FUTURE DIRECTIONS FOR FIBER DEEP HFC DEPLOYMENTS

A CASE STUDY ON HFC TO FTTX MIGRATION STRATEGIES

JOHN ULM
ZORAN MARICEVIC

ARRIS™

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INTRODUCTION

Today in greenfield scenarios, it has become more common for operators to install fiber all the way to the home or MDU (Fiber to the Premise - FTTP), as it is viewed as the ultimate end game from a plant perspective. With the constant tide of broadband speed growth, operators are now starting to consider their HFC transition to FTTP for brownfield scenarios as well. Should they stop investing in HFC and just go right to FTTP? This is a daunting task given the costs involved.

This paper details a case study of several actual node designs and explores the cost impacts of various plant upgrades; from simply splitting nodes to tackle business as usual demands, all the way to FTTP. It also highlights some emerging innovative concepts for a distributed node architecture that cost effectively enables Fiber Deep (FD) designs such as Fiber to the Last Active (FTTLA) or Fiber to the Curb (FTTC).

The paper starts with a comprehensive network capacity analysis that shows what capacities might be needed, and at what time over the coming decades. This allows us to lay out an HFC migration strategy to FTTx over a 10+ year window. A Net Present Value analysis shows that this multi-step approach is more cost effective than diving head first into FTTP. It will also show that for many or most subscribers on today's HFC, FTTP may not necessarily be the end game, rather FTTLA or FTTC may suffice.

The findings from this paper are important in allowing operators to plan their HFC to fiber journey in a pay as you go manner. A companion paper to this [ULM_2016] discusses the energy impacts to both the access network and headend facilities.

NETWORK CAPACITY – PLANNING FOR THE NEXT DECADE

The Internet has been growing at a breakneck speed since its inception. And with it, we have seen a corresponding growth in dedicated network capacity. While Moore's Law is infamous in silicon realms, Nielsen's Law of Internet Bandwidth has become renown in the networking world. It basically states that network connection speeds for high-end home users would increase 50% per year. This law has driven much of the traffic engineering and network capacity planning in the service provider world. It has also led to much research on those topics.

Nielsen's Law and Cloonan's Curves

In [CLOONAN_2014, EMM_2014], this research was expanded to also include traffic utilization in addition to the network connection speed. In his chart below, known as

Cloonan's Curves, Nielsen's Law is represented by the blue line in the middle. Since it is a log scale, the 50% Compounded Annual Growth Rate (CAGR) appears as a straight line. An interesting fact is that the graph starts in 1982 with a 300-baud phone modem. We are now in the fourth decade of closely following this trend.

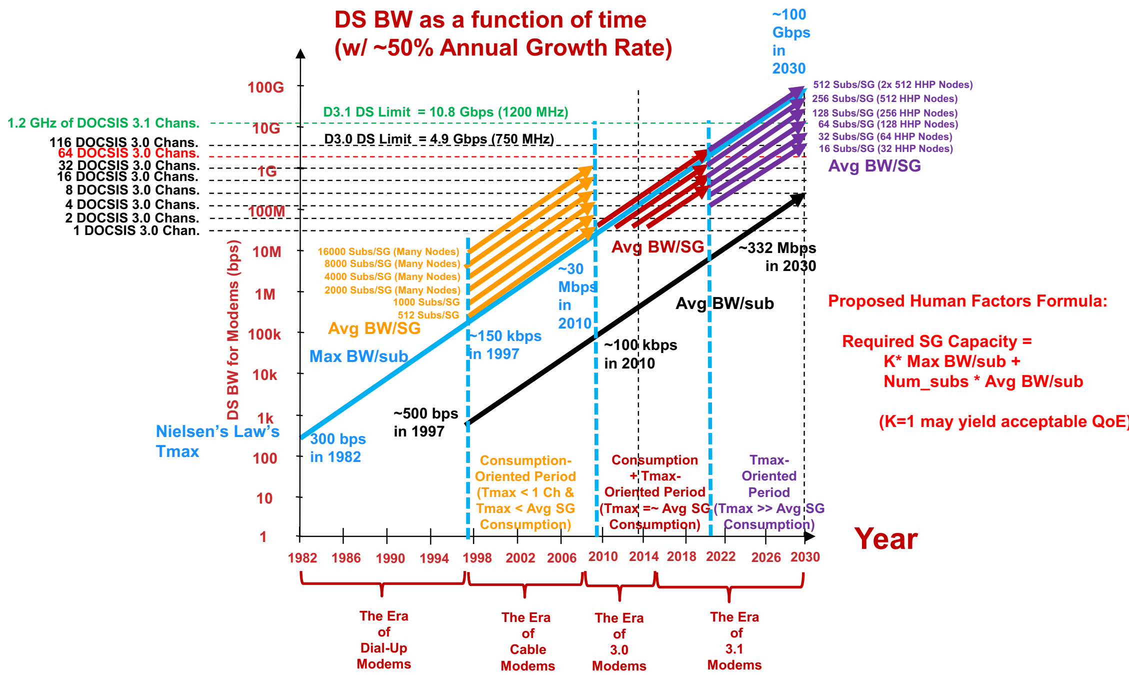


Figure 1 – Cloonan's Curves

Cloonan noted that the primetime average subscriber consumption (a.k.a. Tavg) has also been following this same basic trend as shown in the Figure 1. For service providers, an important metric is the traffic utilization in a Service Group (SG). The SG traffic utilization is a function of the number of subscribers (Nsub) times the average bandwidth per sub (Tavg) and is shown in a series of lines above Nielsen's line.

In the early DOCSIS days, many nodes were combined together and a SG might consist of thousands of subscribers. At this time, the SG traffic was an order of magnitude higher than the maximum network connection speed (a.k.a. Tmax after the DOCSIS parameter that dictates max network rates). Over time, the SG size has been shrinking and with it the ratio between Nsub*Tavg to Tmax. As shown in the chart above, the SG traffic eventually approaches that of Tmax. As SG sizes dip below 100 subs, then Tmax starts to dominate the traffic engineering.

We have been monitoring subscriber usage for many years now. The chart below shows Tavg, the average subscriber downstream consumption during peak busy hours, for a number of MSOs over the last six years. At the start of 2016, Tavg was approximately 850 Kbps. Over this six year period, Tavg has grown at ~45% CAGR. We are expecting that Tavg will break the 1 Mbps barrier sometime in 2016. The chart also maps out Tavg growth through the year 2020 assuming a 45% CAGR.

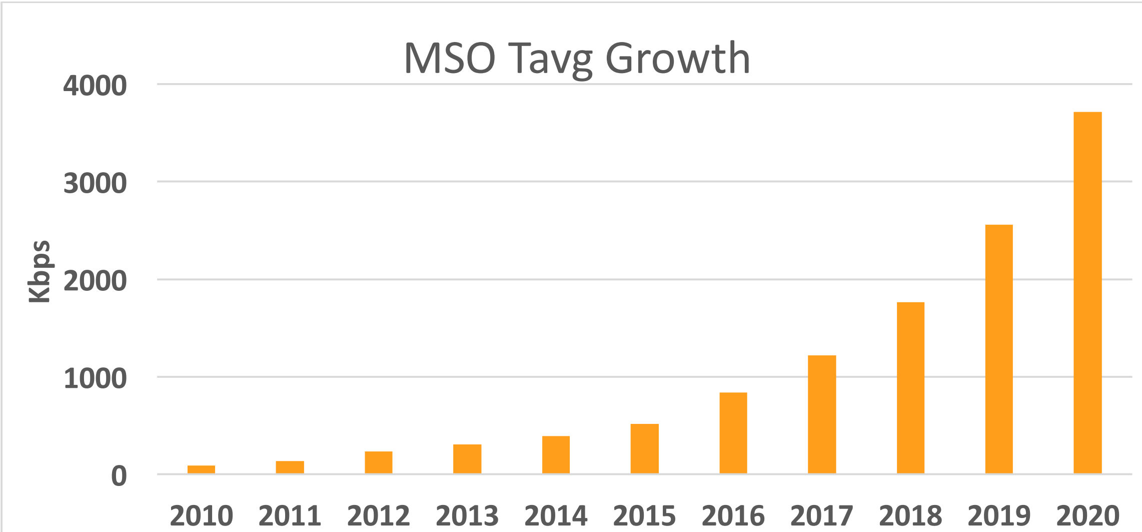


Figure 2 – Tavg, Average Subscriber Consumption

Interestingly, the upstream traffic is growing at a significantly slower rate. During the same six year interval, the upstream Tavg only grew at ~20% CAGR. The industry is seeing more asymmetric traffic with video being the driving application for downstream consumption [see EMMEN_20xx]. At this point, there is about a ten to one ratio in traffic and still expanding.

Selective Subscriber Migration Strategy

As operators approach capacity planning, they are trying to understand how long the HFC architecture might last before they must migrate to a Fiber to the Premise (FTTP) network. To get an insight into this, the chart below zooms in on the Cloonan's Curve & Nielsen's Law over the next two decades. It predicts that top network speeds will reach 10 Gbps by ~2024 and pass 100 Gbps in the early 2030's. The initial DOCSIS 3.1 (D3.1) goal was 10 Gbps, so that implies that the HFC may hit its ceiling by approximately 2024!

At first glance, this is a scary proposition in that HFC networks might be obsolete in 5-7 years while it may take decades to build out an FTTP infrastructure. However, this is not the full story. As was shown in [ULM_2014], Nielsen's Law applies to the top speed tiers, which is only a very small percentage of the entire subscriber base, perhaps less than 1%. So the key question then becomes, "What happens to the vast majority of subscribers on HFC who are not in the top speed tiers (a.k.a. billboard tiers) and when?"

