Options for High-Efficiency HFC Return Architectures

Eric Schweitzer, PhD
Harmonic Inc.

Abstract

The increasing deployment of Internet access, video-on-demand and other two-way services requires operators to use the most efficient means possible to maximize the limited bandwidth available in most HFC systems. A network is only as strong as its weakest link, which makes the return-path portion of a system critical when preparing for the delivery of two-way services.

The issue of return bandwidth becomes even more crucial in networks with minimal fiber counts. Because the return bandwidth is limited, it is inefficient to dedicate a single fiber to each return. Architectures which address these issues can make use of technologies such as Wave Division Multiplexing (WDM), block up conversion (frequency stacking), and digital transmission.

INTRODUCTION

Providing internet access, video-on-demand, and other two-way services presents a great opportunity as well as significant challenges to system operators. Perhaps the greatest challenge is in the return path.

Historically, the return path of a cable system has not been heavily used. Therefore, the bandwidth available is limited. Also, ingress noise is a significant problem in the frequency band of the return path. Finally, because until recently the return was not heavily used, there is limited experience with the return path in the industry.

The bandwidth limitations and ingress problems can be addressed by segmentation. Limiting the number of homes on each segment of the return system increases the available bandwidth per home and limits the amount of ingress the return system must handle.

The fiber portion of a typical Hybrid Fiber/Coaxial (HFC) cable network is in a star topology — there is a direct connection with multiple fiber from either the head end or a hub to each optical node. The coaxial plant following the optical node is a tree and branch topology. It is difficult, if not impossible, to segment a tree and branch network, while it is relatively easy to segment a star network.

Therefore, the optical node is the deepest point in the network at which segmentation can be achieved relatively easily. Furthermore, nodes with multiple ports can be segmented by isolating the ports. This allows placing unique information on each port, segmenting the network even further.

This segmentation creates a network with many dedicated return links. Finding an efficient and cost-effective architecture to transmit the information on the multitude of return links presents a challenge. There are several technologies which can be applied to create many possible network architectures. This paper will explore four technologies as they are used to create ten network architectures.

TECHNOLOGIES

Multiple Fibers

The simplest technology for transmitting multiple returns is to dedicate a separate return transmitter, return receiver, and fiber for each. As the demands on the performance of the link are modest, low-cost transmitters using Fabry-Perot or uncooled DFB lasers can be used.

However, dedicating a fiber to each return path does not use fibers efficiently. Each fiber is being used to transmit only a small fraction of its total bandwidth capacity. This is not a problem if extra fibers are available.

Block Up Conversion

Each return link uses only a modest amount of bandwidth. One way to use fibers more efficiently is to block up convert the return path to use bandwidth in the higher frequency range. Multiple blocks can be stacked together and transmitted on a single fiber using a single transmitter and receiver.

This block up conversion must be done carefully. It is very easy to introduce unacceptably high levels of phase noise and group delay. Allowing sufficiently large guard bands between blocks makes the design of the required filters much less complex. Therefore, these transmitters must have a bandwidth extending to at least 870 MHz to allow a sufficient number of blocks on a single fiber.

A reasonable scenario is ten return blocks on a fiber link using the band from 45 to 870 MHz. This heavy loading of the optical link requires that higher-performance and extended bandwidth transmitters and receivers be used. These have significantly higher cost than the transmitters and receivers required to support only a single return block.

It is also difficult to design a block up converter with acceptable dynamic range and frequency stability. This analysis assumes that block up converters with acceptable performance will be available for a cost similar to block up converters used for cellular phone applications.

Wavelength Division Multiplexing

By using transmitters with defined wavelengths and the appropriate filters, a single fiber can transmit several wavelengths each carrying different information. The maximum number of independent wavelengths depends upon how well the wavelength of each source can be controlled and on the filters used to combine and separate the light.

The simplest form of Wavelength Division Multiplexing (WDM) is to use a single fiber to transmit two wavelengths — one in the window near 1310 nm and one in the window near 1550 nm. This form of WDM can be called Coarse Wavelength Division Multiplexing or CWDM.

