HFC ARCHITECTURE IN THE MAKING

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Abstract

Many architectural realizations of the HFC network successfully support the services ranging from broadcast video (analog and digital), through pay per view and video on demand, to telephony and high-speed data. However, the HFC network and its architectural implementations continuously evolve to fulfill the increasing demand for reliability, high quality, and sufficient capacity to provide a broad array of services to an increasing number of customers.

This paper presents an analysis of various architectural implementations of the HFC network. These implementations range from a traditional Fiber-to-the-Serving-Area approach, through fiber overlay for digital services, to fully-passive coaxial networks fed by dedicated fibers.

INTRODUCTION

In the last several years, cable network operators have embarked on extensive upgrades and on the transition to hybrid fiber coax (HFC) architectures. The main goal has been to evolve the infrastructure from a broadcast-type trunk-and-branch plant to a high capacity, superior quality and reliability, and two-way network ready to deliver advanced telecommunications services.

The need for this evolution is apparent from the list of advanced services, which demand increased network capacity and quality. Even for video services, the competition from alternative broadcast entertainment providers and transition from analog NTSC based video to digital (standard and high-definition) video require additional attention from cable operators.

Services	*Architectures*
Traditional Services: ▪ Broadcast TV ▪ Broadcast Radio ▪ Addressable Services: - Addressable tiering - PPV - Games - Digital radio ▪ Home Shopping **Advanced Services**: ▪ Targeted advertising ▪ Targeted entertainment ▪ Telephony ▪ High speed data ▪ Full multimedia **Competition**: ▪ DBS ▪ LEC ▪ Multimedia mergers	**Requirements**: ▪ Superior reliability ▪ Superior quality ▪ Competitive price ▪ Interactivity (two-way) **Architectural changes**: ▪ Fiber supertrunking and backbone ▪ Regional hub ring ▪ Redundancy (secondary hub rings) ▪ Deep fiber deployment & segmentation

Table 1: Services, Requirements & Solutions

Although cost competitive in comparison to the upgrades of other access networks to the same level of capacity and performance, upgrading from trunk-and-branch coax plant to HFC network requires significant financial effort from cable operators. Therefore, while satisfying the needs listed in Table 1, it is critical that the upgrades accomplish the following objectives:

1. Establish a future-proof network
2. Lower operating cost

3. Significantly improve network reliability (MTTR: mean time to repair; and MTBF: mean time before failure)

All these considerations lead to our continuous efforts in defining and re-defining architectural solutions for HFC networks to capture the ever-changing landscape of service demand and affordability (cost/benefit ratio) of new technological solutions.

ARCHITECTURAL STUDY OBJECTIVES

This section outlines the scope and objectives established and followed by our team for this advanced architecture study.

Services Supported By the Network

The network must be capable of supporting a wide variety of services:

1. Analog video (basic, premium, PPV and IPPV
2. Digital video (broadcast and IPPV)
3. Interactive video (e.g., video on demand (VOD))
4. High speed data access
5. Telephony
6. Telemetry

Architectural Choices

For practical reasons, the analysis concentrated on several architecture alternatives:

1. Fiber-to-the-Serving-Area (FSA) with fiber node segmentation supporting forward and reverse communication services[12]
2. Trunk-and-branch coaxial architecture for traditional services with fiber overlay for advanced services[3]
3. Deep fiber penetration to eliminate RF actives (Multiplexed Fiber Passive Coax — MFPC)

Impact on Powering

The analysis considered the impact of all architectures on powering options for the plant and for terminal equipment. The following issues were analyzed:

1. Impact on overall network power consumption
2. Terminal equipment powering alternatives
3. Optimal network powering architecture (level of centralization)
4. Power distribution in the existing plant and in plant extension or new-builds

Acceptable Performance

All the architecture alternatives were analyzed for the same levels of performance:

1. Forward path end-of-line performance
2. Reverse path performance
3. Network availability

Equipment

The following issues were considered during the analysis:

1. Technology feasibility
2. Equipment availability
3. Equipment price

Fiber Count and Redundancy

To provide the level of reliability required for the advanced services, the network must allow for cost-effective redundancy and low mean time to repair. To achieve these objectives, the following issues were analyzed:

1. Number of fiber in single cable sheet
2. Redundancy in different network sections
3. Number of homes served per optical cable route without redundancy
4. Restoration time

Network Characteristics

While optimizing network topology to support different services with different characteristics, it is desirable to maintain transparency and flexibility in introducing new services. The team therefore defined and evaluated options and balances of:

1. Ultimate topology for backward compatibility and migration feasibility
2. Network transparency between terminal unit locations
3. Functionality of network terminals
4. Centralized vs. distributed network terminals

Cost Comparison

After taking into account the considerations listed above, the analysis concentrated on cost comparison for the architecture alternatives. The initial capital costs were compared against benefits and life-cycle savings. Some additional cost elements were also analyzed qualitatively (for example, terminal equipment cost).

Additional Considerations

The following additional items were considered:

1. Terminal equipment standardization
2. Time to market for the architectures (construction time and equipment development time)
3. Suitability for MDUs and plant expansions

This paper will provide a snap shot of this study with emphasis on the architecture alternatives, related features, and cost comparison. It will be seen throughout the paper that the differentiation among the alternatives are related to:

1. Bandwidth per home passed
2. Network power consumption
3. Network availability (reliability and MTTR)
4. Efforts of network alignment and certification
5. Maintenance cost

ARCHITECTURAL ALTERNATIVES

Generic HFC Architecture

Most of the existing HFC networks in markets exceeding 100,000 homes are based on ring configurations (single or dual). Traditional headends are consolidated, and are interconnected by the market rings (primary hub rings) with additional processing centers dubbed primary hubs (PH). The secondary hub rings are introduced to enable the headend consolidation. In this configuration, secondary hubs (SH) serve as signal concentration and distribution 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 (redundancy). These two elements are common to most of the HFC networks used by cable operators. The differences are limited to technological choices in these rings.[456]

This generic architecture is depicted in Figure 1. The network sections marked as 'C' and 'D' (access network) provide the last links to the customers. The architectural solutions for this network section differ from operator to operator. However, most of them deploy fiber-node-based configuration followed by active RF coaxial networks. The differences are reflected in the node sizes and in the level of redundancy. This access network is a subject of continuous architectural analysis by almost all major HFC network operators.

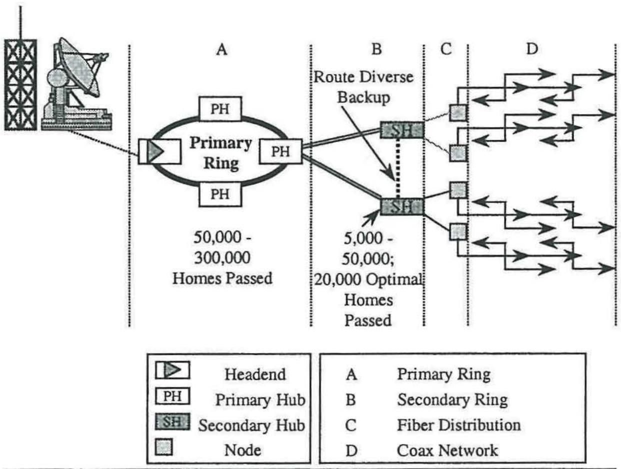

Figure 1: Modern HFC Network: Generic Configuration

Access Network Alternatives

Physically and logically, the last-mile access network can be categorized into two categories: Point-to-point (PTP) and point-to multi-point (PTMP). Examples of the PTP architecture include copper-pair based double star networks (traditional local telephone networks), certain FTTC networks, and WDM-based PON. Among the PTMP networks are such networks as HFC-based networks, certain TDMA-based PON, and wireless networks. Each network was historically defined to support certain type of services with their intrinsic characteristics. The challenge we are facing today is how to evolve the network architecture to support a wide variety of services with characteristics that the embedded system was not originally designed for.