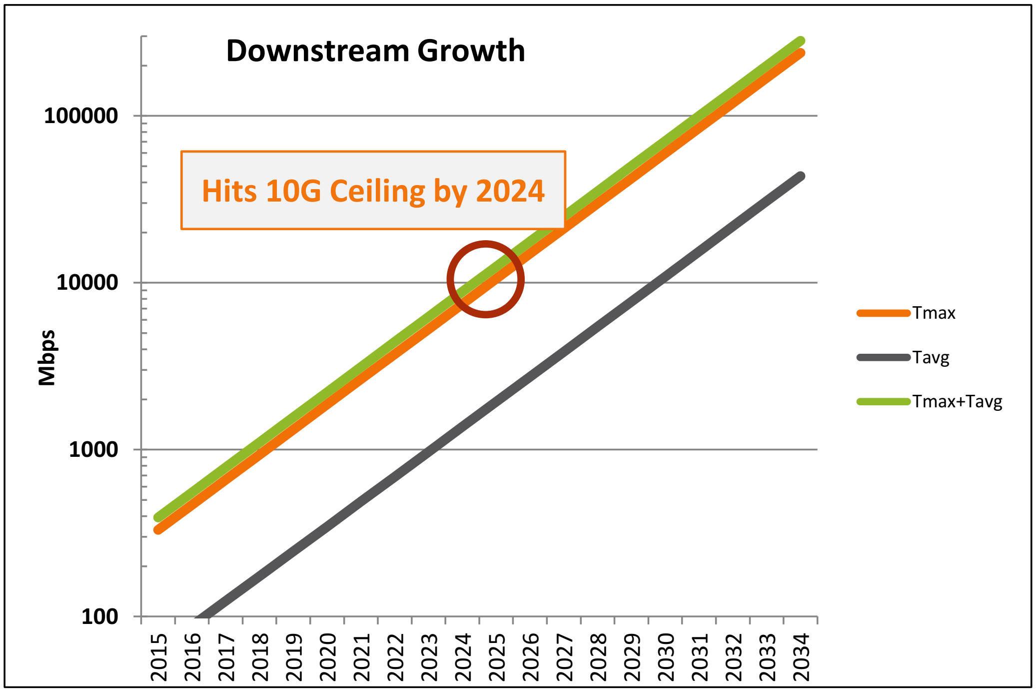


Figure 3 – Downstream Growth over Next Two Decades

The [ULM_2014] case study took a look at service tier evolution at a few MSOs. Table 1 lays out results from that study. Perhaps the key finding from this study is that the different service tiers are growing at different rates. While the top billboard tier continues to follow Nielsen's Law 50%, each subsequent lower speed tier is growing at a slower rate. Hence, the lower the service tier rate, the lower its CAGR.

Table 1 – MSO Case Study on Multiple Service Tier Levels

2014 Service Tier Levels on HFC	% of Subs	Tmax (Mbps)	Tmax CAGR
Top Tier – Billboard Rate	1%	300	50%
Performance Tier	14%	75	32%
Basic Tier	65%	25	26%
Economy Tier	20%	5	15%

Figure 4 maps out the various service tier growth over the next two decades. While the 1% of subs in the top billboard tier hit 10 Gbps in ~2024, the 14% of subs in the performance tier don't hit that mark until ~2032. Notice that 85% of subscribers in the flagship basic tier and economy tier stay below this mark for several decades.

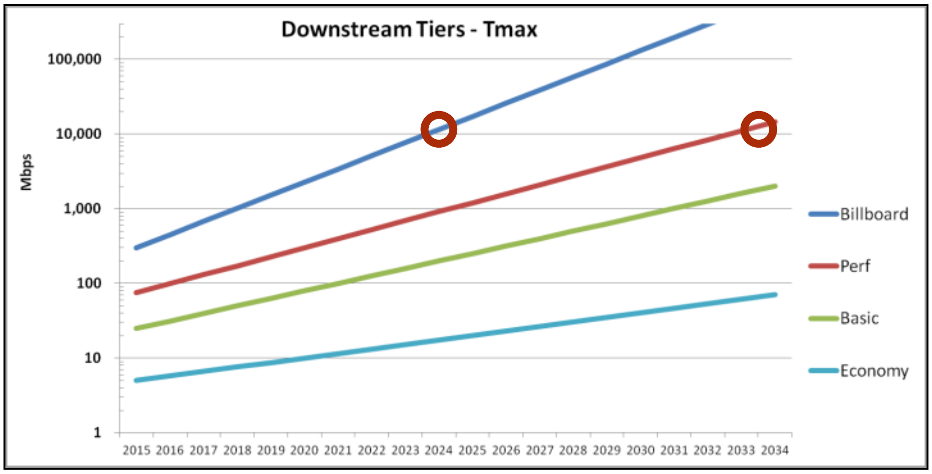


Figure 4 – Downstream Growth with Multiple Service Tiers

Data was input into the ARRIS Network Capacity model to take a closer look at the network traffic growth. Table 2 shows the Tmax migration used for each tier level over the next decade. Note that by 2021, the top billboard tier starts to exceed the capacity of the initial D3.1 modems that are being used today. And by 2026, this tier is forecast to hit 40 Gbps. This will require new technology, which might be a newer generation of DOCSIS (e.g. Extended Spectrum) or possibly a next generation of PON technology (e.g. 100G EPON).

Table 2 – Service Tier Migration for Network Capacity Model

MSO Case Study DS Service Tiers	% of Subs	Tmax CAGR	2014	2016	2021	2026
Top Billboard Tier	<1%	50%	300	675	5G	40G
Performance Tier	14%	32%	75	125	500	2G
Basic Tier	65%	26%	25	40	150	400
Economy Tier	20%	15%	5	10	20	50

It is important to note that 99% of the subscribers are still comfortably using today's DOCSIS technology on HFC a decade from now.

Some results from the ARRIS Network Capacity model are shown in Figure 5. It provides an insight into both Tmax and SG Tavg behavior. During the next 5-7 years, the Tmax component dominates traffic engineering as it is driven by Nielsen's Law. The bandwidth needed by the top billboard tier dominates compared to the SG Tavg.

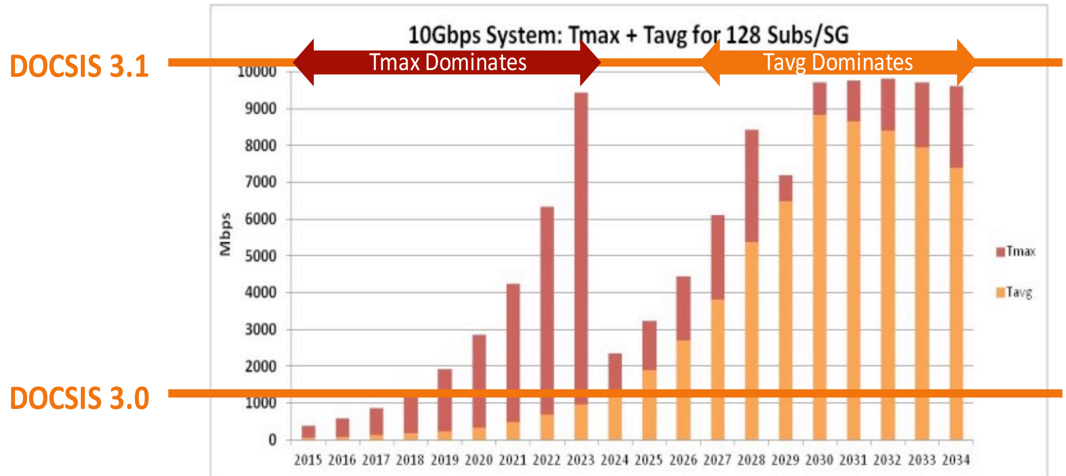


Figure 5 – Network Capacity Model Results

This leads us to a Selective Subscriber Migration strategy that will need to start in the next 5-8 years. By moving the top billboard tier to a Fiber Deep access network that is separate from the general HFC plant, there is a significant reduction in the required DOCSIS capacity. This reduction can be seen in year 2024, in Figure 5, after the top billboard tier is removed from the HFC network. The performance tier is then moved in 2029, in this example, for a smaller drop.

Note that the Fiber Deep access network might be any one of several FTTx options including: FTTP, Fiber to the Curb (FTTC), Fiber to the Tap (FTTT), Fiber to the Last Active (FTTLA), or Node+0 HFC. These options are discussed in detail in the next section.

Eventually, with the top tiers migrated to FTTx, the SG Tavg finally catches up and operators will need to consider reducing SG sizes again. The model in this example predicts that this will be roughly 10-15 years from now.

Another observation from this analysis is that D3.1 is a key technology to extend HFC life for decades to come, especially for the vast majority (e.g. 65-95%) that are in the flagship basic and economy tiers. Any brownfield FTTx transition may take decades, so D3.1 successfully gets operators through that window.

In summary, Selective Subscriber Migration strategy is a sensible approach to the topic of an HFC to FTTx transition. Moving top tiers to FTTx can buy HFC extra decades for 80-95% of subscribers in the flagship basic/economy tiers. Tmax dominates for the next 5-7 years, so it is more important to increase the HFC capacity to at least 1 GHz spectrum rather than split nodes. However, Tavg finally catches up 8-10+ years from now; and SG size reductions come back into vogue. Operators should push Fiber Deep enough to enable Selective FTTx for top tiers on demand and be prepared for the next round of SG splits.

And which FTTx is the best option is another interesting debate. DOCSIS continues to evolve with work on Full Duplex (FDX) and Extended Spectrum DOCSIS. Some of this research was highlighted in [CLOONAN_2016]. These new technologies promise to do for DOCSIS & cable what G.fast is attempting to do for DSL and twisted pair. Figure 6 shows some results from that paper for both FTTC and FTTLA systems. As can be seen, the system capacity can increase significantly as fiber is pushed closer to the premise.

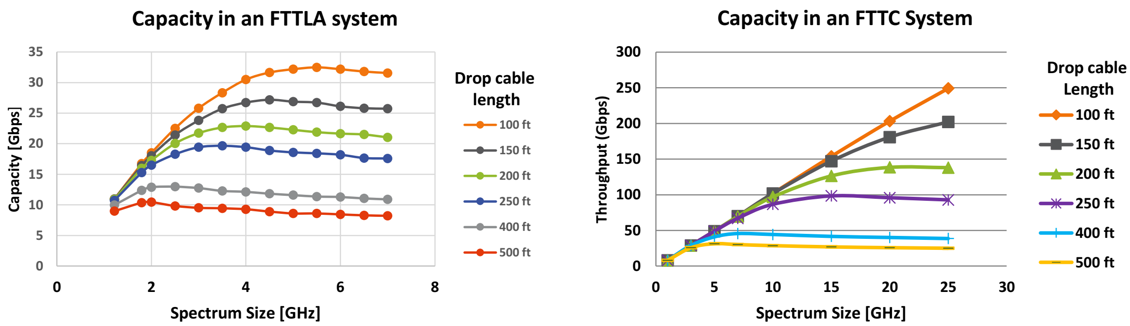


Figure 6 – Network Capacity Model Results

ACCESS NETWORK CASE STUDY

The network capacity planning shows that operators will need to evolve their existing Hybrid Fiber Coax (HFC) networks to remain competitive with FTTP service providers such as Google Fiber and Verizon FiOS [VENK_2016, VENK_2015 and ULM_2015]. For cable operators, they can utilize their existing fiber investments as a starting point to get a jump start compared to new entrants that must start their fiber installation from scratch. But the critical question for cable operators is how deep should they pull the fiber? They are presented with a toolbox of architectural choices to consider:

- “Business as usual” (BAU) – a node split where needed, and a refresh of the HFC field actives, with perhaps an upgrade to 5-85 MHz in the return and 104-1002 MHz in the forward
- Fiber Deep (FD) Node+0 (N+0) pushes fiber much deeper into the HFC and eliminates all of the active RF elements. There is an array of potential options including:
    - Traditional Fiber Deep Node+0 “FD N+0” which redesigns existing HFC (e.g. N+3 to N+6 with 3-6 actives after the fiber node) into “node as the last active”. The typical way to do this is to rewire the coax plant in a way to minimize how many of these standard-size new nodes need to be added. Each new node may ultimately become its own service group, and in addition to the RF and optical modules, it may house Remote PHY Devices (RPDs) and PON OLTs

  - Fiber to the last active (FTTLA) is a variant of the Fiber Deep N+0 architecture. However, in this case the nodes are located precisely at legacy RF amp locations. These nodes then get aggregated into a properly-sized service group. This aggregation can be done by using an “active splitter / combiner”, housed in a virtual hub, which is located precisely at the legacy node location to save on optics costs & space in the facility
  - Fiber to the curb (FTTC) or Fiber to the tap (FTTT) where fiber is run down the street but the existing cable drop cables are reused
- Fiber to the Premise (FTTP) – this is what is being deployed today with traditional PON systems as well as RFoG systems

Collectively, these fiber deeper options are referred to as FTTx or Fiber to the “x”, where “x” might be Premise, Curb, Tap, Last Active, or Fiber Deep node. For cable operators to build out any of the above architectures in today’s brownfields, the new fiber construction begins from an existing fiber node; unlike the new entrants who must build the fiber construction from the central office / headend.

