SYNCHRONIZING DEEP FIBER BASEBAND ACCESS NETWORK DESIGN WITH TRADITIONAL HFC INFASTRUCTURE

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Abstract

Increasingly optical network technologies are being evaluated for their suitability as a residential access network platform. Clearly optical networking holds promise for the distant future as networked applications evolve to demand greater transport capabilities. However, today and for years to come HFC based access systems with their low cost structures and evolving performances will remain the dominant access network of choice for delivery of interactive multimedia services in the majority of the served residential markets. In a contemporary context it is quite likely that an all-optical access platform could be best utilized as a strategic tool tailored to delivering high-value business class services to 10% or less of a residential serving area. A low first cost optical access network may be an ideal strategic/offensive overlay to an existing or new HFC network.

This paper explores the key applications engineering issues associated with such an overlay and proposes a methodology for synchronizing key optical access and HFC network elements. The paper concludes with a detailed analysis of how optical split ratios and cable sheath fiber counts can impact plant first costs. This work is focused on the engineering issues associated with layer 1, physical layer, of the 7-layer OSI network model. Commentary on upper layer requirements and protocols are limited to issues that impact the logistics of an overlay deployment and subscriber provisioning.

HFC AND FTTx ARCHITECTURES

The overlay of contemporary deep fiber architecture on an existing or new HFC plant is facilitated by effectively coordinating the location and functionality of key network elements. A brief review of each access method's legacy and contemporary structural fundamentals will serve as a useful point of reference as various design and cost sensitivities are explored later in the analysis to follow.

Hybrid Fiber Coax (HFC)

Routinely the architectural details of HFC plants are varied to meet a host of constraints associated with factors such as geography, home density, up-grade logistics, costs as well as many other details. However fundamentally most plants adopt a variant of a ring(s) – star(s) – bus configuration, as illustrated in Figure #1. Typically one or more fiber rings interconnect primary headend and hub facilities, in some cases secondary rings link headends with secondary hubs or **optical termination nodes** (OTN's) that commonly serve tens of thousands of subscribers. In turn fiber nodes are typically linked to hubs, OTN's or headends in a star configuration.

Ring and meshed configurations offer physical path diversity and associated enhancements in plant reliability. As high performance service and business models stimulate the need to extend fiber deeper into the plant a greater use of rings is anticipated at deeper levels. Within this trend network functionality is also on the move, network process functions are migrating to the edge of the plant where they can be better tailored and incrementally scaled to meet subscriber and new business demands. A third ring extending from a secondary hub through a series of smaller serving areas to remote star locations at the one to four thousand homes passed level effectively enables the deployment of advanced video and cable data services [1] and, is a logistical requirement for the deployment of an all-fiber access overlay, as will be shown later in this paper.

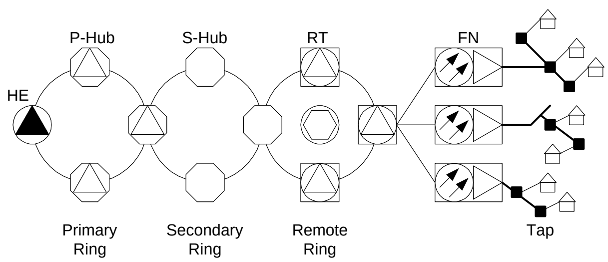

Figure #1

Optical Access Network Overlay

Various all-optical access networks are increasingly seen as:

- The enabler of high value services to a large underserved population of small business and home offices.
- A low risk infrastructure enhancement that has the potential to extend a plant's useful life well beyond that of copper based technologies.

A contemporary all-optical access architecture must be optimized to cost efficiently deliver advanced services to a small percentage of a wide subscriber market base being passed.

To insure the integrity of these services and an extended useful plant life the network must be reliable and easily scaled with increasing take rates without major upgrade or modification.

By contrast to most copper based networks all-optical access networks do not utilize active amplification or signal processing elements in the transmission path and are referred to as **passive optical networks** or PON's. Ideally the active elements at both the subscriber and service provider ends of the network are safely housed in conditioned facilities, and only passive components such as fiber cable and splicing devices suffer the environmental rigors of the outside plant, as shown in Figure #2.