CWDM does not require accurate control of the wavelength of the laser within the transmitter. Therefore, transmitters used for CWDM can use low-cost Fabry-Perot or uncooled DFB lasers. Also, couplers to combine and separate these two wavelengths are readily available at modest cost.

The next level of WDM would be to use several wavelengths near 1550 nm together with 1310 nm. Uncooled DFB lasers with three different wavelengths near 1550 nm are commercially available. I will call this technology Medium Wavelength Division Multiplexing (MWDM). These uncooled

DFB lasers for MDWM are slightly more costly than similar lasers for CWDM.

The uncooled DFB lasers used for MWDM will vary by up to 15 nm over the operating temperature range of a node. Therefore, the wavelengths used must be separated by at least 15 nm. Couplers to combine and separate these wavelengths are more difficult to build, but readily available at modest cost.

The finest level of WDM involves using multiple sources near 1550 nm on a single fiber, each with accurately controlled wavelengths. This is frequently designated Dense Wavelength Division Multiplexing or DWDM. The International Telecommunications Union (ITU) has defined a standard set of DWDM wavelengths for communications applications.

Laser sources on the ITU wavelength grid are readily available. Couplers to combine and separate these wavelengths are also readily available. However, to accurately control the wavelength of the source and response of the filters in the couplers is complex. These devices are fairly expensive today, although costs are decreasing rapidly.

Current technology can achieve acceptable analog[1] performance with eight wavelengths per fiber. This is the assumption used in this analysis. It is clear that this will be increased to 16 and 32 wavelengths in the future, making this option more attractive.

Digital

The most basic digital return is to digitize the analog waveform. Achieving acceptable dynamic range requires an eight or 10 bit analog to digital converter and a sampling rate near 100 MHz. Therefore, a 1.8 G bit per second digital link can transmit two independent returns.

Digital transmission does not require high performance. Therefore, low-cost transmitters can be used over long distances. In addition, digital DWDM lasers are readily available, allowing these two technologies to be combined.

SINGLE-LINK NETWORK ARCHITECTURES

Networks in which there is a single optical link do not require cascaded optical links to transmit information from the node back to the location at which it is processed. There are two common network architectures for which this is true.

In one architecture there is a direct fiber connection from each node to the head end. In the other architecture the hub contains most, not all, of the equipment used to support the dedicated services. An example of the latter architecture in a network supporting cable modem communications would have the Cable Modem Termination System (CMTS) and connection to the internet in the hub.

[1] In this context, analog includes schemes for transmitting digital information on analog carriers. Examples of this are Frequency Shift Keying (FSK), Quadurature Phase Shift Keying (QPSK), and Quadurature Amplitude Modulation (QAM).

