Invisible Hub or End-to-End Transparency

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During the last decade, the tree-and-branch cable TV architectures have evolved into HFC architectures. These changes were inevitable due to advanced service requirements for increased quality, increased reliability, and interactivity.

Most of the advanced HFC networks introduce secondary hubs with a star configuration from secondary hubs to the nodes and a ring between the primary hub and the secondary hubs.

This paper analyzes the transport layer choices in this ring. Four basic alternatives are presented and compared. The three of them have been analyzed before, the fourth, dense wavelength division multiplexing (DWDM), became a feasible alternative in 1997. The paper compares advantages and disadvantages for all four of them and their capital and operating costs. Finally, it presents a possible implementation path for DWDM transport system.

NETWORKING IMPERATIVE

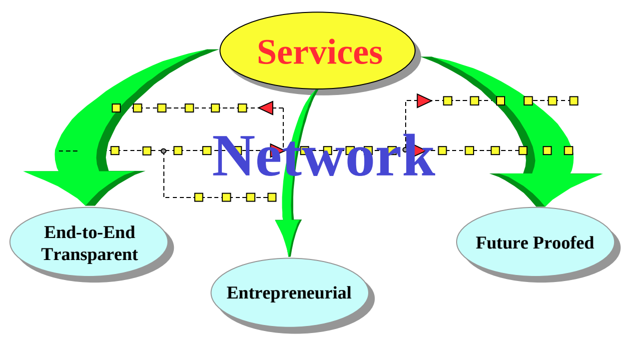
Networking Paradigm

One of the major objectives of telecommunications engineers is to design and build a network that is transparent, scaleable, and future-proofed. Such a network would allow us:

- to introduce any services that we can anticipate
- as soon as the demand for them is high enough to justify the investment
- in a timely fashion to outdistance the competition
- by adding required terminal equipment at the customer premises and signal processing centers only with no or almost no changes to the network.

The authors have presented the thoughts listed above before. However, they are repeated here to emphasize the leading imperative of network design. This imperative never became so obvious as during the implementation of the digital TV services over the HFC network. The entrepreneurial character of our network and its transparency allowed for fast implementation at significant savings.

Figure 1: Network Design Paradigm



Smart or Not-So-Smart Network

One of the most heated debates relates to the question of how smart the network should be. To be more accurate, the question is whether the smartness should extend to the final user or should stop at some higher network level. The HFC operators tend to design the network that does not require a complex OAM&P (Operations, Administration, Maintenance and Provisioning) systems beyond the primary hub or headend. Except for limited monitoring (secondary hubs, optical nodes, and stand-by power supply) and redundancy switching in the primary and secondary (optional) hub rings designed for improved reliability, the network operations, maintenance and provisioning relies on smartness in terminal equipment and in transmission protocols.

On the other hand, telecommunications network operators invest significant effort and capital in designing and building intelligent networks with the OAM&P elements deployed to the level extending to the very last interface. Even the customer interfaces in some proposed solutions include switching and multiplexing and provision for a multitude of physical layer protocols. This approach involves high risk of network obsolescence caused by technology progress, and requires high level of capital invested in the network (fixed cost). Moreover, this approach is not scalable. The fixed costs that have to be born in the initial stages of network provisioning are prohibitive to any single telecommunications company. The broadband access intelligent network plans are being abandoned as soon as the players have to put their money where their mouth is. The same players build the broadband access network based on copper plant with smart terminals (xDSL). On the other hand, asking the public to finance this network through a tax system involves very high risk of spending public funds on the network that can be obsolete before it is ready.

The situation with these two different approaches to the network intelligence reminds many other similar dilemmas. The closest parallel can be drawn between this debate and the debate about centralized computing (very high capacity mainframe computers with “dumb” terminals connected to it) and distributed computing (smart terminals interconnected to create a network). The pace of progress in processing power and storage capacity so far favors the latter approach, especially in residential and business environment.

HISTORICAL OVERVIEW

The tree-and-branch cable TV architectures served the public with great success that was rooted in the perfect match with the services demanded. Over time, they have evolved into HFC architectures to satisfy the advanced service requirements for increased quality, reliability, and interactivity. This evolution was enabled through the deployment of fiber optic technology deep into the plant. This node based deployment has also satisfied the requirement for spatial division multiplexing (SDM) that allowed for effective reverse path problem management, and for effective traffic engineering.