The HFC network was originally designed for broadcast services with PTMP architecture. Utilizing emerging lightwave technology with different levels of fiber deployment, our study concentrated on defining upgrade alternatives to support new service needs that may be optimized with certain degree of virtual PTP configuration. The alternatives were:

1. Fiber to the Serving Area with fiber node segmentation supporting forward and reverse communication services
2. Trunk-and-branch coaxial architecture for traditional services with fiber overlay for advanced services
3. Deep fiber penetration to eliminate RF actives (Multiplexed Fiber Passive Coax — MFPC)

FSA with FN Segmentation

This network architecture (Fig. 2) has been used by many HFC network operators. The differences are mostly related to the node sizes, with particular emphasis on the design effort (optimization for power consumption, time-to-market, or end-of-line performance and bandwidth) and the level of redundancy (refer to Cox's ring-in-ring topology). In the analysis performed by the team, this architecture was used as a baseline[7] and was characterized by the following parameters:

1. Node size is between 600 and 1,200 household passed (HHP)
2. Each FN can be segmented with up to four 300 HHP buses
3. Number of fibers from secondary hub to the node are between 4 and 6,
4. Number of amplifiers in cascade are between 5 and 8,
5. Upstream is in 5-40 MHz, and downstream is in 50-750 MHz with 50-550 MHz being allocated for analog video and the rest of the bandwidth for digital services

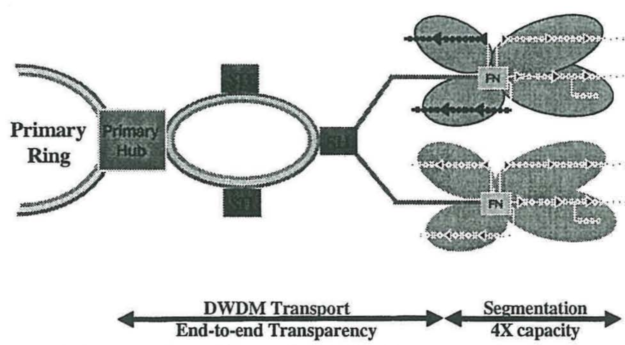

Figure 2: FSA with FN Segmentation

Mini Fiber Node for Fiber Overlay

To resolve upstream limitations (ingress noise and bandwidth) and to simplify terminal operation, we proposed and evaluated the mini fiber node technology. Using emerging lightwave technology, the existing network is overlaid with a fiber-to-the-bridger architecture to exploit the large ingress-free bandwidth at high frequency for two-way digital services. As shown in Fig. 3, independent of existing systems, the mFNs couple directly into the passive coax legs (with drop taps) after each distribution coax amplifier (i.e. line extender). Each mFN contains a low-cost laser diode and a low-cost PIN diode, and is connected to the headend with separate fiber.

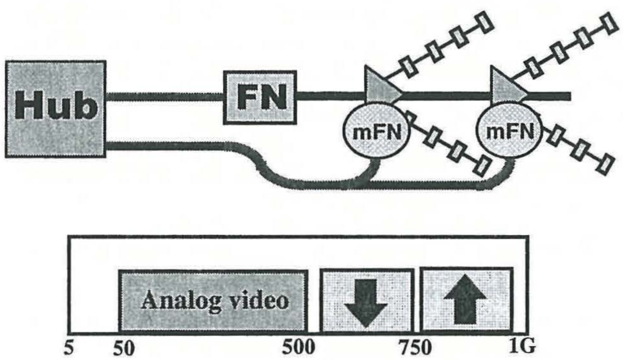

Figure 3: Mini Fiber Node for digital overlay

Based on this strategy, the mFNs subdivide the FN serving areas into small cells (typically 50 HHP/mFN) and exploit the clean and large bandwidth at high frequency for both upstream and downstream transmission. The mFN therefore creates a new path for digital services without affecting analog TV services carried by conventional FN/amplified-coax paths. All services are then merged over passive coax distribution legs.