Each MSO will make changes to their own HFC plant to optimize for the attributes that they deem to be the most important. Different MSOs will likely prioritize the many attributes in different ways. For example, some MSOs may choose to optimize their network evolution by moving as rapidly as possible to end-state technologies of the future. These MSOs will likely move rapidly towards (passive optical network) PON or Point-to-Point Ethernet solutions. Other MSOs will choose to optimize their network evolution to reduce headend power and rack-space requirements by moving towards Fiber Deep architectures with Distributed Access Architecture sub-systems that remove functionality from the headend. These MSOs will likely deploy (Remote PHY) RPHY or (Remote MACPHY) RMACPHY sub-systems within their nodes. Other MSOs will want to preserve much of their current architectures while capitalizing on improved technologies.

In order to calibrate our conceptual thinking against reality, a set of five real-life HFC nodes was identified for evaluation, representing a diversity of implementations. These are representative of low, medium, and high densities, as measured by how many homes are passed per mile in each area. The five node areas, labeled A, B, C, D, & E possess other attributes of interest: miles of hardline coax plant, percentage of aerial plant, number of RF actives, number of homes passed per node, and HP/mile, as shown in Table 3.

Figure 7 shows the topology of one of the nodes: Node C. The headend (upper left) is fiber-linked to the node (center-left in pink), which RF-feeds into RF amps (blue triangles) RF splitters (blue circles), and taps (orange diamonds). Two 15A field power supplies provide enough power for the whole node area. Node C contains 3.5 miles of coax plant (excluding drop cables) with 21 actives and 398 Homes Passed (HP). So this might represent ~200 subscribers @ 50% penetration.

Node C will be used as a baseline example to show how the other architectures might be implemented.

Table 3 – Properties of 5 Node Areas Under Study

Node	**A**	**B**	**C**	**D**	**E**	**Overall**	**Average**
Plant Coax Mileage	4.2	6.2	3.5	2.5	1.9	18.3	3.7
% Aerial	20%	77%	97%	87%	91%	70%	70%
Total Active	21	30	21	19	14	105	21
Actives/Mile	5.0	4.9	5.9	7.6	7.4	5.7	5.7
Cascade Depth	N+3	N+3	N+3	N+3	N+2		N+3
Total Homes Passed	153	352	398	469	520	1892	378
HP/Mile	37	57	112	187	274	104	104

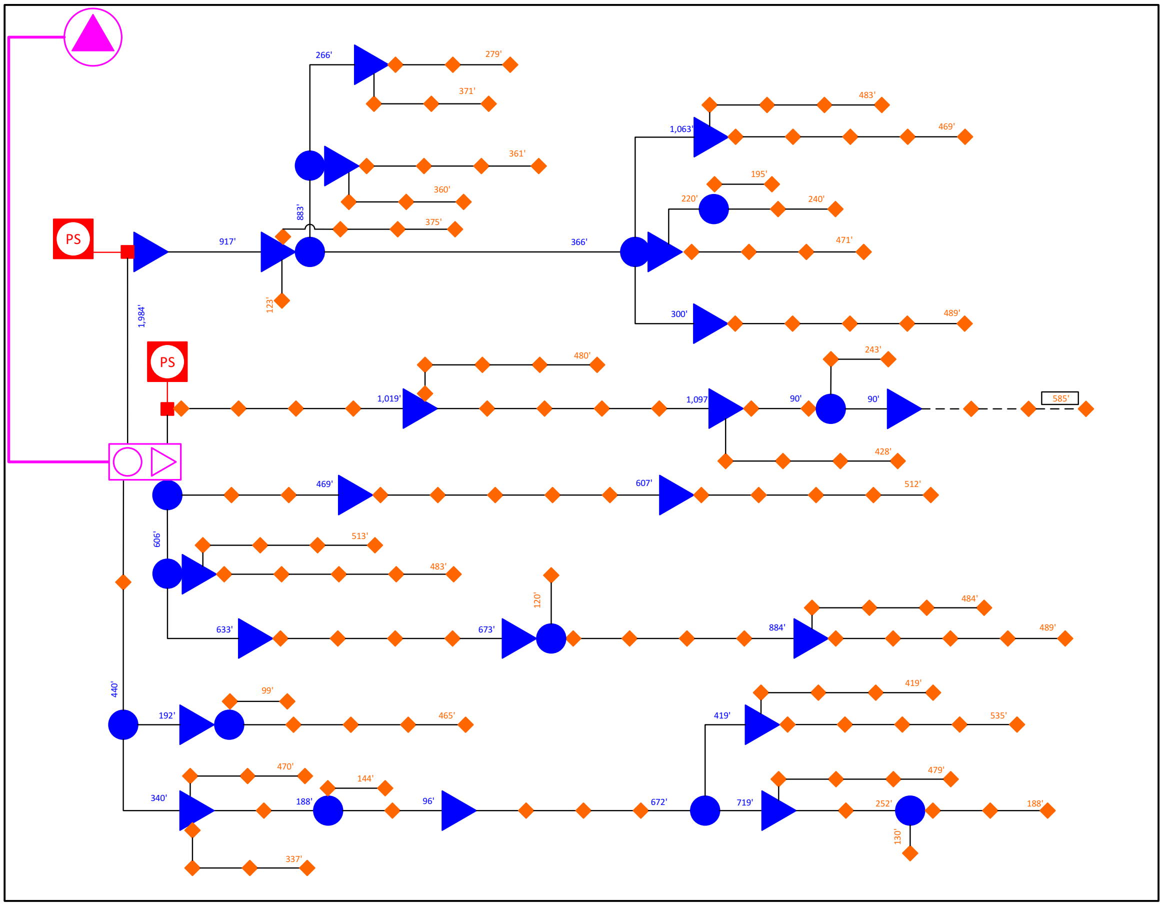


Figure 7 – Topology of the Node C Area

"Business as usual", as the name implies, applies no topology changes. The idea is to refresh all the actives, typically by replacing the existing RF modules with 5-85 / 103-1003 "e-packs". Taps are assumed to function to at least 1 GHz. Node segmentation can be done "in place" by converting this 1x1 node up to 4x4 node, with optical transport multiplexed over the same fiber. While the segmentation can drop the average size down to 100 HP (~50 subs), the distribution is often unbalanced between the RF legs.

Fiber Deep (FD) N+0 will eliminate all the RF amps and reconfigure the network in a way to deploy the minimum number of new nodes, possibly in a new location. Figure 8 shows one such implementation for Node C, where the total number of new actives is reduced, from the original 1 node and 21 RF amps down to just 6 nodes. Note that the new nodes might need augmented output power, e.g. 64 dBmV, to drive the additional coax to reduce the node count. This is one of many trade-offs to be made in a fiber deep design.

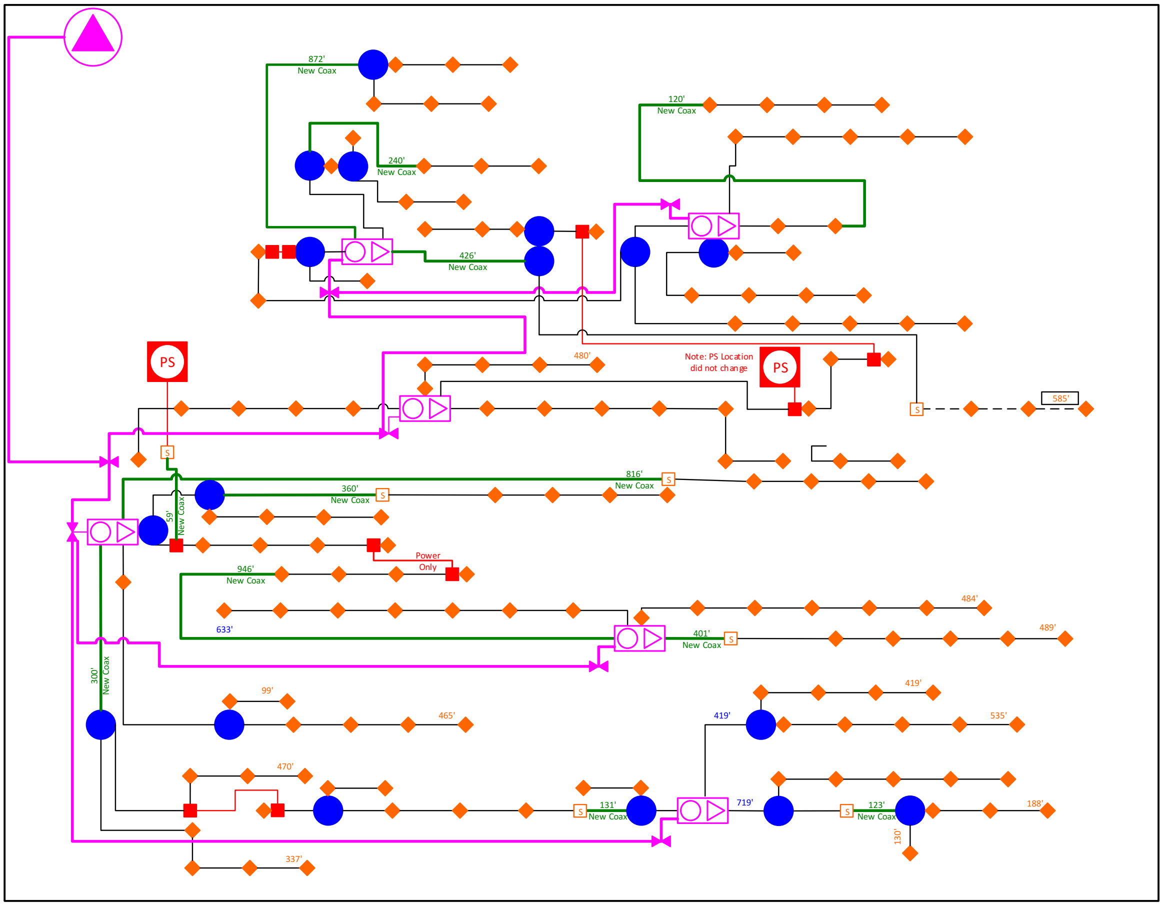


Figure 8 – Node C Area Reconfigured as Fiber Deep N+0

In addition to the new fiber required to feed those nodes, there is a need to add some coax plant, too. The new coax segments are shown in green. A significant redesign of the tap values and orientations is required, too. However, if an operator already plans to upgrade the taps to 1.2 GHz performance, then the argument is the tap rework may not be so onerous of an extra step. The additional new fiber to connect the new nodes is the reason this approach is called “Fiber Deep”. For FD N+0 in Node C, this step takes fiber to as close as 195 feet to the last tap, while the furthest tap is at 1,448 feet. On average, taps are 1,007 feet away from the fiber plant. The new nodes are also capable of housing Remote PHY Devices (RPDs) and PON OLTs, if and when needed.