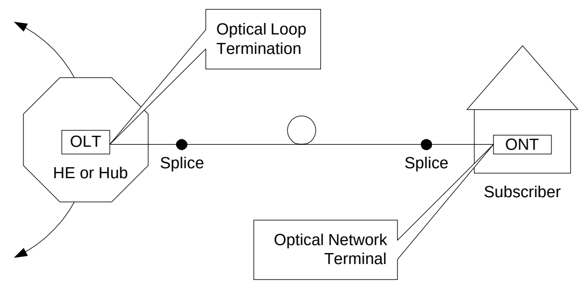

Figure #2

Rarely would a dedicated fiber connection between the service provider's internal network and a residential or small business subscriber be cost effective. To distribute costs a means of allowing multiple subscribers to access a network fiber is implemented through the use of multi-port optical splitter or coupler, Figure #3a.

In this instance each PON fiber becomes a shared media. Downstream traffic is broadcast to all of the subscribers served by a splitter, and upstream access is controlled via a suitable **media access control** (MAC) protocol, a number of which are competing for industry acceptance. For reasons relating to cost and operational logistics it is often not desirable to lump the splitting function into one physical location [2,3]. As shown in Figure #3b the splitting function can be divided between multiple locations along the fiber path. The product of the split ratios at each location becomes the PON's overall return fiber to subscriber ratio.

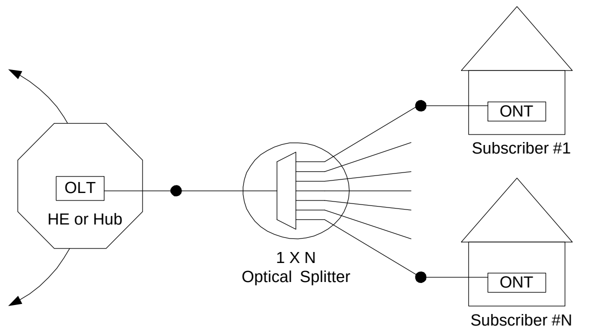

Figure #3a

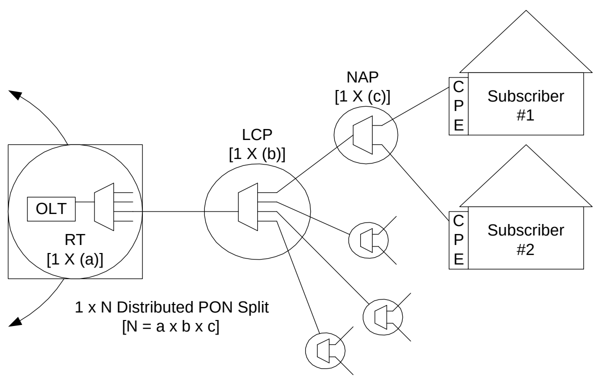

Figure #3b

The sizing and distribution of the PON splitter function is the principal tool used to synchronize an optical access network's elements with an existing or new HFC plant.

As previously mentioned, ideally a PON's active elements are housed in conditioned environments. However the realities of applying an optical network design to a wide serving area typically demand that active electronics be placed in the outside plant. At the subscriber side of the network the logistical realities of service activation place the **optical network terminal** [4] (ONT) outdoors on the exterior of the subscriber premise as **customer premise equipment** (CPE). At the network side construction costs and operational issues typically demand a high degree of fiber aggregation deep in the design. Without such measures fiber counts quickly become difficult to manage with even the highest of PON split ratios. Network reliability and scalability suffer; typically it is not practical to provide path redundancy on one or a few PON fibers, however when hundreds of fibers collect on their way to a network facility the failure group size and recovery time from a fiber cut become unacceptable. Further, high fiber-count headend or hub runs are very likely to exceed existing fiber inventories and subsequently adversely impact plant first costs.

