# Reverse Path for Advanced Services — Architecture and Technology

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*Abstract*

*This paper presents several methods of provisioning for frequency reuse in the reverse path. It analyzes several optical technologies existing today or feasible in near future. These technologies range from a traditional 1310 DFB lasers technology through ITU grid 1550 nm lasers to external modulators with distributed access. These transport technologies are augmented by several methods of multiplexing to achieve frequency reuse:*

1) *spatial division multiplexing (physical segmentation of the reverse plant)*
2) *wavelength division multiplexing (coarse or dense)*
3) *frequency division multiplexing (frequency stacking or frequency block conversion), and*
4) *time division multiplexing (either after digitization of the reverse signals or after demodulation of the reverse signals).*

*This multiplexing may take place in optical nodes or secondary hubs. Besides allowing for frequency reuse, the multiplexing schemes allow for fewer fibers and make the redundancy switching feasible.*

*The paper presents architectural implementation of these optical technologies and multiplexing methods. Further, the paper presents the results of the cost analysis for all these methods based on the most up-to-date pricing or estimated cost of the technologies being developed. Finally, the paper provides performance allocation for different segments of the reverse paths for the architectures analyzed, and achievable or projected end-of-line performance of the reverse path.*

## INTRODUCTION

One of the main drivers for upgrading HFC networks is to provide two-way communication for interactive services. The HFC networks support services that require bidirectional transport system to a dedicated group of potential subscribers. An increasing demand for these services leads to increasing demand for bandwidth in forward and reverse paths. The forward path of the HFC network has a plentiful of bandwidth and can support significantly higher modulation levels, thus increasing bandwidth efficiency. Traditional HFC reverse path, on the other hand, has lower bandwidth resources and can support only lower modulation levels. This shortcoming is partially remedied by the highly asymmetrical demand for capacity in most high-speed data access applications. However, with the advance of the communications services that require symmetrical rates in both directions, the only way to increase the throughput is by frequency reuse in the reverse path.

## FORWARD PATH SEGMENTATION TECHNIQUES

Figure 1 presents a generic HFC architecture. It is applicable to large markets but its elements are also present in networks serving smaller markets. This architecture in most major markets is based on dual ring topology. These rings serve HFC plant streaming off the secondary hubs. The HFC network can be based on optical nodes (traditional fiber serving areas) or can deploy fiber significantly deeper.[1] Primary hub ring transport and multiplexing technologies have been described in many papers and are reasonably mature.[2,3] In these rings, technological progress is being implemented as it becomes mature and cost-effective. The other elements of the HFC network are undergoing a much faster evolution.

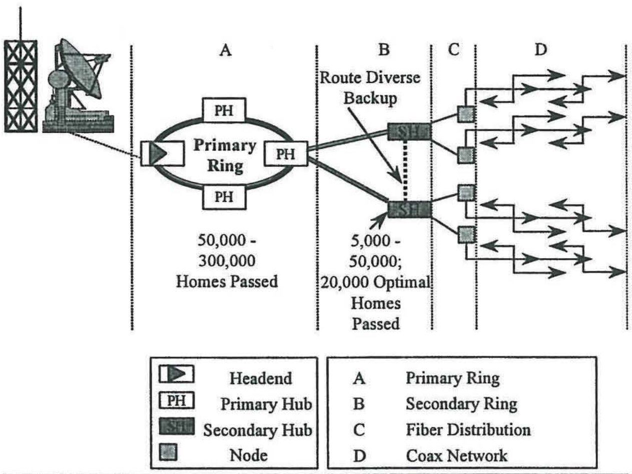


Figure 1: Modern HFC Network

## Forward Primary Hub to Secondary Hub Links

The secondary hub rings provide redundancy and eliminate needs for high fiber count optical cables. They serve as signal multiplexing points to limit the number of fibers between primary hub ring and secondary hubs to achieve cost reduction, improve MTTR, and allow for cost-effective backup switching. AT&T Broadcast & Internet Services uses DWDM systems[4,5] in these rings or TDM systems (mostly SONET transport) for locations that could not deploy DWDM for technical or other reasons.

