Hybrid/Fiber Coax (HFC) and Dense Wavelength Division Multiplexing (DWDM) Networks

Definition

The latest generation of optoelectronics products provides a major increase in the capacity of hybrid fiber/coax (HFC) networks, allowing the delivery of new interactive video, data, and voice services. This tutorial summarizes the capabilities of these products and discusses methods of successful implementation.

Overview

As cable and telecommunications operators strive to introduce new services, they must find new ways to increase their network capacities at a reasonable cost. An excellent solution to this dilemma is the implementation of optoelectronics in HFC systems. Optoelectronics is having a tremendous impact on the evolution of the HFC networks required for high-volume, interactive multimedia traffic. The introduction of this technology enables networks originally designed for video services to provide reliable bandwidth for all types of interactive video, data, and voice services.

Optoelectronic technology allows operators to drive fiber deep into the network more effectively, make better use of existing bandwidth, economically increase bandwidth, and target programming to specific areas. Most important, optoelectronics enable the efficient delivery of many revenue-generating interactive services, which can make operators more profitable and competitive. In addition, the larger telecom industry can cost-effectively overlay video on fiber in the loop (FITL) architectures, efficiently carry analog video on synchronous optical network (SONET) backbones, and solve the power challenge the dense wave division multiplexing (DWDM) deployments impose on optical amplifiers in the long-haul network.

Both the computer and telecommunications industries have shown a great deal of recent interest in HFC networks, as the pending AT&T–TCI transaction, Microsoft's investment in Comcast, and Paul Allen's purchase of both Marcus Cable and Charter Cable indicate. Some large, sophisticated players are betting on the long-term viability of HFC networks for broadband services.

This tutorial examines the effect optoelectronics is having on HFC networks and how this technology can be applied to deliver a variety of interactive services successfully.

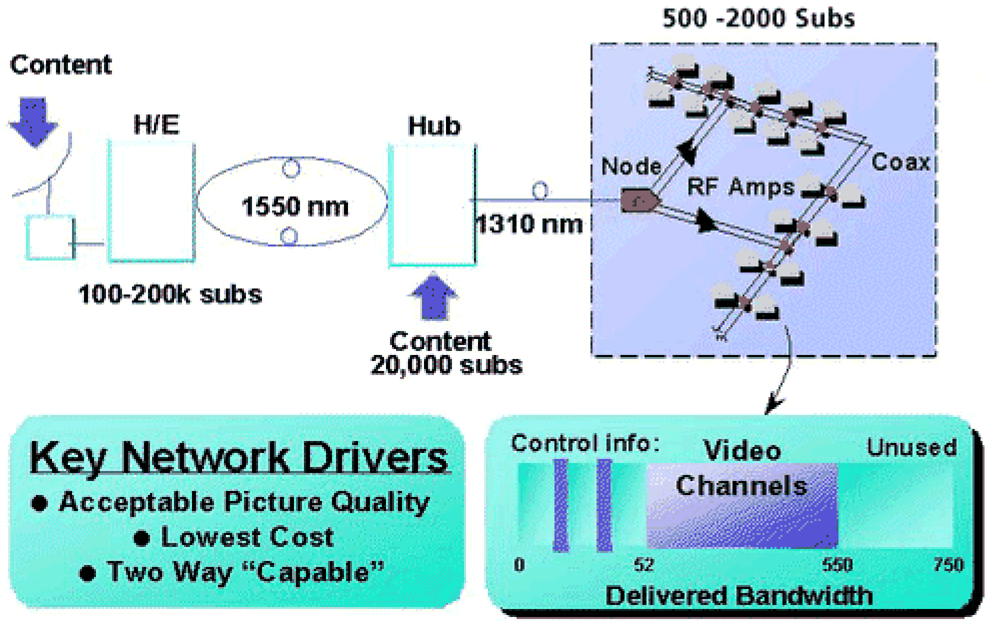
Topics

1. Effective Use of Fiber Deeper

It has become generally accepted that the closer to the customers the virtually unlimited bandwidth offered by fiber is deployed, the more service capability and flexibility it offers. The long-range prospect of 1,000 wavelengths per fiber promised by Lucent's new ALLWAVE fiber gives even more impetus to increase fiber deployment.

With the ever-deeper migration of fiber, the key architectural issue becomes how to use the last-mile media most effectively, whether coax or copper-based. Gigahertz-based coax pipes, with 1,000 times the bandwidth of copper, can effectively be used to offer a wide range of interactive video, data, and voice services. As an example of how these networks can evolve, let us look at a typical HFC network being developed today. Fiber optics has been utilized in cable TV networks since 1991. Initially, 1310-nm-based optical transmitters and fiber nodes were dropped into the middle of long cascades of radio frequency (RF) coax amplifiers, hence the term *hybrid fiber/coax*. *Figure 1* depicts this type of analog television broadcast-based network with upstream capabilities used for set-top controls and network management. The HFC transport network is typically limited to the use of 1550-nm analog transmitters to extend the reach of the cable plant. Usually, each optical node serves 500 to 2,000 homes. The key network drivers are low cost and good performance of the analog video signal in terms of noise and distortion. The user receives up to 78 channels of video and optional control of premium channels and pay-per-view via an analog set-top.