*The location of **optical loop termination** [4] (OLT) synchronizes quite well with the evolution of the third ring nodes or **remote terminals** [1] (RT's) in advanced HFC architectures.*

Commonly an OLT or RT location will service a 1000 to 4000 home area. Construction practices demand the consolidation of fiber cable sheaths as they route to the RT. These **local consolidation points** [2] (LCP's), Figure #3b, provide another physical location to easily distribute a portion of the network's total split ratio.

The proper allocation of PON split ratio to the LCP can be used to synchronize its physical location in the network with that of each physical HFC fiber node, thus providing a convenient fiber path for the HFC node and common physical point of equipment access.

Access to the PON fibers passing a subscriber premise is achieved in manner similar to an HFC coax tap. The principal difference being that the equivalent PON tap is fed by a dedicated PON fiber that is not shared by other up or downstream PON taps, Figure #3b. To logically clarify this difference the PON fiber tap point is referred to as a **network access point** [2] or NAP. Fundamentally a NAP is composed of a suitably sized ground or aerial mounted fiber splice enclosure near a small group of subscribers. The optical service drop to the subscriber is terminated at the CPE using an optical splice or connector. At the NAP the drop will be spliced either directly on one of the PON fibers passing through the NAP or onto a port of an optical splitter located in the NAP.

The installed first cost and service activation cost of a PON are quite sensitive to the fraction of the total PON split ratio allocated in the NAP. In general a higher split ratio at the NAP yields a lower first cost of construction and slightly higher cost per subscriber served should the take rate at the NAP exceed 50% of its capacity.

Another challenging issue regarding PON architectures is that of remote active element powering. Historically remote network device power has been supplied via the metallic signaling media. Without such a media a PON must either include some form of copper based powering network or its remote actives must be locally or subscriber powered. Both alternatives have their advantages and difficulties, a selection between which will largely be determined by business and public policy issues.

The issue of powering remote PON equipment in an HFC overlay is facilitated by utilizing the powering signal commonly available from the underlying CATV distribution coax.

By including a light gage twisted pair with the subscriber's optical drop network power can be provided to the CPE using industry standard power passing tap devices. In those cases where spare power capacity is not available from the HFC network other twisted pair powering alternatives exist that can be implemented at the time of plant construction at a modest percentage of total PON overlay cost.

NETWORK DESIGN CONSTRAINTS

The practical objective of a design is the implementation of a serviceable network that meets near and long term needs for the lowest possible cost. Compliance with this objective in legacy copper based technologies are strongly enforced by well understood and refined engineering practices. In part the scope of these practices must be expanded when new technologies such as PON are adopted. The following material outlines key engineering, construction and operational considerations that will act to constrain the design variables associated with implementing a PON overlay.

Serving as a reference point for the following discussion, Figure #4 is a simplified illustration of a PON overlaying an HFC fiber node with a physical size 256 **homes-passed** (HP). In turn the **physical node** (PN) is fed by a 1000 HP **logical node** (LN) or **remote terminal** (RT).

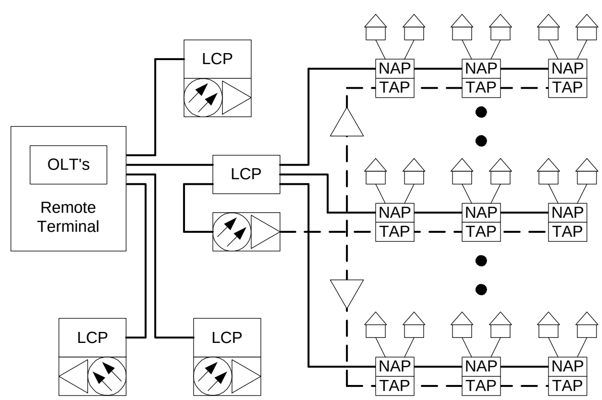

Figure #4

Network Engineering Considerations

Routinely more than one communications service provider serves a residential or commercial market area. This implies a reduced initial service activation rate as market share is obtained. Accordingly new plant designs of any type are commonly engineered for a lowest possible first cost that enables the network to physically address the market area. This condition is particularly true with regard to PON deployment. It is anticipated that early take rates for PON based services will be quite low, less than 10% of HP. This condition is likely to remain until the value of service portfolios, exclusively deliverable via an optical network, increase and construction cost associated with PON decrease.

