Network Migration to 1.8 GHz

Operational "Spectral Analysis" Measured in nano-Hertz, a 30-Year Perspective

A Technical Paper prepared for SCTE by

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1. Introduction

Frequency is the number of cycles per unit time. Communications often use signals occupying MHz and GHz spectrum. But when it comes to the network's operational health, it is the 1 to 10 nano-Hertz frequencies that matter the most!

How so? Those frequencies correspond to 30- and 3-year cycles, respectively. And most activities affecting the network's health (construction, upgrade, and maintenance cycles) fall within this range. This paper investigates the 5 W's of network upgrades around the pending Extended Spectrum DOCSIS 4.0 (ESD) rollout and its alternatives. It looks holistically at what makes economic sense over the full 30-year cycle, not just the next incremental step.

What network components are impacted? Over 30 years, a Hybrid Fiber-Coax (HFC) plant sees taps, amps and nodes going through 1 or more upgrade cycles, while Cable Modem Termination Systems (CMTS) and consumer premises equipment (CPE) upgrade even more often. Until now, these cycles were all independent. However, Distributed Access Architecture (DAA) and ESD now lock these together. Accounting for this, applying average per cycle costs and integrating over the "spectrum" is akin to performing a financial "spectral analysis." Both capital and operating expenditures may be captured this way, giving operators a *long-term total cost of ownership* (TCO) of the network.

When is the right time for various upgrades? Doing Fiber to the Premises (FTTP) now spends the bulk of the upgrade budget up front when 99% of its capacity goes unused. Can operators be wiser on when to invest in the network? When will the capacity be needed? Recent broadband bandwidth trends are reviewed and show a sharp decrease in subscriber consumption compounded annual growth rates (CAGR) over recent years. As an example, this might cause the network upgrade cycle to go from every 10 years to every 30 years with resultant economic impact. Upgrading too aggressively may be throwing away dollars in the near term.

Where do multi-system operators (MSOs) touch the network? Is it a complete overlay or just a surgical strike? Swap tap faceplates or go for 3 GHz tap housings? Keep existing amp cascade or push fiber deeper? Walking through the process forces operators to quantify materials, inventories, and project execution times.

Why choose a particular technology direction? Many upgrade decisions must be made soon and made well with the long term, full cycle consideration. Should operators upgrade amps to mid or high split or ESD?

Who will benefit from this? Network operators, small and large. From the long-term, big picture view this analysis gives, they'll be able to focus on just the near-term network operation and upgrade aspects, and plan for the budgets over the next 3-5 years with ease while keeping aligned with their 10- to 30-year cycle objectives. These are the 1-10 nano-Hertz frequencies that are our major concerns.

2. Broadband Traffic Engineering and BW Growth Trends Overview

2.1.1. Broadband Traffic Engineering

The CommScope (formerly ARRIS) team has led industry traffic engineering research for over a decade. [CLO_2014] introduced broadband Quality of Experience (QoE) using a simple formula with basic network capacity components. This evolved and [ULM_2019] gave an updated insight into calculating the service group (SG) capacity requirements:

Modified "COMMSCOPE/CLOONAN'S CAPACITY EQUATION" Traffic Eng Formula:

$$\mathbf{C \geq (Nsub * Tavg) + (K\text{-}1) * Tmax\_max + Tmax\_max} \tag{1}$$

The subtle change is that there are now three main components to the traffic engineering formula:

1. Peak Busy Period Average Consumption (i.e., Nsub * Tavg)
2. Peak Busy Period Ripple for managing QoE (i.e. (K-1) * Tmax_max)
3. Headroom for maximum Service Tier Burst (i.e., 1 * Tmax_max)

While burst and ripple components manage a subscriber's QoE, the consumption component is key to SG sizing. The Tavg growth rate has seen much research. ARRIS/CommScope has the most extensive broadband capacity monitoring history in the industry, collecting continuously since 2010 from the same MSOs. The 2022 data is in and downstream (DS) Tavg growth continues to slow.

The real multi-billion-dollar question is what's the consumption growth for coming decades? For this paper, it is a three-decade window being considered. This growth drives our network investment strategies. Has Tavg growth slowed to a lower rate or is it no longer exponential? A companion paper by these authors [ULM_2022] investigated several possible growth trendlines including exponential, linear, Adoption S-curve and others. Our research measures how accurately each trendline matches last decade's data. These bandwidth (BW) growth trajectories in [ULM_2022] were mapped out for 5/10/15 years. The resultant spaghetti plots in Figure 1 show a cone of uncertainty that grows over time, roughly doubling every 5 yrs.

2.1.2. Growth Rates for Broadband Peak Period Consumption

To understand the impact of these slowing growth rates, consider the following comparison to projections from just four years ago:

- 2018 DS Growth (43% CAGR) projection => DS Tavg = 100 Mbps/sub **by 2030**
- 2022 DS High Growth (21% CAGR) projection => DS Tavg = 100 Mbps/sub **by 2040**
- 2022 DS Low Growth (Linear) projection => DS Tavg = 100 Mbps/sub **in 200+ years**

[ULM_2022] implied that *the need for FTTP to all subscribers may be pushed back multiple decades*. This paper takes an economic view of different upgrade options for each of the low, medium, and high growth rate scenarios. From a network capacity planning perspective, [ULM_2022] conclusions on multiple growth trendline options were:

- the 5-year window provides a reasonably high confidence for near-term planning
- 10-yr window provides high, moderate, and slow growth ranges for longer term planning
- the 15-yr window shows too much variance and is more of an academic exercise.

This paper considers a 30-year window, so it is clearly noted that this falls under the academic exercise scenarios. However, it is still informative to see how this wide "cone of uncertainty" might impact our network migration economics.

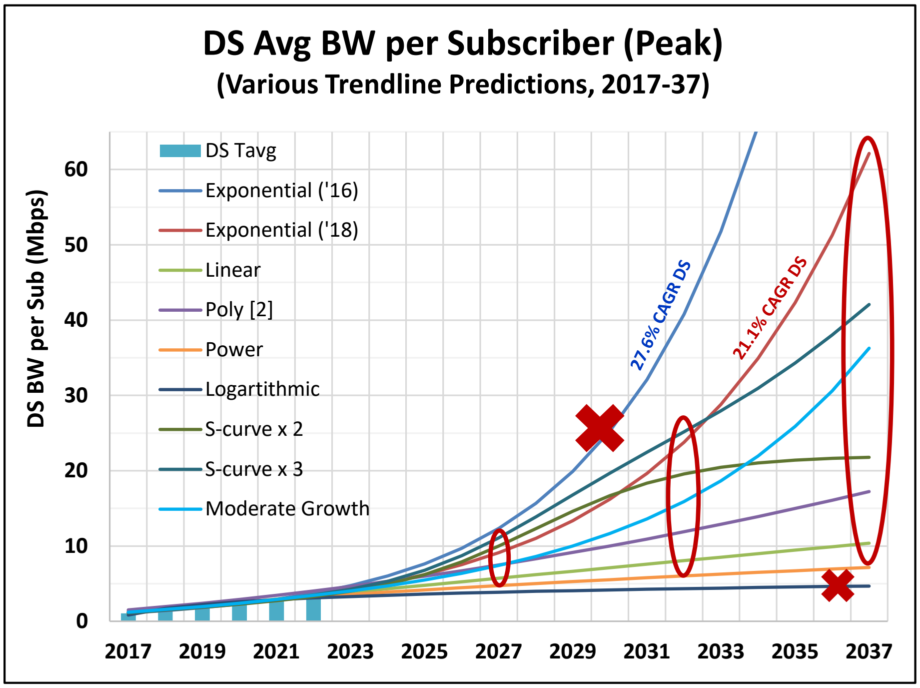

Figure 1 – DS Tavg Growth Projections for 2022 to 2037

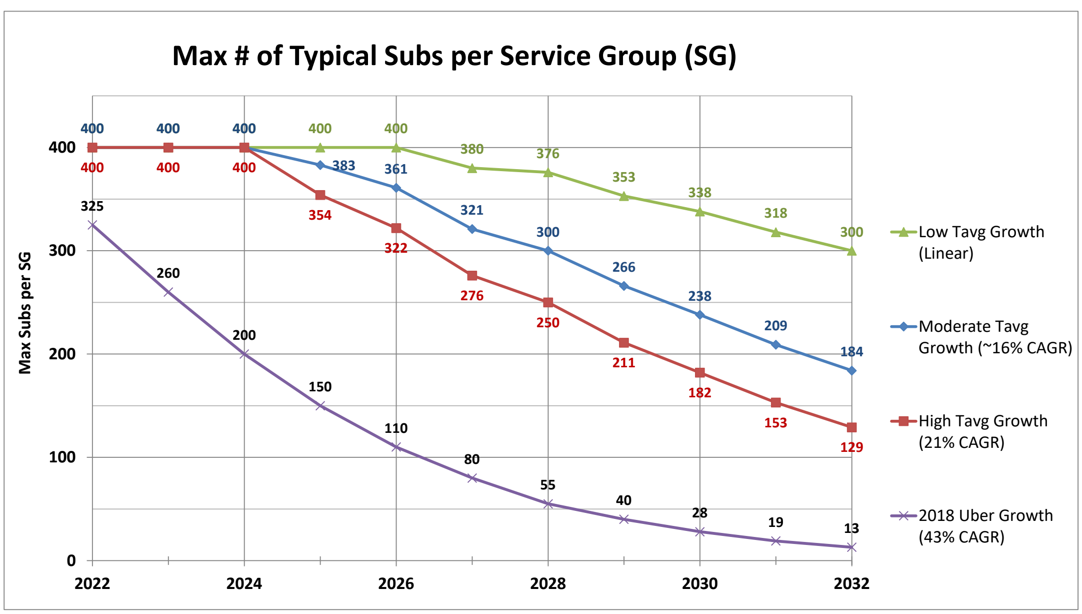

Figure 2 – Max Subs per SG for Low, Moderate & High DS Tavg growth, 1794/396 MHz

[ULM_2022] used the CommScope network capacity model to investigate several upgrade case studies. The 1794/396 MHz case study seen in Figure 2 showed that a node with 150+ subs can offer multi-gigabit service tiers; but the timing of additional node splits on the ESD plant is sensitive to which DS Tavg growth trendline it tracks. It shows there is no pressing need to push the HFC to very small (but inefficient!) Node + 0 (N+0) SG sizes in a 10-year window. This paper extends that analysis to 30-years to see how various upgrade options are impacted by the different growth trendlines.

2.1.3. Extending Tavg Growth Trendlines to 2052

The goal is to minimize up front investments while maintaining flexibility to increase network capacity and manage uncertainty risks. In this paper, there are several primary cases being considered in detail:

- Low growth scenario enabling 1.2 GHz DOCSIS 3.1 (D3.1) high-split to last 30 years
- Moderate growth scenario with a 1.8 GHz DOCSIS 4.0 ESD upgrade over 30 years
- High growth scenario with a 1.8 GHz DOCSIS 4.0 ESD upgrade in ’23 and FTTP overlay in ‘44
- High growth scenario with a FTTP upgrade in ‘23

The impact of the other growth trendlines will also be investigated for each upgrade path to ascertain the operator’s risk with each path.

The first step in projecting SG sizes out to 2052 is to extend the Tavg growth trendlines from [ULM_2022]. The DS Tavg growth trendlines are shown in Figure 3 and the upstream (US) Tavg growth trendlines in Figure 4. Because of the divergence of the various trendlines over the 30-year window, note that the Y-axis is now a log scale. Our studies will consider low, medium, and high growth scenarios.