In the most recent architectural study by AT&T[6], a TDM technology is proposed to supplement the DWDM for future-proofing of the HFC network. However, in this application, the TDM technology is transparent to the services provided since it is overlaid throughout the network to the customer premises.

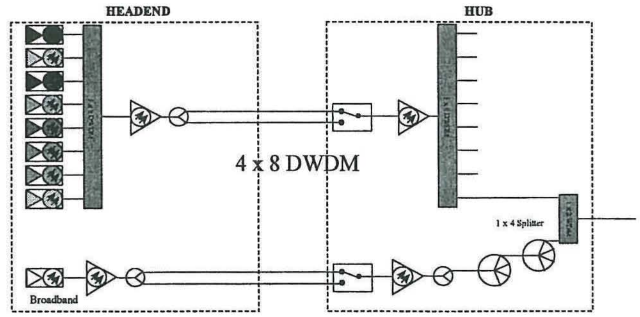


Figure 2: Configuration of DWDM in Forward Direction — Example

## Forward Secondary Hub to Optical Node Links

The network sections (access network) marked as 'C' and 'D' in Figure 1 extend passed the secondary hubs and provide the last links to the customers. The architectural solutions for this network section differ from operator to operator. However, most of them deploy optical node-based configuration followed by active RF coaxial network. The differences are reflected in the node sizes and in the level of redundancy. Due to high bandwidth capacity requirements in the forward path, frequency-stacking techniques cannot be used in this section. The multiplexing (frequency reuse) is mostly based on SDM.

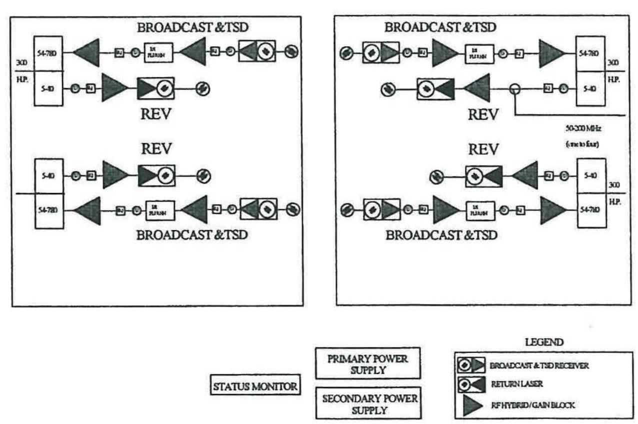


Figure 3: Spatial Division Multiplexing in Optical Node — Example

## REVERSE PATH MULTIPLEXING TECHNIQUES

The reverse path in secondary hub rings and in the access network can use several multiplexing technologies to implement frequency reuse. The higher number of choices results from the fact that the reverse bandwidth is narrower. These multiplexing choices are:

1) spatial division multiplexing
2) wavelength division multiplexing (coarse or dense)
3) frequency division multiplexing (frequency stacking), and
4) time division multiplexing.

### Reverse Primary Hub to Secondary Hub Links

Pure SDM techniques do not achieve the goals required of these links. They must be used with other multiplexing techniques such as WDM, FDM, or TDM. The advantage of WDM techniques is that they are transparent to any services and signals distributed (they simply mimic the SDM techniques with separate wavelengths) and can be combined with the remaining two techniques. These solutions are presented in Figures 4 through 6. It is apparent that the level of multiplexing can vary depending on availability and cost-effectiveness of the components as well as on the level of required performance. An alternative to the options described above, a baseband TDM technology (for example based on SONET transport used in forward and reverse paths) can be used but then secondary hubs become primary hubs, which in turn results in an increase in operating cost.

#### *Dense Wavelength Division Multiplexing (DWDM)*

The number of wavelengths per channel can range from 2 to 16 (or even 32) dependent on the level of multiplexing required and number of available fibers. However, this may lead to a higher cost of spares due to the higher wavelength number unless variable wavelength transmitters are developed and used.

