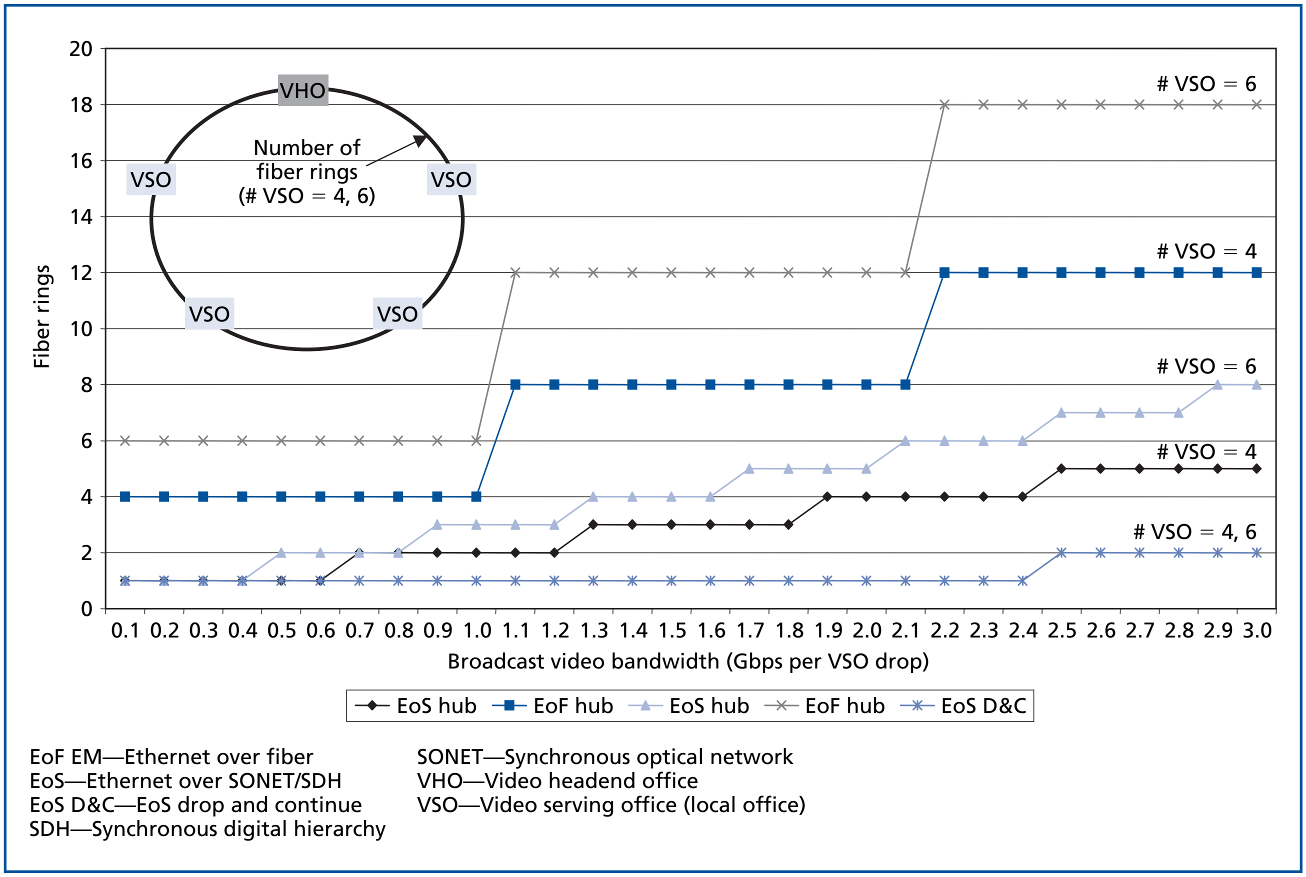


Figure 9.
Aggregate network fiber usage for broadcast video hubbed transport options.

The hub option centralizes packet switching equipment and reduces associated costs while it increases the assigned transport bandwidth requirements. In the next section, we consider a mix of broadcast video and unicast traffic to reflect the future direction of traffic mix in these networks.

Transport Network Model Results—Broadcast Video and Unicast Traffic

As mentioned earlier, service providers can base their business model on a broadcast video-only service (e.g., broadcast over the air, CATV model, and/or custom package) or base their business model heavily on more personalized (e.g., unicast) video services (e.g., as ILECs in the U.S. have done with emphasis on video on demand or network personal video recorder services). Therefore, we also consider a variable percentage of broadcast traffic to the total (broadcast plus unicast) traffic for the above transport options. In the numerical results presented in Figures 10, 11, 12 and 13, the total traffic is fixed and we compute the aggregate bandwidth assignment, aggregate network fiber usage and the relative costs of assigned bandwidth as we vary the ratio of broadcast video traffic to the total (broadcast video plus unicast video) traffic.

As **Figure 10** shows, aggregate assigned bandwidth decreases as the percentage of broadcast video traffic increases, as expected, for the EoS D&C, EOF EM and EOF w/LA EM options. These require bandwidth assignment corresponding to one broadcast video stream and this is independent of the number of VSOs on the fiber ring. The step change for EoF reflects the coarse granularity (1 GE or equivalent