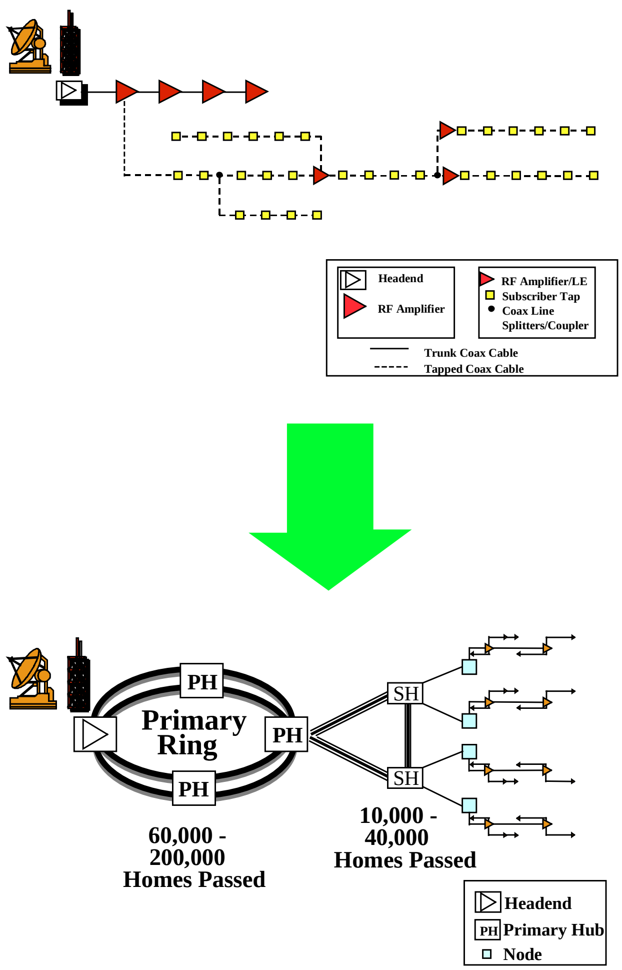
Table 1: Perfect Historical Match

Services	*Architectures*
Broadcast TV	Coaxial Tree & Branch
Broadcast Radio	Fiber Supertrunk
Addressable Services:	Fiber Backbone
• addressable tiering	Fiber-to-the-Feeder
• PPV	
• games	
• digital radio	
Home Shopping	

Table 2: New Services -- New Solutions

Services	*Architectures*
Services:	**Requirements**:
• targeted advertising	• superior reliability
• targeted entertainment	• competitive quality
• telephony	• competitive price
• high speed data	**Architectural changes**:
• full multimedia	• fiber supertrunking and fiber backbone
Competition:	• regional hub ring
• DBS	• redundancy (secondary hub rings)
• telephone companies	• deep fiber deployment & segmentation
• multimedia mergers	

Figure 2: Network Evolution: from Tree-&-Branch to HFC



Most of the HFC architectures closely resemble CableLabs’ Active Coaxial Network Architecture. In the largest metropolitan areas, numerous headends are most likely to be connected in a ring to provide a fully redundant and survivable platform. In many cases, primary hubs are established to maintain signal quality delivered to the distribution network. These hubs serve from 60K to 100K homes passed. In most implementations, these rings deploy one of the following transmission technologies:

1. Proprietary Digital Systems,
2. Synchronous Optical Network (SONET), or
3. 1550 nm optical links with Erbium Doped Fiber Amplifiers (EDFA).

A choice of the particular technology is based on the market size, distances, and network complexity. In most markets, the transport system is based on a digital baseband (TDM) transport and, in many cases, deploys both SONET and proprietary digital transports.

SECONDARY HUB RING

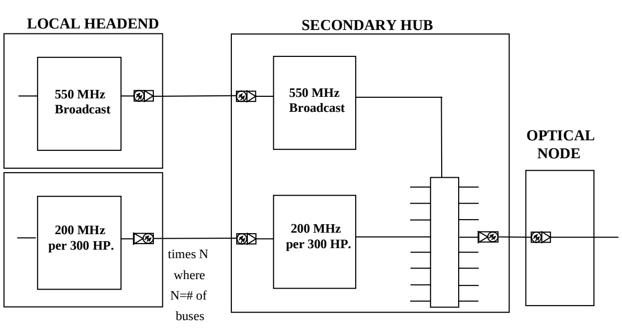
Topology

The choice of the transmission technology for the secondary hub ring is not that apparent. It is strongly dependent on the topology selected for the optical section of the HFC plant. Two basic topology choices are:

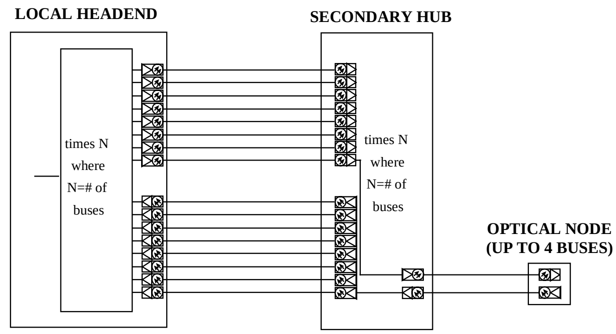
1. star architecture (home run forward and reverse fiber) from headend/primary hub ring (ring-star-bus architecture) to the nodes, or
2. ring architecture where secondary hubs are interconnected with the primary hub in a ring, with star architecture from secondary hubs to the nodes (ring-ring-star-bus architecture).

Figure 3: Home-Run Optical Links

a) Forward Split Bandwidth, TSD Overlay



a) Forward and Reverse, Combined Bandwidth



The first alternative results in a simple architecture that is largely both passive and transparent between the headend or primary hub and the optical node. Unfortunately, it employs high fiber count cables that increase capital cost and allow for single point of failure with long mean time to repair. This architecture is also impractical to employ in a ring configuration for path redundancy. Other technical challenges are related to the reverse path implementation.