Figure 1. An Analog Television Broadcast-Based Network with Upstream Capabilities



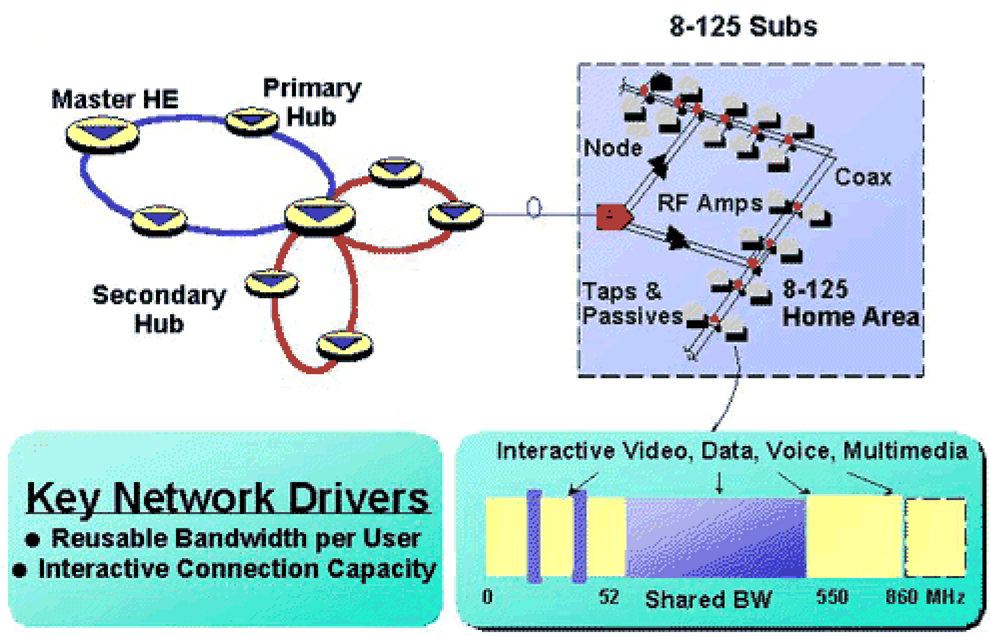
What if, however, there were no video signals in these networks? One of the key advantages of the HFC architecture is the ability to carry multiple types of information in multiple formats shared by a scalable number of users. If the video is eliminated and the pipes are used entirely for data through a spectrally efficient modulation scheme such as 256 QAM, which yields 7 bits per hertz, the result is a 5-gigabit pipe. Taking the coax up to a gigahertz would yield 7 gigabits of data capacity. As analog video usage declines and this bandwidth is reused for other purposes, an enormous potential for new services, in any medium or combination, becomes available. The flexibility to use bandwidth for different services in multiple formats is an essential strength of HFC networks.

The reason that much of the bandwidth today is utilized for analog video highlights a fundamental difference between HFC and copper-based networks. Almost 300 million televisions, many of which are cable-ready, are already in use in this country alone. In fact, more households in this country have televisions than telephones. HFC gives sufficient bandwidth to broadcast services to these appliances, yielding a low-cost video distribution. Limitations of copper bandwidth, notwithstanding significant advances in digital subscriber line (DSL) technology, force a switched approach, which, though technically feasible, results in an untenable in-home cost for interface devices, at least in terms of mass deployment. To expand the service set offered over HFC, certain network changes are needed, both in access and transport.

2. Increasing Reusable Bandwidth

As new services are added to the broadcast video suite, the first network goal is to increase the reusable bandwidth per user. This can be accomplished in two ways: by making the pipe bigger and, as the interactive services are shared, by decreasing the number of users on a given node (see *Figure 2*). Bigger pipes, in the form of 862-MHz systems, currently are being deployed in larger metropolitan areas. Fiber-deeper architectures are beginning to be deployed as well, taking node size down to 50 homes, which yields up to 10 times the interactive bandwidth per user.

Figure 2. Increasing Reusable Bandwidth



As the volume of interactive traffic grows, the transport network must be enhanced to provide flexible, efficient connections to servers. These servers may be located anywhere in the network, but they typically start out in a centralized manner at the primary head end, putting a significant strain on today's transport structures. A key consideration for network design is to be able, as much as possible, to match the equipment deployment expense with the expected revenue from the service.

Network evolution goals thus are twofold: an access goal of maximizing reusable bandwidth per user and a transport goal of efficient flexible connection to servers anywhere in the network.

Four key technologies are needed to address these goals:

1. High-power 1550-nm optics can be used both in the transport area to carry multiple quadrature amplitude modulation (QAM) bundles for interactive traffic and in the access area to lower the network costs to facilitate fiber-deeper architectures.

2. Digital transmission, using video-optimized SONET multiplexers, is critical to building high-speed multimedia backbones.

3. Wave division multiplexing (WDM) is used not only for increased bandwidth, but also for optical routing and reduction in access cost.