With a lowest possible first cost a PON overlay must address 100% of a market service area, and with minimal provisioning or manipulation the network can be made available any one of the subscribers passed.

In keeping with a low first cost and take-rate assumptions it is anticipated that PON split ratios will be under subscribed by as much as 50% and that initial RT data processing capacity will be oversubscribed by as much as 10:1. These two factors substantially lower first costs with regard to OLT ports, associated packet switching and fiber counts and/or advanced optical wavelength provisioning in the upper network transport rings. A 50% under subscription of a PON split ratio implies that less than 50% of a PON's available optical splitter ports will be terminated and in service at any one time. To enable this engineering option the selected MAC protocol must have the ability to dynamically allocate access to the PON over a specified range of possible subscriber counts. This capability greatly simplifies provisioning and record keeping while allowing the network to provide bandwidth to customers based upon the terms of their subscription agreements without regard to the number of subscribers terminated on a given PON. Conversely, and based upon optical budget limits - discussed later, under subscription allows the network engineer to pass lit fiber by all of the homes in a given serving area without excessive OLT costs.

Selection of the proper MAC protocol and the planned under subscription of a multi-port PON allows the network to distribute lit fiber past 100% of the subscriber base without encumbering excessive OLT provisioning cost or degrading subscriber data throughput.

If the PON is to be under-subscribed it is advisable to take measures that help ensure the under subscription through the life of the network. This can be achieved by distributing a portion of the PON split ratio to the LCP. By doing so each of the PON's ports can be spread across multiple distribution branches or NAP locations that are not geographically adjacent. Routinely subscription rates in small clusters of homes passed can reach 100%, by spreading a PON's ports across multiple distribution branches the likelihood of 100% utilization is diminished.

The PON network must be capable of supporting the eventual migration of standard services delivered today via copper media. This requirement principally impacts optical budget limits that in turn drive PON split ratios and passive device performance limits. Large PON split ratios such as 1:32 demand optical **physical interface** (PHY) transmitter power levels of up to +20dbm. Elevated levels such as this are achieved at a cost premium and bandwidth penalty over more common PHY transmit levels of +10dbm or less.

In years to come the need to operate the PON at multi-gigabit speeds is almost certain. Large PON split ratios and the associated elevated PHY transmit power levels are likely to delay the point in time where an *existing network can be easily upgraded to multi-gigabit operation.*

Thus PON splits such as 1:8 or 1:16 are attractive from the point of keeping CPE PHY-device costs down and ensuring early migration to higher data rates. It may also be advantageous to allocate some portion of the PON split ratio to the OLT side of the network. For example, a 4-port directional coupler can facilitate insertion of overlaying λ's to support additional services in the future.

Construction Engineering

Minimizing construction first costs are key to the financial success of a PON overlay. Low first cost enables early economic business models that rely on the delivery of high value services to a selected few of the subscribers passed by the network. Unfortunately only a small number of PON networks have been deployed and related experiential knowledge is limited at best. The following points address construction issues impacted directly by PON architecture decisions.

Through the analysis to follow it has been found that PON construction costs are reasonably insensitive to actual fiber counts. However costs are particularly sensitive to the labor associated with fiber management, termination and optical splitters along with related outside plant enclosures and places to locate them. Again the size and distribution of PON split ratios can be optimized to minimize these initial costs.

Analysis has shown that poorly designed 1:32 or 1:16 PON can be significantly more expensive than an optical network based on a dedicated home-run fiber for every home passed!