Secondary Hub Ring Technologies

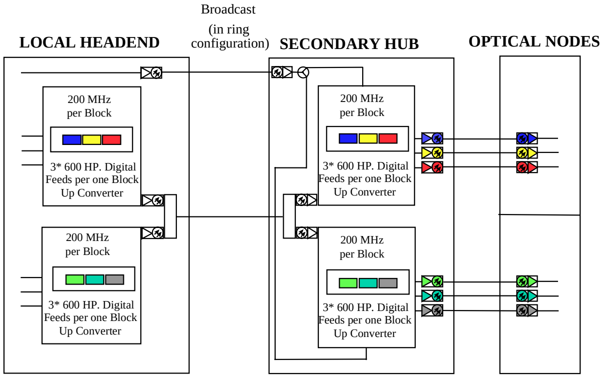
The ring topology provides an opportunity for a cost-effective and highly reliable network with a limited number of fibers between the primary and secondary hubs. and is deployed in some form by all major MSOs. However, there are several technology choices that can be used to implement the ring configuration:

1. Analog FDM for broadcast and FDM with frequency conversion (frequency stacking) overlay for targeted signals;
2. Hybrid analog FDM for broadcast and SONET or Ethernet (TDM) for targeted signals;
3. Analog FDM for broadcast and all optical DWDM (dense wavelength division multiplexing) for targeted services.

Furthermore, the choice of the technology for downstream transport can be different than the choice for upstream transport. The final decision will depend on many factors.

Figure 4: FDM & Frequency Stacking

a) Forward Split Bandwidth, TSD Overlay



b) Reverse

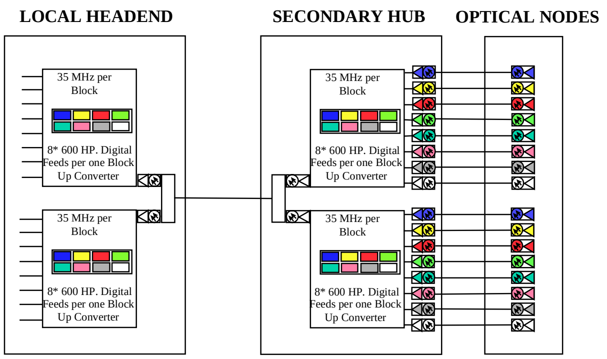
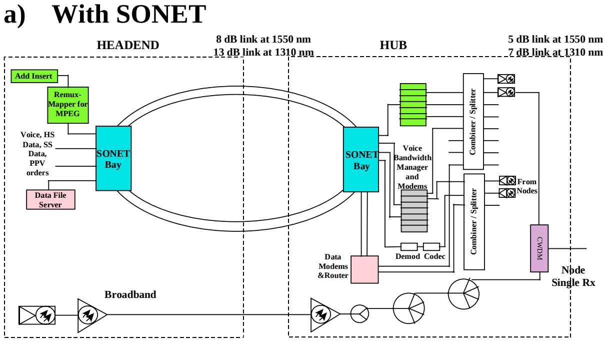


Figure 5: Hybrid Analog and Digital

a) With SONET



b) With 100BaseT

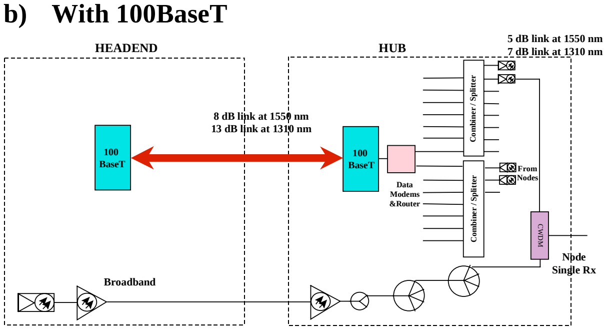
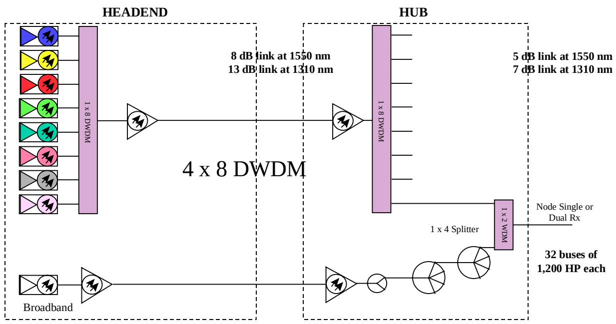
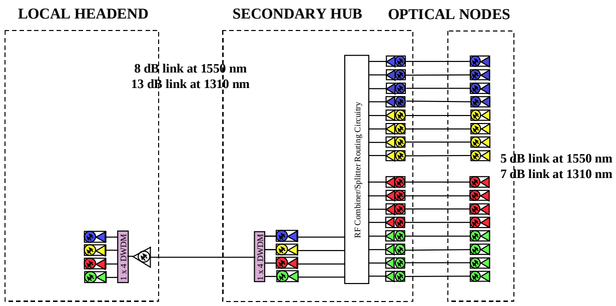


Figure 6: DWDM

a) Forward



b) Reverse



Comparison

When choosing a technology, we have to take into account the network design paradigm but at the same time we have to consider the technology status. The DWDM technology has been considered by the authors as a very desirable solution for some time [1] yet not mature for field deployment with FDM signals in cable TV environment. During the last couple of years, the technology matured and became practical. The DWDM has been applied first to the baseband digital transport and systems with 40 and 64 wavelengths multiplexed in telecommunications backbone links are commercially available. Our industry has been using this technology in regional and primary hub interconnects for the last two years. The scalability and flexibility of this technology makes it almost a perfect match for the HFC network. The advantages of this technology are compared against characteristics of the remaining alternatives in Table 3.