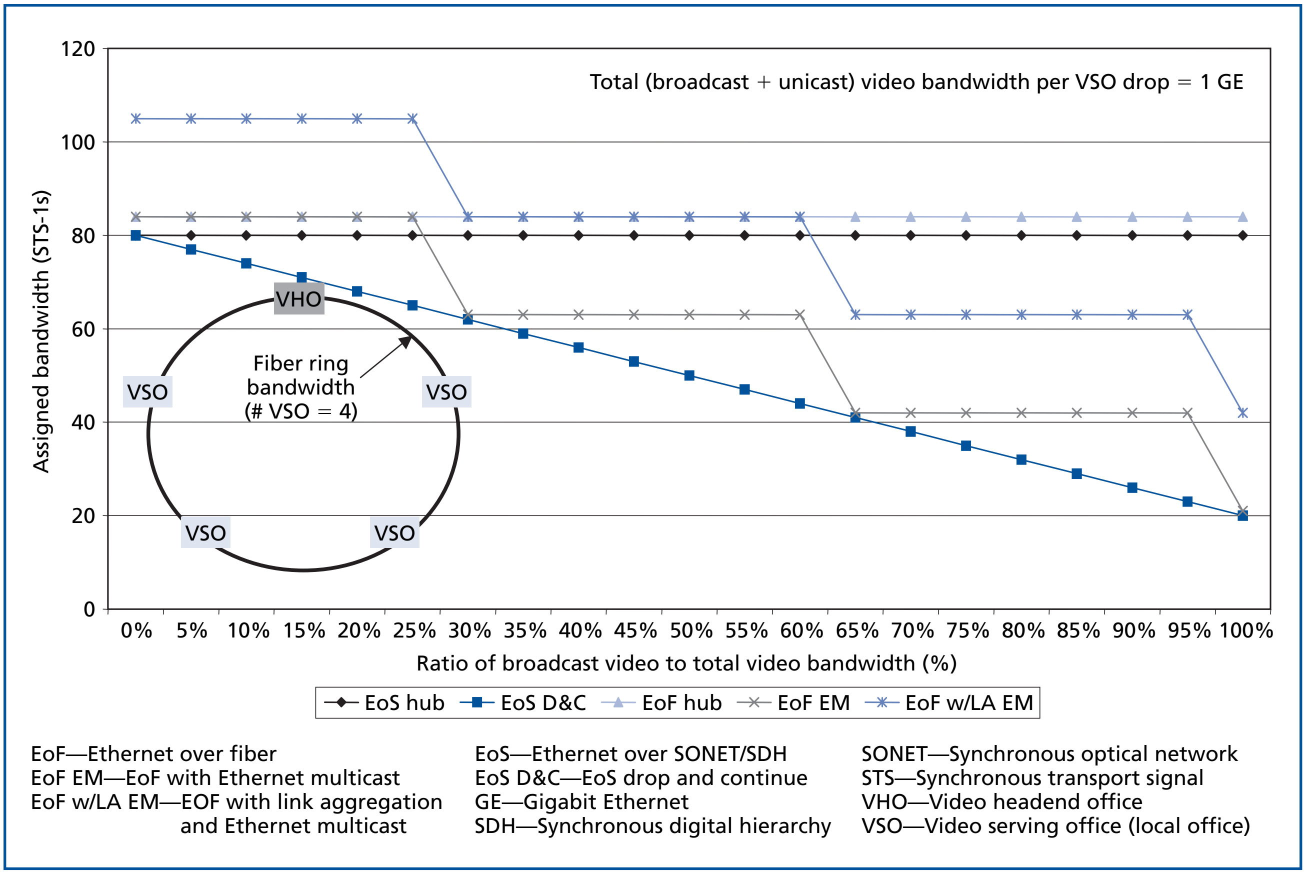


Figure 10.
Aggregate network assigned bandwidth for total (broadcast video + unicast) traffic.

of 21 STS-1s) of assigned bandwidth. In the hub options, a separate bandwidth assignment is required for the total traffic to each VSO, including the broadcast traffic. Note that the EoS and EoF bandwidth assignments for the hub option may be different due to bandwidth granularity and rounding effects. With the exception of scenarios where link aggregation is supported, the assigned bandwidth is same (and proportional to the number of VSOs) for all the transport options if there is no broadcast video traffic. The difference in this aggregate assigned bandwidth increases between hub and non-hub options, as the percentage of broadcast video traffic increases. A service provider with a significant percentage of broadcast traffic could save on the assigned aggregate bandwidth by choosing one of the non-hub transport options. As shown in **Figure 11**, the corresponding fiber usage also decreases with increased percentage of broadcast traffic. The EoS D&C uses fewer fibers due to its finer (STS-1) bandwidth granularity and the higher (OC-48) capacity of UPSR rings. As noted before, if the fiber capacity is increased (e.g., OC-192 or 10 GE), the number of fibers used will be lower and the difference in fiber use between EoS and EoF will also tend to be lower.

Again, we compute the relative bandwidth costs assuming that the equivalent bandwidth for SONET is at a 100%, 150%, or 200% premium of aggregate assigned bandwidth. **Figure 12** shows that relative cost for the D&C option is lower than for the EM transport option at a high percentage of broadcast video traffic when the SONET bandwidth cost is assigned a premium of 150%. If the total bandwidth per VSO is increased from 1 GE to 4 GE as shown in