Fiber to the last active (FTTLA) is also an N+0 implementation. However, the number of actives is not minimized. Rather, the locations (and even the housings, if warranted) of the existing RF actives are preserved – and reserved for the last-active nodes. Figure 9 shows topology of such a network, if implemented for Node C. This results in 21 nodes for this design replacing the original actives.

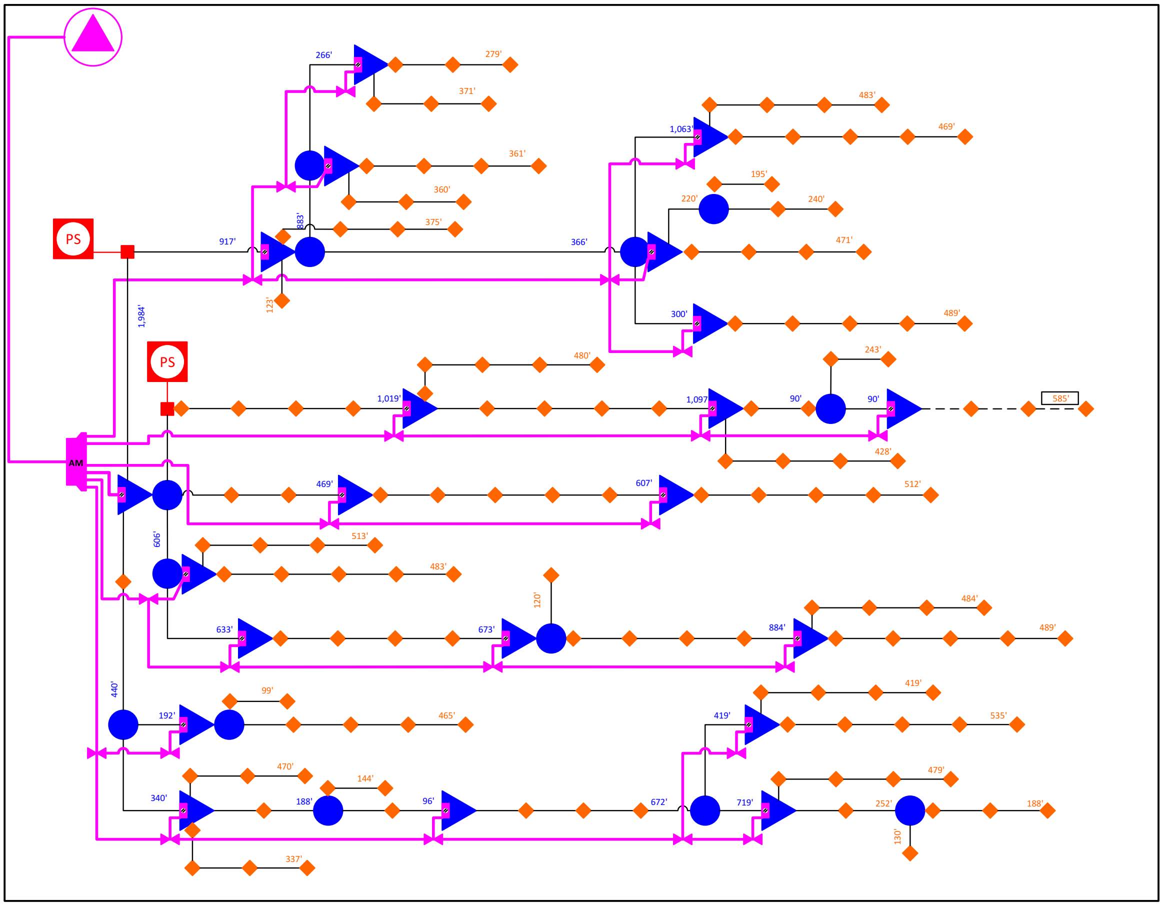


Figure 9 – Node C Area Implemented as an FTTLA in DNA Style

This approach is an even deeper Fiber Deep architecture. In case of FTTLA in node C area, fiber gets as close as 99 feet to the last tap, while the furthest tap is at 585 feet. On average, taps are 408 feet away from the fiber plant. Table 4 shows how much of the new fiber is required for the five areas under study.

For FTTLA, there is no need to touch the coax plant – hardline, taps, even levels for the existing services – so the whole plant upgrade investment is applied to getting fiber-deeper, rather than spending part of it on reconfiguring the coax plant. This simplification and getting the fiber even deeper, however, are a trade-off against the number of actives required in the plant. Replacing the taps for 1.2 GHz is an option if an operator wants the additional capacity.

Table 4 – New Fiber Construction Required for FTTLA Implementation for the 5 Nodes

Node	A	B	C	D	E	Overall	Average
New Fiber Mileage	2.1	4.0	2.4	1.4	1.2	11.0	2.2
Aerial	0.6	2.8	2.4	1.4	1.1	8.2	1.6
Underground	1.5	1.2	0	0	0.1	2.8	0.6
New Fiber as % of hardline plant	51%	64%	67%	54%	62%	60%	

FTTLA may be favored by those that don't want to touch the taps and passives and put more of their investment dollars into pushing fiber much closer to the premise. FD N+0 is more feasible when the taps are being replaced anyways and the operator wishes to minimize the number of active elements in the plant. FD N+0 also has much fewer nodes which reduces overall maintenance costs as well as cable power losses. In reality, there is a spectrum of fiber deep choices between these two extremes that an operator can optimize for any given location.

FTTLA in particular aids the Selective Subscriber Migration strategy in a few ways. In this strategy described earlier, a small number of high performance subscribers are moved onto a separate FTTx network. In the near term, an operator might pull fiber to the last active only for the location associated with the high performance subscriber. In the Node C example with ~200 subscribers, perhaps two subscribers get the top billboard tier. The operator only needs to upgrade two actives to effectively put them on their own separate upgraded SG, leaving the other 19 actives alone. And while pulling fiber to these two actives, it may enable FTTLA for several other actives along the way. Longer term, the operator may want to start migrating the top tiers to FTTC or FTTP. Using the FTTLA as a launching pad gets them much closer to the homes (e.g. 408' to tap on average for Node C). Selective Subscriber Migration strategy can be implemented with FD N+0 as well. It just requires more work to upgrade the HFC around that node and the fiber is not quite as deep as FTTLA.

DOCSIS Full Duplex (FDX) may require a Fiber Deep system with no actives beyond the node. So from an FDX perspective, both FTTLA and FD N+0 will meet these requirements.

The Fiber to the Curb (FTTC) architecture effectively replaces all of the plant's hardline coax with a fiber overlay. So the new fiber mileage required would essentially be equal to the plant coax mileage from the first row of Table 3. The Fiber to the Premise (FTTP) architecture would require all of the FTTC fiber plus the drop cable for each subscriber. No picture is needed as these simply overlay the existing HFC coax with fiber.

ACCESS NETWORK UPGRADE OPTIONS: COST IMPACTS

As was noted in [VENK_2015], getting fiber deep is a journey, not a single event. Venk shows that at current plant investment rates, it will take at least several decades to achieve FTTP everywhere. So it is a slow and steady evolution, as opposed to a revolution. This next section takes a look at the cost implications for the various HFC upgrade options. It first reviews some previous findings on comparing FTTH deployments vs. “Business as usual” (BAU), HFC upgrades. The paper then looks at the cost impacts for each upgrade option for the five node areas under study.

HFC BAU v FTTH – Previous Findings

There has been extensive analysis done previously in [EMM_2016, EMM_2015] on comparing investments into HFC with a complete switch to a full Fiber to the Home (FTTH) overlay in existing brownfield areas. These reports take a look at the entire system cost from headend facility costs, to plant investments, and includes the home/CPE investments as well.

Two separate business models are discussed to offer 1G services across the operator’s footprint. The first approach is known as system wide and the second is known as success based builds. The system wide approach is used for greenfield builds and may also be used for brownfield overbuilds. Its key advantage is that it offers the services across an operator’s entire footprint. If any customer calls to get the service, it can be turned on rapidly. This requires that the operator build out enough of the plant to enable this service. This is known as the enablement costs. Once the customer calls to obtain the service, there are additional costs such as the truck roll, CPE costs, and the fiber drop installation for FTTH. These are referred to as success-based costs.

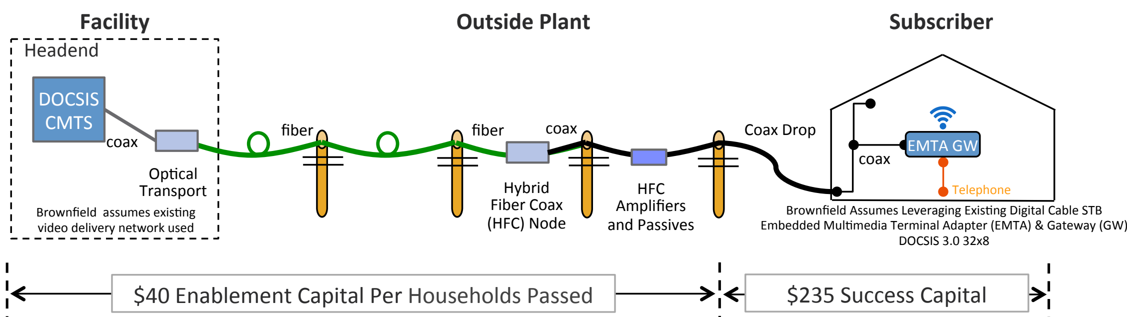
For the success based approach, no enablement costs are incurred in advance. It is only once the customer orders the service that the plant is built out and the other success-based costs are shouldered. The key benefit here is that it saves the operator tremendous upfront investment, but it now requires a potentially lengthy period to install and activate services. This is more effective when the penetration rate on these services are very low.