Table 3: Comparison between Technologies

Feature	Space Division Multiplexing	FDM	SONET/100BaseT	DWDM
Transparent	Fully transparent, only O/E repeaters at SH	Partially transparent, FDM equipment at SH	Partially transparent, RF/SONET interfaces at SH	Fully transparent, all optical network PH-to-Node
Entrepreneurial	Services added at any time (O/E repeaters to install)	Services added with little upgrade at SH (for further segmentation)	Only new service equipment added at SH (if interfaces are available & standard)	Services added with little upgrade at SH (for further segmentation)
Future Proofed	Basic network is service independent, problem with reverse (long distances)	Problems with frequency conversion, locked into frequency bandwidth in forward and reverse	In predictable future	Basic network is service independent, fully flexible frequency allocation in forward and reverse, flexible reverse/forward split
Comments	Very high initial cost and full cost, redundancy impractical	Moderate cost, partially scalable (high fixed cost)	The most cost-effective, only partially scalable (very high fixed cost)	Moderate cost, highly scalable, steep cost curve; allows for further segmentation with frequency conversion in the nodes

The quick review of Table 3 clearly indicates that DWDM should be the preferred choice for secondary hub rings in HFC networks. It provides the required level of segmentation for targeted services with limited requirements for fiber. It matches the advantages of the home-run architecture while avoiding its pitfalls of high fiber counts and related to it problems with providing redundancy. The next two tables add to the comparison of the three secondary hub technologies.

Table 4: Comparison of Positives

Desirable Feature	FDM or Block Conversion	SONET	DWDM
Low cost interface to RF	+		+
Many vendors		+	+
Standard system		+	+
Standard network management		+	
Limited number of fibers required	+	++	++
Interfaces with digital systems	+	+	+
Good reliability record		+	+
Survivability	+	++	+
Same system for forward and reverse		+	
Drop/add capability		+	under development

Table 5: Comparison of Negatives

Undesirable Feature	FDM or Block Conversion	SONET	DWDM
Possible problems of instability	✔		
Potential of becoming obsolete	✔		
Potential of becoming single-vendor product	✔		
Fixed system frequency bandwidth split between broadcast and targeted services	✔		
High cost of RF interfaces		✔	

Cost/Scalability

Besides comparing qualitative characteristics of the technologies, the authors prepared a case study to compare the cost of these alternatives. The following system was analyzed:

1) One primary hub feeding 160K homes passed;
2) Four secondary hubs with 120K homes passed (2 with 40K homes and 2 with 20K homes) configured in a ring (optional);
3) Distances:
   - ⇒ 14 miles from primary to 40K secondary hubs,
   - ⇒ 26 miles from primary to 20K secondary hubs (12 miles from 40K secondary hubs to 20K secondary hubs),
   - ⇒ 6 miles between 20K secondary hubs (to close the ring)
4) Optical nodes off each secondary hub with 1500HP per node and three buses of 500HP per bus;
5) The following scenarios were analyzed:
   - ⇒ low segmentation case (A) without redundancy in the secondary hub ring (today's prices),
   - ⇒ low segmentation case (B) with redundancy in the secondary hub ring (today's prices),
   - ⇒ high segmentation case (C) with equipment prices at initial level and without redundancy in the secondary hub ring,
   - ⇒ high segmentation case (D) with equipment prices at initial level and with redundancy in the secondary hub ring,

⇒ high segmentation case (E) with price projection for 3 years and with redundancy in secondary hub ring.

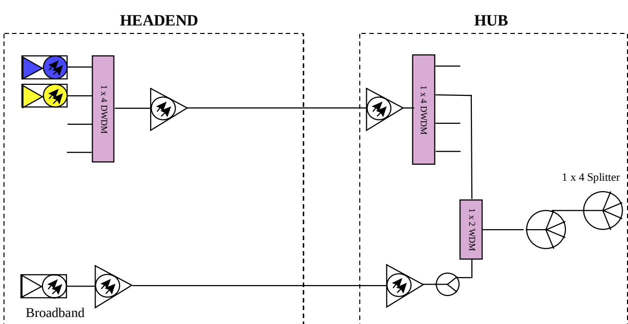
The equipment prices were collected from two vendors that have the DWDM systems ready for deployment. Table 6 summarizes the results of the analysis. The shaded areas indicate recommended deployment strategy.