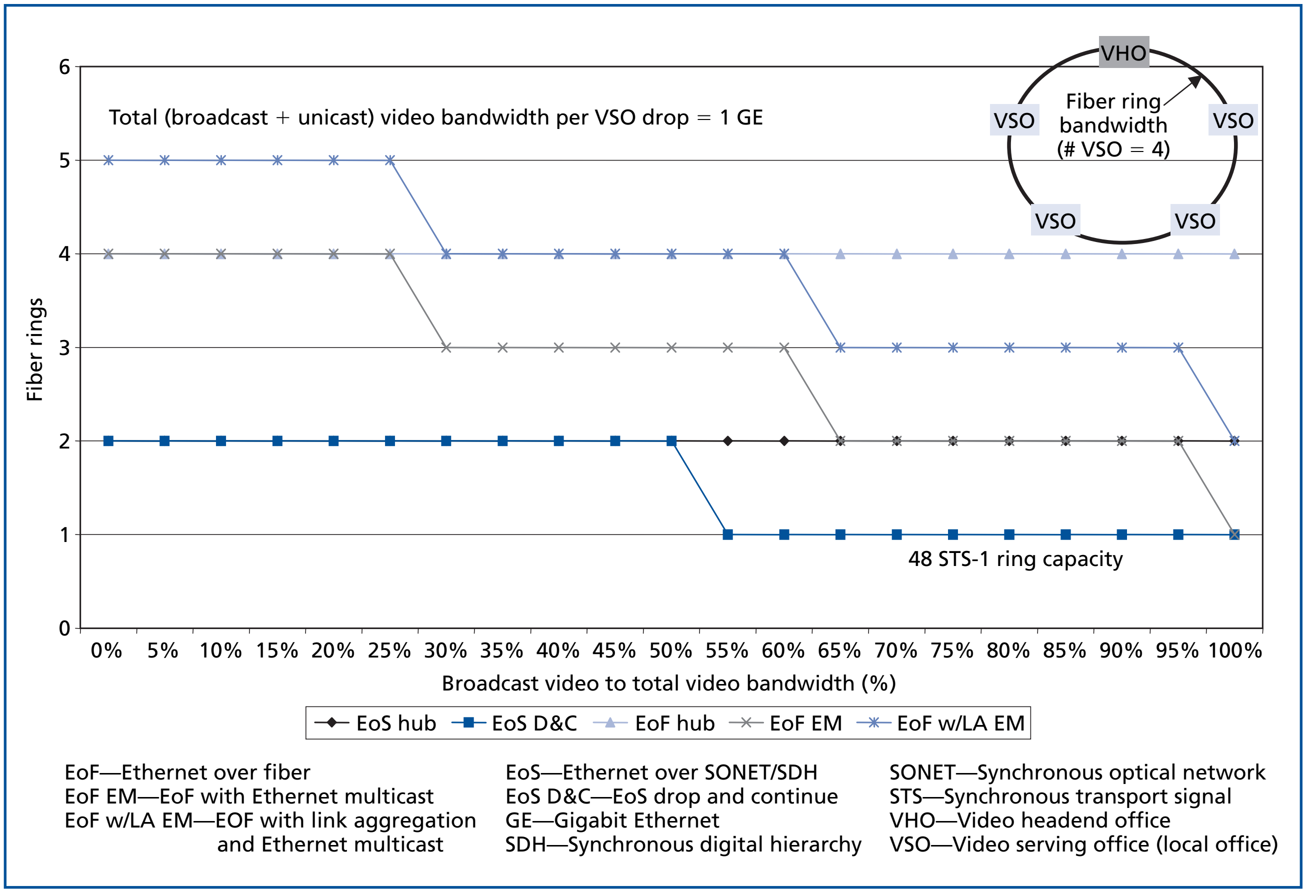


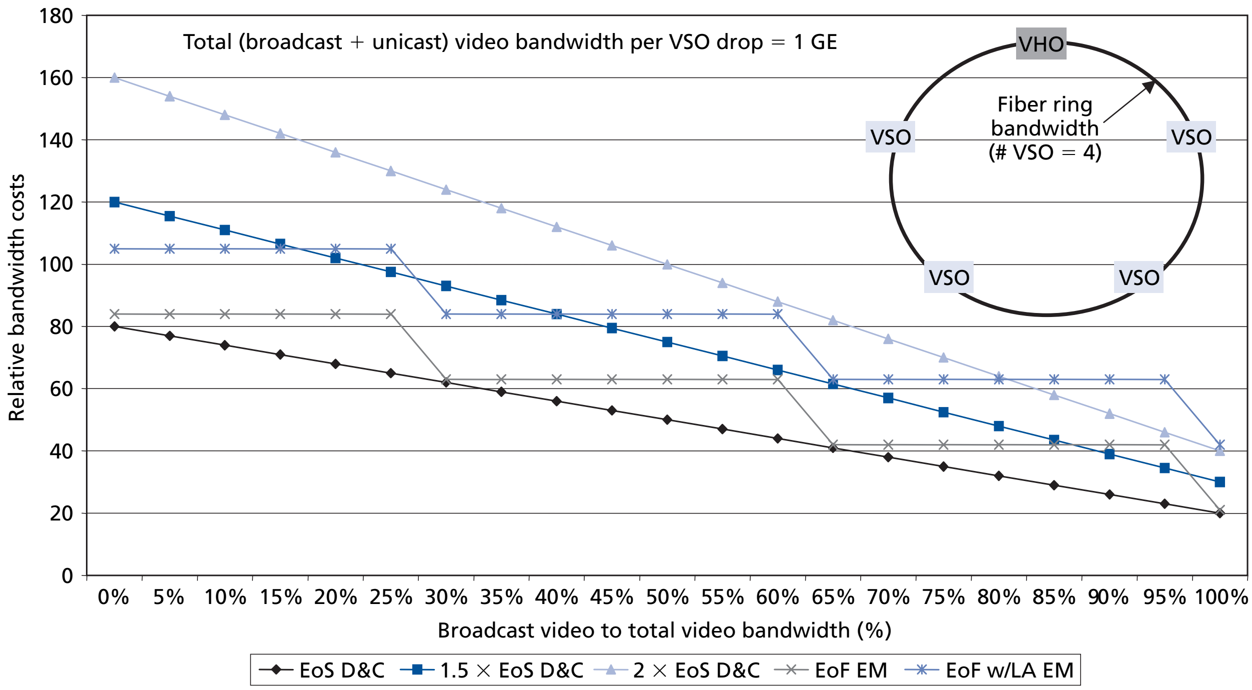
Figure 11.
Aggregate network fiber usage for total (broadcast video + unicast) traffic.

Figure 13, and SONET bandwidth cost is assigned a premium of 150%, the EoS option does not provide a lower relative cost even when the broadcast traffic accounts for 100% of the total traffic. This is due to the granularity of EoF being sufficiently small at higher total traffic (4 GE per VSO) so that the finer (STS-1) granularity of EoS does not provide a sufficient difference in the assigned bandwidth compared to EoF to overcome the bandwidth premium of 150%.