4. Passive optical technology becomes critical to both cost and performance as the amount of fiber in the network grows.

The first consideration for determining the optimal access architecture is the amount of necessary bandwidth, either broadcast and interactive or narrowcast. An HFC network has four dimensions involved with delivering interactive bandwidth: frequency, spatial multiplexing, spectral efficiency, and wavelength.

Frequency gives the ability both to decide the size of the pipe (750 MHz, 862 MHz, or 1 GHz) and to determine what type of signal a given subcarrier offers. Each frequency can be reused over time as the service set changes, providing a unique flexibility in comparison to other architectures. Spatial multiplexing determines how many fibers to run in the backbone and to each node and how to load them. Spectral efficiency allows migrating over time to modulation techniques such as 256 versus 64 QAM, which effectively increases bandwidth. Finally, multiple wavelengths, whether DWDM or 1310/1550 combinations, can be used within a given fiber to increase capacity.

3. Determining Node Size

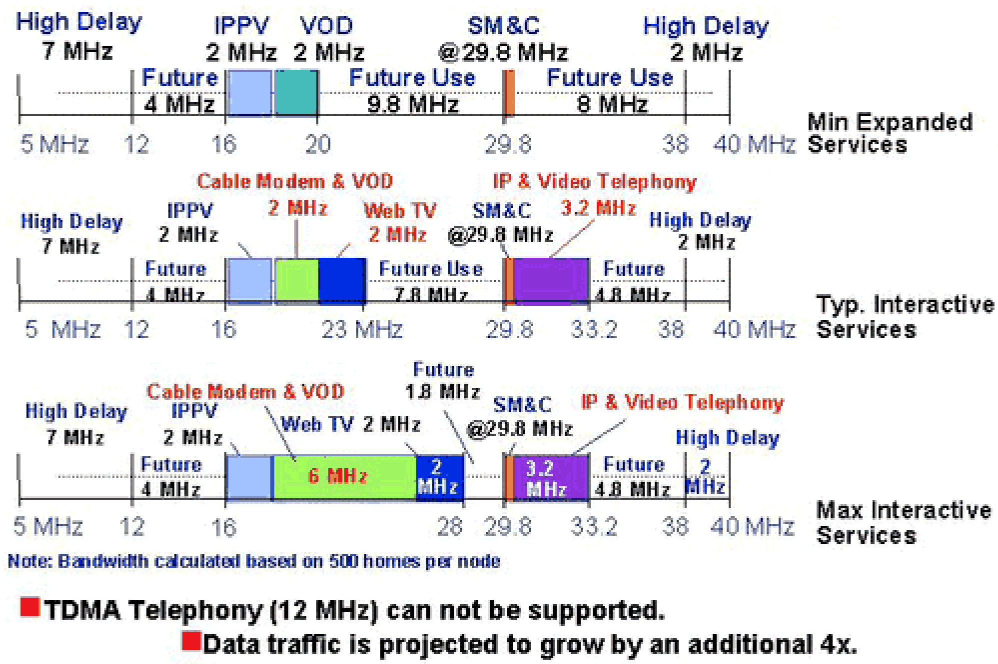
Figure 3 indicates the typical bandwidth range needed, both forward and reverse, for a number of video, data, advertising, telephony, and multimedia services, assuming a node size of 500 homes and reasonable penetration rates. This figure indicates that the 500-home node will not be sufficient in the long run, assuming analog broadcast cannot be eliminated for some years to come. The goal then is to find ways of economically driving the fiber deeper into the access network.

Figure 3. Determining Node Size

Service	Fwd Bandwidth Range(MHz)	Rev. Bandwidth Range (MHz)
Broadcast Analog	500-700	2
Broadcast Digital	18 - 24	2
NVOD	36 - 96	2
VOD	24 - 36	2
HDTV	12 - 66+	---
WEBTV	6	2
TV-Based Data Services	6	2
PC-Based Data Services	6	4
Worldgate	---	2
Targeted Advertising	12 - 36	TBD
Cable Telephony	12	12
IP Telephony	3 - 6	1 - 3
IP Videoconferencing	3 - 6	6 - 12
Multimedia	TBD	TBD
	638 - 1000MHz	35 - 44MHz

The ability of the reverse or upstream path of HFC networks to handle the full suite of interactive services is the subject of much concern. To address potential performance issues, both Fabry Perot and uncooled distributed feedback lasers (DFB) are being used in networks today, depending on the services being carried. Over 250,000 high-speed cable modems already are deployed in North America, giving large-scale credence to the two-way integrity of the HFC network. The deeper the fiber is deployed, the smaller the ingress problem becomes. *Figure 4* shows the loading of the reverse path, given 500 homes passed per node, for three different business models. Unless cable telephony is being deployed, this node size is reasonably sufficient from a traffic point of view. To address the performance dimension, however, as fiber is pushed deeper to handle the forward traffic, the RF cascade length is reduced in length, limiting ingress, improving reliability, and lowering power costs. If the fiber-deeper concept is extended to its logical limit, it leads to a very interesting point, which will be examined next.