Table 6: Cost per Home Passed

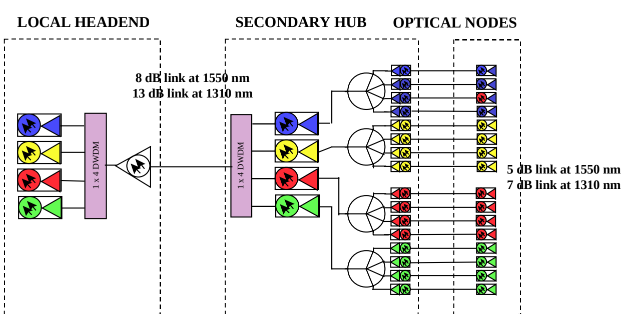
Technology	A	B	C	D	E
FDM with frequency conversion	$11.48	$15.21	$22.71	$29.07	$24.38
Hybrid with SONET	$15.59	$16.73	$24.35	$25.32	$21.91
Hybrid with 10BaseT	$14.07	$20.45	$20.48	$29.39	$27.47
DWDM with 4 wavelengths/fiber	$8.93	$14.28	$34.93	$45.54	$29.83
DWDM with 8 wavelengths/fiber	$8.95	$12.56	$35.37	$42.52	$26.67

Figure 7: Scaled Down DWDM Configuration

a) Forward



b) Reverse



The results indicate the high scalability of the DWDM technology (see Figure 7). Even at today's prices for DWDM elements, the cost per home passed for this technology is significantly lower than the cost of any other technology. The DWDM element prices are on a very steep part of the price curve, which resembles the situation with 1310 analog technology between 1991 and 1995. Within these four years, prices for 1310 analog systems dropped by more than 50%.

The comparison between technologies was performed for a similar capacity/home passed provided by each technology. Table 7 compares the capacity for the technologies for low and high segmentation cases. As presented in [4], the capacity provided at the low segmentation scenario should be sufficient at very high HFC resource usage level. Although the segmentation analyzed in scenarios C through E is provisioned by the network design, fiber count, and node location and configuration, the resources provided by the high level of segmentation will not be required for several years.

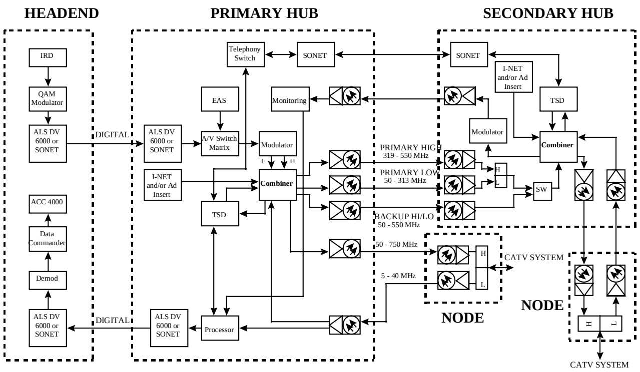
Table 7: Network Capacity per Home Passed

	Capacity (kbps)							
	64QAM/QPSK				256QAM/16QAM			
	Fwd	R	Fwd	R	Fwd	R	Fwd	R
Technology	Low segmentation		High segmentation		Low segmentation		High segmentation	
FDM	16	5	162	54	20	9	204	108
Hybrid with SONET	21		167		21		167	
Hybrid with 10BaseT	20		200		20		200	
DWDM with 4 wavelengths	22	5	216	54	27	9	272	108
DWDM with 8 wavelengths	22	5	216	54	27	9	272	108

To achieve the capacity required while using SONET or 100BaseT transport, caching was assumed at secondary hubs to stop 75% of the traffic generated in the secondary hub area. This will further increase the cost of deployment for these two technologies since caching will have to be deployed in very early service implementation stages. This deployment will lower the efficiency of caching (the same information will be cached at many locations).

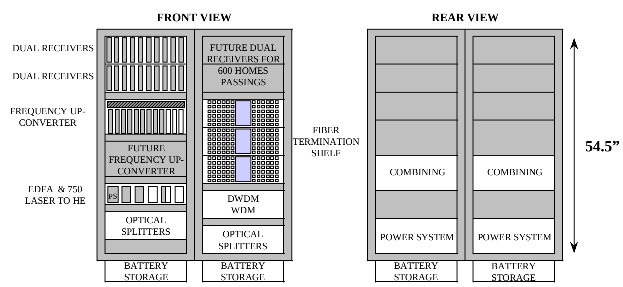
The data in Table 6 indicates that the SONET based architecture has some cost advantages at the high segmentation level and with full redundancy (low incremental cost of redundancy due to inherently redundant SONET transport systems). However, high scalability of the DWDM technology and the extremely high operating cost of secondary hubs, with signal processing equipment and SONET transport installed there, make the DWDM technology extremely attractive. Figure 8 depicts the complexity of SONET based network at the secondary hub level.

Figure 8: SONET Based Network



The DWDM equipment, on the other hand, requires little maintenance and little space. The secondary hub DWDM equipment, scalable to feed 40K homes, fits comfortably into 3x4x5 feet air-conditioned enclosure (see Figure 9).

Figure 9: DWDM Secondary Hub Equipment



Technical Challenges

Before a transmission technology can be deployed, one must analyze all possible impairment sources, design the testing scenarios to test each source independently (separation of impairments), and collect data to prove the technology or to indicate its shortcomings and means to correct them.