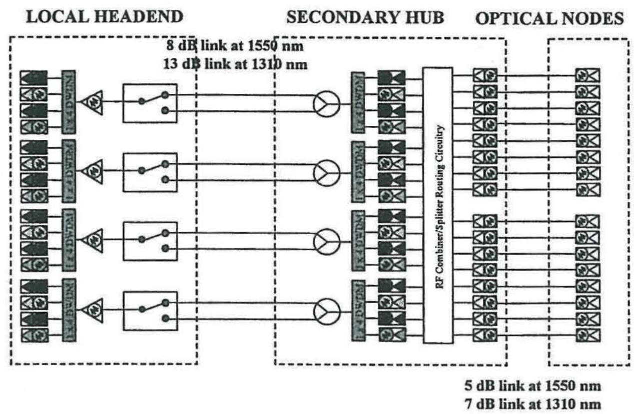


**Figure 4: DWDM in Secondary Hub Links**

#### *Frequency Division Multiplexing (FDM) a.k.a. Frequency Stacking*

The number of channels in frequency stackers/destackers depends on cost, equipment availability and level of performance required. It can range from 2 to 18 channels (up to 1 GHz).

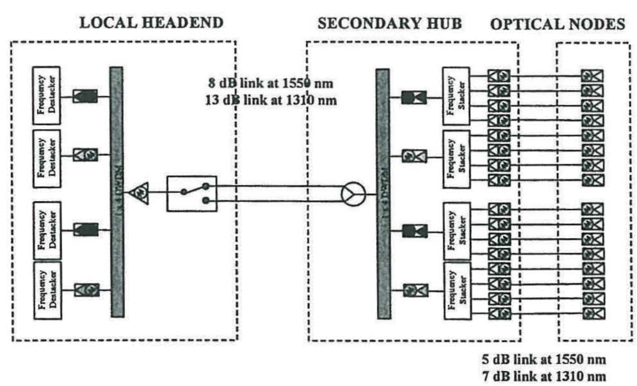


**Figure 5: DWDM Combined with FDM in Secondary Hub Links**

*Time Division Multiplexing (TDM) after Digitization*

Similarly, the number of channels multiplexed after digitization depends on the required performance, availability of the technology and its cost. It can range from 2 to 4 (or 16 at OC192 rates of multiplexing). Moreover, with simple arithmetical addition, an equivalent to RF combining topology (without its disadvantages) can be achieved at initial deployment stages before high frequency reuse is required.

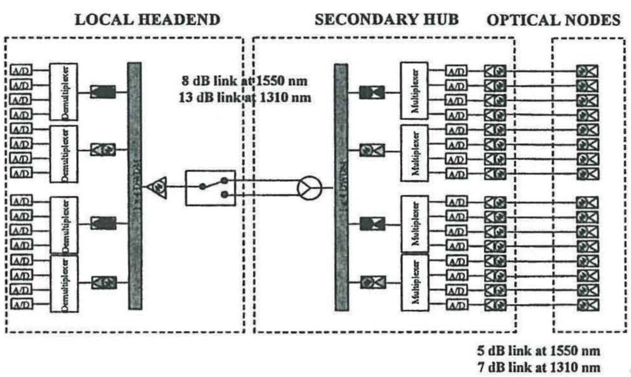


**Figure 6: DWDM Combined with TDM in Secondary Hub Links**

## Secondary Hub to Optical Node Links

The same techniques that are used in primary to secondary hub links can be used in optical nodes. These techniques can be later repeated in secondary hubs for higher level of multiplexing. The choice is purely dependent on the equipment availability and cost as well as on the performance required. Some examples are presented in Figures 7 through 9.

*ITU 1550 Lasers in Nodes*

The lasers in the node can be 1310 or 1550 nm with wavelengths from ITU grid for transparent multiplexing in the secondary hub. The multiplexing may take place in the node if the number of fibers in the link is limited. The number of ITU lasers can range from 1 to 4.