The DS high growth scenario follows the 21% CAGR exponential trendline for the first 15 years. By the end of 30-years, the spread between the linear trendline and the 21% CAGR eventually becomes an almost absurd amount – 17 Mbps compared to 1,100 Mbps. For this study, the authors decided to drop the two extreme trendlines (upper and lower) for the 30-year point, maintaining that the probability of staying at the extreme for 30 consecutive years would be very low. The red ovals in Figures 3 and 4 indicate the trendlines used at 15-years and 30-years with a transition period between them.

For the 30-year period, the DS high growth then transitions to a more moderate 16% CAGR exponential trendline. The DS Tavg window being considered in 2052 still ranges from 22 Mbps to 356 Mbps. Note, even if DS Tavg stayed on the 21% CAGR for 30 straight years, the only impact on our analysis is that the 2052 numbers get pulled in 5-7 years earlier which is a minor impact to the overall financial analysis.

The US high growth scenario follows a similar methodology. It follows the 23% CAGR exponential trendline for the first 15 years, then transitions to a more moderate 18.5% CAGR exponential trendline. The US Tavg window being considered in 2052 ranges from 6 Mbps to 48 Mbps.

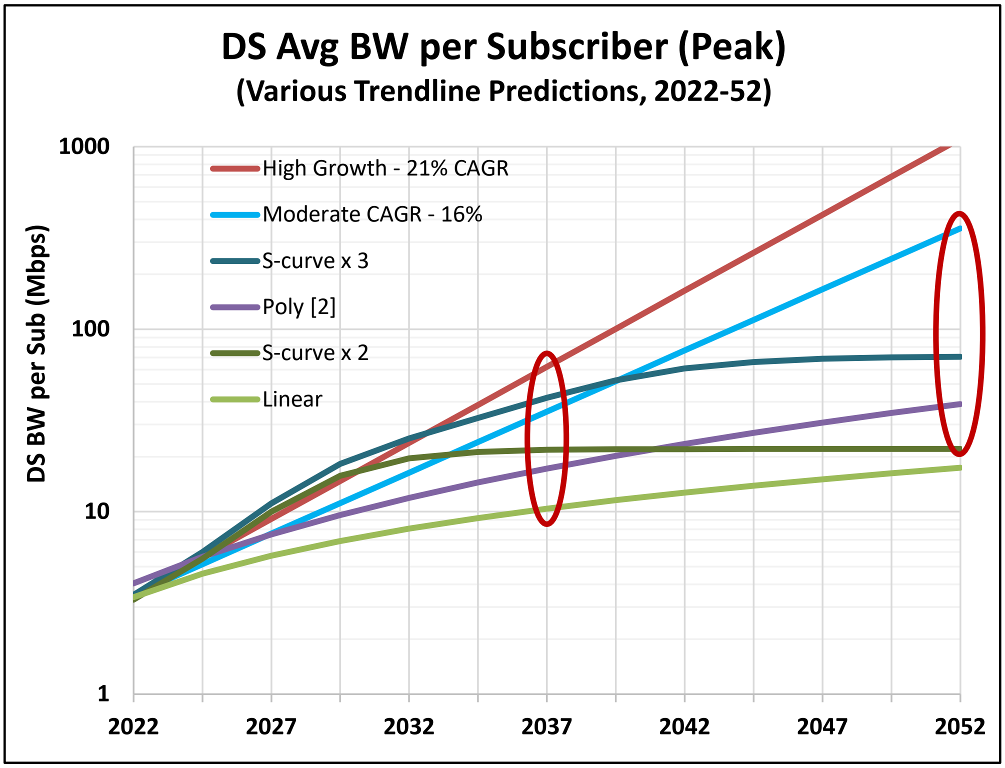

Figure 3 – Downstream Tavg Trendline Predictions, 2022 – 52

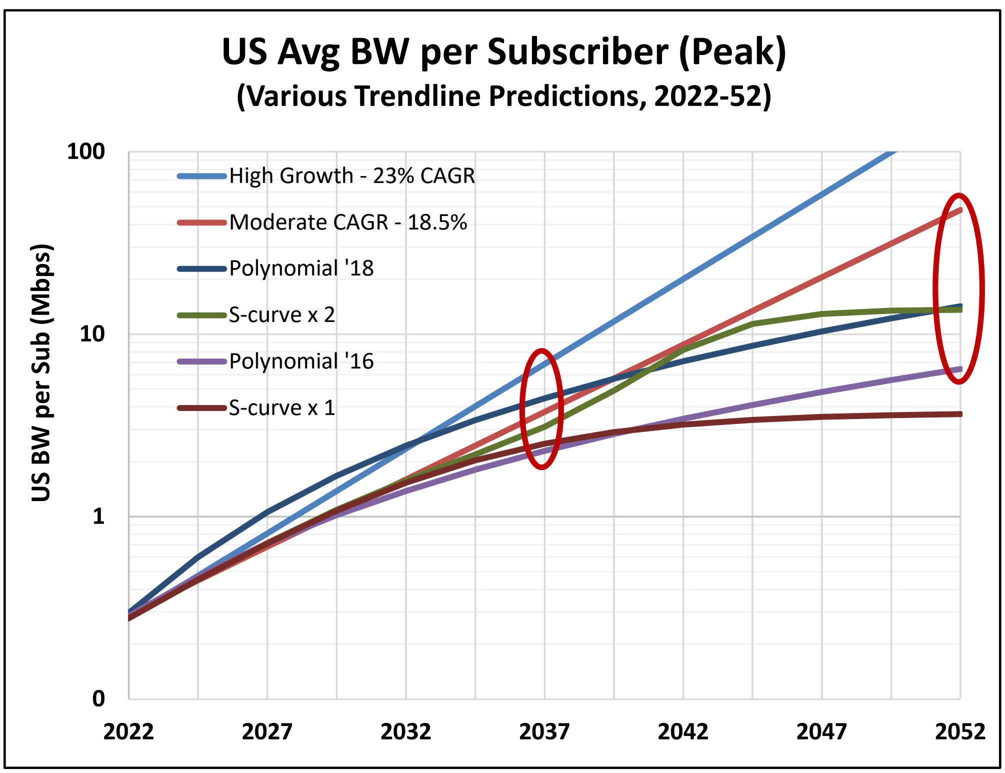

Figure 4 – Upstream Tavg Trendline Predictions, 2022 – 52

2.1.4. Projecting Service Group (SG) Sizes for a 30-year window

The ARRIS/CommScope Traffic Engineering formula shown earlier provides guidance on calculating SG sizes. For a given network (e.g., 1218/204 MHz HFC plant), the available capacity is known. Once Tavg and Tmax_max are defined, then the maximum number of subscribers, Nsub, can be calculated. The DS and US Tavg for a given year are derived from the growth trendlines in the previous section. Low, medium, and high growth scenarios are considered.

The final piece to the puzzle is determining what to use for Tmax_max. The authors decided to set the DS Tmax_max to 5 Gbps. The rationale being that this can handle any known application today. If an application like virtual reality (VR) or augmented reality (AR) really takes off, then that will drive a higher Tavg growth trendline. Having a 5 Gbps service tier burst on top of that high Tavg should be more than sufficient. History has shown that it often takes a decade or more before new technologies become mainstream. This can be seen in how long it took High Definition (HD) video streams to become dominant. Ultra-HD 4K video stream has been around almost a decade and still is not dominant yet.

The max US service tier is defined by the particular type of network upgrade. The 204 MHz high split plant supports a 1 Gbps US tier. The 396 MHz ultra-high ESD split supports a 2.5 Gbps US tier. The 10G Passive Optical Network (PON) supports a symmetric 5 Gbps US tier. Again, there is no mainstream application in sight that would need more than a gigabit of burst speed.

Our analysis starts with a typical HFC SG with 200 subscribers (e.g., 400 homes passed (HP) @ 50% penetration). The CommScope network capacity model is then run for low, medium, and high scenarios to determine the maximum number of typical subs that can be support in each year through 2052. When that growth line passes through the 200 sub/SG limit, then the SG needs to be segmented (e.g., 1x1 Remote MACPHY Device (RMD) upgraded to 2x2 RMD). Similarly, once a growth line passes through the 100 sub/SG limit, then the SG needs to be segmented a second time (e.g., 2x2 RMD upgraded to 4x4 RMD). In reality, the number of homes passed per radio frequency (RF) leg is often unbalanced, so a 4x4 RMD may be of limited use and a node split is required instead. As will be seen in the upcoming results, the need for 4x4 segmentation is still 15+ years away for today's 200 sub service groups.

2.1.5. Network Capacity Modeling results for 1.2 GHz HFC Plant

The network capacity modeling results for a 258-1218 MHz HFC DS is shown in Figure 5. The low growth scenario can support 200 typical subs all the way until 2049 when the SG needs a 2x2 segmentation. The moderate growth scenario supports 200 subs per SG through 2033 when it needs a 2x2 segmentation. The network then supports 100 subs per SG until 2040 when a 4x4 segmentation is required. So, an MSO has a clear path to 2052 with a 1.2 GHz HFC DS for both the low and medium growth scenarios.

The high growth scenario is much more challenging for the 1.2 GHz HFC DS. The first 2x2 segmentation comes around 2030 while the next 4x4 segmentation is needed by 2035. The 4x4 segmentation then runs out of capacity around 2040. In reality, the operator will probably switch to either 1.8 GHz or 10G PON sometime in the 2035-40 timeframe.

The network capacity modeling results for a 204 MHz HFC US is shown in Figure 6. In the low growth scenario, US capacity is depleted sooner than the previous DS example. By 2037, the US needs to be segmented. This can be done with a 1x2 RMD replacing the 1x1 RMD. For medium growth, the US timeline is like the DS, although the 2x4/4x4 US does run out of capacity around 2045. This would then require further node splits or a switch to one of the other technologies. The US high growth scenario is very close timeline to the DS timeline.