Figure 4. The Loading of the Reverse Path



4. Using 1550-nm Transmitters

By using high-power 1550-nm transmission and taking the node size down to twelve homes, the HFC architecture merges quite nicely with a copper-based fiber in the loop (FITL) system to arrive at a powerful, full-service architecture. As *Figure 5* shows, an HFC–based video overlay can be added to an FITL network conveniently. The 1550-nm externally modulated transmitter and a high-power optical amplifier are located at the central office (CO), distributing the broadband signal to as many as 16 remote terminals (RTs) or 32,000 subscribers. Out at the remote terminal, another optical amplifier boosts the signal, feeding very low-power video receivers. This receiver can stand alone, be contained in a tap housing, or take the form of a plug-in card in the optical network unit (ONU). Because the video operates at 1550 nm and the voice/data at 1310 nm, a single fiber can be used. With shared housings, power, fiber, and installation labor, the video overlay can be economically added to the FITL system. Crucial to making this architecture work, both technically and commercially, are high-power 1550 optics and low-cost, low-power video receivers.

Figure 5. HFC–Based Video Overlay

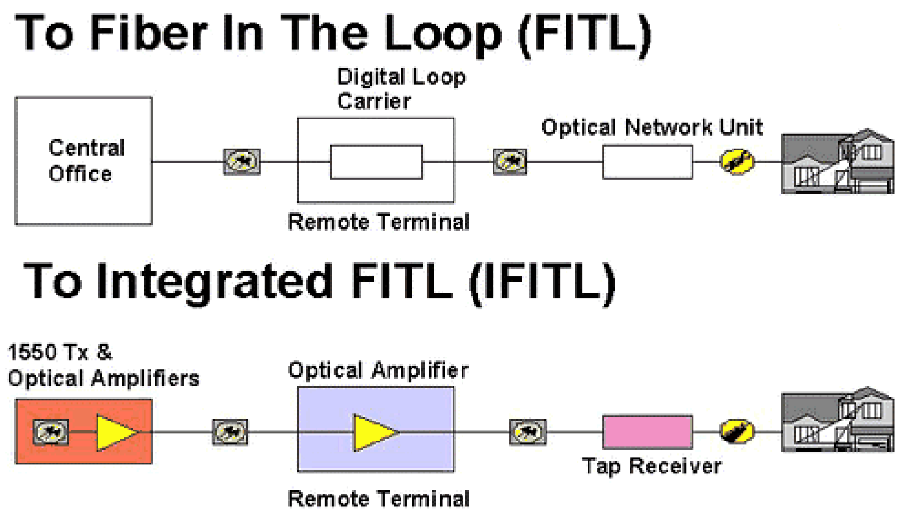
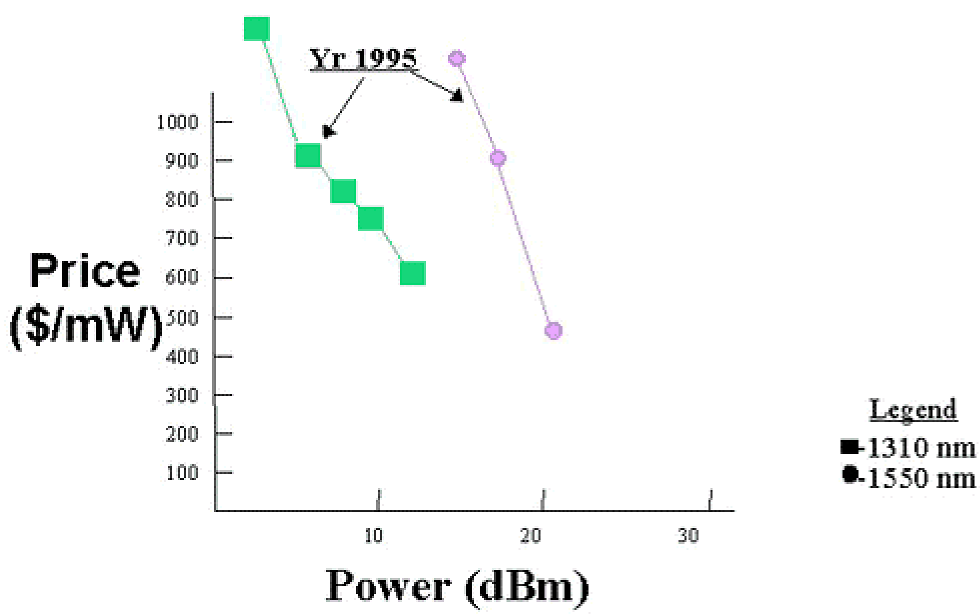


Figure 6 shows how the relative costs of 1310-nm and 1550-nm technology have progressed over time. This plot shows the cost of light measured in dollars per milliwatt versus the total output power in 1995, when HFC networks began to deploy 1550. These costs may seem high to operators with baseband digital networks, but these transmitters can carry up to 110 6-MHz analog subcarriers with carrier-to-noise ratios (CNRs) in the 50s and second- and third-order distortions in the high 60s. As shown, 1550-nm technology was quite expensive and hence was limited to those applications requiring high output power, typically in the transport network.