PON fiber counts at a single location in the network can easily escalate to levels that are exceedingly difficult and costly to manage. Additionally, in the event of a fiber cut a large count represents a correspondingly large failure group size. For example; 200 - 1:16 PON fibers under subscribed by 50% still represents 1,600 high-value paying subscribers that will lose service when a pole falls or a cable is dug up. With cable restoration time in mind it is advisable to keep individual fiber sheath counts below 50 if possible and fiber aggregation point (LCP and RT) counts well below 150. This can be achieved by adjusting the amount of PON split ratio performed at the NAP and LCP.

Increasing NAP split ratios reduce fiber counts at the LCP and move the LCP into the network, which can be used to synchronize the LCP location with an existing or planned HFC fiber node. Correspondingly higher LCP split ratios have the same effect on the RT.

A uniform bill of materials composed of industry standard elements that are frequently reapplied throughout the construction footprint enforces cost control and reduces construction schedule delay risks. The selection of one standard cable sheath fiber count for all distribution branch runs and another for feeder runs between the LCP and RT is beneficial. The variables involved in selecting a distribution branch fiber count are NAP split ratio(s), anticipated home density range, HFC distribution branch length (typically on a per active basis) and an allocation for spare fiber. Table #1 illustrated how NAP split ratios can be selected based upon home density and branch length. In this case higher NAP port counts are implemented using two smaller optical splitters. Such an approach allows the deferral of the optical splitter and its associated cost.

Distribution Branch Cable Sheath Fiber Count Scaling			
Length	900' Typical		
Homes Passed	8 HP	16 HP	32 HP
CATV Tap Size	2 Port	4 Port	8 Port
Taps / Branch	4	4	4
NAP Split	1:1	2x1:2	2x1:4
PON Fibers	8	8	8
Spare Fibers	4	4	4
Total Fibers	12	12	12

Table #1

A generous allocation of spare fiber throughout the design will insure restoration and application flexibility in the future, and possibly aid in addressing legislative issues associated with equal-access. Adding individual fibers to sheath counts has a relatively minor impact on first cost. Later these fibers can be used to deliver high value multi-gigabit services via dedicated port connections from facilities remote to the subscriber such as a primary headend or hub.

At the time of this paper's authorship the industry does not provide a selection of low cost standard NAP enclosures suitable for co-location with standard and power-passing cable television taps. This condition will change as PON deployments become more routine.

Operations Engineering

Easy PON subscriber provisioning and low or no PON equipment maintenance are key operations cost control objectives. To meet these objective measures must be taken at each physical level of the PON as well as at the MAC protocol layer.

Installation of a subscriber service drop and CPE must be executable by a technician with a relatively low craft skill level and without the need of advanced tooling or diagnostic equipment.

Turn-up of the CPE must be a plug-n-play event with the MAC protocol automatically handling provisioning and network access issues in much the same way as done today by cable modems via the **data-over-cable service interface specification** (DOCSIS) protocol.

Optical budgets, noise and return loss margins must allow the use of industry standard mechanical fiber splice devices at both ends of the service drop. Experience has shown [3] that cable drop damage due to bending or dirty connections can occur during the installation process. The ability to easily open connections for **optical time-domain reflectometer (**OTDR) measurements at the NAP and below the last optical splitter is convenient. Additionally the PHY receivers at both at both ends of the PON must provide a dynamic input range that can tolerate the initial exclusion of the NAP's optical splitter.

The ability of the PON to tolerate the exclusion of the NAP splitter for the first NAP subscriber is more difficult to achieve when high optical split ratios are applied at the NAP.

The service technician cannot be required to access or open adjacent NAP or LCP enclosures to establish which PON fiber the subscriber's NAP has been allocated nor to activate or light the PON fiber. Having to access other devices during the provisioning process can be logistically difficult and is certain to significantly drive labor costs up on a per-home served basis. Again this objective is directly influenced by the allocations of splitter ratios at the NAP and LCP as well as cable sheath fiber count.

The LCP must be affordably provisioned such that each distribution cable sheath has *at least one dedicated fiber for each NAP on the sheath.*

This fact coupled with a desire to keep first costs down encourages higher branch cable sheath fiber counts and lower LCP split ratios. During plant construction the appropriate fiber color for each individual NAP is tagged with color marker on or in the NAP, or alternatively the appropriate fiber can be ring-cut from the sheath and stored ready for use.