Described later in this paper is a middle ground approach that can be reached on these two business models using fiber deep technology such as FD N+0 or FTTLA. Fiber deep HFC is a system wide approach for offering symmetric gigabit services without the total cost of FTTP. But it also enables a success-based FTTP approach since the fiber is pulled much closer to every homes (e.g. less than 1000'). So in this sense, it becomes a blend of the two approaches described by Emmendorfer.

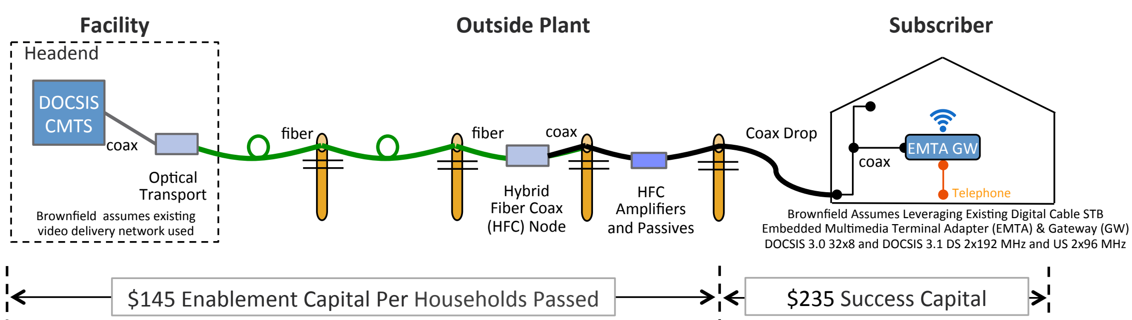
Figure 10 shows three different use cases from [EMM 2016]. Use cases 1 and 2 are a simple upgrade to DOCSIS 3.1 in the CMTS/CCAP platform. This only impacts the headend facility to enable 1G services across the entire HFC footprint. The D3.1 upgrade is the enablement costs. The success capital includes the cost of the D3.1 modem along with a truck roll to install it.

Use Case 3 in Figure 10 upgrades the HFC in addition to the D3.1 CMTS/CCAP upgrade. The HFC is upgraded to 1002/85 MHz. The node is also split and a small amount of fiber is also installed. The enablement costs rise accordingly while the success based capital remains unchanged.

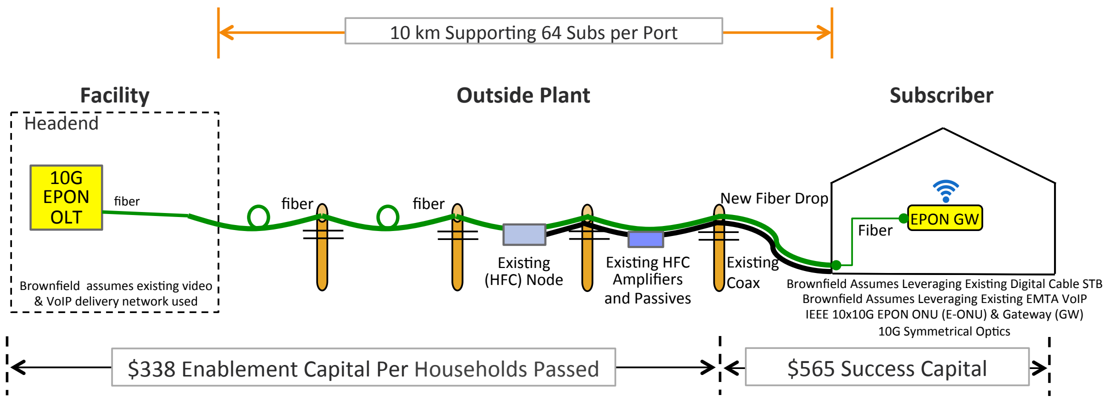
Use Case 4 looks at a 10G EPON FTTH solution. The enablement costs include the OLT in the facility along with the cost of building out fiber to every neighborhood. The fiber costs dominate. The fiber is now close enough to the home to allow a timely installation once a customer orders the service. The success-based capital is more expensive for this approach as it also includes the installation of the fiber drop cable to the home.



Use Case 1 and 2: HFC 2G DOCSIS



Use Case 3: HFC Mid-split 2G x 500M DOCSIS



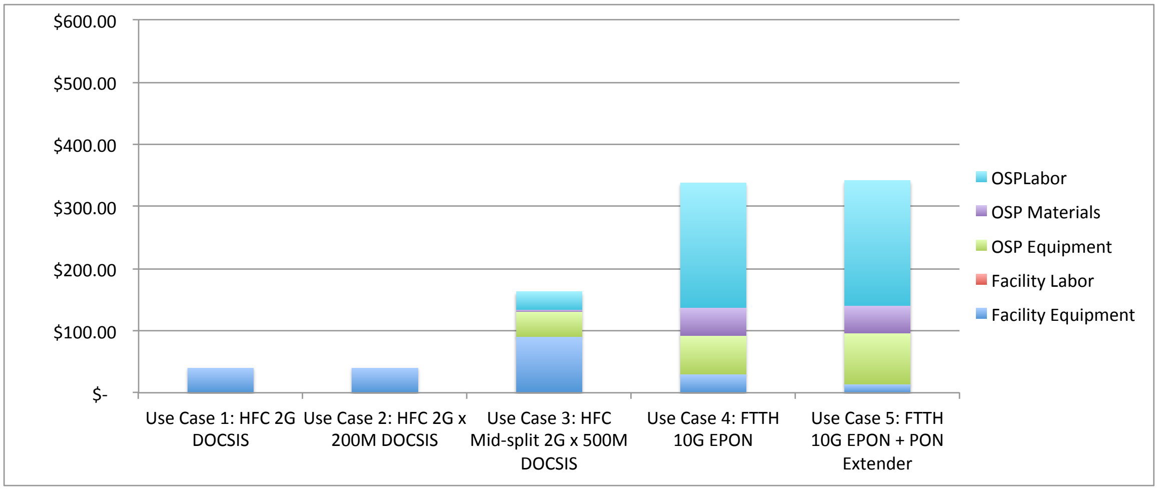
Use Case 4: FTTH 10G EPON

Figure 10 – Enablement Cost (Per HHP) and Success Capital (Per Customer)

Figure 11 from [EMM_2016] shows the relative enablement and success-based costs for five use cases. Use Case 2 adds a D3.1 upstream to the D3.1 downstream in Use Case 1. Use Case 5 includes a PON extender in the FTTH solution.

As can be seen in Figure 11, the enablement costs of FTTH is significantly higher than upgrading to D3.1 and improving the HFC.

Enablement Capital Composition (Per HHP)



Success Capital Composition (Per Customer)

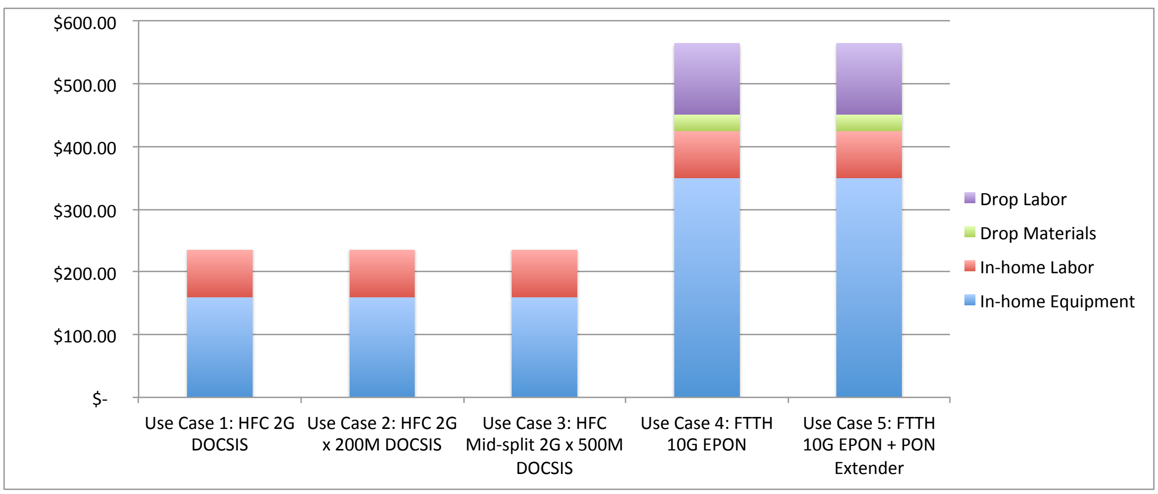


Figure 11 – Cost Comparison: Enablement and Success Based

Cost Comparison of Various HFC Upgrade Options

HFC plants vary significantly. Not only do they vary operator to operator, but their characteristics can vary dramatically from node to node within the same community. The cost analysis in [EMM_2016] was done on one particular sample node whose characteristics are described in that paper, and for one type of HFC upgrade.

One of the key considerations for this paper was to investigate the impact of these various HFC architecture upgrades across a very wide spectrum of nodes. As was shown in Table 3, the five nodes under study varied from a very rural 37 HP/mile to a very dense urban setting of 274 HP/mile. This can dramatically impact the cost of upgrades.

In this section, the focus is on analyzing various HFC upgrade options for the five nodes under study. It takes a look at the following upgrade scenarios:

1. Upgrading HFC actives to 1002/85 MHz without touching the taps and passives
2. Upgrading HFC actives, taps and passives to 1218/85 MHz
3. Upgrading HFC actives to 1002/85 MHz; add 2nd & 3rd node; don't touch taps/passives
4. Upgrading HFC actives, taps and passives to 1218/85 MHz; add 2nd & 3rd node
5. Upgrading HFC to FTTLA without touching the taps and passives
6. Upgrading HFC to FTTLA with new taps/passives

Figure 12 shows the relative costs for these six scenarios. For each scenario, it shows the range of costs across the five nodes under study along with the average costs across the five nodes.