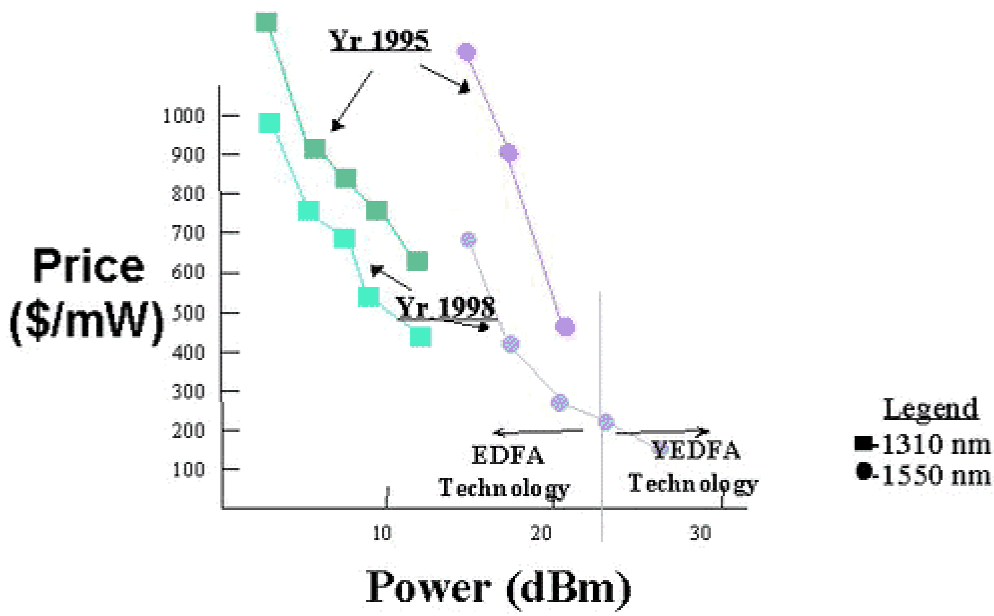
Figure 6. The Costs of 1310 and 1550 Technology



5. Technology Offers Lower Cost, Higher Value

Today, both technologies, as expected, have dropped in price, but the 1550 has improved significantly in relative value. The right side of the curve in *Figure 7* represents an extension in capability over the typical 980-nm pumped erbium-doped amplifiers, using a codoped ytterbium-erbium technology. This technology increases the power output to 25 dBm, while significantly lowering the per-milliwatt cost.

Figure 7. Extension in Capability over the Typical 980-nm Pumped Erbium-Doped Amplifiers



Self-healing dual-pumped systems using this technology can be constructed to deliver the common or broadcast information to many nodes in the access network. Because the output is being split many ways to feed a large number of fiber nodes, the 17-dBm stimulated billouin scattering (SBS) suppression limitation is not relevant.

To further improve the ability of 1550 optics to facilitate fiber- deeper penetration, a next-generation amplifier using cladding pump technology is currently under development. This technology is expected to increase power and reduce cost significantly, yielding a dollars-per-milliwatt cost at 30 dBm or 1 watt of somewhat less than $50, a major improvement in pure cost of light over today's 1310 technology.

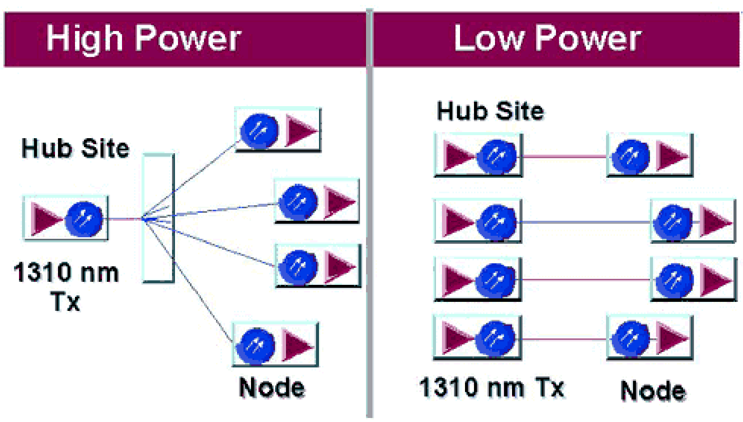
This technology shows great promise for addressing the optical amplifier spacing issues being created by the high-channel DWDM systems currently deployed in the long-haul baseband networks today. Using these advanced 1550 optical technologies significantly lowers the cost of delivering broadcast services, thereby enabling fiber-deeper access networks.

6. Using 1310 nm for Narrowcasting

At the hub site, which typically serves up to 20,000 homes, broadcast video signals are received over 1550-nm transmission, converted to RF, and then released at 1310 nm. The 1310 transmitters contain two RF inputs, a common, or broadcast port, and a unique or narrowcast port. In this manner, local video, advertising, and any interactive services, such as data and voice, can be inserted.