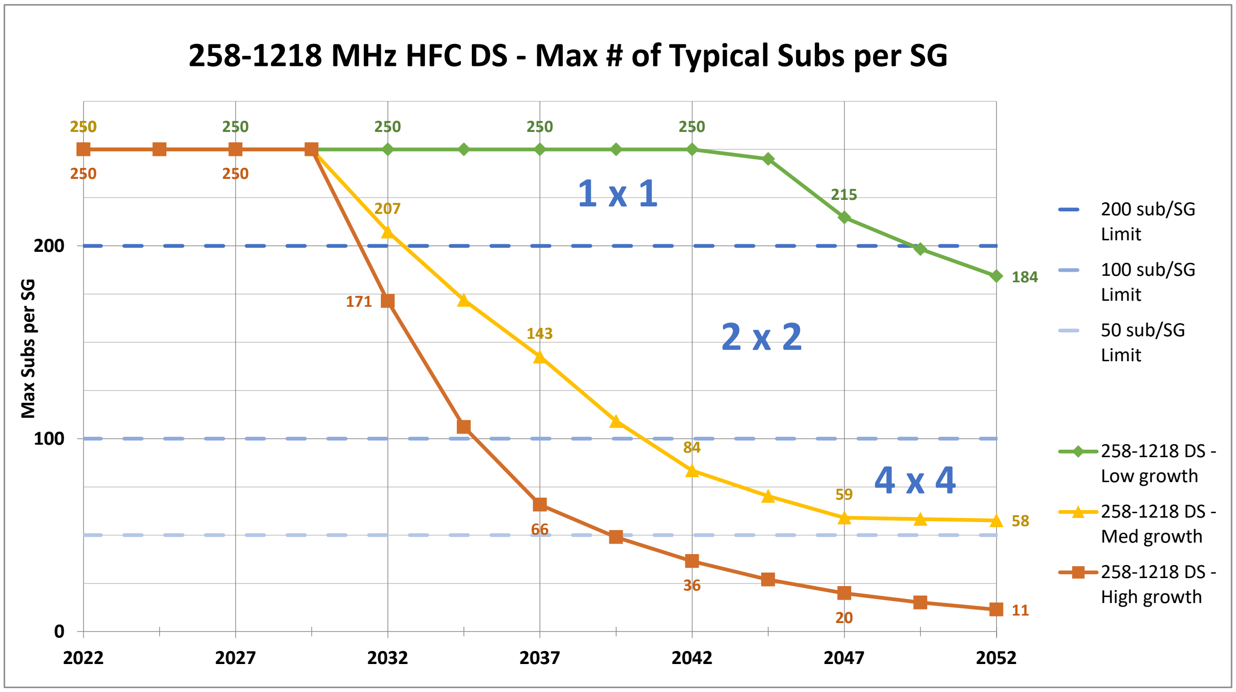

Figure 5 – Max # of Typical Subs per SG – 258-1218 MHz HFC DS

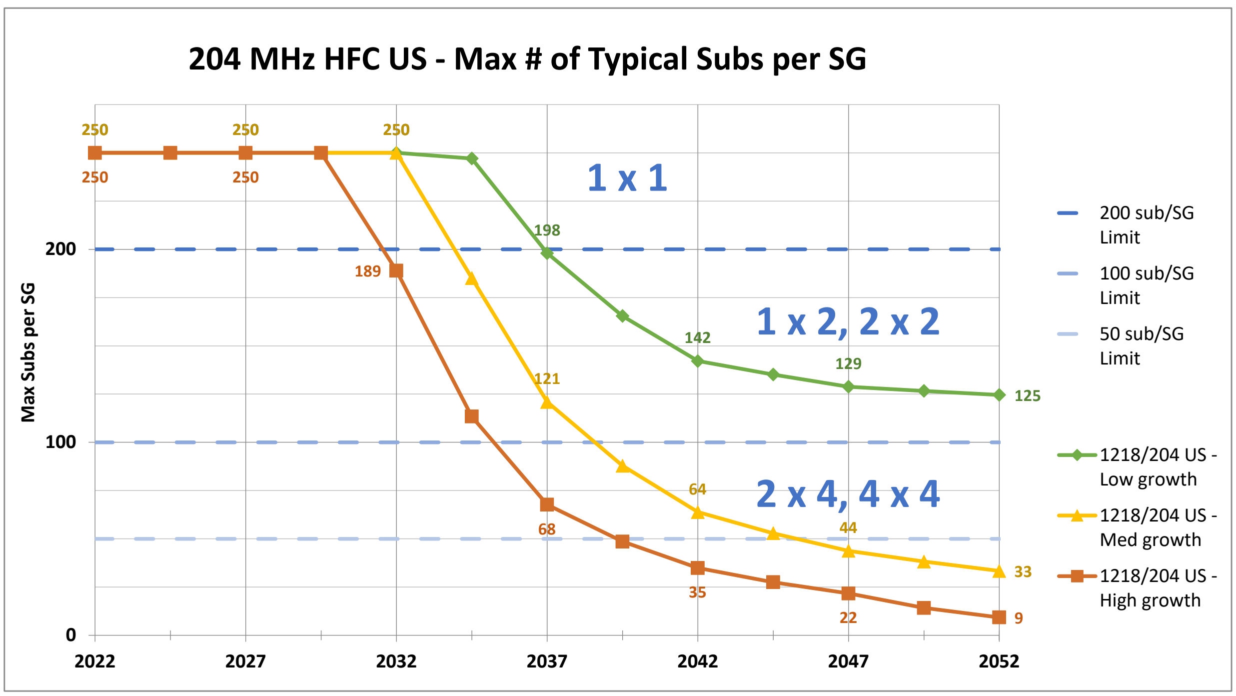

Figure 6 – Max # of Typical Subs per SG – 204 MHz HFC US

2.1.6. Network Capacity Modeling results for 1.8 GHz ESD Plant

The network capacity modeling results for a 492-1794 MHz ESD DS is shown in Figure 7. The low growth scenario can support 200 typical subs through 2052 with no segmentation required. The moderate growth scenario supports 200 subs per SG through 2039 when it needs a 2x2 segmentation. The network then supports 100 subs per SG until 2047 when a 4x4 segmentation might be needed. Again, an MSO has a clear path to 2052 with a 1.8 GHz ESD DS for both the low and medium growth scenarios.

The high growth scenario is more interesting with the 1.8 GHz ESD DS. The first 2x2 segmentation is not until 2034. The next 4x4 segmentation is needed by 2038. The 4x4 segmentation capacity then holds out until 2044. At this point, the operator has at least three potential paths:

1. Continue to pull fiber deeper and split ESD nodes into smaller SG
2. Switch to FTTP for all customers
3. Do an FTTP overlay and selectively migrate heavy users to PON

The economics of the third option above is looked at in more detail in the upcoming sections.

The network capacity modeling results for a 396 MHz ESD US is shown in Figure 8. In general, all three US growth scenarios have very similar breakpoints as the DS scenarios. The only point that is different is with the medium growth scenario. The 2x2 US runs out of capacity around 2045 where a switch to 2x4 RMD might be needed.

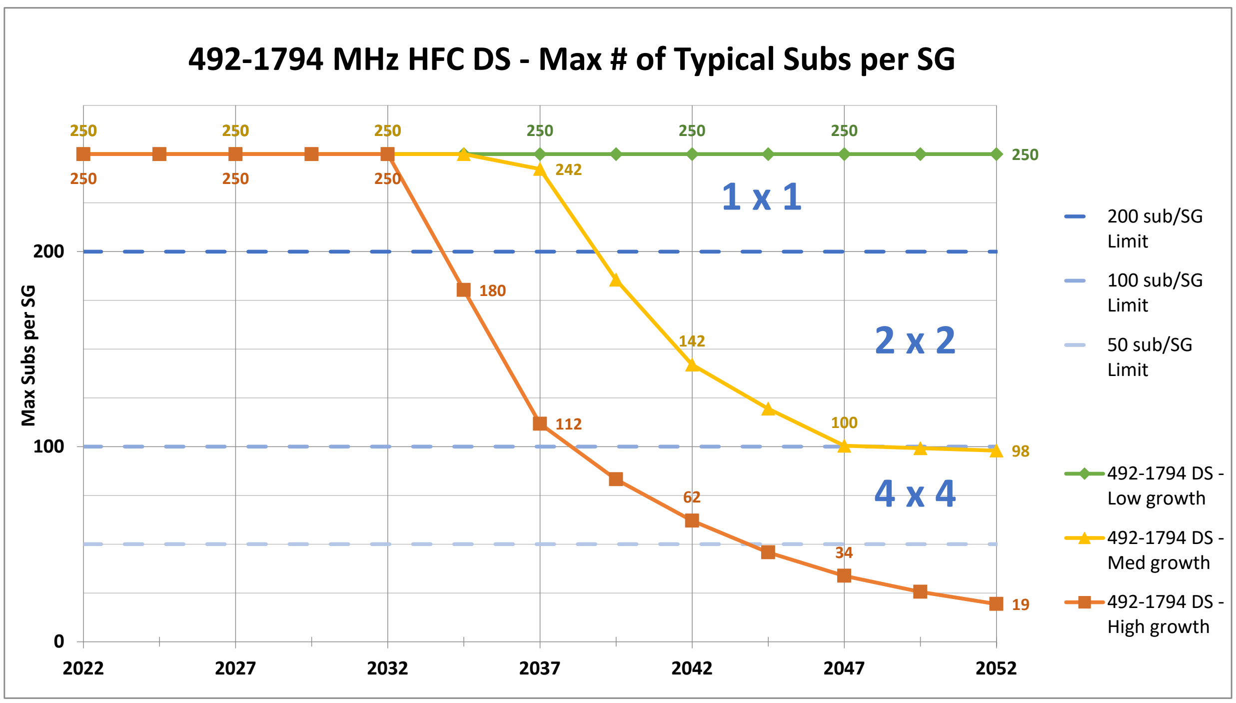

Figure 7 – Max # of Typical Subs per SG – 492-1794 MHz ESD DS

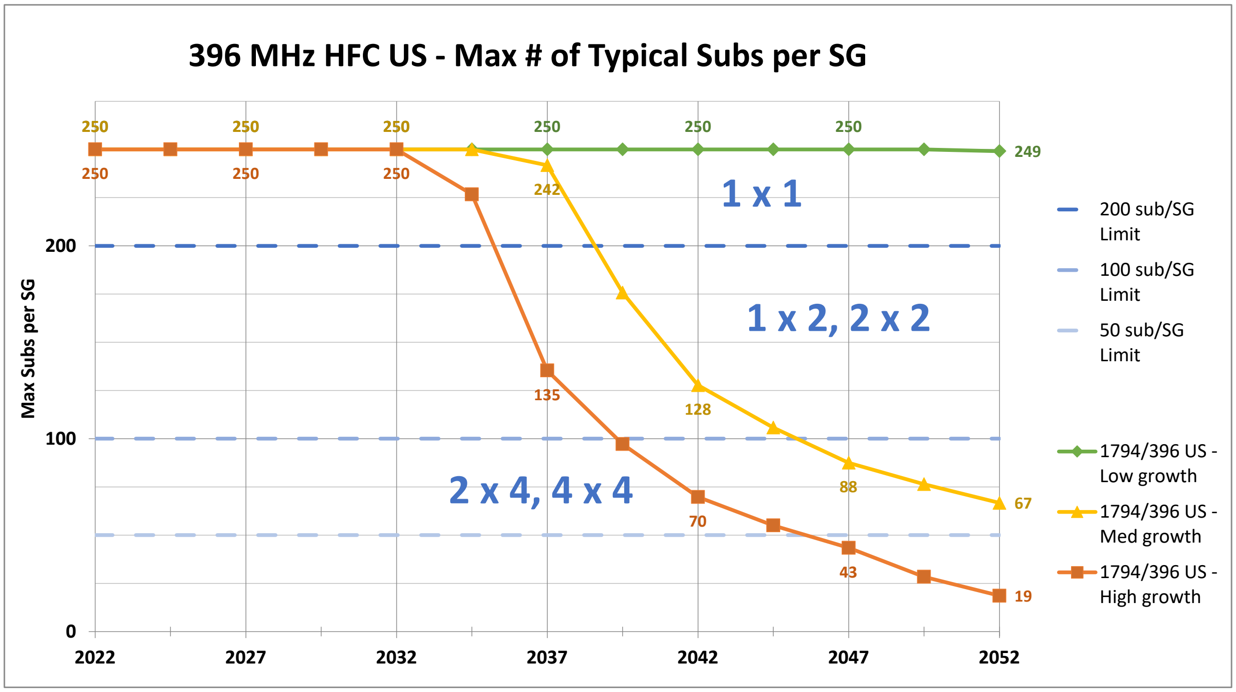

Figure 8 – Max # of Typical Subs per SG – 396 MHz ESD US

2.1.7. Network Capacity Modeling results for 10G PON Plant

The 10G PON modeling assumes 128 HP per Remote Optical Line Terminal (R-OLT) port with 64 subs. The network capacity modeling results for a 10G PON DS is shown in Figure 9. The low growth scenario can support 64 typical subs through 2052 with no segmentation required. The moderate growth scenario supports 64 subs per SG through 2043 when it needs to drop to 64 HP and up to 49 subs through 2052.