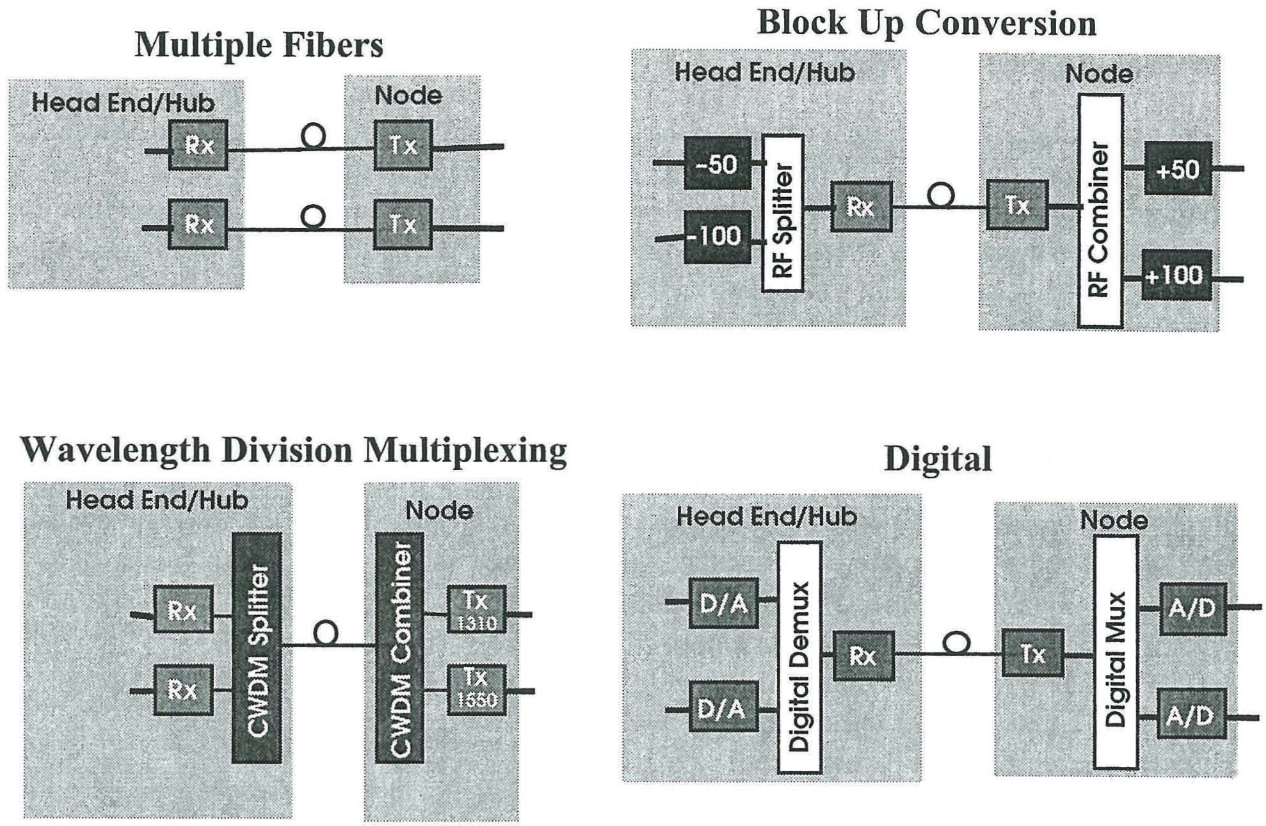


Figure 1 — Block diagrams of four architectures in which there is a direct connection from the node to the site at which the dedicated information is processed.

	Relative Cost		
Architecture/Technology	**One Return per Node**	**Two Returns per Node**	**Four Returns per Node**
Multiple Fibers	1.00	2.00	4.00
Block Up Conversion		8.82	13.77
Wavelength Division Multiplexing		3.07	5.14
Digital		9.56	19.12

Table 1 — Comparison of the cost of the four architectures shown in **Figure 1**. Costs for one, two and four separate returns per node are shown. A single return is a trivial case using only a single fiber. Using any of the more complex technologies has no benefit and is, therefore, not shown. The costs are estimates and include only the equipment. The cost of fiber, patch panels, etc. is not included.

	Fibers Needed		
Architecture/Technology	**One Return per Node**	**Two Returns per Node**	**Four Returns per Node**
Multiple Fibers	1	2	4
Block Up Conversion		1	1
Wavelength Division Multiplexing		1	1
Digital		1	2

Table 2 — Comparison of the fiber requirements of the four architectures shown in **Figure 1**.

There are many feasible network architectures which use the technologies mentioned previously. Four of these will be addressed as being typical. Block diagrams of these four architectures are shown in **Figure 1**. To save space, the figure shows only the scenario with two returns per node. It is straight forward to extrapolate these block diagrams to a single return and four returns.

A table comparing the approximate costs of the four architectures is shown in **Table 1** and the fiber requirements of the four are shown in **Table 2**. The costs are estimates and include only the equipment — transmitters, receivers, bock converters, couplers, platforms, etc. The cost of fiber, patch panels, etc. is not included.

The costs and fiber requirements are tabulated for a single return from each node, two returns from each node, and four returns from each node. This allows comparisons for future scaling.