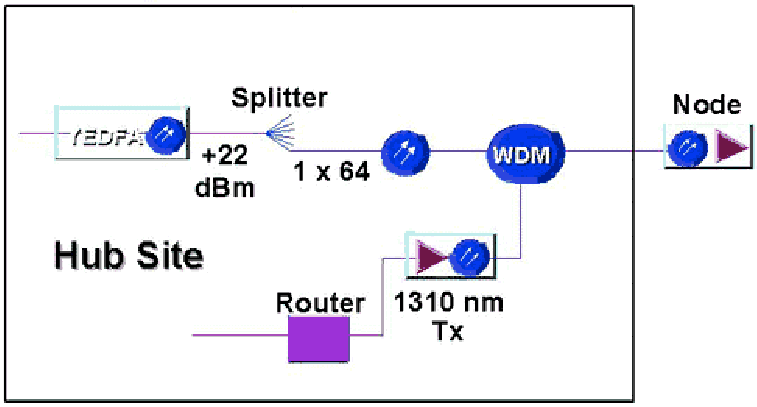
Power ranges such as 1012 dBm, as shown on the left in *Figure 8*, target about 2,000 homes, assuming 500 home nodes. On the right, lower-power 4-dBm or 6-dBm transmitters take the narrowcasting down to 500 homes, with a 20-percent to 30-percent cost premium on the transmitters. Each transmitter carries both broadcast and narrowcast or interactive information.

Figure 8. Power Ranges



High-power 1550 technology is used to carry only the broadcast information. As indicated in *Figure 9*, a 22-dBm ytterbium erbium-doped fiber amplifier (YEDFA) can hit 64 nodes or 32,000 subscribers, yielding a significantly lower broadcast cost. For the narrowcast information, a low-cost 1310 transmitter, optimized for carrying only QAM channels, is used. The two wavelengths are then optically combined for delivery to the node.

Figure 9. YEDFA Technology



Aside from lowering the cost of deployment, this architecture logically separates the two types of information, allowing each to evolve independently. The narrowcast path now also becomes optional, only being deployed when and if required. This architecture, although just beginning to be deployed by the major multiple service operators (MSOs), is almost universally used by new network operators in the United States, as well as new builds in countries such as Spain, Italy, and China. This combination of low broadcast cost and zero narrowcast cost is what drives the feasibility of the integrated FITL network shown earlier.

7. Raising Bandwidth While Lowering Costs

Figure 10 indicates how those economics play out in a typical cable network. For the base case, shown for three samples, the node size is roughly 900 homes, with four to five active devices per mile. The middle of the diagram shows deployment of a near-passive architecture, meaning one RF amplifier. This architecture yields six to eight times more available interactive bandwidth, at a very small cost in increased investment. At the same time, the active count is cut in half, meaning higher reliability with lower power and maintenance costs. In a passive architecture, two to three times more bandwidth is obtained for a reasonable cost premium. At this point, a fully interactive system goes above the median in the cost curve.

Figure 10. Raising Bandwidth While Lowering Costs

		Hub A	Hub B	Hub C
Base Case	Homes Passed	837	962	948
	Cost/HP	$187	$134	$183
	Actives/Mile	4.3	5.3	4.5
Near Passive (100-150 HP per Node)	Cost/HP	$225	$143	$204
	% Increase	21%	7%	11%
	Actives/Mile	2.1	2.4	2.6
Passive (50 HP/Node)	Cost	$264	$200	$278
	% Increase	41%	49%	52%
	Actives/Mile	1.6	2.1	2.1

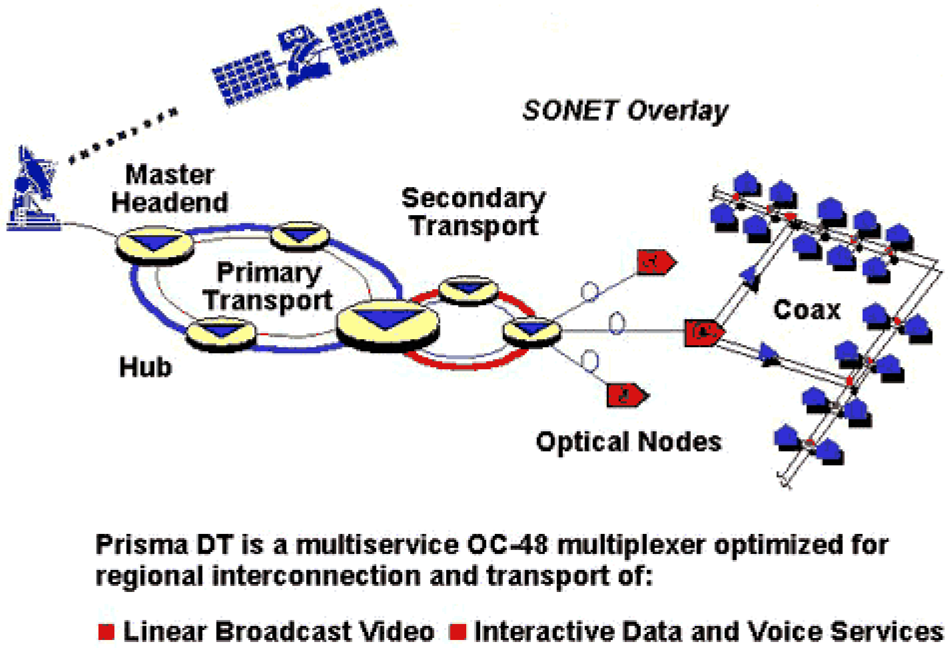
Today's deployable technology thus allows construction of fiber-deep, flexible broadband access networks capable of handling interactive video, data, and voice services. Again, the ultimate goal is to be able to connect to servers anywhere in the network, efficiently and flexibly. Achieving this goal requires a multimedia backbone transport network capable of carrying voice, data, and the various forms of video traffic.