The high growth DS scenario pushes the 10G PON capacity, just like it did ESD. Around 2036, it needs to drop to 64 HP and 32 subs. By 2042, the 10G PON needs to segment again to get to 32 HP and smaller SG sizes. This will probably be the time where an operator needs to start transferring heavy users to one of the next generations of PON technology (e.g., 25+ Gbps).

The 10G PON has plenty of US capacity and can handle low, medium, and high growth scenarios for 128 HP and 64 subs per SG through 2052, as is shown in Figure 10.

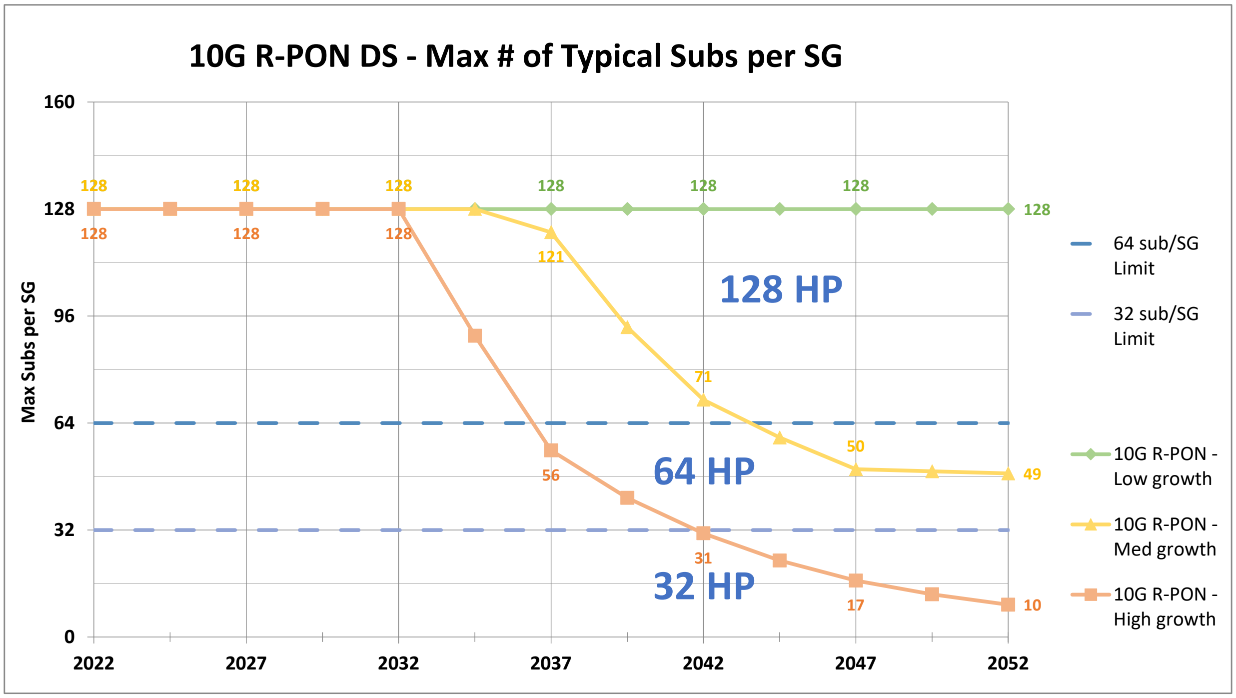

Figure 9 – Max # of Typical Subs per SG – 10G PON DS

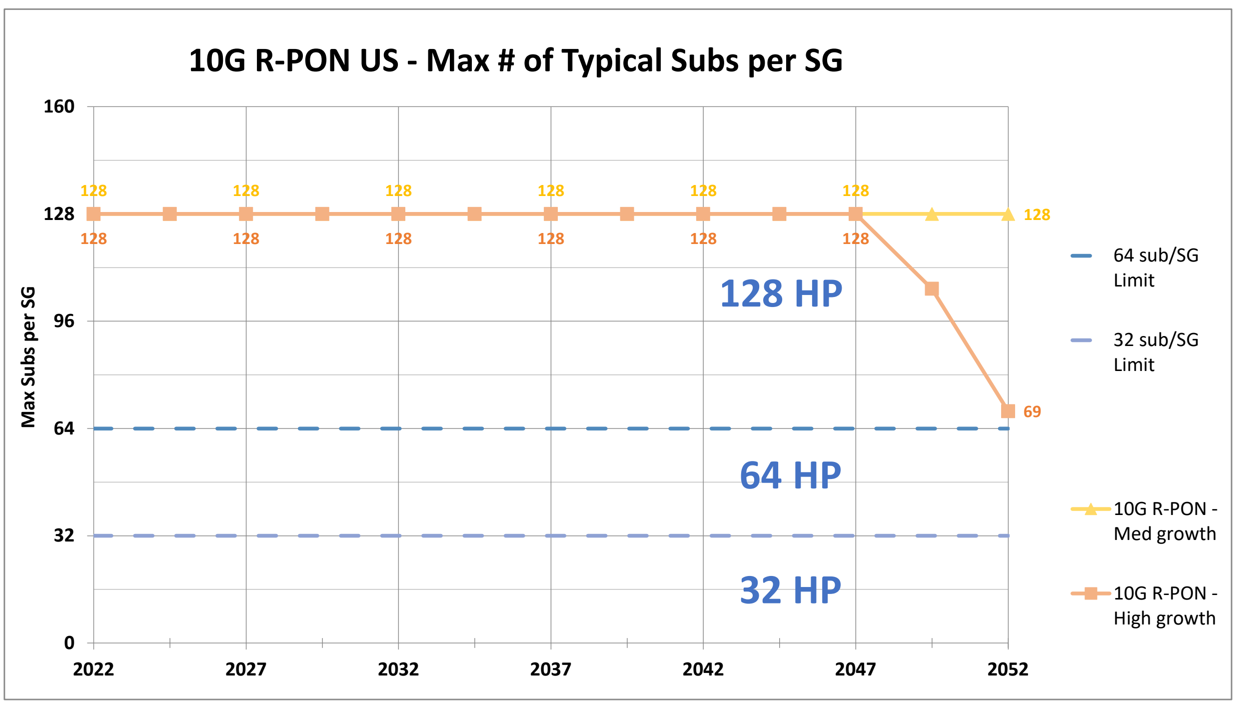

Figure 10 – Max # of Typical Subs per SG – 10G PON US

3. Total Cost of Ownership for Various Network Upgrade Options

3.1. Network Upgrade Considerations

3.1.1. Network Evolution Example

Over the past ~30 years, HFC networks progressed from ragtag one-way community antenna video distribution networks to modern high-capacity video, voice, and data bi-directional networks of today. Figure 11 shows a high-level view of such a network. This example falls under the centralized architecture model, where all the sophisticated communication layer processing takes place in the Head-End. Here, signals are 'packaged,' and then 'shipped' over a more or less transparent physical network. The other side of processing takes place at the CPE / cable modem (CM).

The way the network was built is best described as an evolution: first the cables were installed; with the RF amplifiers and taps placed where required, and the same with the headend and customer premise gear. Once every ~30 years, the taps get a refresh – typically via faceplate upgrade – for example, 750 MHz taps would get upgraded to 1 GHz or 1.2 GHz taps. Amplifiers get renewed every ~15 years, either due to technological obsolescence or to reaching the end of reliable operation lifetime. Fiber nodes may get a refresh even more often than every 15 years. Node splitting, for example, is still an effective way to boost total capacity and service levels, in otherwise over-subscribed service groups. Finally, the headend and customer premise equipment refresh-cycles fall under just in time schedule – perhaps every 3-5 years, allowing for capacity boosts as needed, in the most cost-efficient way.

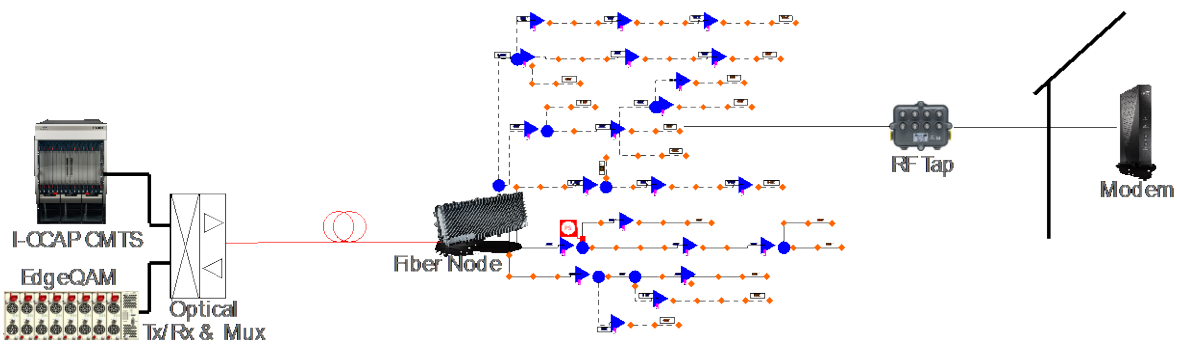

Figure 11: I-CCAP HFC network with head-end, field, & CPE network elements

The example network of Figure 11 may have 1 GHz taps installed 25 years ago, 750/870 or 1000 MHz RF amplifiers with 42/54 MHz RF split, updated 15 years ago, and perhaps 1 GHz nodes, with the same 42/54 MHz sub-split, updated 10 years ago. Headend and CPE may have been upgraded as recently as 5 years ago, with the latest wave of DOCSIS 3.1 (D3.1) deployments, correlated with introduction of 1 Gbps downstream data rates.

As learned in these COVID times, the networks delivered, and delivered marvelously, especially in the downstream. The 42 MHz upstream capacity was severely tested all day long with working and school from home. Some nodes struggled but were quickly upgraded with additional capacity. With FTTP/PON competition offering gigabit rates in the upstream - it is now imperative for MSOs to resolve the network's 42 MHz upstream capacity limitations. So, many operators are now considering their next network migration steps.

3.1.2. Network Upgrade Options to consider

CableLabs DOCSIS spec creators have envisioned these types of scenarios. Many paths exist to upgrade networks and boost its capacity in both downstream and upstream to extend the useful life of the network. Out of many options discussed in [Broadband Pie], the following upgrade scenarios of most interest are considered in this paper:

1. DOCSIS 3.1 Integrated Converged Cable Access Platform (I-CCAP) "high-split" (HS) upgrade
    - With 5-204 MHz upstream, 258 - 1,218 MHz downstream
2. DOCSIS 4.0 RMD ESD "ultra-high-split" (UHS) upgrade
    - With 5-396 MHz upstream, 492 - 1,794 MHz downstream, one of several ESD options
3. FTTP 10G R-PON (Remote OLT PON) upgrade
    - Effectively overbuilding the coaxial portion of the plant with fiber, and providing fiber drops to those homes that have signed up for the service

The FTTP upgrade provides lower operating costs (OPEX), in comparison to HFC networks [bbcmag FTTH OPEX] and [FTTH OPEX]. The more important question is: will those operating cost savings offset a much larger capital expenditure (CAPEX) required upfront to build an all-fiber network? Last year's SCTE Cable-Tec Expo paper [Broadband Pie] considered this question, by looking into "total cost of ownership" (TCO) of nine various upgrade paths, including the three mentioned above. It used a fifteen-year period for which the total cost was calculated. This paper expands that analysis to consider a 30-year period, and in part to answer if the 15-year timeframe was too limiting.