Features of the mFN architecture:

By exploiting the clean and large bandwidth, this strategy increases overall system bandwidth beyond current coax amplifier limitations, for new digital services, without replacing coax amplifiers and changing amplifier spacing. It also avoids the complexities of noise reduction (e.g., frequency agility) and related signal processing and RF techniques. This therefore simplifies system operation and reduces terminal cost.

Also, because mFNs only carry digital subcarrier signals over a clean high-frequency band, low-cost, low power consumption and space-saving optical and RF components can be used in the mFNs and also at the headend.

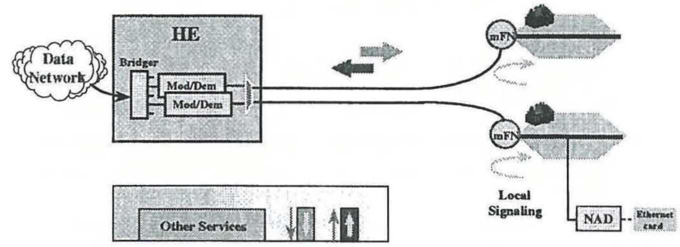

Figure 4: mFN Local Access Control Protocol

The unique position of each mFN enables a considerable simplification in defining media access control (MAC) protocols. Each mFN can do local policing, and resolve upstream contention within its serving area without involving other parts of the networks (Fig.4). This can be accomplished by incorporating a simple out-of-band signaling loopback scheme such that users know the upstream channel status prior to transmission. This enables the use of standard, but full-duplex, Ethernet protocol (CSMA/CD), and therefore the use of standard and low-cost terminals (modified Ethernet transceiver, Ethernet bridger and Ethernet card). No ranging is needed, and the headend becomes virtually operation-free. The relatively small round-trip delay between each user and the mFN (~2000ft) also substantially increases bandwidth efficiency and reduces contention delay. This is appealing for VBR (variable bit rate) type of services. For CBR (constant bit rate) services, certain scheduling or priority provisioning may be necessary, and can be easily added to the above protocol (Fig. 5).

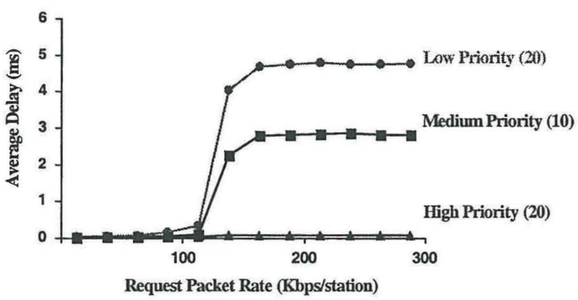

Figure 5: mFN-based priority provisioning protocol

The large bandwidth supported by the mFN infrastructure also enables the use of efficient but much simpler modulation schemes such as multi-level FSK or even ASK. This therefore provides a low-cost, low-power-consumption alternative to the current cable modem technique.

Open Issues:

The mFN technology explores a radical path to resolve the network limitations. Unfortunately, the existing system for broadcast video and DOCSIS-modem-based services is left behind with no benefits from the mFN strategy.

Bringing fiber deeper into the network incurs certain incremental cost. Reducing the cost of fibering (material and labor) then becomes critical. The mFN strategy will simplify system operation for new services and reduce terminal cost. However, it will be more compelling if the front-end cost can be justified by operational savings over the *entire* network, both embedded and mFN overlay.

Convergence: Multiplexed Fiber Passive Coax Networks

To resolve those issues and to establish a platform that can improve the performance of the embedded system while also evolving to meet future needs and simplifying operations across the entire network, we proposed a new architecture called Multiplexed Fiber Passive Coax (MFPC). As shown in Fig. 6, instead of overlaying over existing coax amplifiers, mFNs eliminate all the coax amplifiers. (our design indicated that 2-3 coax amplifiers will be eliminated by one mFN). Between each mFN and customers, passive coax plant is used to carry both current and new services.