The review of technical publications and the discussions with engineering R&D teams from vendors resulted in a list of the following possible impairment sources in DWDM transmission systems:

1. Nonlinear Effects:
   - 1.1. stimulated Raman scattering (SRS),
   - 1.2. stimulated Brillouin scattering (SBS),
   - 1.3. self-phase modulation (SPM),
   - 1.4. cross-phase modulation (XPM),
   - 1.5. four-photon mixing (FPM),
   - 1.6. linewidth dependent frequency roll-off;
2. Linear Effects:
   - 2.1. CSO caused by laser chirp and fiber dispersion,
   - 2.2. PM-IM conversion on amplifier tilt and filter slope.

Nonlinear effects in fiber are often interdependent. Moreover, an effective correction of one problem may lead to another problem becoming a dominating contributor. Examples of such interdependency are:

1. SBS mitigation may lead to noise floor rise at higher frequencies due to PM-IM conversion,
2. Four-photon mixing is lower when the laser chirp and the fiber dispersion are higher, on the other hand higher chirp and dispersion result in CSO.

The theoretical analysis indicates that FPM and SBS can be disregarded for the fiber type (dispersion) and power levels present in the DWDM system. Moreover, SPM considerations for DWDM system with digital signals are no different than the same considerations for analog single wavelength system.

SRS and XPM will result in a crosstalk between the same channels carried on different wavelengths. Both effects increase with the total optical power in the fiber. SRS effect increases with the difference between wavelengths. Fortunately, both effects affect only the RF channels shared between the wavelengths.

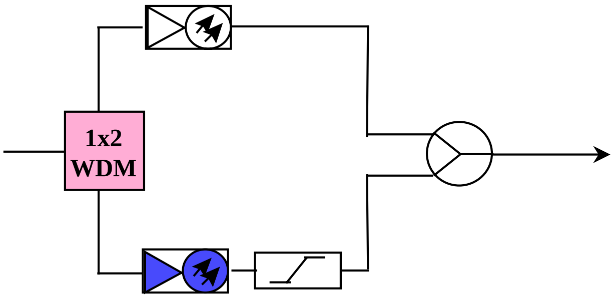
The last nonlinear effect, frequency roll-off, should not be a contributing factor but should be monitored during testing.

Linear effects may cause higher level of impairments and may be more difficult or costly to control. The most visible should be CSO caused by laser chirp and fiber chromatic dispersion. The control of the CSO level is possible by controlling either the sources (for example by using narrow linewidth external modulated lasers or non-zero dispersion shifted fibers) or the effects (by using dual receiver and clearly defined frequency assignment with adequate filtering, see Figure 8 for details). However, the means to control it may be too costly, impractical, or limiting the flexibility of the system operator.

The PM-IM conversion effects (such as higher noise floor at higher frequencies and CSO) should be also monitored during the testing process.

Besides controlling the impairment level, the system designer must define the alignment process (optical power levels at different points of the system, optical modulation index, etc.) that would allow meeting the performance requirements.

Figure 10: CSO Elimination in Dual Receiver



- **Dual RX**
  - ✓ **Broadcast F1-F2**
  - ✓ **Narrowcast F3-F4**
  - ✓ **F4-F3<F3**
  - ✓ **F3>0.5*max(F2,F4)**

Performance Requirements

Any new technology introduced to the HFC network should provide at least the same or equivalent level of performance as the technology being replaced. This approach allows for preserving the remaining sections of the HFC plant without a major redesign or upgrade. The following performance requirements were established for DWDM technology as equivalent to the performance of the complete optical link(s) between primary hub and the nodes (usually two analog 1310 nm links cascaded):

Forward:

1) Broadcast (@ node receiver output) for 50-870 MHz/82 analog channels:

   ⇒ CNR≥51.5 dB,

   ⇒ C/CTB≥65 dB,

   ⇒ C/CSO≥63 dB;

2) Narrowcast (@ node receiver output):

   ⇒ OOB C/N+I≥50 dB,

   ⇒ IB C/N+I≥46,

   ⇒ Flexible frequency allocation;

3) Combined (@ node receiver output):

   ⇒ Broadcast for digital signals at -10 dBc in respect to analog channel equivalent levels:

   i) CNR≥51 dB,

   ii) C/CTB≥65 dB,

   iii) C/CSO≥63 dB;

   ⇒ Broadcast for digital signals at -6 dBc in respect to analog channel equivalent levels:

   i) CNR≥50.5 dB,

   ii) C/CTB≥65 dB,

   iii) C/CSO≥63 dB;

   ⇒ Narrowcast:

   i) C/N+I≥40 dB.

Reverse:

1) RF:

   ⇒ CNR≥40 dB over temp. range,

   ⇒ ≥15 dB DR, 7 dB optical loss at 1310 nm plus 8-10 dB optical loss at 1550 nm,

   ⇒ level stability within ±1 dB;

2) BER performance:

   ⇒ ≤10^(-9) over operating range,

3) Reliability:

   ⇒ 15 years of MTBF,

   ⇒ redundancy for the key shared elements.

Test Results

The technology was tested in several stages:

1) R&D tests were performed by two vendors,

2) Technology feasibility test was performed in the lab environment with all system elements,

3) System tests were conducted on complete forward and reverse systems, and included thermal cycling.

The next stage (in April) will be performed in the field during pilot implementation of the technology.

All the results collected so far support the theoretical analysis. The main concerns were related to optimizing the alignment to achieve adequate CNR after combining and to minimizing CSO caused by laser chirp and fiber chromatic dispersion.