Overall, these results show that for lower total traffic (1 GE per VSO) and at a higher percentage of broadcast traffic, EoS provides better network economics even if there is a bandwidth premium of 150%. However, as the total traffic volume increases (4 GE per VSO) EoF provides better network economics. In addition to the transport network models and options that provide insight into the trends, we studied actual regional network fiber topologies and example traffic scenarios for broadcast video and total traffic. These case study results are discussed next.

Case Study

Our case study involves the design of an IPTV optical transport wide-area network, spanning three metropolitan regions. There is one primary video headend office for content acquisition and merging related to broadcast TV, and the video-on-demand servers are also assumed to be co-located here. The video from the VHO is transported to the 20 video serving offices distributed in the three metro regions over the core



EoF—Ethernet over fiber
EoF EM—EoF with Ethernet multicast
EoF w/LA EM—EOF with link aggregation and Ethernet multicast
EoS—Ethernet over SONET/SDH
EoS D&C—EoS drop and continue
GE—Gigabit Ethernet
SDH—Synchronous digital hierarchy
SONET—Synchronous optical network
VHO—Video headend office
VSO—Video serving office (local office)

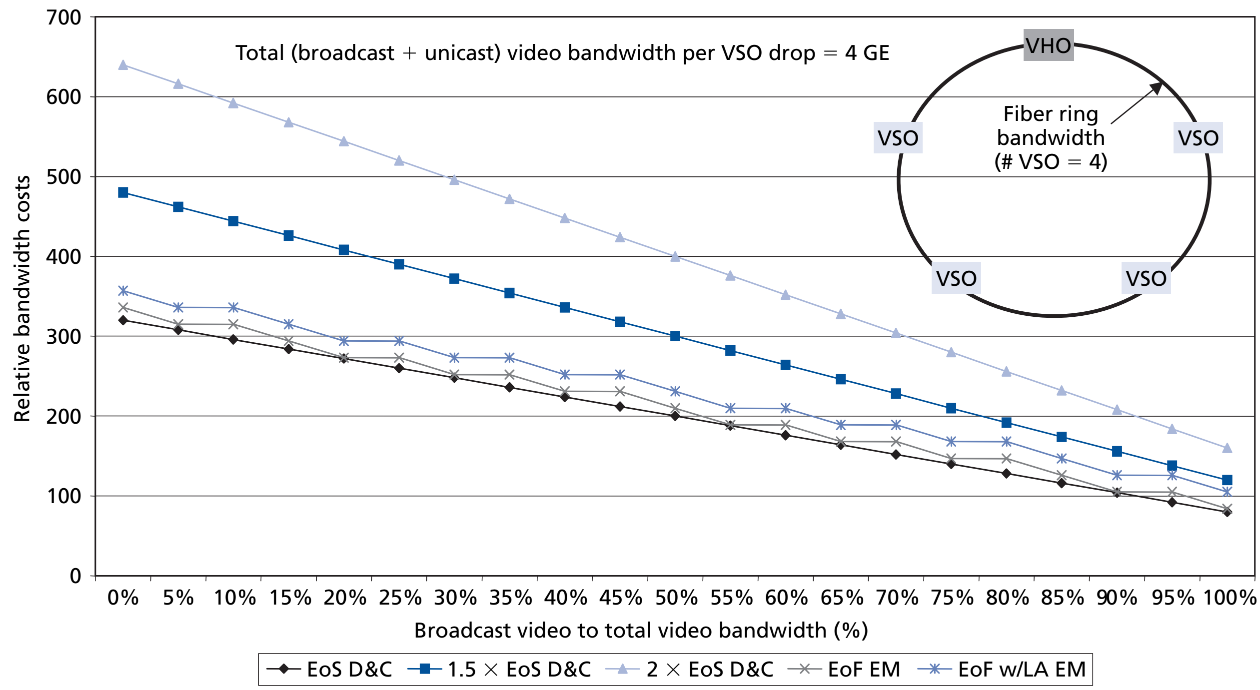
Figure 12.
Aggregate network bandwidth costs for total (broadcast video + unicast) traffic of 1GE per VSO.

network. The access transport network is designed to distribute traffic to the DSLAMs from each of the VSOs. The remote DSLAMs also subtend compact DSLAMs in some parts of the network. The combined core and access network architecture model is shown in **Figure 14**. The technology options for the core and access transport network are taken to be independent and we consider them separately. It is possible to use the same network technology and combine network elements and/or to consolidate the traffic moving between the core and the access networks.

In this case study, the core video network is designed to deliver both broadcast and unicast (VoD) traffic. The broadcast traffic model assumes 700 Mbps of transport bandwidth capacity is required. This provides sufficient bandwidth for approximately 230 SDTV channels encoded as MPEG-4 and 30 HDTV channels encoded as MPEG-4 with roughly 2 Mbps and 8 Mbps of bandwidth per IPTV channel respectively. All the broadcast channels are delivered to the local COs (which are same as the VSOs).

The unicast traffic model, estimated by the service provider based on an assumed business model and take-rates, has two levels of VoD subscription on average per CO. A low traffic level VoD assumes one STS-1 (~52 Mbps) equivalent bandwidth per CO, and a relatively high traffic level VoD assumes four STS-1 (~208 Mbps) equivalent bandwidth per CO. We want to note here that the take rates of VoD in this particular model is in the single digits percentage-wise.

In network planning for a core optical transport network, the service provider specifies the CO locations and fiber topology based on existing infrastructure. Therefore, the VHO and VSO locations were specified, and the initial fiber topology was provided. This is



EoF—Ethernet over fiber
EoF EM—EoF with Ethernet multicast
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EoS—Ethernet over SONET/SDH
EoS D&C—EoS drop and continue
GE—Gigabit Ethernet
SDH—Synchronous digital hierarchy
SONET—Synchronous optical network
VHO—Video headend office
VSO—Video serving office (local office)

Figure 13.
Aggregate network bandwidth costs for total (broadcast video + unicast) traffic of 4GE per VSO.

shown at the top of **Figure 15**, in 15(a). The fiber topology is such that the network has many spur nodes (or nodes connected to only one other node) and, hence, the rings are typically folded or collapsed. This topology typically exists because of geographical constraints in laying fiber.