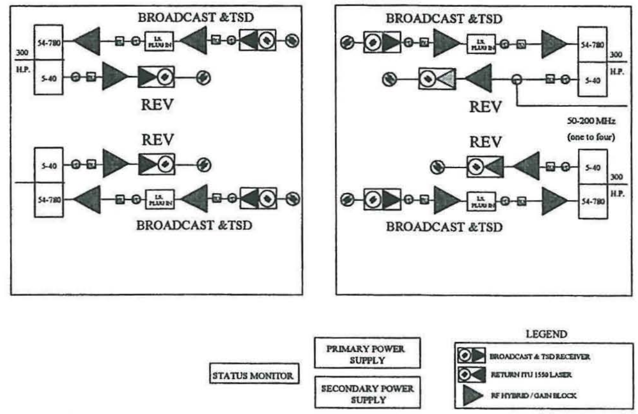


**Figure 7: ITU Lasers from Optical Node**

*Frequency Stacking in Nodes*

The number of FDM channels can range from 1 to 4 and they can be carried on 1310 or 1550 ITU laser.

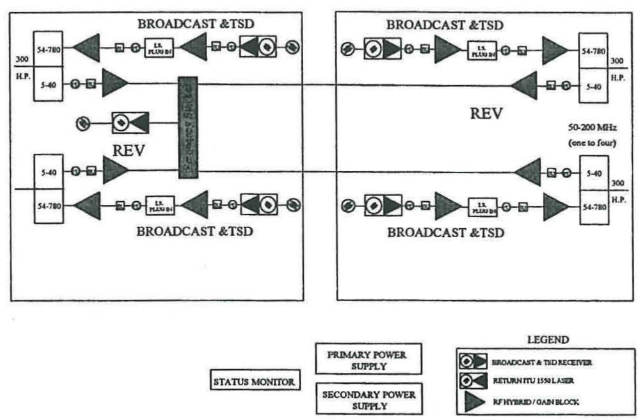


**Figure 8: FDM from Optical Node**

*Digitizing and Time Division Multiplexing in Nodes*

The number of channels multiplexed at the node can range from 2 to 4 (or 16 in a MuxNode[7]). They can be transported on 1310 or 1550 ITU lasers of digital quality and can be passed through or further multiplexed in the secondary hub.

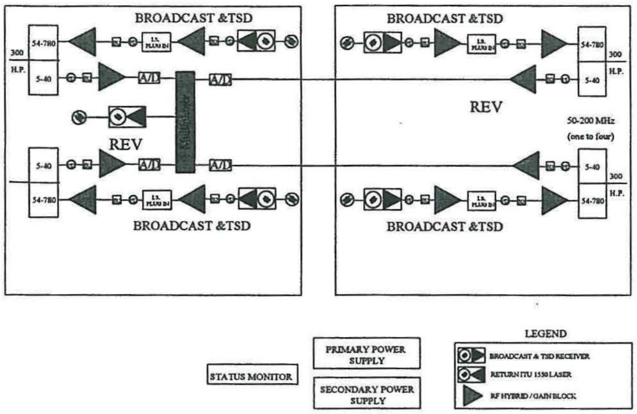


**Figure 9: TDM from Optical Node**

<u>**Multi-Multiplexing between Nodes and Primary Hub**</u>

All the multiplexing techniques described above can be used in combination and can be cascaded. Some examples of the combinations of the secondary hub and node multiplexing are shown in Figures 10 through 12.