Fibers connecting multiple mFNs will be terminated at the MuxNode that resides either at the original fiber node location or at location that "consolidate" multiple FNs. As its name implies, the MuxNode performs certain concentration and distribution functions. It "multiplexes" the upstream signals and sends them to the primary hub through the secondary hubs. It also "demultiplexes" the downstream signals received from the PH-SH fiber trunks and distributes them to mFNs.

One of the interesting features of this architecture is that it maintains the characteristics of conventional HFC networks of being transparent to different signal formats and protocols, therefore fully supporting the existing operation for current services. To future-proof the network with more capacity and simple terminals, this architecture can also support a distributed-processing strategy for new, purely IP-based services enabled by the mFN and MuxNode, and maintain all the benefits of the initial mFN strategy. The development can be partitioned into two phases.

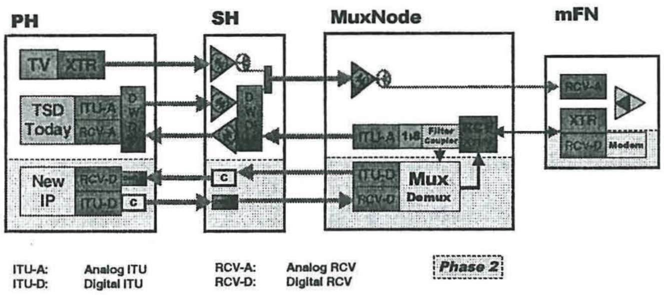

Figure 6: Multiplexed Fiber Passive Coax (MFPC) architecture

Phase1: Current Service Delivery

One preferred approach is to transmit downstream broadcast signals, including analog and digital video, over dedicated fiber from the primary hub to the secondary hub. The existing narrowcast and switched signals, such as telephony and high-speed data using DOCSIS-based cable modems and set top boxes will be DWDM multiplexed at the PH and transmitted over another fiber to the secondary hub. After DWDM demultiplexing, the narrowcast and switched signals will be optically combined with the broadcast signals (in a different RF band) and transmitted to the MuxNode over optical fiber.

At the MuxNode, those combined downstream signals will be optically amplified and distributed to multiple mFNs over optical fiber. Given the short distance between the MuxNode and the mFN, it is also feasible to move the EDFA from the MuxNode to the secondary hub and only keep the optical splitter at the MuxNode, therefore simplifying the MuxNode. Other options, such as re-lasing at the MuxNode, are also promising.

The mFN performs the same function as that of a typical FN. It receives downstream signals and distributes them to customers over passive coax cable. In the upstream direction, the mFN combines upstream signals from all the coax branches it serves and transmits them to the MuxNode over optical fiber.

The MuxNode further performs O/E conversion to those upstream signals from the mFNs, RF combines them, and transmits to the secondary hub using a wavelength specified laser. Upstream signals from multiple MuxNodes will be then DWDM multiplexed at the SH and transmitted to the PH. Besides DWDM multiplexing, another option is to re-lase upstream signals at the SH.

To expand capacity of the system, one can frequency shift the upstream signals at each mFN such that when they are combined at the MuxNode they will be at separate RF bands. If the re-lasing option is used at the SH, the frequency stacking could also be deployed at the MuxNode.

Phase 2: Add-on Distributed Processing Platform

As shown in Fig. 6, a distributed processing platform can be transparently added when it is needed. The new IP-based services could be delivered to the MuxNode in baseband format over a DWDM link separate from the one carrying current services. As an alternative, the baseband signals and RF passband signals could be transmitted over the same DWDM link. At the MuxNode, the baseband signals are demultiplexed and further distributed to multiple mFNs.