PON OVERLAY SYNCHRONIZATION

The proposed methodology of synchronizing a PON overlay with an existing or new HFC plant is driven by the objective of having the PON's key functional elements closely located, both physically and logically, with the corresponding HFC devices. Practically, direct physical co-location is required at the CPE, tap and RT levels. Strict co-location of the LCP with a HFC fiber node may be desirable, but not a requirement. The accomplishment of this objective must of course align with as many of the previously mentioned engineering constraints as possible.

The PON design is driven by three key parameters, the PON split ratio, the ratio's distribution through the network and the sheath/enclosure fiber count limits. These three parameters narrow the field of alternatives such that final selections can be made based upon specific performance or functionality objectives and first cost reduction measures.

PON Split Ratio Analysis

All possible ratio distributions between the NAP, LCP and RT were explored for the combined split ratios of 1:1, 1:2, 1:4, 1:8, 1:16 and 1:32. The first three ratios offer limited flexibility with regard to distribution, but were explored for comparative purposes. The first column of Table #2 list the possible ratio combinations for each overall split ratio.

Limiting the associated fiber counts to a maximum of 136 controls the LCP's position or depth in the network. The LCP fiber counts shown in Table #2 are inclusive of both inbound and outbound fibers. With regard to split ratio allocation the LCP's position in the network is dominated by the NAP. For example, a 1:4 NAP ratio favors a 256 HP LCP position.

Alternatives can also be explored such as creating a 4 port NAP utilizing two 2 Port splitters at the NAP, this will favor a 128 HP position at the expense of doubling the number of fibers in each cable branch. At first such an alternative may be dismissed as costly, but individual fibers are relatively inexpensive compared to optical splitters. Having two fibers available at each NAP further delays the purchase of NAP splitters until 3 or more NAP ports are in service, which may never happen. The measure also reduces the dynamic range requirements imposed on the CPE and OLT PHY receivers.

Strategies that postpone the use of a splitter at the NAP significantly impact the average subscriber provisioning costs, particularly during the early years of plant operation while subscription rates are low.