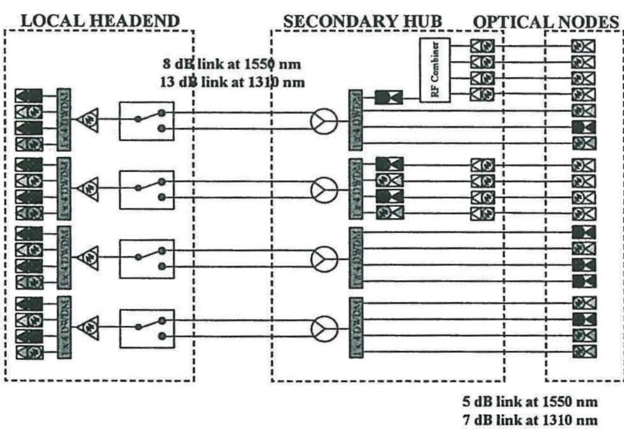


**Figure 10: ITU Lasers from Nodes Multiplexed in Secondary Hub**

The DWDM techniques can be used with ITU grid lasers installed only in secondary hubs and optical node feeds being repeated (and combined before the ITU grid lasers if needed) or with ITU grid lasers installed in the nodes with secondary hub serving a role of passive multiplexer.

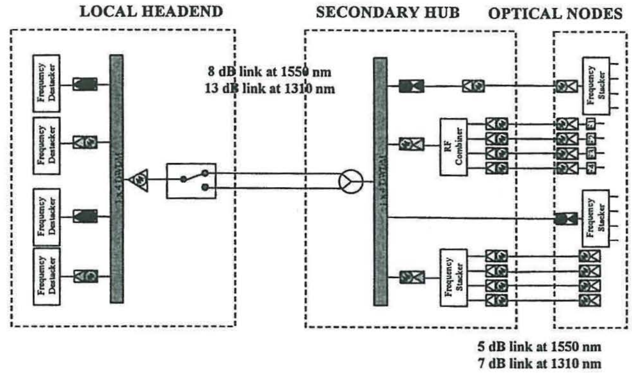


**Figure 11: FDM from Nodes with FDM and DWDM at Secondary Hub**

Frequency stacking can be performed in nodes or in secondary hubs. Alternatively, individual small nodes can be frequency shifted to different bandwidths and RF combined at the secondary hub to feed ITU grid lasers. The frequency stackers in the nodes can feed ITU grid lasers for passive wavelength multiplexing in the hub or feed 1310 lasers for re-lasing into ITU grid and then multiplexing in the hub. Small nodes can be RF combined in the hub after detection and before frequency stacking.

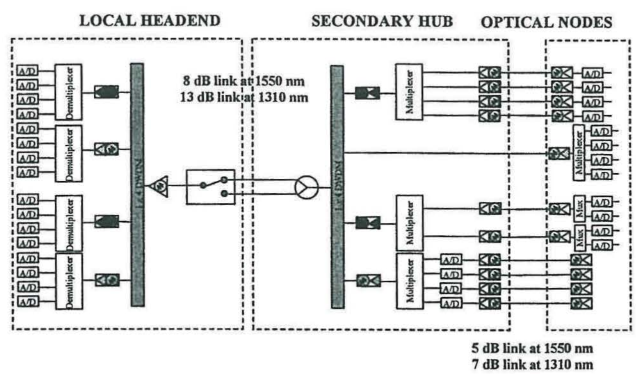


**Figure 12: TDM from Nodes with TDM and DWDM at Secondary Hub**

Similarly, digitization and TDM can take place in nodes or secondary hubs. Moreover, for small nodes with digitization, TDM can take place in the hub (and initially can be equivalent to RF combining). Additionally, after some multiplexing in the nodes, additional multiplexing into higher rates can be performed in the hub. Digitized and multiplexed signals in the nodes can feed ITU grid lasers for passive wavelength multiplexing in the hub or feed 1310 lasers for re-lasing into ITU grid and then time division and/or wavelength multiplexing in the hub. Small nodes can be RF combined in the hub after detection and before digitization.

**Access Network**

AT&T analyzed alternative architectures for access network (downstream of secondary hub). The analysis results[8] show that fiber-deep architecture (MFPC) may be the architecture of choice for HFC network upgrades. In this case, mininodes will be deployed and fed off today's nodes (MuxNodes). All the multiplexing techniques are applicable to this new architecture for both phases of deployment and can be implemented in secondary hubs, MuxNodes and mininodes in any combination.