3.1.3. Time Value of Money

To address any of these various duration questions, the "time value of money" (TVM) concept is one critical element to factor into the analysis. It is incorporated via a "discount rate" for the future years' cash flows. For example, a discount rate at say 5% applied to $100 received a year from now has a value today that would be ~$95, or 1 / (1+5%) = $95.24 exactly. The same applies to the expenses: one postponed by a year is ~5% less of an expense in today's dollars. Similarly, today's $100 is worth $105 a year from now.

Economists employ a dividend discount model (DDM) [Gordon] to estimate the present value of an infinite-series of future cash flows. A perpetual stream of annual $100 expenses would be valued at $2000, $1333, and $1000 in today's dollars, with 5%, 7.5% and 10% discount rates, respectively. A difficult question is what exact discount rate to use – short and long-term interest rates, overall economy growth rate, and inflation rate are contributing factors, and the discount rate chosen affects the present value of future cash flows a lot!

Highlighted points in Figure 12 illustrate what percentages of that present value (PV) is still achieved if the perpetual flow were to cease flowing 15 or 30 years from now – also shown as a function of the discount rate. This concept, applied to TCO analysis, explains that working with a 15-year period considers only between 52% and 76% of the OPEX contributions, provided the discount rates are between 5% and 10%. Moving to 30 years, however, improves those numbers to between 77% and 94%. Given all the uncertainties involved, and that the authors will be thrilled if the overall model accuracy reaches +/-20 %, one may conclude, especially at 7.5% discount rate, to get to the 89% of the total value of OPEX is more than "good enough." The 7.5% discount rate is chosen as a reasonable middle point between 5% (considered low) and 10% (considered high) discount rates.

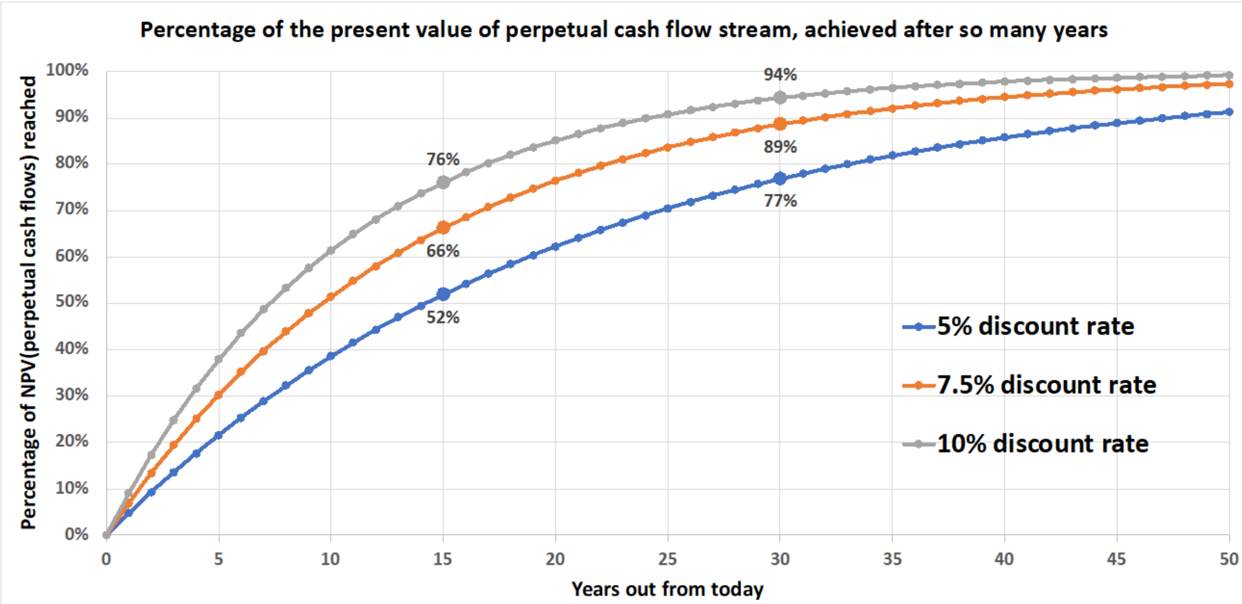

Figure 12: Percentage of PV for an infinite cash flow stream

The 30-year window is also an important consideration for CAPEX too. Components such as amplifiers might need replacing every 15 years. With a 7.5% discount rate, the replacement costs for an amplifier 15-years from now adds an additional ~34% in today's dollars to the amplifier's CAPEX costs. Another replacement after 30-years adds another ~12% to the CAPEX. Looking at the finances from a spectral perspective provides a better insight into these recurring costs for some of the options.

3.2. 30-year Total Cost of Ownership (TCO) Assumptions

To get the total cost of ownership, both CAPEX and OPEX are included over a 30-year period.

3.2.1. Capital Expenditures (CAPEX)

CAPEX is determined by adding cost of materials, plus the cost of labor necessary to install the materials. Headend, field, and customer premise equipment are all accounted for. Breakout of what the initial upgrade CAPEX for the three outlined options is shown in Figure 13.

The network shown in Figure 11 is the starting point for each upgrade option. Its characteristics:

- I-CCAP topology, with 5-42 / 54-860 MHz upstream and downstream
- 21,120 feet of hardline coax plant
- 400 HP with a 50% take rate (i.e., 200 subscribers)
- One fiber node, 7 bridger & 14 line-extender RF amplifiers and 100 RF taps

Statistics for this node area work out to:

- 100 homes-passed per mile
- 5.25 RF amplifiers per mile
- 19 homes-passed per amplifier
- ~5 taps per RF amplifier and ~4 homes-passed per tap

This is very representative of a typical suburban North American HFC plant.

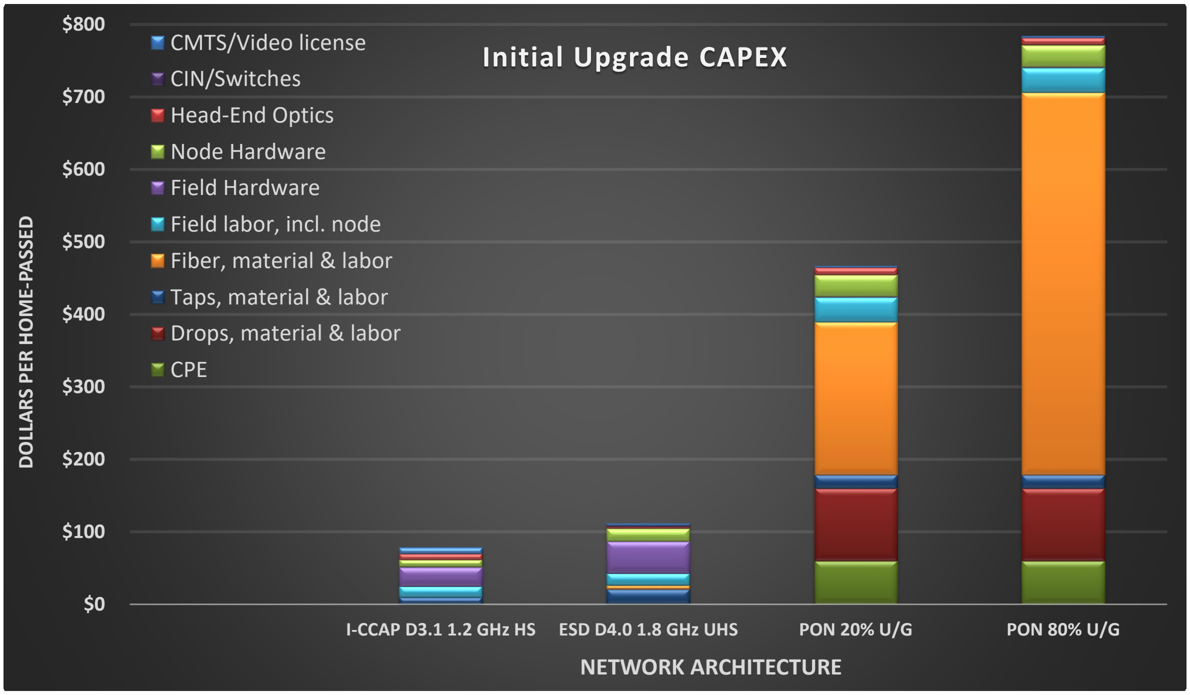

Figure 13: Initial CAPEX ($ per HP) for D3.1 High-split; D4.0 ESD; & 10G R-PON upgrades

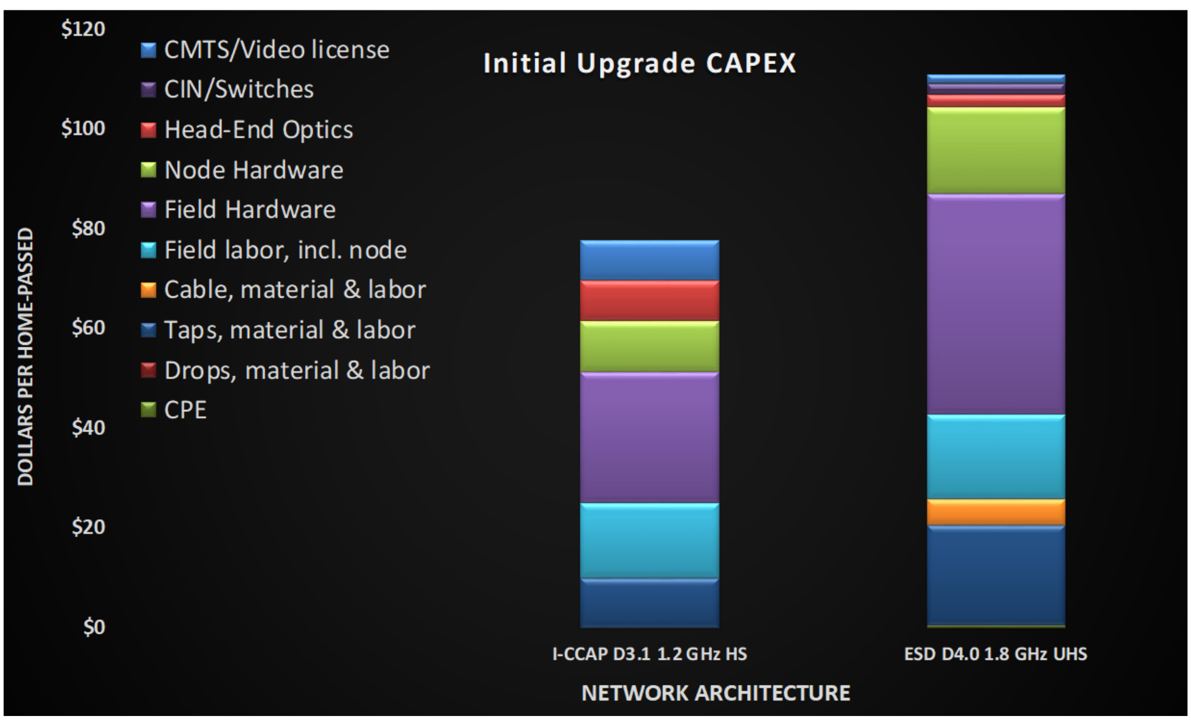

Figure 14: Initial CAPEX ($ per HP) for D3.1 High-split & D4.0 ESD upgrades - detailed

Table 1: Initial upgrade CAPEX, per node area

	I-CCAP 1218/204 MHz High Split	DAA 1794/396 MHz UHS ESD	FTTP 10G R-PON 20% Underground	FTTP 10G R-PON 80% Underground
CMTS / Video license	$3,250	$800	$800	$800
CIN / Ethernet Switches		$871	$3,485	$3,485
Head-End Optics	$3,210	$1,000	$4,000	$4,000
Node Hardware	$4,100	$7,000	$11,875	$11,875
Field Hardware	$10,500	$17,640	$500	$500
Field labor, incl node	$6,050	$6,800	$13,563	$13,563
Fiber, material + labor		$2,112	$84,480	$211,200
Taps/splitters, mtrl + lbr	$4,000	$8,000	$7,500	$7,500
Drops, material + labor			$40,000	$40,000
CPE		$240	$24,000	$24,000
Total, per SG or node	**$31,110**	**$44,463**	**$190,203**	**$316,923**
Total, per HP	**$78**	**$111**	**$476**	**$792**

**** Disclaimer: Price points discussed and shown in this document are meant to provide indicative general trends for these architectures, and as such should not be construed as an offer for selling any products at any of the price points shown. ****

Material and labor per node area are best-effort estimates, shown in Figure 14 and detailed in Table 1.