Table #2

Split Combo NAP-LCP-RT	LCP / Physical Node Size	LCP / Physical Node Fibers	Rermote Terminal Size	Rermote Terminal Fibers	Normalized First Cost	Normalized Ultimate Cost
1-32 PON Split Ratio						
1-32-1	128 HP	132 F	4096 HP	128 F	2.2	2.2
1-16-2	128 HP	136 F	2048 HP	128 F	2.2	2.2
1-8-4	64 HP	72 F	1024 HP	128 F	1.4	1.4
1-4-8	64 HP	80 F	512 HP	128 F	1.4	1.4
1-2-16	64 HP	96 F	256 HP	128 F	1.4	1.4
1-1-32	64 HP	128 F	128 HP	128 F	1.5	1.5
2-16-1	256 HP	136 F	4096 HP	128 F	2.0	2.2
2-8-2	128 HP	72 F	2048 HP	128 F	1.2	1.3
2-4-4	128 HP	80 F	1024 HP	128 F	1.2	1.4
2-2-8	128 HP	96 F	512 HP	128 F	1.1	1.3
2-1-16	128 HP	128 F	256 HP	128 F	1.2	1.4
4-8-1	256 HP	72 F	4096 HP	128 F	1.0	1.3
4-4-2	256 HP	80 F	2048 HP	128 F	1.1	1.4
4-2-4	256 HP	96 F	1024 HP	128 F	1.1	1.4
4-1-8	256 HP	128 F	512 HP	128 F	1.1	1.4
8-4-1	512 HP	80 F	4096 HP	128 F	1.0	1.3
8-2-2	512 HP	96 F	2048 HP	128 F	1.0	1.3
8-1-4	512 HP	128 F	1024 HP	128 F	1.0	1.4
1-16 PON Split Ratio						
1-16-1	128 HP	136 F	2048 HP	128 F	2.2	2.2
1-8-2	64 HP	72 F	1024 HP	128 F	1.4	1.4
1-4-4	64 HP	80 F	512 HP	128 F	1.4	1.4
1-2-8	64 HP	96 F	256 HP	128 F	1.4	1.4
1-1-16	64 HP	128 F	128 HP	128 F	1.5	1.5
2-8-1	128 HP	72 F	2048 HP	128 F	1.2	1.3
2-4-2	128 HP	80 F	1024 HP	128 F	1.2	1.4
2-2-4	128 HP	96 F	512 HP	128 F	1.2	1.3
2-1-8	128 HP	128 F	256 HP	128 F	1.2	1.4
4-4-1	256 HP	80 F	2048 HP	128 F	1.1	1.4
4-2-2	256 HP	96 F	1024 HP	128 F	1.1	1.4
4-1-4	256 HP	128 F	512 HP	128 F	1.1	1.4
8-2-1	512 HP	96 F	2048 HP	128 F	1.0	1.3
8-1-2	512 HP	128 F	1024 HP	128 F	1.0	1.4
1-8 PON Split Ratio						
1-8-1	64 HP	72 F	1024 HP	128 F	1.4	1.4
1-4-2	64 HP	80 F	512 HP	128 F	1.4	1.4
1-2-4	64 HP	96 F	256 HP	128 F	1.4	1.4
1-1-8	64 HP	128 F	128 HP	128 F	1.6	1.6
2-4-1	128 HP	80 F	1024 HP	128 F	1.2	1.4
2-2-2	128 HP	96 F	512 HP	128 F	1.2	1.3
2-1-4	128 HP	128 F	256 HP	128 F	1.3	1.4
4-2-1	256 HP	96 F	1024 HP	128 F	1.1	1.4
4-1-2	256 HP	128 F	512 HP	128 F	1.1	1.4
8-1-1	512 HP	128 F	1024 HP	128 F	1.1	1.4
1-4 PON Split Ratio						
1-4-1	64 HP	80 F	512 HP	128 F	1.4	1.4
1-2-2	64 HP	96 F	256 HP	128 F	1.4	1.4
1-1-4	64 HP	128 F	128 HP	128 F	1.6	1.6
2-2-1	128 HP	96 F	512 HP	128 F	1.2	1.4
2-1-2	128 HP	128 F	256 HP	128 F	1.3	1.4
4-1-1	256 HP	128 F	512 HP	128 F	1.1	1.4
1-2 PON Split Ratio						
1-2-1	64 HP	96 F	256 HP	128 F	1.5	1.5
1-1-2	64 HP	128 F	128 HP	128 F	1.7	1.7
2-1-1	128 HP	128 F	256 HP	128 F	1.4	1.5
1-1 PON Split Ratio						
1-1-1	64 HP	128 F	128 HP	128 F	1.8	1.8

The RT is positioned in the network by following a process similar to that used with the LCP. The total incoming fiber count is held constant by adjusting the number of LCP's reporting to the RT. As shown in the 5th column of Table #2 the total inbound LCP fiber count was held at 128. This quantity was chosen, rather than the previously mentioned 150, to allow for out-bound or ring fibers and HFC node fibers that were not included in the analysis.

Both NAP and LCP ratios influence the depth or position of the RT in the network. NAP/LCP ratios of 1:4/1:2 favor a 1000 HP RT in the 8, 16 and 32 PON splits.

Physical placement of ground mounted 1000 and 2000 HP RT cabinets is common, particularly with regard to digital loop carrier telephone systems. Small 500 HP RT's can be pole mounted, but become numerous and pose powering challenges when extended backup times are required to ensure network operation during extreme weather conditions.

The cost data provided in Table#2 is based on items that generate a relative cost difference between PON split options. For example, the fiber cost for a PON split of 1 – 1 – 32 would be considerably greater than 32 –1 – 1 this along with other associated impacts such as number of RT's required for each combination. The resulting dollars per home passed were then normalized to the lowest first cost option. Normalization of the data is appropriate since the cost analysis is gauging relative merits rather than absolute values.