## COST COMPARISON

**Model Description**

The costs of the alternatives were analyzed for a secondary hub with 20,000 homes passed. The detail model description is presented in Table 1. The architecture presented in Figure 4 was used as a baseline for cost comparison. Incremental costs (savings) for all other alternatives were calculated on a per node basis, per serving area basis, and per home passed basis.

| Model Parameter | |
|---|---|
| Area Served | Secondary hub |
| Homes Passed | 24,000 |
| Number of Nodes | 32 |
| Number of Nodes at 300 HPs | 8 |
| Number of Nodes at 600 HPs | 8 |
| Number of Nodes at 900 HPs | 8 |
| Number of Nodes at 1200 HPs | 8 |
| Maximum Size of Serving Area | 600 HPs |
| Average Node Size | 750 HPs |

**Table 1: Model Description**

**Alternatives Analyzed**

Table 2 lists all of the alternatives considered during the cost analysis. The high number of alternatives for digital technology combined with TDM supports author's assessment about high flexibility of this technology. A combination of this technology with DWDM allows for building a very robust reverse path with limited number of fibers between primary and secondary hubs. Without DWDM, the number of fibers increases dramatically for this technology unless very high multiplexing rates are used (OC192). Two alternatives for FDM systems and three alternatives for DWDM systems were also analyzed. The most commonly deployed alternative in AT&T HFC network was used as a baseline (presented in Figure 4).

| Code | Description | PH-SH Link | SH-FN Link (for node sizes) | | | |
|---|---|---|---|---|---|---|
| | | | 300 | 600 | 900 | 1,200 |
| DWDM B | Baseline | 1550 ITU Lasers for 8-Wavelength Mux | 1310, combined @ SH for 600 HPs | 1310 | segmented into 450 HPs, 1310 | segmented into 600 HPs, 1310 |
| DWDM P | Pure DWDM | Passive Mux for 8 Wavelengths/Fiber | 1550 ITU | 1550 ITU | segmented into 450 HPs, 1550 ITU | segmented into 600 HPs, 1550 ITU |
| DWDM O | Optimized DWDM | 1550 ITU Lasers and Passive Mux | 1310 combined @ SH for 600 HPs | 1550 ITU | 1550 ITU segmented into 450 HPs | 1550 ITU segmented into 600 HPs |
| FS SH | Frequency Stacking @ SH | Frequency Stacking into 16 Chs, 1310 nm Lasers | 1310 combined @ SH for 600 HPs | 1310 | segmented into 450 HPs, 1310 | segmented into 600 HPs, 1310 |
| FS SH/FN | FS @ SH & FNs | Frequency Stacking into 16 Chs, 1310 nm Lasers | 1310 combined @ SH for 600 HPs | freq. shifted, 1310, combined @ SH | segmented into 450 HPs, FS, 1310 | segmented into 600 HPs, FS, 1310 |
| DIG SH | Digitized & Muxed @ SH | Digitized & 2 Chs Muxed into OC48, 1310 nm Digital OC48 Lasers | 1310 combined @ SH for 600 HPs | 1310 | segmented into 450 HPs, 1310 | segmented into 600 HPs, 1310 |
| HRDIG SH | Digitized & Muxed @ SH | Digitized & 8 Chs Muxed into OC192, 1310 nm Digital OC192 Lasers | 1310 combined @ SH for 600 HPs | 1310 | segmented into 450 HPs, 1310 | segmented into 600 HPs, 1310 |
| DIG/DWDM SH | Digitized, Muxed & DWDM @ SH | Digitized & 2 Chs Muxed, 1550 nm Digital OC48 Lasers, 8-Wavelength Mux | 1310 combined @ SH for 600 HPs | 1310 | segmented into 450 HPs, 1310 | segmented into 600 HPs, 1310 |
| DIG FN/MUX SH | Digitized @ FN, Muxed & DWDM @ SH | 2 Channels Muxed, 1550 nm Digital OC48 Lasers, 8-Wavelength Mux | digitized, 1310 digital OC24 laser | digitized, 1310 digital OC24 laser | segmented to 450 HPs, digitized, 1310 digital OC24 laser | segmented to 600 HPs & digitized, 1310 digital OC24 laser |
| DIG/MUX Mix | Digitized @ FN, Muxed & DWDM @ FN or SH | 2 Channels Muxed, 1550 nm Digital OC48 Lasers, 8-Wavelength Mux | digitized, 1310 digital OC24 laser | digitized, 1310 digital OC24 laser | segmented to 450 HPs, digitized, muxed into OC48, 1550 ITU digital OC48 laser | segmented to 600 HPs, digitized, muxed into OC48, 1550 ITU digital OC48 laser |
| DIG/MUX O | Digitized @ FN, Summed or Muxed & DWDM @ FN and/or SH | 4 Channels Summed, 2 Channels Muxed, 1550 nm Digital OC48 Lasers, 8-Wavelength Mux, Passive Mux | digitized, 1310 digital OC12 laser, summed @ SH | digitized, 1310 digital OC24 laser | segmented to 450 HPs, digitized, muxed into OC48, 1550 ITU digital OC48 laser | segmented to 600 HPs, digitized, muxed into OC48, 1550 ITU digital OC48 laser |