Second order distortions will introduce some limitations to frequency allocation. These limitations will disappear with an advance of low-cost directly modulated lasers (expected in the third quarter of 1998). In the interim, directly modulated lasers with low chirp (≤100 MHz/mA) will provide adequate performance as long as:

- the number of channels is limited (to 10 channels),

- the channels are placed above the middle frequency of the forward operating bandwidth, and
- the difference between the lowest and highest frequency of these channels is kept to a minimum.

The last limitation is not a critical one but will allow for second order intermodulation noise to fall below the forward bandwidth or at very low frequencies (CSO caused by chirp and dispersion at these frequencies is lower). Alternatively, the targeted signal channels can be randomly distributed to avoid multiple beats (accumulated intermodulation noise) at any particular analog channel. The maximum number of beats at any particular channel with 10-channel load will not exceed five beats.

Figure 11: Second Order IM Noise[1]

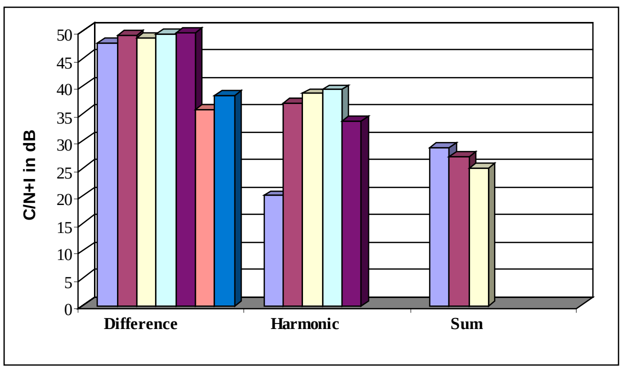


Figure 12: Narrowcast Signal Impact[2]

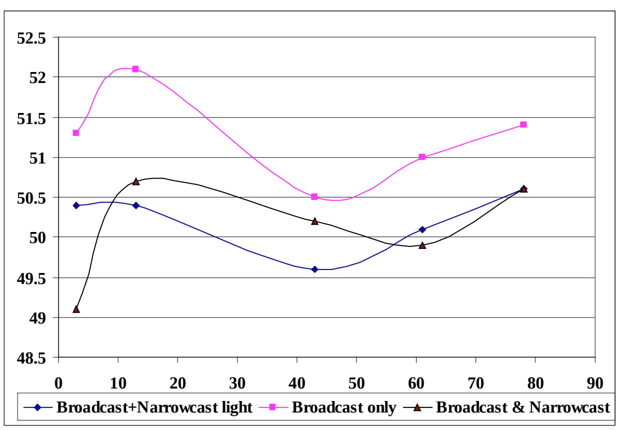


Figure 11 indicates that the second order difference products can be controlled as long as their frequency is below 200 MHz, even with lasers of 300 MHz/mA chirp. The second harmonics and second order sum products are relatively higher even at as low frequencies as channel 2. Placing the targeted service channels above the middle frequency would place these distortions above the highest operating frequency.

Figure 12 illustrates the impact of the second order distortions on the C/N+I. In the test case presented, the targeted signals were placed to produce four difference beats in channel 2. Even in this case (with lasers of 300 MHz/mA chirp and the alignment far from optimal), the performance was quite acceptable.

Alignment and CNR optimization process. Figure 13 shows the sensitivity of the target signal performance to the alignment parameters. The optimal choice of optical modulation index and receiver input power is crucial. For a constant RF output level (constant product of optical input power and OMI), the input power can be optimized to lower the impact of the target service signal laser RIN and fiber RIN on the total CNR.

Figure 13: Alignment Optimization[3]

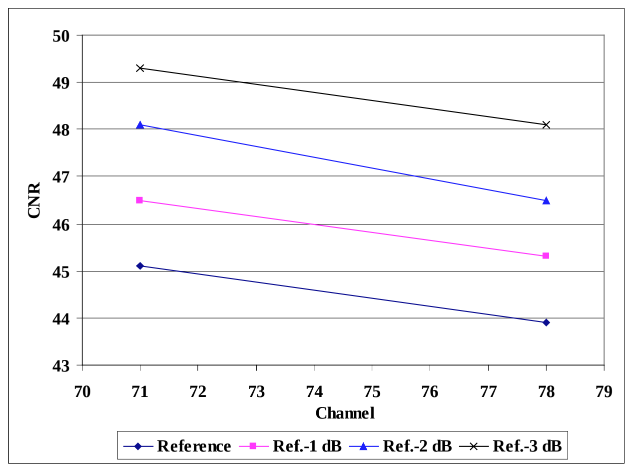
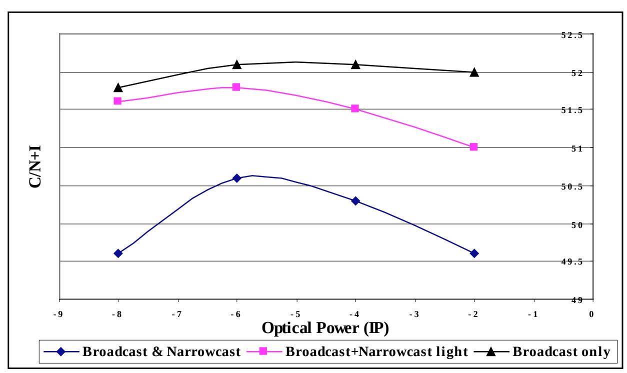