8. SONET Multiplexer Enables Voice, Data, and Video

For voice and data, the obvious choice, at least in the near term, is SONET technology. However, SONET traditionally does not do a good job at video transport. Video coders/decoders (CODECs), which compress one or more video signals to digital service, level 3 (DS–3) rates, are expensive and yield relatively poor performance specs. Furthermore, being an outboard device, the SONET network management sees just the DS–3 circuits; it cannot monitor the video performance. Consequently, many broadband operators install two networks: a SONET system for voice and data, and an analog or proprietary digital system for video. From both an architectural and operational perspective, this is not an optimal solution.

To address this essential transport issue, a video-optimized OC–48 SONET multiplexer has been developed (see *Figure 11*). Video-optimized input/output (I/O) devices take analog video channels in various formats and map them directly in STS–3 slots in the SONET payload. This lets the operator carry analog video in an uncompressed, high-performance manner while maintaining all the benefits of SONET for duplex services such as voice and data. To encode the video, the operator can use 10-bit samples and map both baseband and IF video signals, scrambled or clear channel. This technology allows building a true multimedia backbone in which a single pair of fibers carries a full range of video, voice, and data services. Eliminating service-specific architectures creates the flexibility needed to cope with the uncertainty inherent in new service rollouts.

Figure 11. A Video-Optimized OC–48 SONET Multiplexer



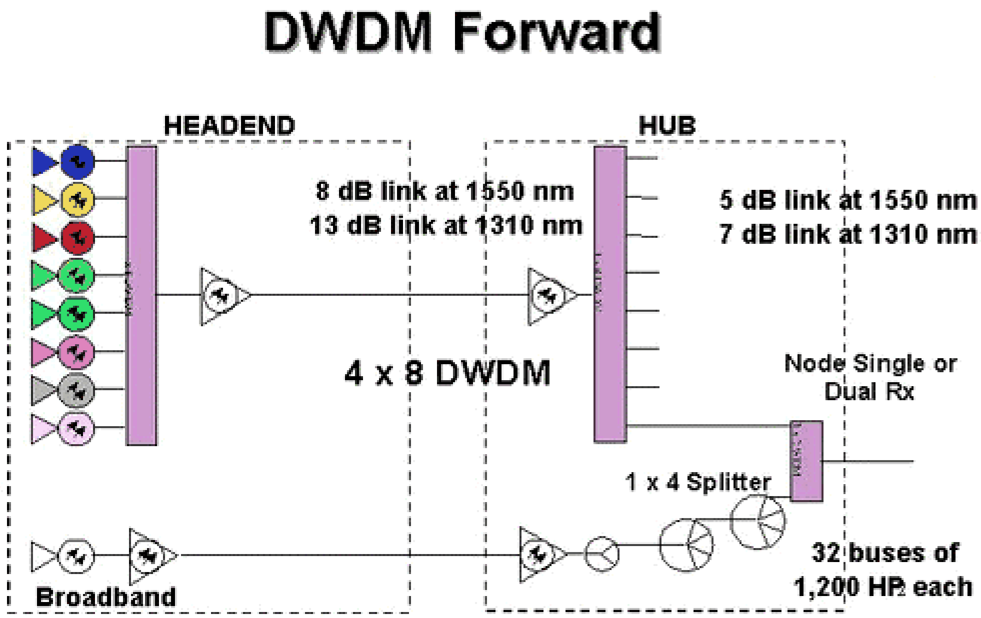
One drawback of carrying uncompressed analog video signals digitally is the large amount of bandwidth needed—16 analog channels occupy an entire OC–48. To address this, DWDM is used to combine up to eight systems on a single fiber. This combination enables the transport of 80 analog video channels and several hundred digital video streams, while maintaining 5 gigabits for voice and data services.

9. Using the Analog Network for Interactive Traffic

The existing analog transport network can also play a role in carrying interactive traffic. For video-on-demand, for example, a typical hub may need to receive several hundred digital streams to meet the traffic requirements for 20-percent or 30-percent penetration.

To deliver this amount of bandwidth, up to eight 1550 transmitters, each carrying 200 MHz of QAM loading, can be multiplexed onto a single fiber and combined at the hub with the broadcast signal (see *Figure 12*). Depending on architectures chosen, either externally modulated or directly modulated transmitters may be used. This technology is also being used in the upstream direction to carry reverse path signals from hubs to head ends.

Figure 12. Using the Analog Network for Interactive Traffic



In the longer term, systems will need to carry, over the same fiber, not only multiple wavelengths of baseband digital, but also multiple QAM channels and an analog tier as well. In this way, backbone metropolitan-area networks (MANs) can be constructed to meet the transport goal of efficient connectivity of multimedia services in multiple formats, avoiding unnecessary conversion and processing costs whenever possible.

10. Conclusion

Optical technology enables providers to achieve the goal of building powerful multimedia networks capable of handling high-volume interactive services cost effectively. High-power 1550 technology, video-optimized SONET, and, most important, wave division multiplexing are being used in all parts of the HFC networks to make these goals a reality.