However, even though the fiber topology was specified, we decided to model a second fiber topology scenario as shown in Figure 15(b). Here we assume that the service provider adds new fiber links to the network and is able to build more span diverse rings that have loops. We assume five new fiber links are added into the network (dashed lines). This helps us study the impact of two different fiber topologies as well as part of the comparative analysis of the various transport technologies.

In the following section, we analyze the results of the optimization on the core transport network with the input parameters discussed above. The core transport network has been optimized for both EoS and EoF solutions and the relative CapEx is computed for each optimized design. The CapEx computation also estimates the cost of regenerating signals for EoS and EoF technologies.

Core Network—Small Fiber Loop Topology

In this scenario, the fiber topology has a number of spur nodes in the network and, hence, the rings are collapsed or folded. **Figure 16** shows the relative CapEx for the three optical transport options—EoS, EoF, EoF w/LA, for three different traffic combinations—no VoD, low VoD, and high VoD.

Broadcast-Only Solution. For p = 1, the normalized height of the columns represent the equivalent optical transport bandwidth used for each of the options compared. Even with a cost premium (p = 2),

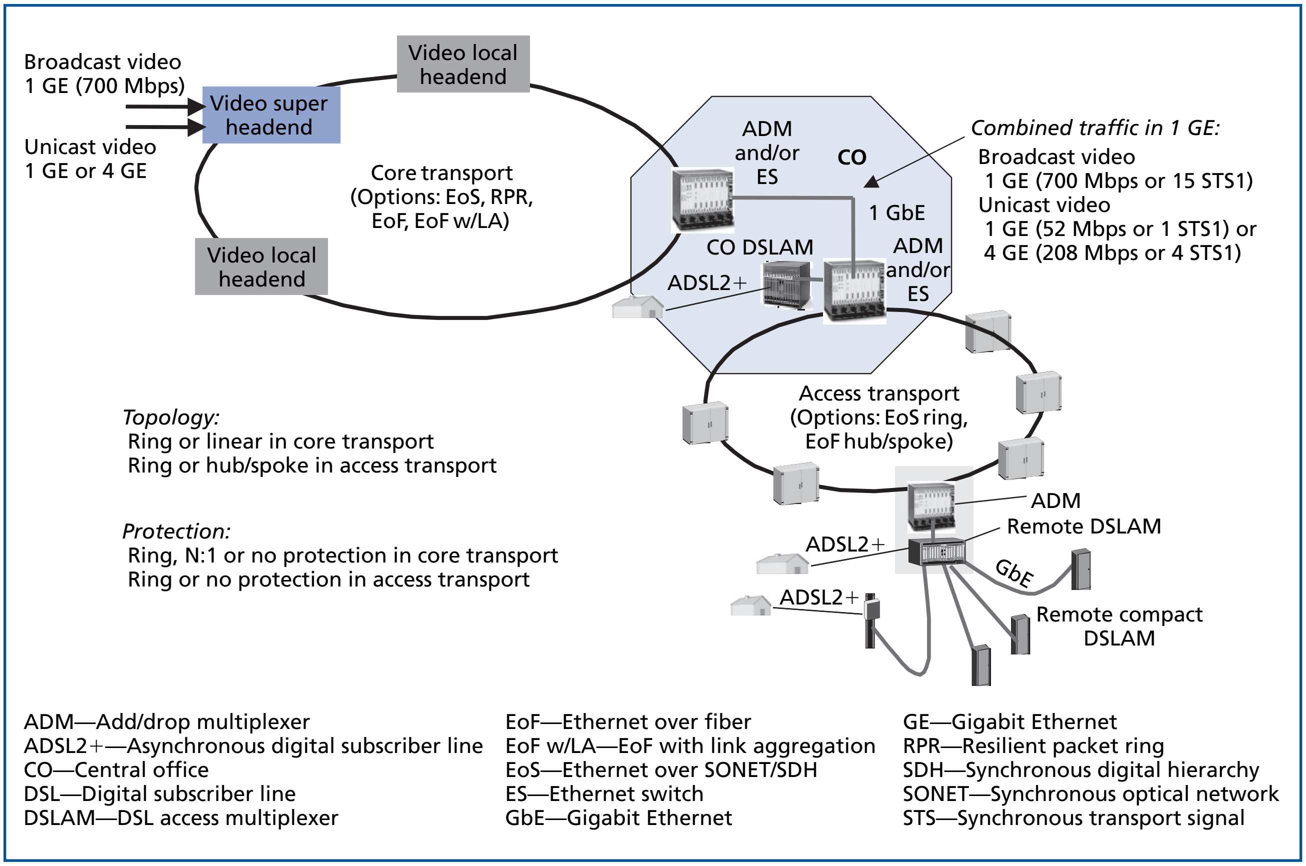

Figure 14.
Core and access network model.

the EoS options provide competitive solutions over EoF w/LA options and the cost savings exceed 20%. This is primarily because the SONET D&C mechanism is efficient to transport the broadcast traffic, and optimizes bandwidth usage while providing guaranteed SONET restoration (typically 50 ms). This result is also consistent with the transport network model and analysis results. (See Figure 6 with VSO drop = 0.7 Gbps).