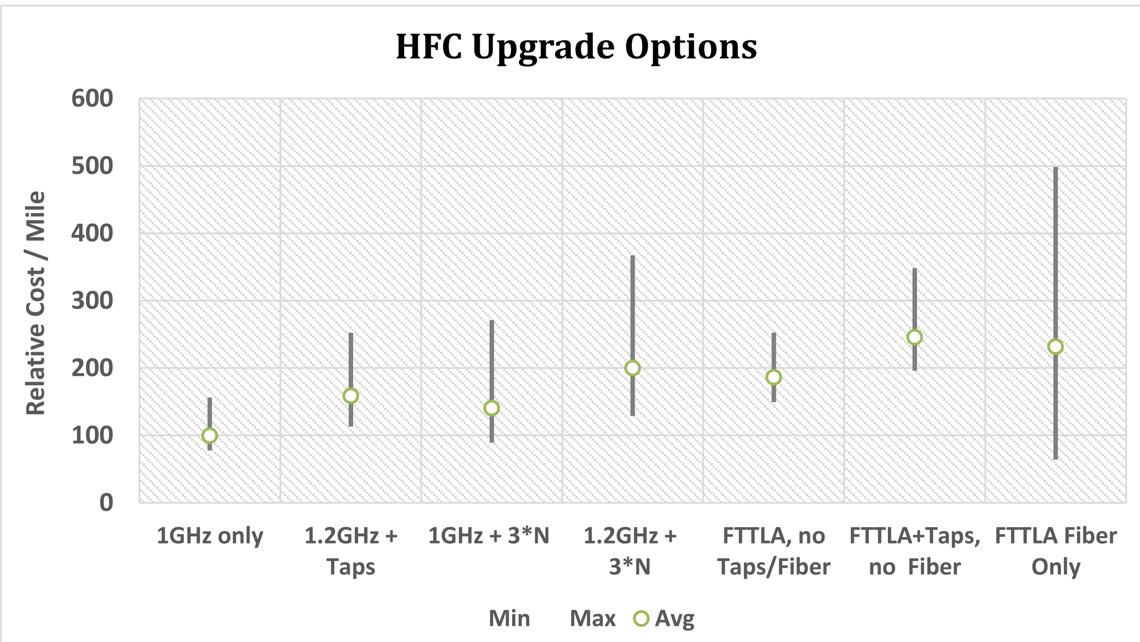


Figure 12 – Relative Cost per Mile for Various HFC Upgrade Options

Relative costs are used since labor is a significant cost variable and varies tremendously from location to location. The average cost for scenario 1 was arbitrarily chosen to equal 100. To no surprise, the average costs increase as fiber is pushed deeper into the network. And as can be seen from scenarios 2, 4, and 6, touching the taps not only adds additional expense, but the variability increases significantly as well.

For FTTLA in Figure 12, the fiber installation costs are significant and pulled out separately. The "FTTLA, no Taps/Fiber" and the "FTTLA + Taps, no Fiber" includes everything except any costs associated with the fiber installation. The FTTLA fiber installation costs are shown separately on the right in Figure 12. The fiber installation costs vary dramatically on whether the plant is aerial or underground. In this study, the underground fiber installation costs were almost 8X that of aerial. Separating the fiber installation component will let the operator more easily apply these results to their own scenarios.

The upgrade costs are not the only story here. As fiber is pulled deeper and more nodes are installed, the overall system capacity is increasing. The total system capacity is a function of both the number of nodes (i.e. potential DOCSIS SG) and the capacity of each link. Figure 13 shows both the average plant upgrade costs and the total system capacity for each scenario. In this figure, the FTTLA scenarios include the associated fiber installation costs.

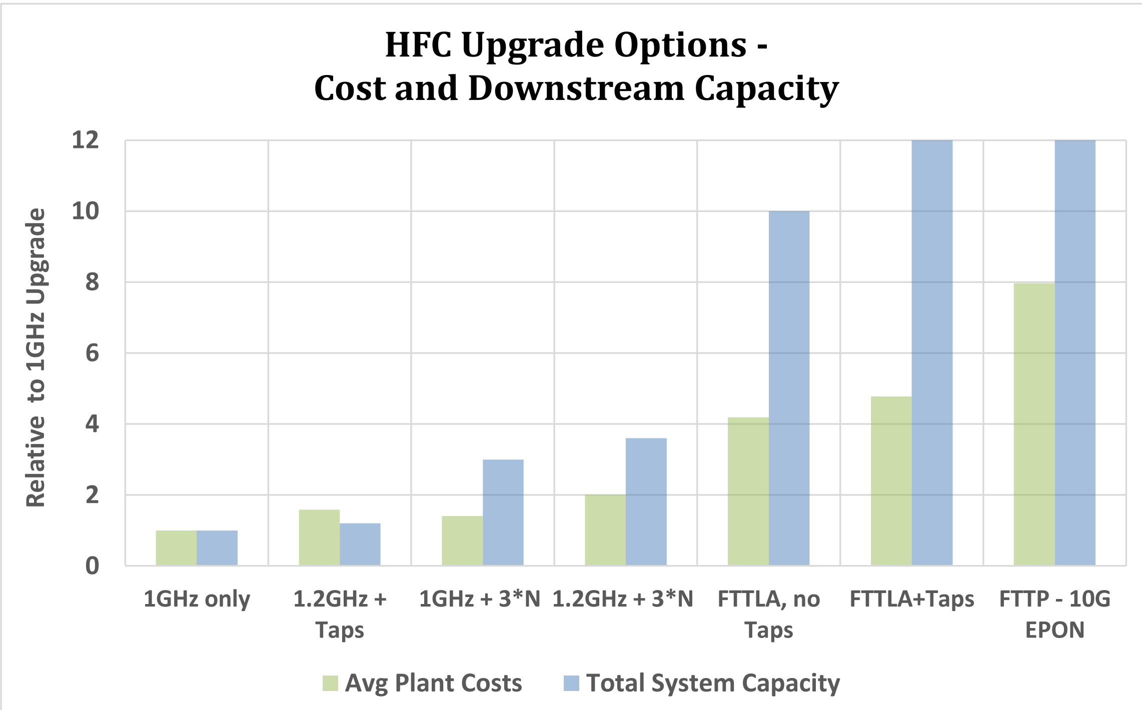


Figure 13 – Relative Cost and Capacity for Various HFC Upgrade Options

Figure 13 also includes a FTTP scenario with 10G EPON. This represents the expected average cost of installing the fiber. This does not include OLT or ONU costs and their installation. Note that the total system capacity for FTTLA with updated taps is identical to 10G EPON. Both offer identical link capacity of ~8.6 Gbps and provide for about 30 to 60 homes passed per serving group.

Fiber installation is a large variable in comparing these various Fiber Deep approaches. For each node in the case study, how much fiber needs to be installed for FTTLA, FTTC, and FTTH systems was analyzed. This is shown in Figure 14. The FTTC and FTTP show the incremental additional fiber required.

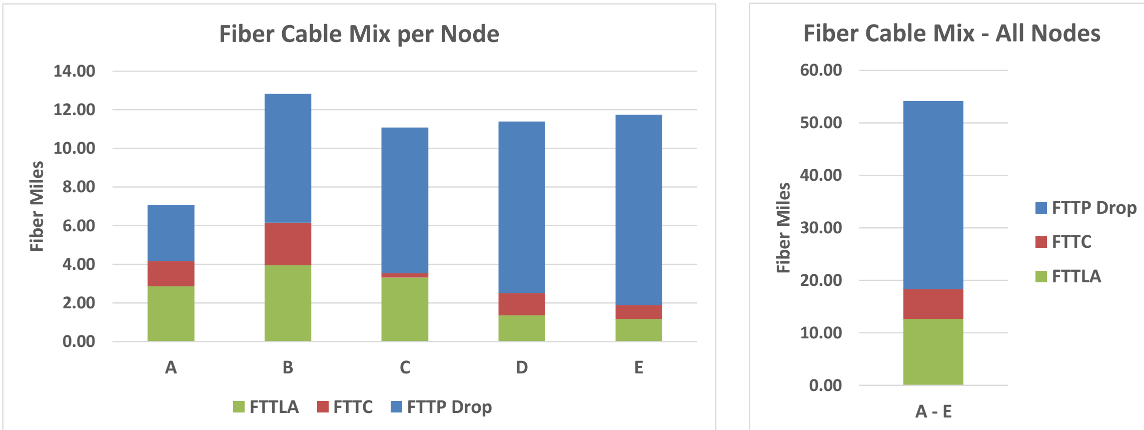


Figure 14 – Fiber Cable Mix: FTTLA, FTTC, FTTP

As can be seen, the mix of fiber between FTTLA/FTTC/FTTP can vary significantly from node to node. The total fiber for all five nodes is shown on the right. On aggregate, the FTTLA required ~24% of the total fiber; FTTC added another 10%; while the final fiber drop for FTTP accounts for ~66% of the total fiber in this case study.

ARRIS has investigated many other nodes besides the five detailed in the case study. As a general rule, it has been found that typically:

- Transport (from fiber node to last active) accounts for 10% to 20% of total FTTP fiber
- Distribution (from last active to HP curb) accounts for another 10% to 25%
- Home Drop (from curb to home) accounts for 60% to 75% of FTTP total fiber

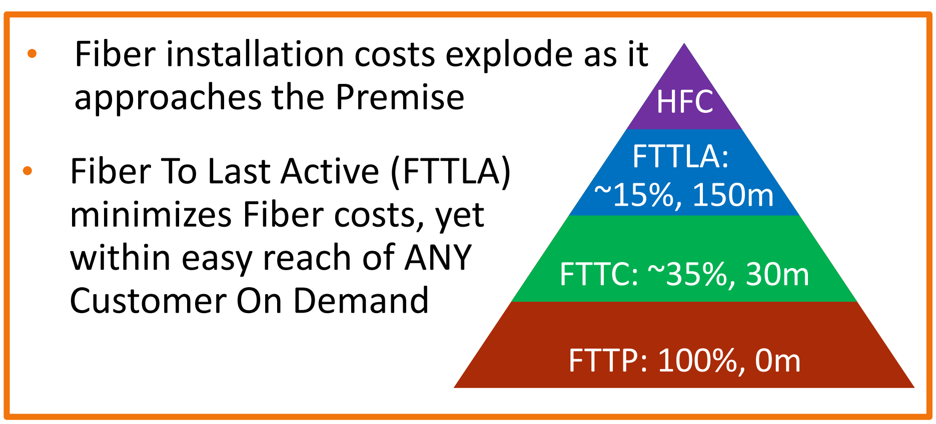


Figure 15 – Fiber Cable Mix: FTTLA, FTTC, FTTP

This is represented pictorially in Figure 15. If FTTP represents 100% of fiber required; then FTTC represents ~35% of the total fiber (e.g. fiber drop is ~65%); and finally FTTLA might only represent ~15% of the total fiber.

The FTTLA approach is more cost effective than FTTP in delivering 10G capacity, yet positions the operator to offer FTTP in the future on a demand basis to select customers. FTTLA makes a great stepping stone to an FTTP end game. But some operators may ask why not just invest directly into FTTP now? One financial consideration has to do with the timing of the migration to FTTP. The cost of a dollar in the future is cheaper than the cost of a dollar today. Figure 16 shows a Net Present Value (NPV) example using an 8% and 12% cost of capital. As can be seen, deferring an investment expense for a decade means an operator will actually be spending $0.28 to $0.43 on today's $1.