At each mFN, the downstream digital baseband signals are received and modulated onto RF carriers. They will then be combined with the received downstream RF signals and transmitted over the coax buses to customers. In the upstream direction, customers transmit the new IP-based upstream signals in a high frequency band (900 MHz – 1 GHz) to the mFN using simple FSK or QPSK modulation scheme. At the mFN, the MAC function is performed for those high frequency signals as discussed before. Those signals are also demodulated to baseband. They will then ASK modulate RF carriers at frequencies above the current 5-40 MHz return band. These signals will be combined with the 5-40 MHz band, and transmitted to the MuxNode over a single fiber. Another option is to frequency shift the 5-40 MHz band and keep the baseband signals untouched.

Between the MuxNode and the mFN, coarse WDM (1.3µm/1.5µm) is used for single fiber bi-directional transmission. At the MuxNode, the combined upstream signals are received and separated. The ASK signals are demodulated and multiplexed, and the 5-40 MHz band signals are RF combined (or frequency stacked). Both signals will be transmitted to the PH over the same or separate DWDM trunks.

COST COMPARISON

Front-end Cost

To evaluate implementation feasibility, we completed more than 600 miles network design of the above three architectures, and compared the front-end cost. An example is shown in Fig. 7. The design was over a medium-density system with 80 HHP/mile. The analysis was based on the existing and emerging lightwave and RF technology, and the parameters used in the cost model, such as labor cost, were based on commonly used industry averages.

It is interesting to see that, with the help of the MuxNode and by eliminating all coax amplifiers, the cost of the passive coax design is comparable to that of initial mFN design. Of course, the value of this architecture is far greater than any other alternative.

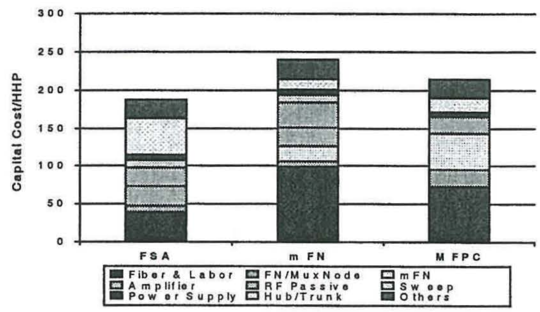

Figure 7: Front-end cost comparison

Life Cycle Cost

One of the biggest advantages of this architecture is the elimination of all the coax amplifiers. This results in substantial reduction in active components and therefore reduction in overall network power consumption (Fig. 8 and 9). In addition, sweeping and maintenance of active components in the field will be reduced, which leads to further operation savings. It is estimated that annual operation savings, including reduction in customer calls. etc, could reach $11/HHP.

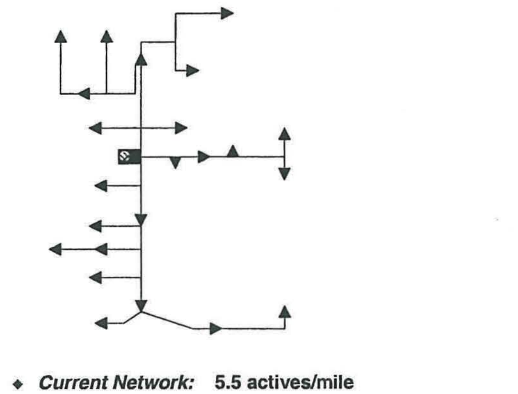

Fig. 8 Current FSA HFC

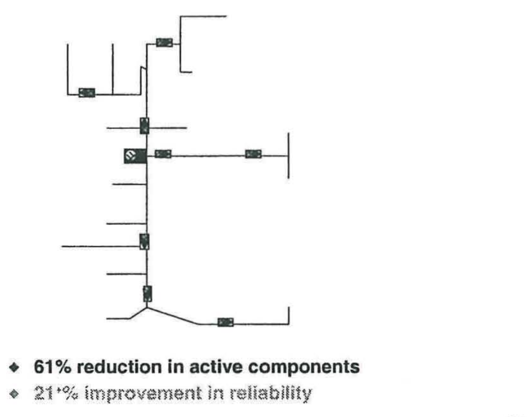

Fig. 9 MFPC

CHARACTERISTICS OF MFPC NETWORKS

Powering

Due to a significant reduction in the number of active devices and the progress in RF active component technology, the power consumption of the network elements will be decreased by at least 50%. This will allow for powering architecture optimization and for less challenging powering of the customer terminal devices.