**Table 2: Reverse Architecture Alternatives Analyzed**

## Multiplexing Savings versus Baseline

The unit price data for DWDM and FDM (FS) systems are based on recent quotes or price/volume projections for the next several months. The unit price data for digital and TDM systems are based on preliminary expectations. More accurate data will be available during the NCTA technical conference in Chicago in June 1999. They may seem too optimistic at first but are supported by at least one quote from a vendor. Other vendors indicated that they are active in implementing this technology into the HFC reverse path elements. Due to preliminary nature of the data, no conclusions are presented. However, the results lead to believe that the most cost-effective combinations are DWDM with TDM of digitized reverse bandwidth.

The digital technology components experience steep decline in prices. The prices are driven down by high volume and related to it high level of integration. Most of these components are standard and the only additional requirements are higher thermal stability and reliability for the components installed in optical nodes.

| Code | Total Cost | Cost/ FN | Cost/ Serving Area | Cost/ HP | Ref. to Baseline | # of Fibers PH-SH |
|---|---|---|---|---|---|---|
| DWDM B | $389,068 | $12,158 | $8,842 | $16.21 | 100.00% | 12 |
| DWDM P | $331,968 | $10,374 | $7,545 | $13.83 | 85.32% | 12 |
| DWDM O | $335,468 | $10,483 | $7,624 | $13.98 | 86.22% | 12 |
| FS SH | $228,674 | $7,146 | $5,197 | $9.53 | 58.77% | 6 |
| FS SH/FN | $250,474 | $7,827 | $5,693 | $10.44 | 64.38% | 6 |
| DIG SH | $192,266 | $6,008 | $4,370 | $8.01 | 49.42% | 44 |
| HRDIG SH | $113,788 | $3,556 | $2,586 | $4.74 | 29.25% | 12 |
| DIG/DWDM SH | $252,814 | $7,900 | $5,746 | $10.53 | 64.98% | 6 |
| DIG FN/MUX SH | $271,154 | $8,474 | $6,163 | $11.30 | 69.69% | 6 |
| DIG/MUX Mix | $234,114 | $7,316 | $5,321 | $9.75 | 60.17% | 6 |
| DIG/MUX O | $220,304 | $6,885 | $5,007 | $9.18 | 56.62% | 6 |

**Table 3: Cost Comparison of Alternatives**

## PERFORMANCE AND FEATURE COMPARISON

### Transparency

The issue of transparency is essential to HFC networks and allows for elimination of terminal equipment from many locations and its concentration in fewer processing centers and on customers' premises. These characteristics also allow for the addition of new services by adding terminal equipment in these few locations and in the customers' homes. The more transparent the network is, the more practical are retail models for customer equipment and the more efficient self-provisioning of the services becomes.