Figure 14: C/N+I Performance @ Channel 2[4]

a) Targeted Signals 10 dB Lower than Analog



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[1] Courtesy of Antec Network Technologies.
[2] Courtesy of Antec Network Technologies.
[3] Courtesy of Antec Network Technologies.
[4] Courtesy of Harmonic Lightwaves

b) Targeted Signals 6 dB Lower than Analog

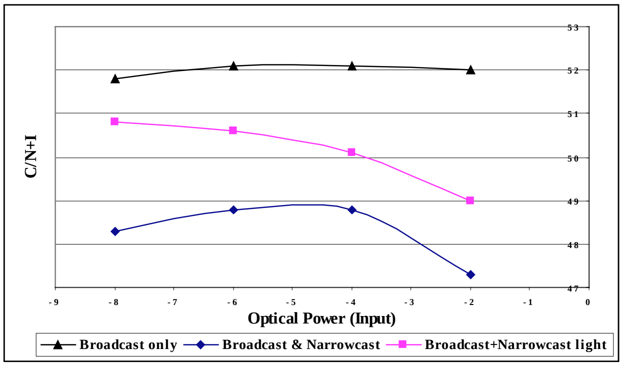
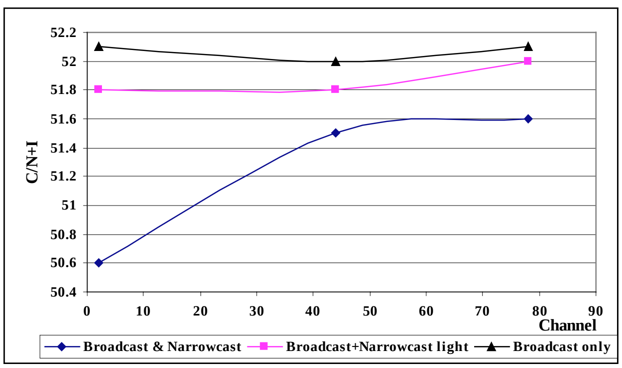


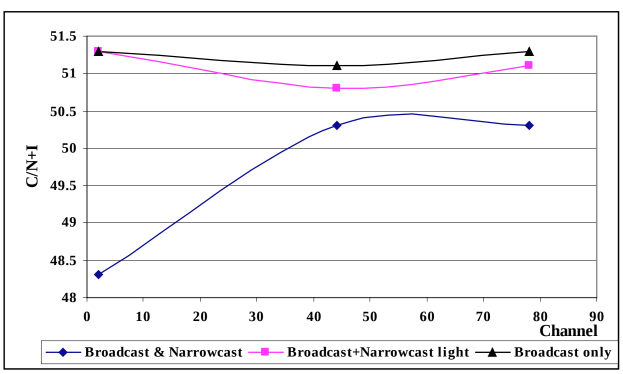
Figure 14 presents the alignment optimization process for targeted signals lower by 10 and 6 dB from the analog broadcast signals. The optimization was performed on the worst channel (channel 2 with second order intermodulation noise). The optimization for the 10 dB lower signals yielded very good results for wide range of optical input levels (CNR≥50 between –7.3 and –3 dBm). The alignment process for 6 dB lower signals achieved 49 dB CNR (worst case channel) for optical input level of –4.7 dBm.

Figure 15: CNR at Optimal Setup[5]

a) Targeted Signals 10 dB Lower than Analog



b) Targeted Signals 6 dB Lower than Analog



[5] Courtesy of Harmonic Lightwaves

Figure 15 illustartes the C/N+I performance of the WDM system afetr the optimization. The graph is misleading since only a few first channels were affected by second order intermodulation noise. All channels above channel 4 met the required 51 dB CNR for targetd signals lower by 10 dB.

Similarly for 6 dB lower targeted signals, all channels above channel 4 approached the required 50.5 dB CNR within the measurement error.

Reverse path testing yielded all the performance required without a significant optimization effort. The only potential risk was related to second order intermodulation noise caused by laser chirp and chromatic dispersion. The test results proved that the system had a performance safety margin.

CONCLUSIONS

The theoretical analysis of the DWDM systems and the testing performed during the last six months proved that the technology is mature for field deployment. The advantages of this technology over any other technology deployable in the secondary hub rings and the affordability and high scalability of this technology, makes it the most desirable alternative for the transport system in this section of the HFC network.

The most difficult to control impairments in the transport system based on this technology is related to second order intermodulation noise. The means to control this type of impairments are available today. However, the most effective ones are expensive or impractical. As long as the frequency allocation is reasonably managed, the second order intermodulation noise can be maintained at low levels with directly modulated lasers of low chirp.

The other major challenge is related to the CNR optimization. The understanding of the technology gained during the testing sessions allows for achieving the optimization during the designing stages in the same way that applies to designing 1310 and 1550 nm optical links.

The outcome of this activity is the authors' conviction that the technology offers major advantages in the secondary hub ring in HFC networks and is field deployable today.

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