A single return from each node is an elementary scenario: Only a single fiber is required and applying any of the technologies discussed adds only cost and no functionality. It only makes sense to consider a single link with a return uncooled DFB laser transmitter and a return receiver. This is used as the baseline for normalizing the costs.

Multiple Fibers

Using multiple fibers for each return from each node can be done easily today by using a node designed for this. The costs in **Table 1** are based on using uncooled DFB lasers. If the poorer performance of Fabry-Perot lasers can be tolerated, the costs would be lower.

Block Up Conversion

Block up conversion requires placing the up converters in the node and corresponding down converters at the receiving site. The costs associated with the increased performance demands on the optical equipment are included in the analysis.

Wave Division Multiplexing

CWDM can be used for two returns from each node while MWDM can be used for four returns from each node. Again, the costs are based on using uncooled DFB lasers which will have acceptable performance for this application. If the lower performance of Fabry-Perot lasers can be tolerated, the costs would be lower.

Digital

Using a digital return from the node enables lower-cost optical components optimized for digital transmission to be used. This is offset by the extra cost of the Analog to Digital converters (A/D) digital multiplexers required. Also, due to the high data rate, digital is limited to two return blocks per wavelength.

DUAL-LINK NETWORK ARCHITECTURES

The most commonly-used network architecture is one where there are several hubs served from the head end with multiple nodes served from each hub. This architecture requires two cascaded optical links — one from the node to the hub and another from the hub to the head end.