In addition, the smaller broadband world can offer the larger telecom industry the ability to overlay video on FITL architectures cost effectively, to carry analog video on SONET backbones efficiently, and to solve the power challenge imposed on optical amplifiers by the DWDM deployments in the long-haul network. These architectures are only the beginning of a long and exciting journey toward an all-optical network.

Self-Test

1. A gigahertz-based coax line is capable of delivering how many times more bandwidth than copper?

    a. 2

    b. 50

    c. 1,000

    d. 2,000

2. As fiber is driven deeper into networks, node size can be reduced to fifty homes, resulting in how many times more bandwidth per user?

    a. 10

    b. 3

    c. 20

    d. 5

3. To overcome the problem of requiring a large amount of bandwidth for uncompressed analog video, operators should _______.

    a. install fiber deeper

    b. use dense wave division multiplexing

    c. use 1550-nm technology

    d. increase the number of nodes

4. As more services are added to broadcast video, the first network goal is to ________.

    a. install more fiber

    b. build two networks, one for video and one for voice and data

    c. increase the reusable bandwidth per user

    d. install more nodes

5. What determines how many fibers a multimedia backbone can run?

    a. wavelength

    b. spectral efficiency

    c. frequency

    d. spatial multiplexing

6. How many high-speed cable modems have been deployed in North America?

    a. 1 million

    b. 2 million

    c. 250,000

    d. 100,000

7. HFC architecture can be combined with a copper-based FITL system by reducing the node size to twelve homes and using _________.

    a. 1550-nm transmission

    b. 1310-nm technology

    c. higher frequency

    d. YEDFA technology

8. 1550-nm technology has experienced a significant increase in value since it was deployed in ________.

    a. 1996

    b. 1992

    c. 1991

    d. 1995

9. In 1310-nm transmitters, local video, advertising, and interactive services can be delivered through ________.

    a. the broadcast port

    b. the narrowcast port

c. either port

d. none of the above

10. Traditional DWDM is capable of multiplexing how many 1550-nm transmitters onto a single fiber?

   a. 2

   b. 12

   c. 8

   d. 4

Correct Answers

1. A gigahertz-based coax line is capable of delivering how many times more bandwidth than copper?

   a. 2

   b. 50

   c. 1,000

   d. 2,000

   See Topic 1.

2. As fiber is driven deeper into networks, node size can be reduced to fifty homes, resulting in how many times more bandwidth per user?

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   b. 3

   c. 20

   d. 5

   See Topic 2.

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See Topic 4.

7. HFC architecture can be combined with a copper-based FITL system by reducing the node size to twelve homes and using _________.

a. 1550-nm transmission

b. 1310-nm technology

c. higher frequency

d. YEDFA technology

See Topic 4.

8. 1550-nm technology has experienced a significant increase in value since it was deployed in ________.

   a. 1996

   b. 1992

   c. 1991

   d. 1995

   See Topic 4.

9. In 1310-nm transmitters, local video, advertising, and interactive services can be delivered through ________.

   a. the broadcast port

   b. the narrowcast port

   c. either port

   d. none of the above

   See Topic 6.

10. Traditional DWDM is capable of multiplexing how many 1550-nm transmitters onto a single fiber?

    a. 2

    b. 12

    c. 8

    d. 4

    See Topic 8.

Glossary

CNR
carrier-to-noise ratio

DFB
distributed feedback laser; a laser used in fiber-optic systems to transmit and receive signals between distributed nodes and centralized nodes

DSL
digital subscriber line; a copper line used to send digital signals between a central office and a subscriber's modem

DWDM
dense wave division multiplexing; a high-speed version of WDM

FITL
fiber in the loop; fiber-optic lines placed in the pair of wires that run from the central office to the system at the customer location

HFC
hybrid fiber/coax; a network featuring optical fiber from a central office to a neighborhood and standard coax cable to individual homes

IF
intermediate frequency

MSO
multiple service operator; a company that operates more than one cable system

ONU
optical network unit

QAM
quadrature amplitude modulation; a sophisticated modulation technique, using variations in signal amplitude, which allows data-encoded symbols to be represented as any of 16 different states; QAM modems allow dial-up data rates of up to 9600 bits per second

RF
radio frequency; electromagnetic waves operating between 10 kHz and 3 MHz propagated without wire or cable in free space

RT
remote terminal; a system in which the local loop terminates at intermediate points closer to the service user to improve service reliability

SBS
stimulated billouin scattering; a phenomenon where the strong electric field from an optical wave in a fiber interacts with high-frequency sound waves in the glass; the result of this interaction is a scattering of the optical wave in a direction reverse to the propagating optical wave

SONET
synchronous optical network; a family of fiber-optic transmission rates created to provide the flexibility needed to transport many digital signals with different capacities and to provide a design standard for manufacturers

WDM
wave division multiplexing; a way of increasing the capacity of an optical fiber by simultaneously operating at more than one wavelength

YEDFA
ytterbium-erbium doped fiber amplifier; it operates at 1550 nm and provides high output for large distribution deployments