Low VoD Solution. For this traffic mix, the savings generated by the EoS option with respect to EoF w/LA are diminished and drops below 5% for p = 2 are noted when compared to the broadcast-only solution. Since the traffic is still primarily broadcast, savings are a result of the D&C feature using bandwidth efficiently. The EoF solution without link aggregation can be up to 10% cheaper than EoS at p = 2 but it does not guarantee fast restoration against fiber cuts like the SONET solution; hence, EoF is not the ideal solution for the deployment of video traffic transport that requires fast restoration time guarantees. The bandwidth efficiency results are also consistent with the transport network model and analysis results shown earlier in Figure 12.

High VoD Solution. Here the EoS option in the case of p = 2 could be up to 18% higher in cost compared to EoF w/LA. This is because the benefits of D&C for the broadcast component of the video traffic are offset by the relatively higher cost of assigning SONET bandwidth (compared to EoF bandwidth) for unicast point-to-point bandwidth demands. The bandwidth efficiency results are also consistent with the transport network model and analysis results as shown in Figure 12.

So in general, EoS is efficient in the use of bandwidth but it is not cost competitive with p = 2 (at a 200% premium) for the high VoD traffic in this model.

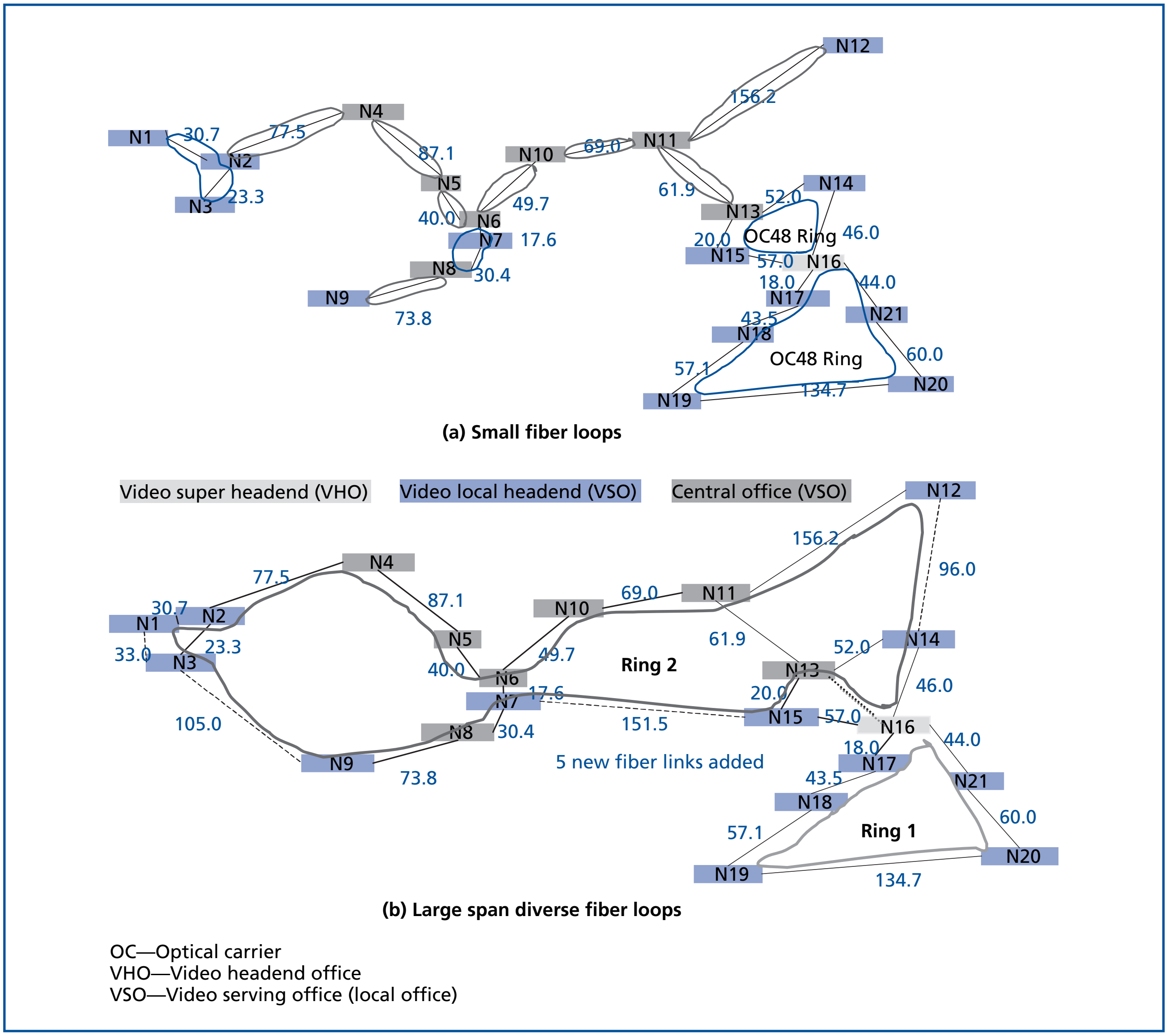

Figure 15.
Fiber topologies.

However for broadcast or low VoD scenarios, or for moderate EoS bandwidth cost (p = 1 to 1.5), EoS is a more cost-effective option with the added benefit of higher availability (50 ms restoration), proven operation, administration, management, and provisioning (OAM&P), while leveraging the existing infrastructure.

Core Network—Large Span Diverse Fiber Topology

Next, we consider the augmented fiber (five new fiber spans) topology that uses two large span diverse rings in the SONET solution. The results of the relative CapEx after optimization are shown in **Figure 17**.