The cost impacts of various subscription take-rates are difficult to predict and are not included in the analysis. This is principally due to the cost of an optical splitter at the NAP if it is needed at the time of service provisioning. In many instances a splitter may not be needed for the early subscriber(s) whose drops can be connected directly to the PON fiber allocated to the NAP. Thus unless there is a great deal of subscriber clustering the impact of NAP splitter costs will be negligible until take rates approach 30% to 50%. Due to this variability the analysis focuses on the initial relative cost and that of a 100% take-rate. The 100% figure reflects the comparative cost between low and high subscription rate pockets.

The principal conclusion drawn from the cost data is that from a relative-economics point of view a plant can be designed by appropriately applying a wide range of split combinations.

This is good news from a plant-engineering point of view, providing the network designer latitude to meet the numerous other non-cost related engineering constraints such as those previously outlined.

OBSERVATIONS

The key take-away observations from this analysis effort and discussion are:

1. Properly executed, PON optical split ratios do not greatly affect network first costs.
2. The appropriate allocation of PON split ratios between key network elements can be effectively used to control the physical and logical location of those elements in the network.
3. Control of sheath fiber counts can be effectively used to defer optical splitter cost at the NAP and to ease performance demands on PHY receivers and transmitters.
4. One or two standard sheath fiber count configurations can be readily adapted to varying subscriber densities and HFC tap configurations.
5. Mechanical fiber splice connections at the NAP and CPE are required to keep provisioning costs down and support drop troubleshooting. The network's optical performance requirements must be tailored accordingly.
6. The eventual migration of the network to gigabit speeds is likely to occur earlier with lower overall PON split ratios.
7. The planned under subscription of a PON split ratio can be leveraged to reduce the cost of the RT while enabling lit fiber to pass by 100% of the serving area's subscriber base.
8. The utilization of a self-provisioning MAC protocol capable of dynamic bandwidth allocation without regard to PON split or subscription is required to maintain high customer satisfaction and low provisioning/maintenance cost.

This analysis was focused on PON split ratios in exponential powers of 2. Clearly other ratios are equally valid and have been used successfully [3] such as multiples of 3. A significant cost benefit would not be anticipated in alternative ratios, however they may offer useful alternatives with regard to LCP and RT placement and provisioning.

SUMMARY

Fundamentally, HFC alone is a proven financial workhorse capable of delivering outstanding residential video, voice and data services. Based upon the work done thus far it is clear that it will be some time before PON alone can compete economically in a standard residential market space with HFC. However, in part this fact is contrasted by three emerging near term trends:

- The growing utilization of e-business practices by small under-served businesses, businesses within easy service provisioning range of an HFC plant.
- The steady demand for advanced data networking and voice services for work-at-home and small branch office employees.

- A strong financial desire to reduce or eliminate the risk of obsolescence in newly constructed plant. Extending the plant's operation during its positive cash flow life by as little as two or three years has significant investment repercussions.

Perhaps the optimal migration compromise between the realities of today's economics and the future's service demands may be the strategic application of optical network overlaying a new or existing HFC plant.

Accordingly this paper has proposed a series of engineering considerations and design methodology for the synchronization of a PON with a modern HFC network. The methodology has been demonstrated analytically to be capable of effectively placing key PON elements at physical and logical locations consistent with an underlying cable TV network.

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BIOGRAPHY

Donald Sorenson is Manager of Advanced Access Planning in the Transmission Network Systems sector of Scientific-Atlanta, Inc.. Mr. Sorenson is responsible for the engineering evaluation and planning of Scientific-Atlanta's next generation access network technologies with particular emphasis on technology migration strategies for HFC networks. Donald obtained his BSEE from South Dakota School of Mines and Technology in 1978 and has maintained a professional engineering focus throughout his career. He brings 23 years of product and technical business development experience to S-A and the telecommunications industry, of which the past ten have been spent in the Cable Television and Telecom market segments.

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