For I-CCAP high-split option, CMTS license covers additional DS and US enabled D3.1 spectrum. Furthermore, complete replacement of head-end optics, node and RF amplifiers is assumed, with digital return for the 5-204 MHz upstream spectrum. Field labor includes $500 for the node replacement, $250 per bridger and $200 per line extender, plus $1,000 for documentation update for the area. Only the tap faceplate is upgraded, at $40 per tap.

For ESD 396/492 MHz ultra-high-split option, the head-end side of Figure 11 gets upgraded to the one shown in Figure 15 – the Cable Modem Termination System (CMTS), digital video Quadrature Amplitude Modulation (QAM) generators and analog headend optics are replaced by converged interconnect network (CIN), interfacing the Ethernet and video core with the node-located Remote PHY device (RPD) and/or RMD devices. Pluggable Dense Wavelength Division Multiplexing (DWDM) enhanced Small Form-factor Pluggable (SFP+) modules are shown at $1,000 each, with one on each end of the digital optical link interfacing CIN and the node. 1.8 GHz Node and RF amplifier hardware are new products and assumed to be at 40% premium over those for 1.2 GHz. The 1.8 GHz ESD upgrade has some additions in comparison to the 1.2 GHz case, including a provision for 5% of aerial plant cable replacement, and an increase in the number of actives, from 7 & 14 to 10 & 14 bridgers & line extenders, respectively. Furthermore, a complete tap housing upgrade to 1.8 GHz is included at $80 per tap, including material & labor.

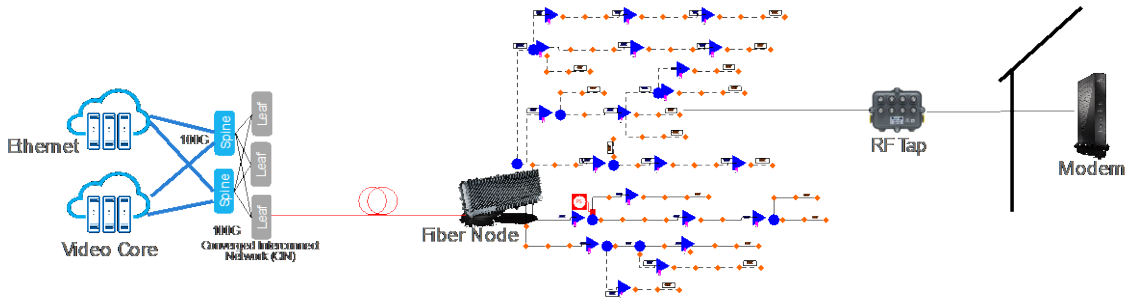

Figure 15: Head-end changes for DAA D4.0 ESD upgrade

For the 10G R-PON upgrade, Figure 15 topology serves as a blueprint, except that the complete hardline coax plant is overbuilt with fiber. The first PON option assumes an 80/20 percent mix of aerial to underground plant, with $2/foot for aerial, and $12/foot for underground - which comes to a blended cost of $4/foot – for both material & labor to install. The second PON option assumes a 20/80 percent mix of aerial/underground plant with a blended cost of $10/foot. The same CIN headend network of Figure 15 feeds node located R-PON remote optical line terminals (R-OLTs), using SFP+ modules at both ends, just like the ESD case. A quantity 4 of optical wavelengths are required, given the 1x 128 splitting ratio presumed for the 10G R-PON case. Field optical splitters costs are shown in taps row; drops, at $200 each, and CPE, at $120 each, are allotted for subscribed premises (50% of homes passed) only.

As can be seen by the results at the bottom of Table 1, the initial PON upgrade costs dwarf the initial HFC upgrade costs, by up to 10x more. The billion-dollar question is whether the PON networks save the operator enough over 30-years in OPEX and additional CAPEX savings to make this investment worthwhile.

3.2.1. *Operational Expenditures (OPEX)*

The OPEX includes headend and field power consumption, plant cable and drop cable repair and maintenance costs, and field actives maintenance (material and labor to address equipment failures).

Field actives maintenance cost in time is based on the heuristics curve from [Broadband Pie] and is repeated in Figure 16. As can be seen, there is a significant rise in failures after year 10.

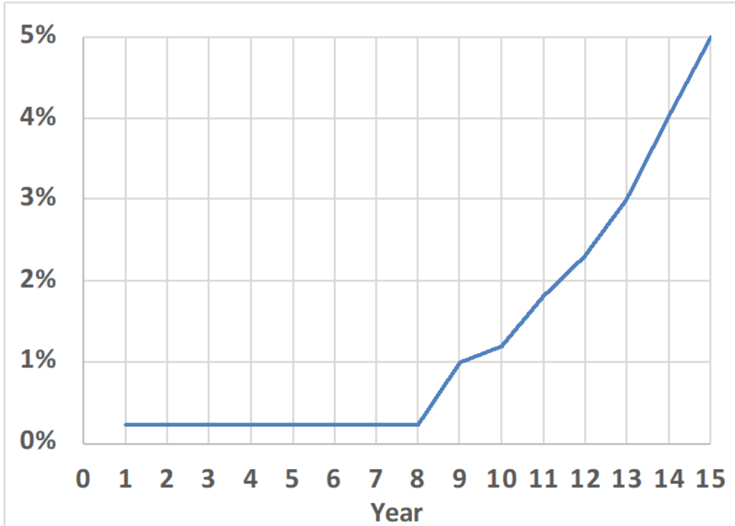

Figure 16: Field actives percentage fail heuristics curve

I-CCAP 1.2 GHz headend powering needs are estimated as 124 Watts (W) per node area, including 50% cooling provision overhead for the buildings Heating, Ventilation and Air Conditioning (HVAC). Field line power supplies are presumed to operate with 85% efficiency, feeding 90W, 45W, and 25W to nodes, bridgers, and line extenders, respectively, assuming 3% in-coax ohmic loss.

For the 1.8 GHz DAA, the headend side consumption drops to 18W, while the field component assumptions change to 150W, 60W, and 35W, for nodes, bridgers, and line extenders, respectively.

The R-PON R-OLTs are modeled at 18W and 22W per 10G OLT port, on the headend and node side, respectively.

With $0.12 per kilowatt-hour (kWh) assumption, the powering cost conveniently comes out to “kilo-dollar per kWh” for the whole year:

- 24 hours x 365.25 days = 8,766 hours in a year, times $0.12 / kWh = $1,052 per kWh per year

For the HFC upgrades, an annual upkeep is expected to be required for 1% of the hardline plant, as well as 1% of the drop-coax. This has also been built into OPEX. For the PON case, however, only 0.35% upkeep assumption of the cables, and 0.5% for the drop fibers has been considered.

3.3. 30-year TCO Cash Flows – in Nominal $

Our economic models take in all the above CAPEX and OPEX assumptions and spit out TCO cash flows, over the 30-year period considered. Figures 17-21 display these cashflows, with plant OPEX, plant CAPEX, and CPE CAPEX color coded. Note the difference in scales. These are in nominal dollars and do not reflect the time value of money mentioned earlier. For each case, the initial upgrade CAPEX shows in year 2023. HFC plant OPEX grows slightly in time, driven by the increase of field actives failures, per Figure 16. Year 2038 shows the next big CAPEX investment, to address the aging of the HFC plant actives. HFC CPE CAPEX assumes 20% of all CPEs getting replaced every 3 years, in the D3.1 and D4.0 cases; and 25% of all CPEs replaced every 5 years in the case of the 10G PON.

Different Tavg growth rates were used with different scenarios to show the potential range of costs. The 1.2 GHz high-split upgrade scenario assumes a low growth rate. This shows a best-case scenario from a cost perspective. The 1.8 GHz ESD upgrade uses the medium growth rate to represent a middle of the road scenario. Both R-PON scenarios and the ESD to R-PON migration assume a high growth rate.

The 2049 CAPEX upgrade in Figure 17 reflects the need to split the 1.2 GHz I-CCAP service group in order to keep up with the low-CAGR growth assumption. Similarly, the 2046 and 2042 CAPEX upgrades in Figures 18-20 reflect the need to split 1.8 GHz ESD and 10G PON service groups, in order to keep up with the moderate and high-CAGR scenarios, respectively.