Broadcast-Only Solution. For p = 1, the normalized height of the columns represents the equivalent optical transport bandwidth used for these options. Even for a 200% cost premium (p = 2), the EoS option provides a cost competitive solution over the EoF w/LA option and the cost savings exceed 40%. This is primarily because the SONET D&C mechanism is efficient to transport broadcast traffic, and optimizes bandwidth usage while providing the additional guaranteed SONET-based restoration (typically 50 ms). Also, the savings here are better than in a case where fiber topology consists of many small

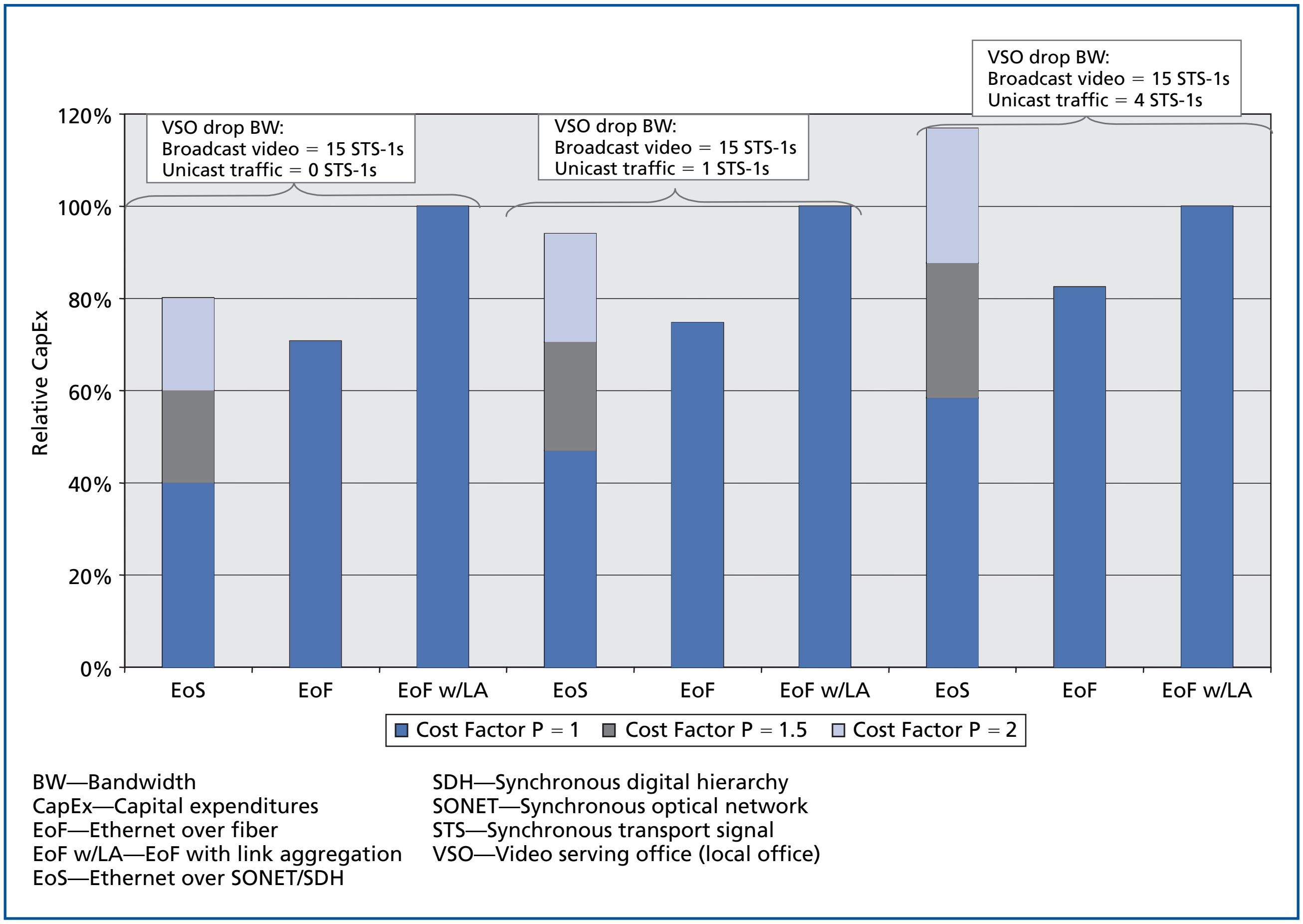

Figure 16.
Relative CapEx for small folded rings topology.

folded rings. This result is also consistent with the transport network model and analysis results as seen in Figure 6, where the VSO drop is equal to 0.7 Gbps.

Low VoD Solution. For this traffic mix, the EoS option's CapEx savings exceed 20% compared to EoF w/LA. Since the traffic is still primarily broadcast, savings are a result of the D&C mechanism using bandwidth efficiently. However, the EoF option without link aggregation can be up to 20% cheaper compared to EoS but does not guarantee fast restoration against fiber cuts like the SONET solution. Note that as the EoS ring size increases, VoD traffic for all the VSOs will have to be carried around the ring.

High VoD Solution. For cost factor p = 2, the EoS option is approximately 18% higher in cost compared to EoF w/LA. This is primarily because the cost increase due to the 200% premium in SONET STS-1 provisioning (compared to EoF w/LA) is more than the savings in cost that D&C provides.

It is worthwhile to note that the trend here again is similar to that observed for the optical transport model analysis and the conclusions for the small fiber loop topology case.

Overall, for the EoS option, the large fiber loop topology results in lower CapEx compared to the EoF w/LA option in the cases of broadcast and low VoD traffic. This is because the SONET D&C is very bandwidth efficient when all nodes being served are on the same ring compared to multiple ring hops. However with increased VoD, the cost increase from SONET offsets the benefit gained by D&C and large loop topologies. Besides, as EoS ring size increases, the VoD traffic for all the VSOs will have to be carried around the ring.