Network Availability

The network availability increases dramatically, especially after the implementation of phase 2. In phase 1, elimination of the active cascade and the lower number of actives will allow for reduction in number of failures per MuxNode area. Moreover, due to the star configuration, the failure group size will be significantly lower (especially in the case of optoelectronics failure). Additional improvement in network availability will be realized thanks to lower MTTR (easier network troubleshooting). This feature will be significantly enhanced after implementation of phase 2 (dedicated bandwidth to smaller group of homes). Optimized powering will further improve the network availability.

Flexibility

The MFPC architecture maintains the transparency of the HFC network. In phase 1 of the implementation, the architecture does not differ from the traditional node-based architecture except for the fiber depth. When phase 2 is deployed, the network combines all the benefits of the HFC network and the cell-based multistage multiplexing architecture. Any new service can be implemented by addition of the terminal equipment at the customer premises and in few network centers.

This MFPC supports today's terminals, while paving an easy migration path to enable high-performance terminals and simple operation scheme. The DOCSIS-based cable modems can operate normally with better performance due to reduced bandwidth sharing and potential elimination of the noisy 5-15 MHz band. The simple modems, based on simple modulation and local access control ("Ethernet-like") protocol, can be added on when they are needed.

Capacity Growth and Future-Proofing

In phase 1, the network can deliver several (up to 10) TSD channels downstream with either 64 or 256 QAM modulation (presented in reference [1]). The reverse capacity per home passed can be increased by 50% if 64QAM modulation can be used (the MFPC architecture will provide significantly better reverse performance from the point of view ingress and interference management).

In addition, this architecture provides several unique paths for bandwidth expansion that other networks cannot match. In phase 1, this can be accomplished by:

1. Expansion of the traditional reverse bandwidth to 45/48 MHz (no filter cascading)
2. Wider implementation of concentration at the MuxNode (instead of conventional RF combining)

More important, the MFPC ensures that the major part of the network stretching between the primary hub ring and the mini fiber node is future-proof and provides large bandwidth capacity (a bandwidth upgrade for this part will require upgrading some equipment in the primary hub, secondary hub, MuxNodes and mFN). In the passive coax plant, up to 100 Mbps capacity can be added and shared among 100-200 homes passed. This capacity can be provided with QPSK modulation and will be symmetrical. An increase in this capacity can be further achieved by deploying more efficient modulation schemes. Positioning the mFN closer to customers further paves a simple path to even bring fiber to the homes when it is needed.

CONCLUSION

HFC is no doubt the first economically viable means for broadband services. The need to further upgrade networks for future-proofing motivates industry to explore new architectural solutions. We studied three architecture alternatives, analyzed their capabilities, and compared their costs. The results demonstrated that, by utilizing multi-stage multiplexing topology and emerging lightwave and RF technology, deep fiber penetration offers a future-proof network. The new MFPC architecture supports all current system operation with better performance, and enables abundant noise-free bandwidth for future growth. The advantageous architecture reduces the number of active components in the field, therefore simplifying network powering and operation. The incremental front-end cost can therefore be justified by life-cycle savings. More operation savings can be further realized with simplified terminal equipment. Yet the capacity, reliability, and performance of this new network are far better than that of other alternatives.

ACKNOWLEDGMENT

The authors would like to thank their colleagues: Adel Saleh, former division manager of AT&T Labs, and Mark Dzuban, Cameron Gough, Marty Davidson from AT&T Broadband Services Engineering for their support and assistance to the advanced architecture study.

The authors also would like to express their gratitude to Bogdan Lomnicki and his team at Quasar Inc for designing the advanced architecture over our cable networks.

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