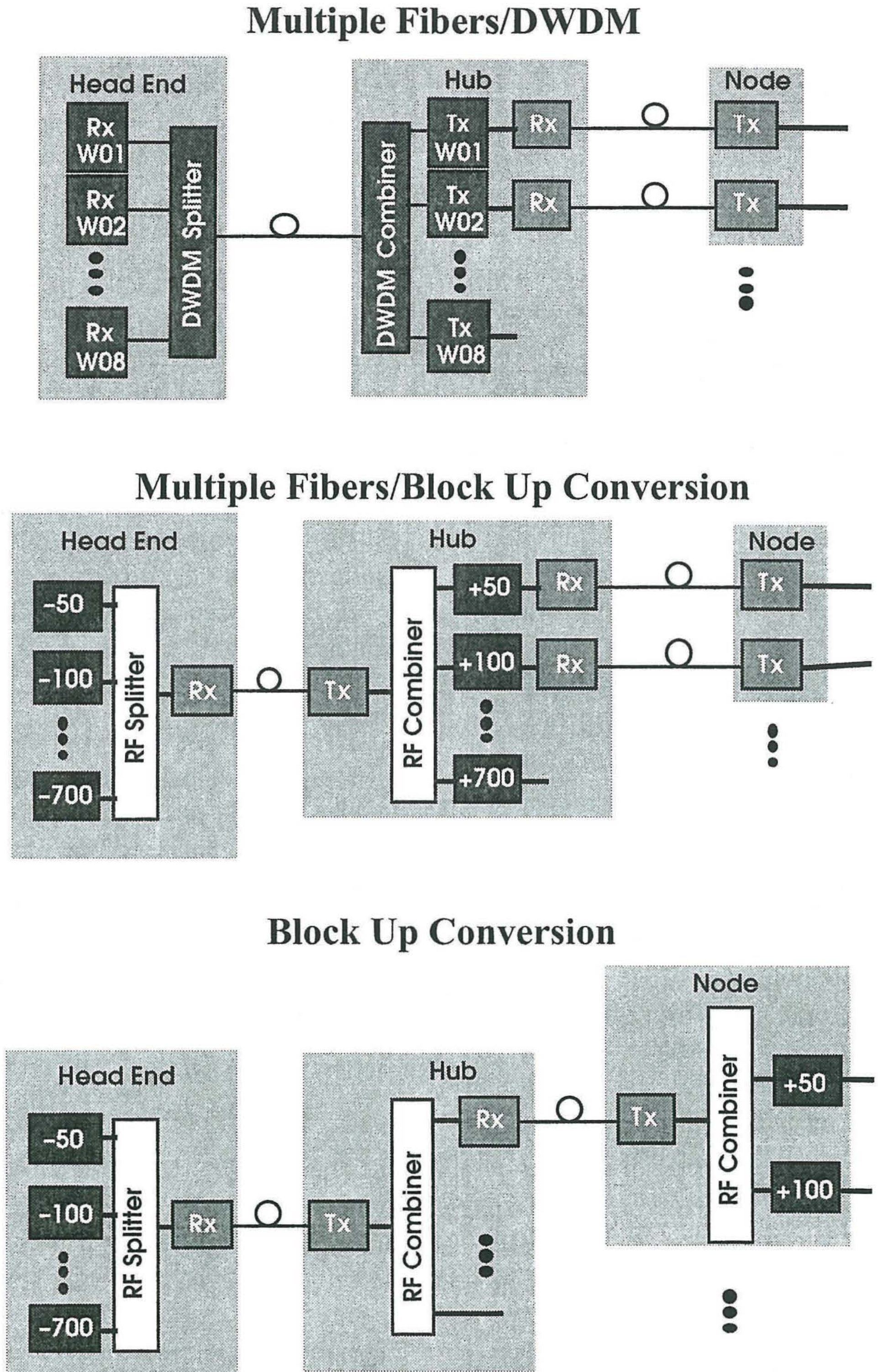
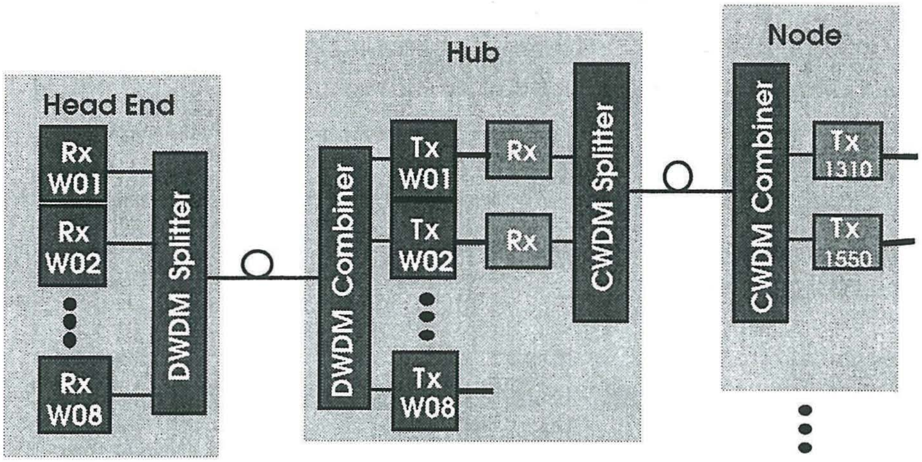
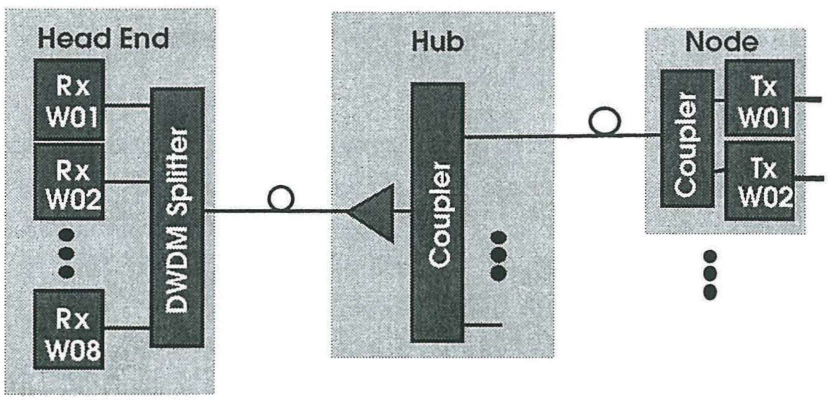


Figure 2 — Block diagrams of three architectures which require cascaded optical links. Block diagrams of the other three which are discussed are shown in **Figure 3**.