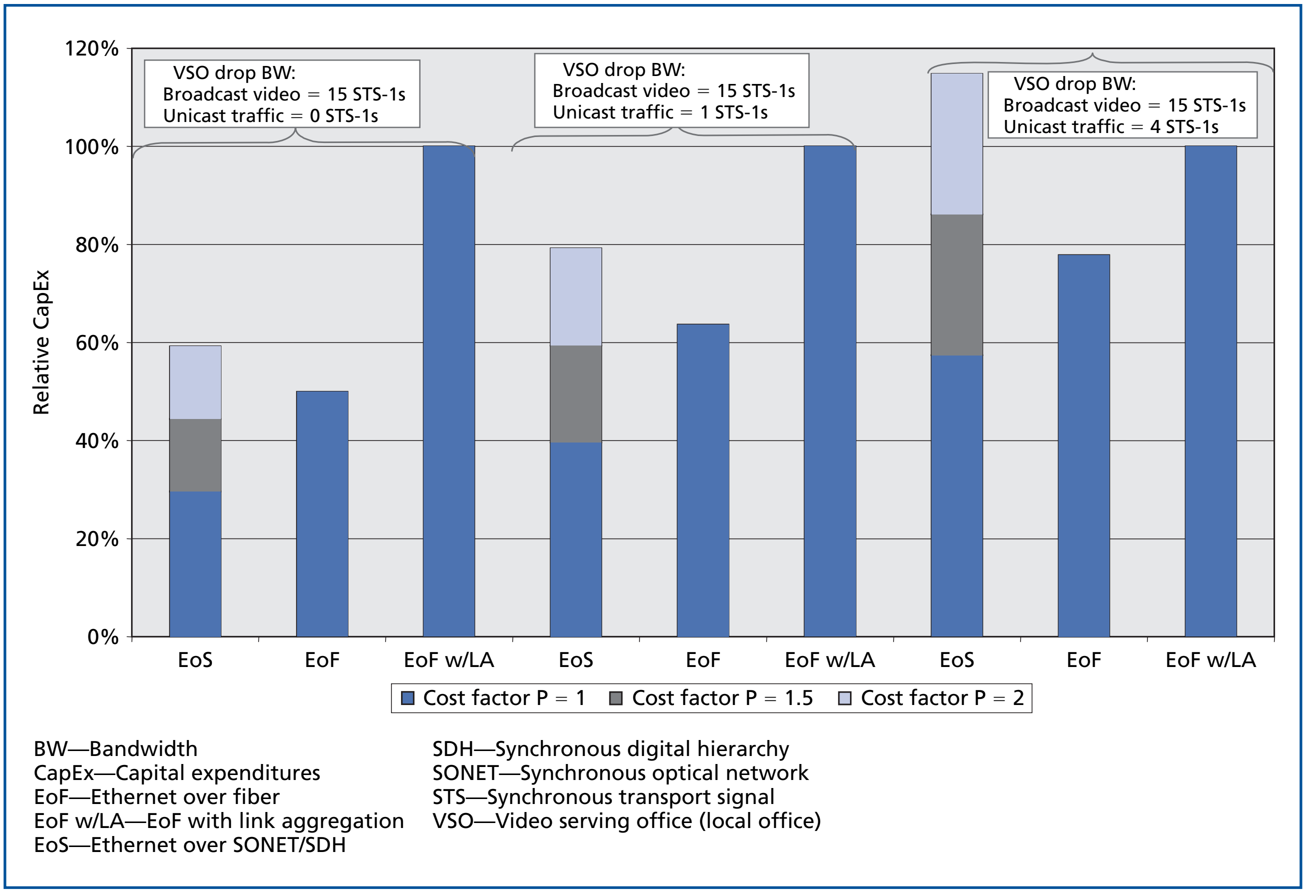

Figure 17.
Relative CapEx for large span diverse ring topology.

Access Network Case Study Results

The purpose of the access transport network is to distribute the video traffic (delivered from the VHO) via the core network to each of the local central offices (same as VSOs) to the outside plant DSLAM locations. A typical access network, modeled in Figure 14, serves OSP locations with large remote DSLAMs that subtend compact remote DSLAMs. In an EoS solution, an ADM is co-located with the remote DSLAM and carries video traffic on a SONET ring from the CO. The EoF solution consists of an Ethernet switch at the CO in a hub-and-spoke architecture to connect to the remote DSLAMs.

In this particular access network model, given the take-rates for ADSL2+ and the size of the DSLAMs, the average number of DSLAM locations per CO is six subtending an average of four DSLAMs. Since the cost of CapEx investment for the DSLAMs is the same for both EoS and EoF transport, this equipment cost component is not included in the analysis.

The model of the access network now is exactly the same as the single ring optical transport model used in the earlier analysis with the number of VSOs equal to six. Hence, we refer to those results and conclusions in that section, for a comparison of EoS versus EoF access transport network options.

Conclusion

We considered the optical transport technologies for IPTV video distribution in a service provider environment. We included Ethernet over SONET/SDH as well as Ethernet over fiber based optical transport technologies along with their variations that included drop and continue, multicast, link aggregation, and hubbed traffic. We developed a transport network model and analysis methodology for comparison of these optical transport technology options, and quantified the bandwidth and fiber efficiencies of the drop and continue and Ethernet multicast options for broadcast video traffic. In the case of mixed (broadcast video and unicast) traffic, we identified the zones where SONET/SDH and fiber-based Ethernet transport provide attractive network economics. The case study results confirm the trends identified in this transport model for the actual fiber topologies of the regional optical transport network. The transport model is applicable to the access network as well, where the focus is distributing video from the central office to the outside plant locations.

Overall, EoS solutions can provide a balance between network economics and reliability compared to EoF solutions, in the near term. Due to a large embedded base and good recovery mechanisms from fiber cut or node failures, EoS is an attractive solution for video transport in core and access IPTV distribution networks. Over time, as unicast video traffic increases, the network can evolve to meet mixed traffic needs. Given the zones of advantage identified here for the optical transport options, a network designer has to consider the traffic mix, fiber topology, and services reliability requirements in order to design a reliable and cost-optimized optical transport network solution that meets both immediate and longer term network needs.

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*Trademarks

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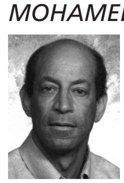

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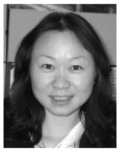

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