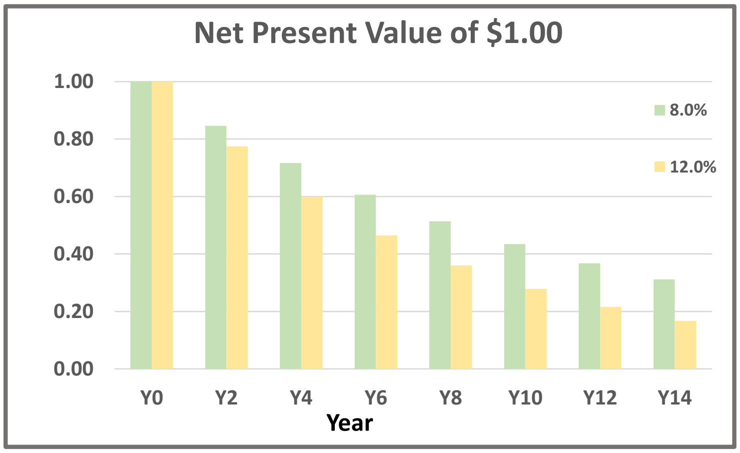


Figure 16 – Net Present Value Example

Remembering Figures 4 and 5 from the Network Capacity Planning section, the vast majority of subscribers can remain on HFC for several decades. By upgrading to FTTLA or other fiber deep such as FD N+0, an operator has enabled FTTP on demand. The final fiber drop represents two thirds of the total fiber in a FTTP system, so the operator can defer most of that for decades to come. From the network capacity planning, the top 1% might need to move to FTTx within the next 5-8 years, with another 5-15% following that in the next decade. Fiber Deep enables this transition with the minimum costs up front. So this begs the question, "Should an FTTH migration strategy really mean Fiber to the Hood?"

DOCSIS Pay-as-You-Grow Strategy

While the primary focus of this paper is on the comparisons of various access network options, it does utilize the same "pay-as-you-grow" philosophy that DOCSIS has leveraged for years. Deferring HFC upgrade costs until needed goes hand-in-hand with deploying additional DOCSIS resources when they are needed. Since these two are tightly coupled when doing a full system evaluation, the paper looks at the cost impacts of pay-as-you-grow on DOCSIS costs.

This philosophy really took hold with the advent of DOCSIS 3.0 and channel bonding. DOCSIS has embraced a pay-as-you-grow mentality since then. It basically says to install enough capacity now to satisfy customer requirements; then grow capacity later leveraging newer technology and innovations. Some factors that allow this work include:

- Minimize initial up-front investments
- Add additional capacity only when and as much as you need
- Take advantage of reducing costs over time

Figure 17 provides a historical perspective on CMTS/CCAP costs over the last decade. This is from data that has been collected over the years by Infonetics [IHS_2010-16]. The chart on the left shows CMTS revenue per downstream channel over the last decade. It is shown on a log scale because of the magnitude and also to show the consistent decrease in prices.

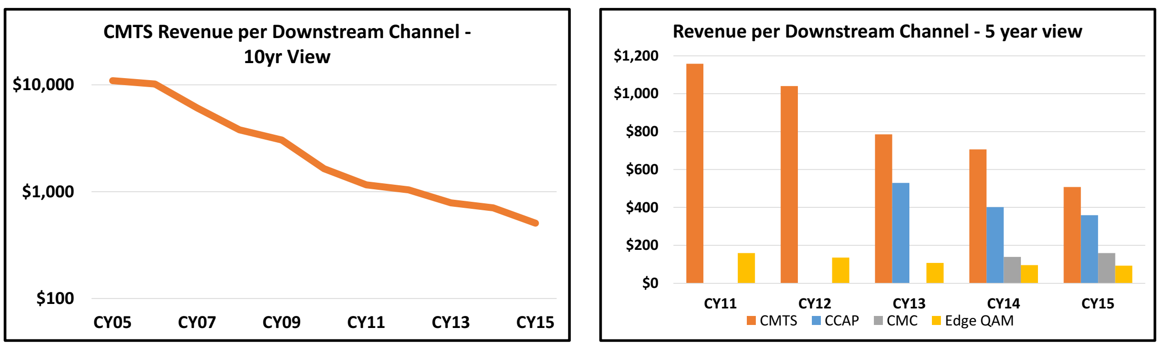


Figure 17 – CMTS/CCAP Costs – Historical Perspective

The chart on the right in Figure 17 zooms in on the last 5 years and shows several products including: CMTS, CCAP, EQAM, and CMC. The revenue per downstream DOCSIS channel has dropped ~25% per year over last 5 years. This is down from ~32% per year for previous 5 years. Even the relatively mature EQAM market has dropped ~13% per year over last 5 years.

Will DOCSIS revenue per downstream channel continue to decline? As any stockbroker will tell you, it is impossible to predict future prices based on past performances. To get a handle on this it is important to consider: Is DOCSIS technology maturing or is it innovating? If it is maturing, then the rate of decline may slow. If it is innovating, then new technologies can fuel further decreases. Looking at recent DOCSIS technologies, DOCSIS 3.1 is now entering its production phase and will dramatically increase DOCSIS capacity from 1 Gbps to 10 Gbps.

Additionally, there are a lot of other innovations going on in the DOCSIS world. New distributed architectures such as Remote PHY, Remote MACPHY, and Remote CCAP are bringing new solutions and new competitors to the DOCSIS world. There is a significant effort at CableLabs to finalize the DOCSIS Full-duplex specification. This is significant as it enables symmetric Gbps services. It also requires an N+0/FTTLA plant for operation. And with fiber pushing deeper, DOCSIS will also see spectrum extended as described in [CLOONAN_2016]. FTTLA could enable 25 Gbps DOCSIS systems while FTTC might enable 100 Gbps or higher.

Finally, much industry work is going into Software Defined Networks (SDN) and Network Function Virtualization (NFV). This will help drive the virtualization of DOCSIS platforms.

DOCSIS has seen more innovation in last couple years than previous two decades combined. This should help continue the downward pressure on DOCSIS costs.

So, what is the cost impact of this pay-as-you-grow philosophy? To analyze this, a hypothetical case is considered that starts with 16-bonded 3.0 channels in Year 0. The DOCSIS capacity is then roughly doubled every other year to keep up with network traffic growth as described earlier in this paper. At the end of 8 years, the DOCSIS system has reached 32-bonded 3.0 channels with 4 x 192 MHz OFDM channels. This represents a data rate of ~8.6 Gbps which is practically identical to 10G EPON. This capacity growth is shown in Figure 18. The capacity has grown by a factor of 14 over the 8 years.

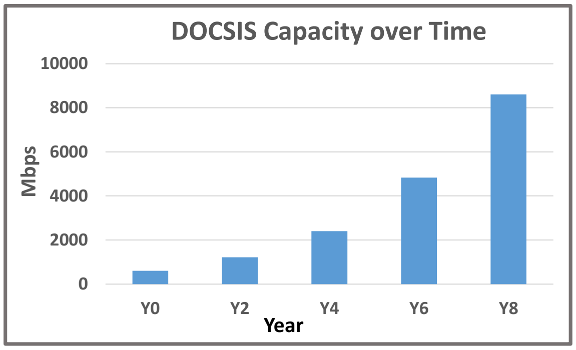


Figure 18 – DOCSIS Capacity Migration Example

As can be seen in Figure 18, most of the network capacity is added in later years. Some may say that the total DOCSIS costs will end up being 14 times the Year 0 costs using today's DOCSIS prices. Let's take a look at the impact on cost per bit of delaying those capacity purchases. This is vastly different than 10G EPON where the entire capacity must be purchased up front.

There are two important factors that will affect the overall cost. These are the continuing decline of CMTS/CCAP prices and the effect of NPV. These are shown in Figure 19.

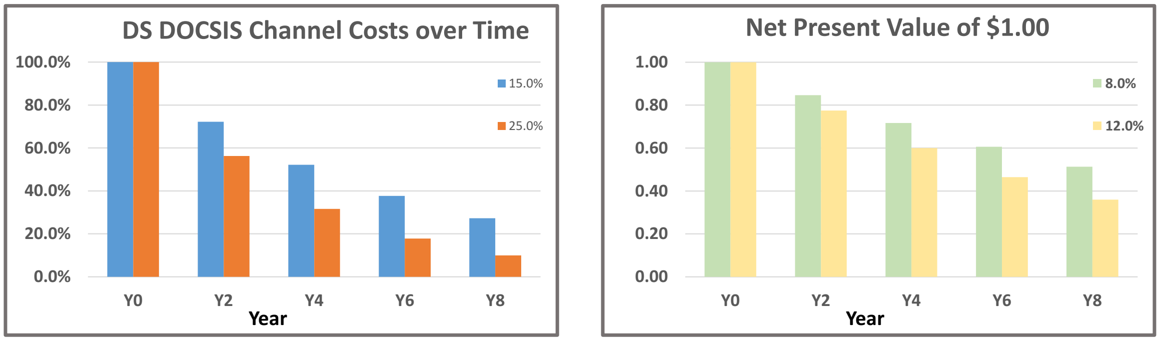


Figure 19 – DOCSIS Channel Costs, NPV Over an 8 Year Period

For future DOCSIS costs, a range of values are considered. On one end, a continuation of the 25% per year decline is assumed. On the other end, a slowing to 15% per year is used, similar to what has been experienced in the EQAM market. This is shown on the left of Figure 18. Note that by Year 8 when the largest amount of DOCSIS capacity is added, DOCSIS Channel costs are projected to be 10% to 27% of the original Year 0 costs.

The right hand side of Figure 19 shows the cost impact of NPV for 8% and 12% cost of capital. Note that by Year 8, the NPV is between $0.36 and $0.51 on today's $1. Both of these factors work together to reduce the cost per bit of DOCSIS. This causes the relative cost per DOCSIS bit to fall as shown on the right in Figure 20. One case looks at 15% a year DOCSIS price declines with 8% cost of capital while the other case uses 25% a year and 12% respectively. By Year 8, the relative cost per DOCSIS bit in today's dollars has fallen to somewhere between 4% and 14% of the original cost for the largest purchases of DOCSIS resources.