Wavelength Division Multiplexing



Dense Wavelength Division Multiplexing



Digital

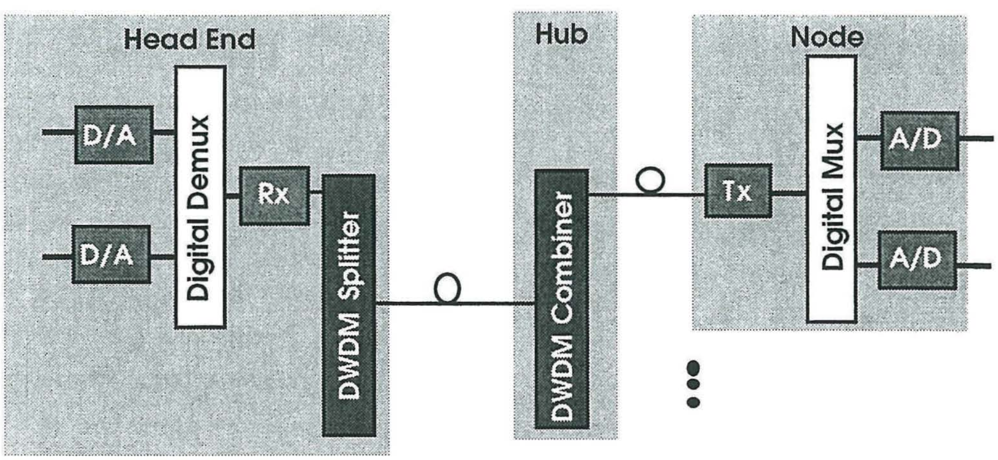


Figure 3 — Block diagrams of three architectures which require cascaded optical links. Block diagrams of the other three which are discussed are shown in **Figure 2**.

The fact that there are two links opens up may options for applying the technologies mentioned previously. Six options will be addressed. Block diagrams of these six architectures are shown in **Figure 2** and **Figure 3**. Again, to save space the figure shows only the scenario with two returns per node. Extrapolating to one and four returns per node should be straight-forward.

The relative costs of the six architectures are shown in **Table 3**. Again, estimated costs for a single return, two returns, and four returns from each node are listed. The costs include only the equipment

As it is possible and desirable to consolidate returns in the hub; there is no elementary scenario to which the others can be normalized. The architecture with a single return from each node and which uses DWDM from the hub to the head end was arbitrarily chosen as the reference.

The number of fibers required from the node to the hub for each architecture are shown in **Table 4** while the number of nodes which can share each fiber from the hub to the head end for each architecture are shown in **Table 5**. Both of these tables include a single return, two returns, and four returns from each node.

Multiple Fibers/DWDM

In this architecture, a dedicated fiber is used for each separate return from the node. DWDM transmitters at the hub are used to consolidate eight returns onto a single fiber. The costs for this architecture are based on using transmitters with uncooled DFB lasers in the node.

Multiple Fibers/Block Up Conversion

This architecture is very similar to the previous. The difference is that block up conversion between the hub and head end is used instead of DWDM.

Block Up Conversion

This architecture places the block up converters in the node. Converters in different nodes can be assigned different frequency blocks allowing direct combining of 10 return blocks in the hub.

These blocks can be combined onto a single transmitter/fiber in the node for the link to he hub. However, this does require return equipment with an extended bandwidth in the node. The cost of this is included in the analysis.

Wavelength Division Multiplexing

This architecture uses some form of WDM for both links. DWDM is used from the hub to the head end in all three scenarios.

The technology used for the links from the node to the hub changes with each scenario. In the scenario when there is a single return from each node, this architecture is identical to using Multiple Fibers/DWDM. When there are two returns from each node CDWM is used is used for these links. MWDM is used when there are four returns from each node.