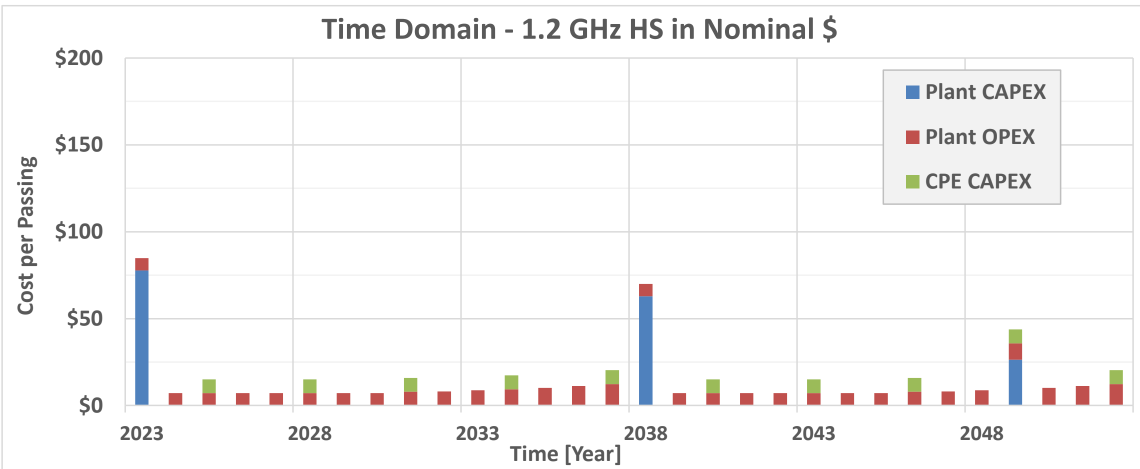

Figure 17: TCO of 1.2 GHz HS upgrade, with plant CAPEX + OPEX, and CPE CAPEX

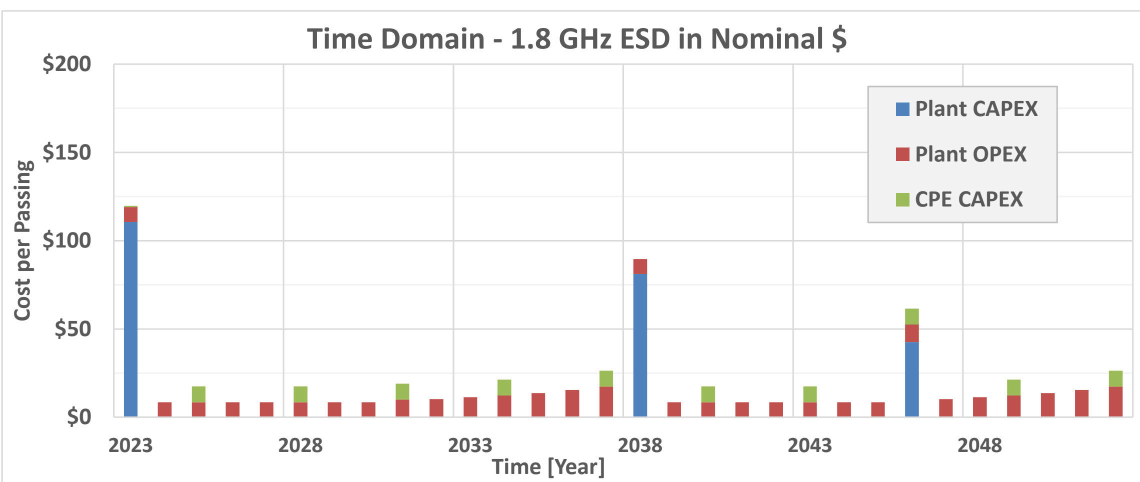

Figure 18: TCO of 1.8 GHz ESD upgrade, with plant CAPEX + OPEX, and CPE CAPEX

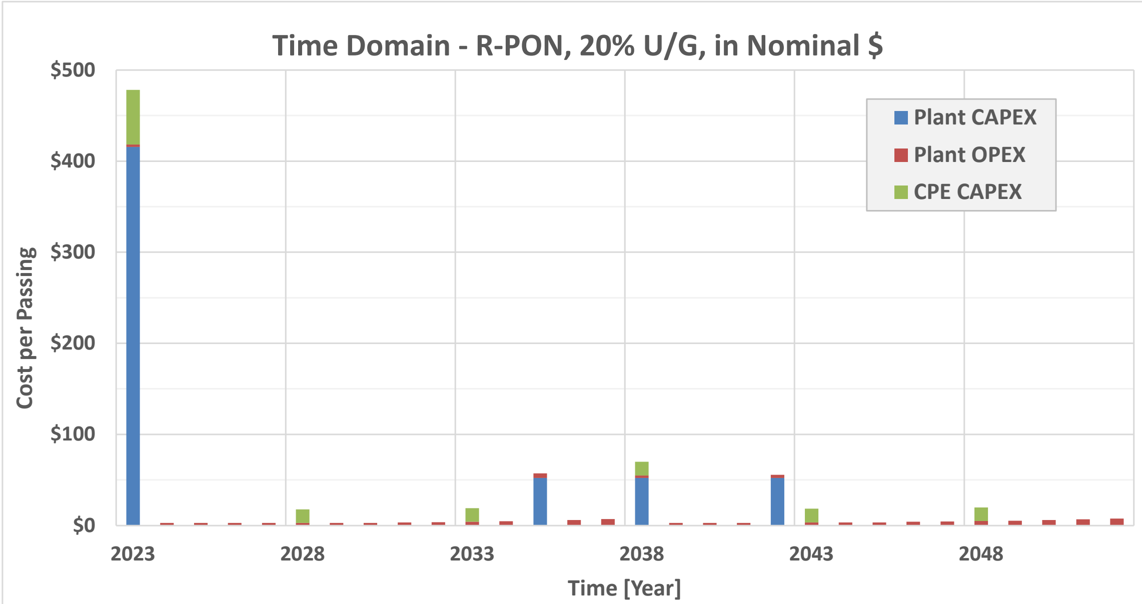

Figure 19: TCO for 10G R-PON, 20% U/G, with plant CAPEX + OPEX, & CPE CAPEX

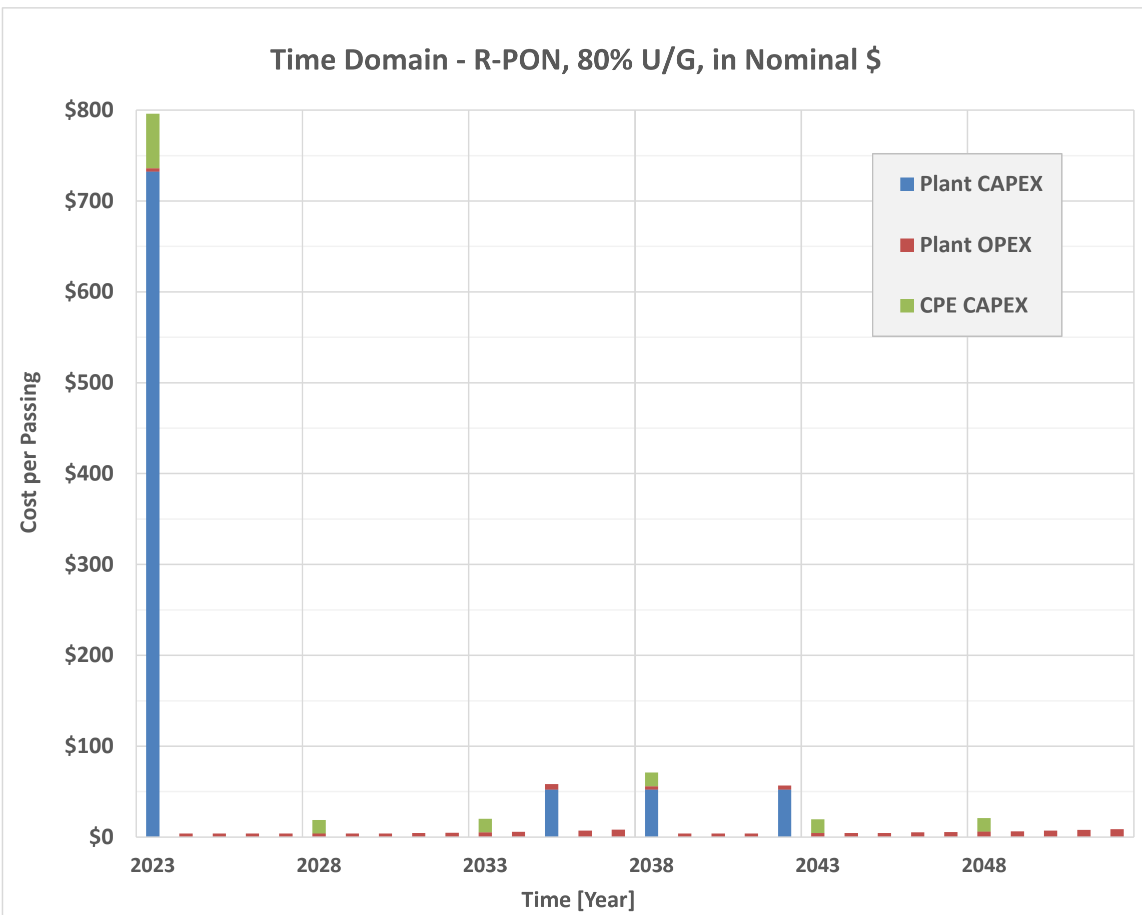

Figure 20: TCO for 10G R-PON, 80% U/G, with plant CAPEX + OPEX, & CPE CAPEX

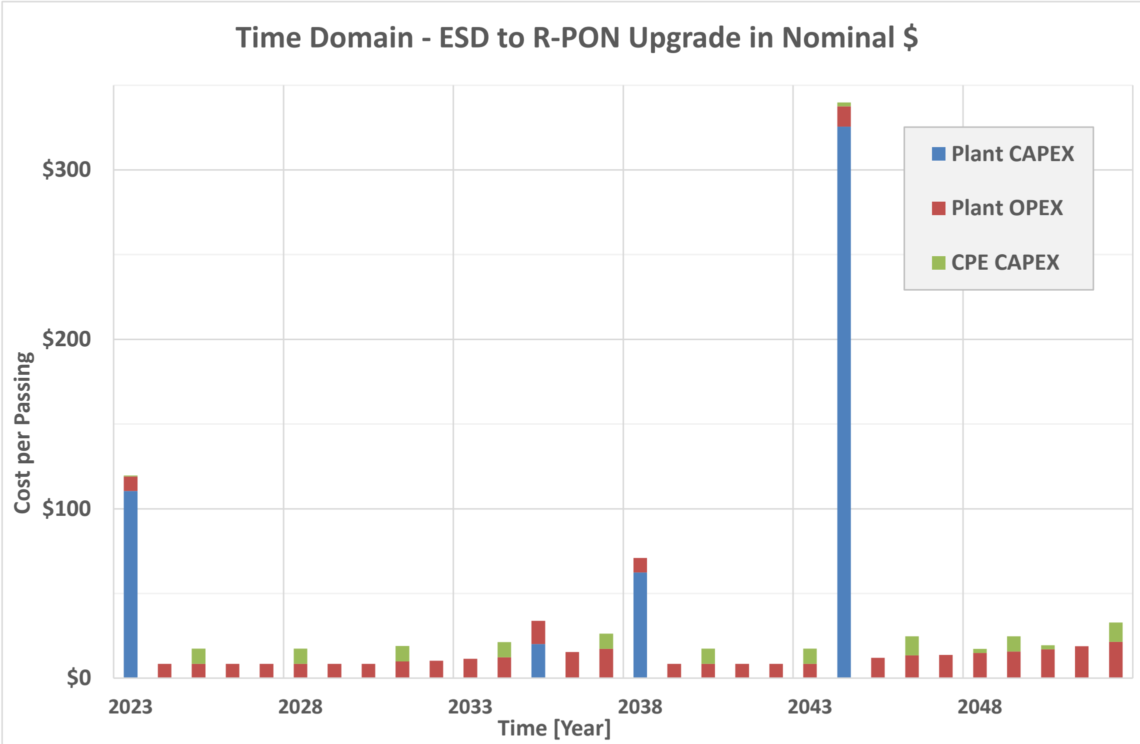

Figure 21: TCO for ESD to R-PON upgrade with plant CAPEX + OPEX, & CPE CAPEX

Figure 21 represents an interesting scenario where the operator invests in an ESD upgrade in 2023. However, if a high growth scenario is followed for 20+ years, then the ESD plant SG sizes start to become challenged in the '40s decade. This case study assumes a FTTP overlay that starts in 2044 and assumes 20% underground plant. The "heavy" DOCSIS users are migrated to FTTP. For our analysis, the 20/80 rule was followed where the top 20% move to FTTP while the lower 80% remain on ESD. With the 20/80 rule, the top 20% represent 80% of the BW usage (i.e., FTTP) while the lower 80% represents only 20% of total BW consumption. A blended approach like this can keep the majority of subscribers on HFC for many, many decades.

3.4. 30-year TCO Cash Flows – in 2023 $

CAPEX and OPEX cash flows over time, as shown in Figures 17-21 above, provide lots of information, however, are hard to compare to each other given the different timing of different expenses. One way to deal with this issue is to bring valuation of all the future flows back to the present time – or, as shown in Figures 22-26 - to bring the valuations to 2023 dollars. As stated previously, a 7.5% annual discount rate has been used to perform this "cash travel in time." In particular, note the decrease in the cost components that are 15-30 years in the future. This is perhaps most dramatic in figure 24 for the ESD to R-PON migration scenario. Compare Figure 24 to Figure 21 to see the effect of TVM.