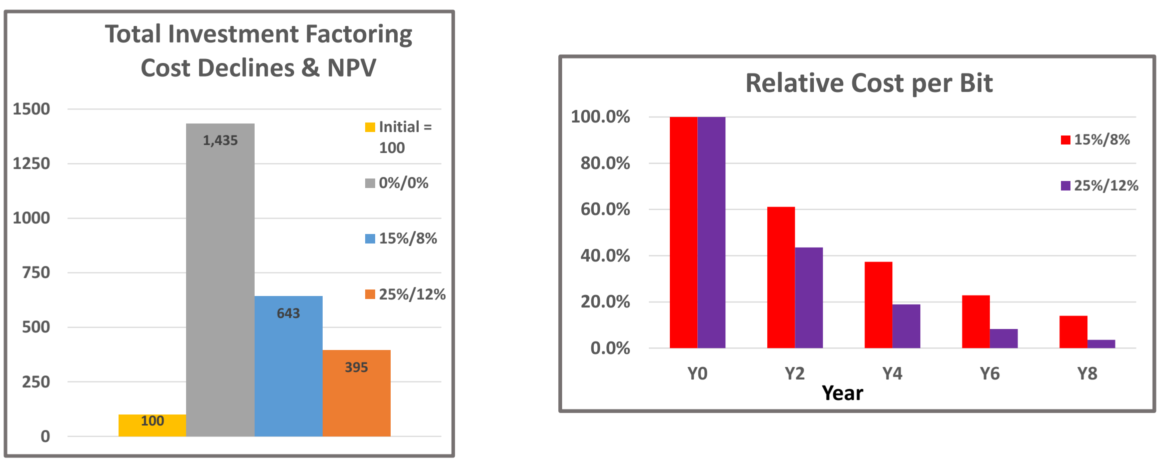


Figure 20 – DOCSIS Weighted Cost per Bit

The weighted average of the DOCSIS investments over the entire eight year period is shown on the left in Figure 20. The initial investment of 16 DOCSIS channels in Year 0 is used as a baseline and assigned a value of 100. If the entire DOCSIS capacity is purchased up front in Year 0, it would cost more than 14X the initial investment. However, factoring downstream channel cost reductions and NPV reduces total investment for 8.6 Gbps to the range of 4x to 6.4x the initial investment.

This shows the benefits of pay-as-you-grow over initial upfront investment of the full capacity. Some folks will argue that the cost per bit is much less for technology like 10G EPON. There are some caveats with this line of thought. In reality, cost per bit is actually cost per bandwidth or capacity.

Let's take a look at the validity of this metric. From a utilization perspective, it was noted that residential subscribers are barely consuming 1 Mbps on average as discussed earlier in this paper. For a 32 sub GPON system, this is ~1% utilization, while a 64 sub 10G EPON is being utilized less than one-half of 1%! So, is this a valid metric if 99%+ of bits are going unused?!

What about peak speeds? Streaming video is the dominant residential application today. Adaptive Bit Rate (ABR) protocols operate optimally when given 2-3X average video rate. So the dominant application, even with 4K UHD streams, can easily handle a couple UHD streams with a 100 Mbps service tier. The need for widespread 2.5G or 10G burst rates are still on the horizon.

While Cost per Bit is an interesting data point, one should not use this in isolation. Also consider Total Cost of Operation (TCO) and cost per subscriber as well when comparing solutions.

CONCLUSION

In summary, Selective Subscriber Migration strategy is a sensible approach for an HFC to FTTx transition. Moving top tiers to FTTx can buy HFC extra decades for 80-95% of subscribers in the flagship basic/economy tiers. Tmax dominates for the next 5-7 years, so it is more important to increase the HFC capacity to at least 1 GHz spectrum rather than split nodes. However, Tavg finally catches up 8-10+ years from now; and SG size reductions come back into vogue. Operators should push fiber deep enough to enable Selective FTTx for top tiers on demand and be prepared for the next round of SG splits.

To understand what the best option is to enable this migration, the paper analyzed in detail 5 very unique real nodes that varied from sparse rural node to a very dense urban node. Design work was then done on these five nodes for each of the following scenarios:

- "Business as usual" 1 GHz active drop in upgrade with node split as needed
- Fiber Deep – FTTLA
- FTTC
- FTTP

The results show that there is significant cost variations from use case to use case. Every operator must look at each individual scenario to determine what is best for that situation. However, some trends did emerge that should help guide the operators. The fiber deep approaches such as FTTLA provide some significant benefits such as:

1. Maximizes DOCSIS 3.1 performance
    a. Data capacity that matches 10 Gbps PON
2. Provides excellent stepping stone to FTTP on-demand
    a. Selective Subscriber Migration to FTTP as needed
    b. On average, fiber is less than 1000’ from any tap
3. Provides fine granularity for optimizing DOCSIS SG sizes
    a. Same SG sizes as PON: ~30-60 homes
    b. Maximize DOCSIS CMTS/CCAP resources
4. Reduces maintenance, power, and operational expenses compared to today’s HFC
5. Future proof architecture
    a. N+0 enables DOCSIS Full-duplex (FDX) and extended spectrum
    b. These new technologies promise to do for DOCSIS & cable what G.fast is attempting to do for DSL and twisted pair.

The FTTLA analysis shows that it is an effective fiber deep FTTx migration strategy that is an economical stepping stone to FTTP. It can add decades to the life of the vast majority of customers remaining on HFC while enabling a selective migration of the top tiers to FTTP. Other N+0 fiber deep approaches were not explicitly discussed in this paper but are expected that they would show similar costs and benefits as FTTLA.

ACKNOWLEDGEMENTS

The authors would like to gratefully acknowledge the assistance of Stuart Eastman and members of his team who helped immensely with analyzing, dissecting, and creating data and material for the use cases that are the backbone of this paper. We also would like to acknowledge Venk Mutalik for his inputs on FTTLA and other fiber deep architectural choices.

ABBREVIATIONS

ABR	Adaptive Bit Rate
ASC	Active Splitter-Combiner
BAU	Business as Usual
Bcast	Broadcast
Bps	Bits Per Second
CAA	Centralized Access Architecture
CAGR	Compounded Annual Growth Rate
CAPEX	Capital Expense
CCAP	Converged Cable Access Platform
CM	Cable Modem
CMTS	Cable Modem Termination System
CPE	Consumer Premise Equipment
D3.1	Data Over Cable Service Interface Specification 3.1
DAA	Distributed Access Architecture
DCA	Distributed CCAP Architecture
DEPI	Downstream External PHY Interface
DNA	Distributed Node Architecture
DOCSIS	Data Over Cable Service Interface Specification
DS	Downstream
DWDM	Dense Wave Division Multiplexing
E2E	End to end
EPON	Ethernet Passive Optical Network (aka GE-PON)
EQAM	Edge Quadrature Amplitude Modulator
FD	Fiber Deep
FDX	Full Duplex (i.e. DOCSIS)
FEC	Forward error correction
FTTC	Fiber to the Curb
FTTH	Fiber to the Home
FTTLA	Fiber to the Last Active
FTTP	Fiber to the Premise
FTTT	Fiber to the Tap
FTTx	Fiber to the ‘x’ where ‘x’ can be any of the above
Gbps	Gigabits Per Second
GHz	Gigahertz
GPON	Gigabit-Passive Optical Network
HFC	Hybrid Fiber-Coax
HP	Homes Passed
HPON	Hybrid Passive Optical Network

HSD	High Speed Data
I-CCAP	Integrated Converged Cable Access Platform
IEEE	Institute of Electrical and Electronics Engineers
IEQ	Integrated Edge QAM
LDPC	Low Density Parity Check FEC Code
MAC	Media Access Control interface
MACPHY	DCA instantiation that places both MAC & PHY in the Node
Mbps	Mega Bits Per Second
MDU	Multiple Dwelling Unit
MHz	Megahertz
MSO	Multiple System Operator
N+0	Node+0 actives
Ncast	Narrowcast
NFV	Network Function Virtualization
NPV	Net Present Value
NSI	Network Side Interface
OBI	Optical Beat Interference
ODN	Optical Distribution Network
OFDM	Orthogonal Frequency Division Multiplexing
OFDMA	Orthogonal Frequency Division Multiplexing Access (Upstream)
OLT	Optical Line Termination
ONU	Optical Network Unit
OOB	Out of Band
OPEX	Operating Expense
OTT	Over the Top
PHY	Physical interface
PNM	Proactive Network Maintenance
PON	Passive Optical Network
QAM	Quadrature Amplitude Modulation
QoE	Quality of Experience
QoS	Quality of Service
RF	Radio frequency
RFoG	RF Over Glass
ROI	Return on Investment
R-OLT	Remote OLT
RPD	Remote PHY Device
R-MACPHY	Remote MAC-PHY
R-PHY	Remote PHY
RX	Receive
SDN	Software Defined Network
SG	Service Group

SCTE	Society of Cable Telecommunications Engineers
SNR	Signal to Noise Ratio
TaFDM	Time and Frequency Division Multiplexing
Tavg	Average bandwidth per subscriber
TCO	Total Cost of Operation
Tmax	Maximum Sustained Traffic Rate – DOCSIS Service Flow parameter
TX	Transmit
UHD	Ultra High Definition
US	Upstream
VOD	Video on demand
WDM	Wavelength Division Multiplexing

RELATED READINGS

- **The Yin and the Yang of a Move to All Fiber: Transforming HFC to an All Fiber Network While Leveraging the Deployed HFC Assets** – This paper provides critical insights into the innovations that enable OBI free RFoG transmissions and discusses intrinsic capabilities of Hybrid PON (HPON) technology, explaining how this technology works with existing HFC analog and QAM video and D3.0 and D3.1 signals while also being completely transparent with traditional PON standards such as the 10G EPON, 1G EPON, GPON and XGPON1.

- **Powering PON with HFC - A Hybrid for a New Generation** – In the past 10-15 years, fiber-to-the-premises (FTTP) networks have been deployed in many regions of the world. This paper compares the total end-to-end costs and throughput of the most common types of PONs and demonstrates how the HFC node can be used to enable cable operators to deliver HFC and fiber-to-the-premises (FTTP) services simultaneously from the same node.

- **Comparing the DOCSIS 3.1 and HFC Evolution to the FTTH Revolution** – This paper describers the existing network migration options including different migration paths for the existing coax-to-the-home (CTTH) network supporting more IP/data capacity with DOCSIS 3.0/3.1 over HFC.

MEET ONE OF OUR EXPERTS: John Ulm

John Ulm holds the position of Engineering Fellow, Broadband Systems for ARRIS within the Network Solutions CTO group. In this role he investigates Advanced Technologies for Broadband Systems including strategic technical directions for multiscreen services and bandwidth expansion. Recent activities include research into next generation CCAP architectures; HFC to FTTx migration including Hybrid PON (HPON), distributed access architectures such as Remote-CCAP and Remote-PHY; next generation protocols including DOCSIS 3.1 and NG-EPON; and Multi-screen IP Video solutions including multicast-assisted ABR.

John's three decades in the Broadband industry began as designer, architect, and MAC protocol developer at LANcity, pioneering the industry's first cable modem systems. He was primary author for the Cable Industry's DOCSIS 1.0 and 1.1 specifications that drove early cable modem success. He also spent time as Network Processor architect for Nortel and as senior technical consultant to the Broadband industry with YAS Corp.

John holds a BSEE and MSEE from RPI and has a multitude of papers and patents to his name.

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