Architecture/Technology		Relative Cost		
Node to Hub	Hub to Head End	One Return per Node	Two Returns per Node	Four Returns per Node
Multiple Fibers	DWDM	1.00	2.00	4.00
Multiple Fibers	Block Up Conversion	0.70	1.40	2.80
Block Up Conversion		1.17	1.67	2.68
Wavelength Division Multiplexing		1.00	2.10	4.11
Dense Wavelength Division Multiplexing		0.69	1.40	2.79
Digital		1.18	1.87	3.74

Table 3 — Relative cost of six architectures which use two cascaded optical links. These are diagrammed in **Figures 2** and **3**. Estimates for one, two and three separate returns from each node to the head end are shown.

Architecture/Technology		Fibers Needed from Node to Hub		
Node to Hub	Hub to Head End	One Return per Node	Two Returns per Node	Four Returns per Node
Multiple Fibers	DWDM	1	2	4
Multiple Fibers	Block Up Conversion	1	2	4
Block Up Conversion		1	1	1
Wavelength Division Multiplexing		1	1	1
Dense Wavelength Division Multiplexing		1	1	1
Digital		1	1	2

Table 4 — Number of fibers needed between the node and the hub for the six architectures which use two cascaded optical links. These are diagrammed in **Figures 2** and **3**.

Architecture/Technology		Nodes per Fiber from Hub to Head End		
Node to Hub	Hub to Head End	One Return per Node	Two Returns per Node	Four Returns per Node
Multiple Fibers	DWDM	8	4	2
Multiple Fibers	Block Up Conversion	10	5	2.5
Block Up Conversion		10	5	2.5
Wavelength Division Multiplexing		8	4	2
Dense Wavelength Division Multiplexing		8	4	2
Digital		8	8	4

Table 5 — Number nodes per fiber for the link between the node and the hub for the six architectures which use two cascaded optical links. These are diagrammed in **Figures 2** and **3**.

Dense Wavelength Division Multiplexing

This architecture uses DWDM transmitters in the node. The wavelengths are chosen such that eight returns from multiple nodes can be combined. If there is more than one transmitter in a node, the output from the transmitters is combined onto a single fiber within the node. Fibers from multiple nodes can be combined in the hub.

There are both cost and performance benefits to using couplers, rather than a DWDM multiplexer, to combine the light from multiple transmitters. However, a DWDM demultiplexer must be used to separate the light at the receiving site.

Link losses in this architecture can be high. This requires that there be an Erbium Doped Fiber Amplifier (EDFA) in the hub. This

EDFA can have modest power and performance compared to those used for forward path applications. Therefore, the cost of this EDFA is also modest.

Digital

This architecture uses digital DWDM transmitters in the node. The wavelengths are chosen so that eight returns can be combined onto a single fiber in the hub.

As in DWDM, a fiber for each DWDM transmitter is used between the node an the hub. There is sufficient data capacity on each fiber for up to two separate returns. A single return from each node would use only half the data capacity.

CONCLUSION

Providing internet access, video-on-demand, and other two-way services will require one or more dedicated return links from each node. There are numerous architectures using any of several technologies which can be used to support this.

In networks without cascaded optical links, the cost of using extra fibers for multiple returns is always lowest provided the fibers are available. If the fiber are not available, using some form of wavelength division multiplexing is probably less expensive than installing new fibers and seems to be the least expensive option.

In networks with cascaded optical links, several architectures have lower cost than using multiple fibers. Using DWDM from the node has nearly the same cost as using block up conversion — either in the node or in the hub. The least expensive option varies with the number of returns from each node, but the differences are small in all three scenarios.

However, block up conversion places a significant quantity of equipment in the hub. At the very least, a set of receivers and transmitters is required. This requires larger hub sites and makes maintenance and repair more difficult. In contrast, DWDM from the node requires only a low-cost EDFA in the hub. This makes the hub completely optical — no RF equipment is required in the hub.

While today the performance and the cost of DWDM from the node and block up conversion in the hub are very similar, there are significant operational advantages of DWDM. Also, it is clear that the cost of DWDM equipment will be decreasing in the future. These factors make DWDM from the node the best option for a high-efficiency return architecture.