From among the technologies analyzed, the most transparent is pure DWDM. The other two technologies are reasonably transparent and implement little processing. This processing is transparent to the signals transported on HFC network. At network interfaces (processing centers and customer terminals), the signals are present in their native form and hence are compatible with the terminal equipment.

### Flexibility

DWDM technology is very flexible to the changes in frequency allocation. Only a few components are frequency limited but these limits are significantly outside of today's frequency operating ranges. The other two technologies may require (dependent on implementation) and upgrade or replacement. The TDM system is easier to upgrade in case the frequency allocation changes (reverse frequency bandwidth increases). FDM technology would require a replacement and the change might affect other network components (filters).

### Reliability

Both FDM and TDM technologies introduce additional active components into the reverse path. Therefore, they inherently lower the reliability. To address this concern, they must be carefully designed for long MTBF. The elements of the DWDM technology have been proven in the field and do not differ significantly from the optical link components that have been deployed in the HFC network for the last 10 years.

### Other Considerations

Digitization and TDM technology have one significant advantage: practical transparency of this technology from the point of view of signal performance. The link of a quality not sufficient for QPSK or QAM signals is mostly transparent for digital baseband signals. Hence, the end-to-end performance requirements can be allocated to the A/D converter (the first stage of the digital link). Once signals are digitized, the network becomes transparent to them and does not cause a noticeable degradation under normal operating conditions. Moreover, once digitized, the signals can be processed to eliminate impairments contributed before digitization.

Additional advantage comes from the fact that all components of this technology are standard and widely used by the telecommunications and computer industries. Technological progress is also driven by these industries. Due to the volume, the components are on a steep price curve. Moreover, they are being continuously improved upon.

The combination of this technology with DWDM technology is very promising and allows to find a reasonable compromise between the cost of the reverse path at the cost of transparency and flexibility but with some positive characteristics added to the mix.

On the other hand, FDM systems tested by the author showed a range of performance from almost complete transparency to a significant degradation in link quality (main contributor to the reverse path constraints). They are being developed by a handful number of small manufactures and are highly proprietary. In most cases, they require a pilot to maintain synchronization. Despite these facts, they are a valuable tool in lowering the reverse path cost and allowing for space-saving in locations with limited space.

## CONCLUSION

The results of the analysis described in the paper show that, although the pure DWDM technology provides the highest level of transparency and flexibility (future-proofing), a reasonable compromise can be achieved by combing this technology with digitizing the reverse path signals and TD multiplexing them. Although some level of flexibility is lost, additional benefits such as increased link robustness and performance transparency offset this lost. Moreover, the cost analysis based on the preliminary estimates indicates a potential of significant saving in the reverse path network cost. The author is participating in the testing of this technology with several manufacturers. Initial test results confirm the theoretical analysis. The technology is in its prototype stages and may be implemented in the field in the third quarter of 1999.

Frequency stacking and FDM technology, if implemented properly, will also allow for some cost and space requirement reduction without noticeable performance degradation. It introduces similar limitations to network flexibility without the additional benefits coming from digitization and TDM technology. The FDM and frequency stacking technology will most likely be ready for implementation at the same timeframe as the TDM technology.

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[1] Oleh Sniezko, Tony Werner, Doug Combs, Esteban Sandino, Xiaolin Lu, Ted Darcie, Alan Gnauck, Sheryl Woodward, Bhavesh Desai, HFC Architecture in the Making, 1999 NCTA Technical Papers.

[2] Tony E. Werner, Regional and Metropolitan Hub Architecture Considerations, SCTE 1995 Conference on Emerging Technologies.

[3] Oleh J. Sniezko, Video and Data Transmission in Evolving HFC Network, 1998 OFC Conference.

[4] Same as [3]

[5] Thomas G. Elliot and Oleh J. Sniezko, Transmission Technologies in Secondary Hub Rings — SONET versus FDM Once More, 1996 NCTA Technical Papers.

[6] Same as [1]

[7] Same as [1]

[8] Same as [1]