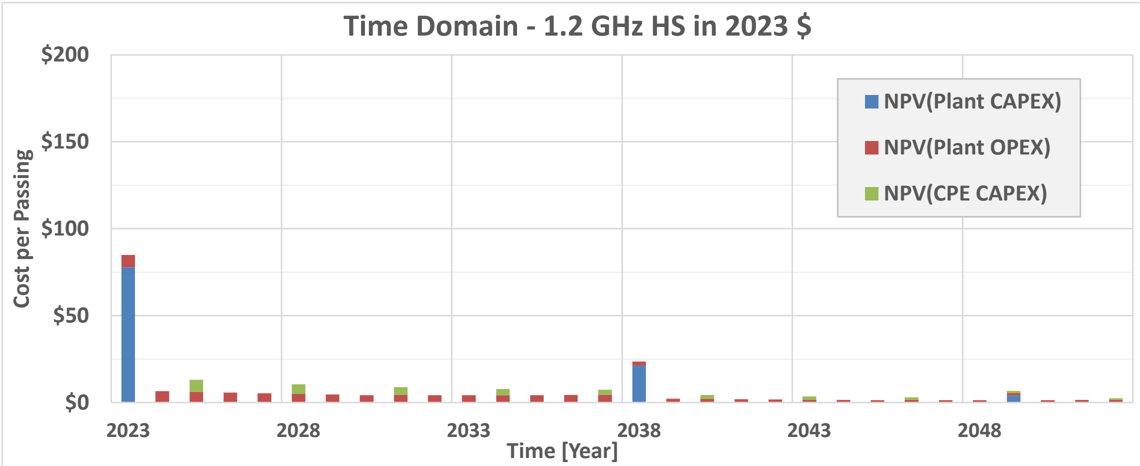

Figure 22: TCO of 1.2 GHz high-split upgrade over time, in ‘23 dollars

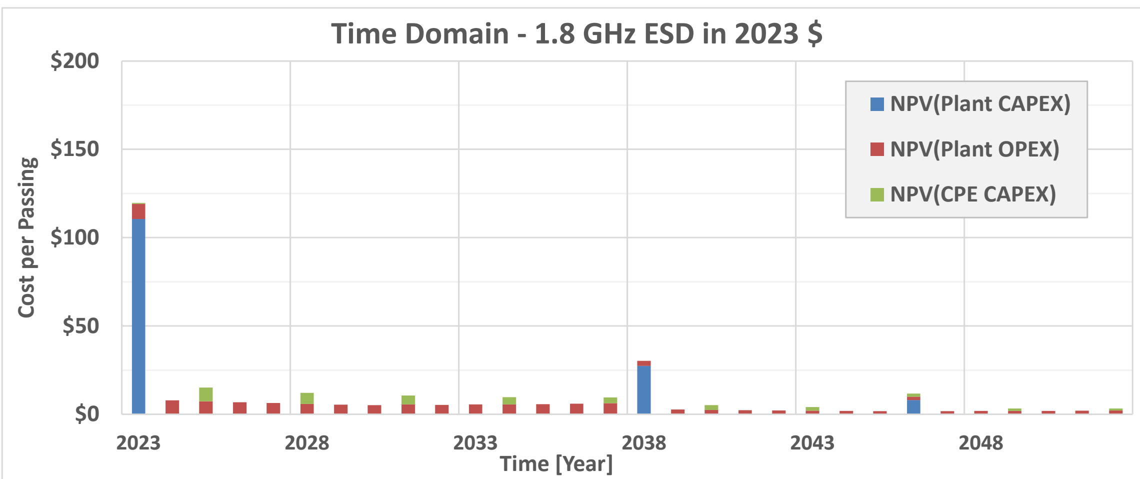

Figure 23: TCO of 1.8 GHz ESD upgrade over time, in ‘23 dollars

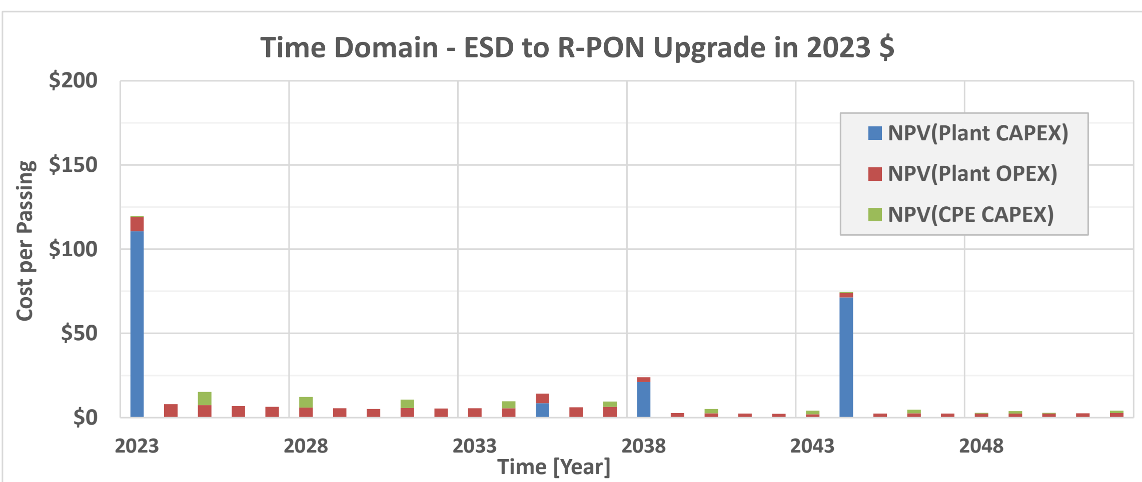

Figure 24: TCO of ESD to R-PON upgrade in ‘23 dollars

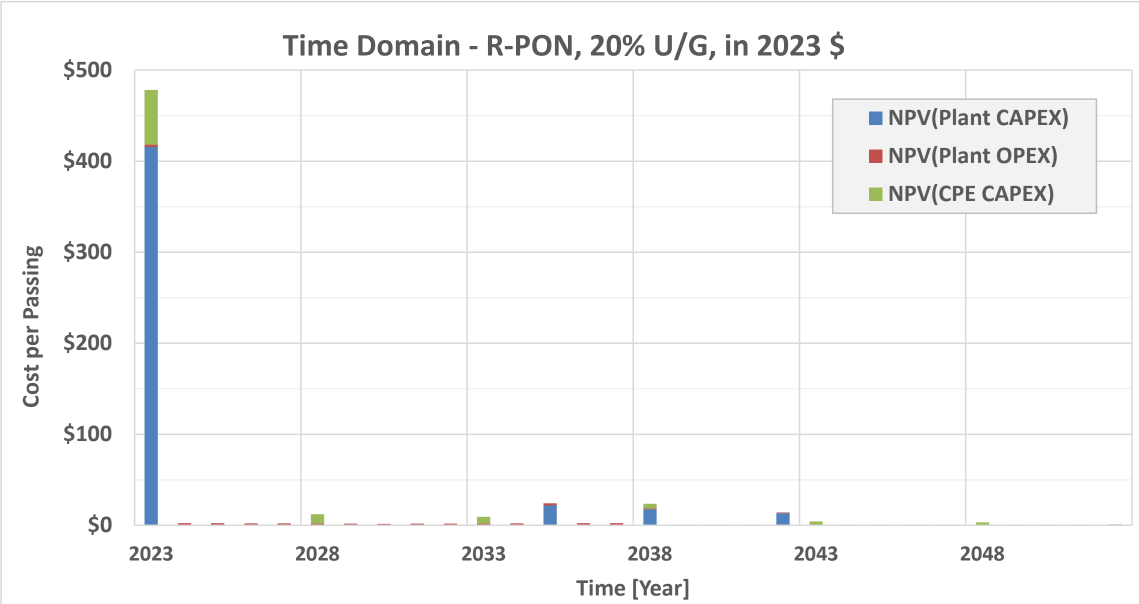

Figure 25: TCO of 10G R- PON upgrade, 20% U/G, in '23 dollars

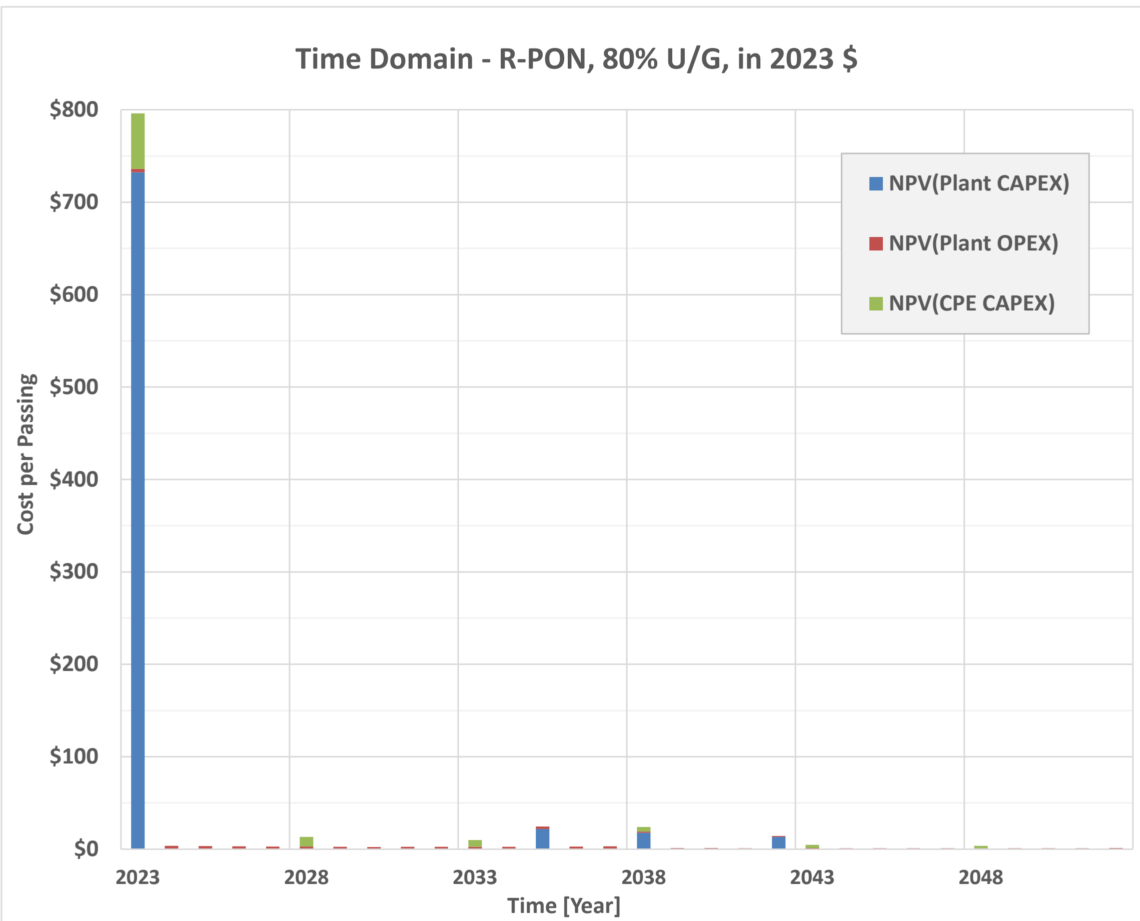

Figure 26: TCO of 10G R- PON upgrade, 80% U/G, in '23 dollars

3.5. A Nano-Hertz Spectral Analysis

Looking at these 'cash flows over time' graphs, a clear pattern emerges: some CAPEX takes place only once in 30 years (fiber plant build, HFC tap upgrade, demand-driven service group splits), every 15 years (aged actives upgrade), every 5 years (PON ONUs), 3 years (HFC CPEs), and some annually (OPEX). "Your mileage may vary" adage applies here, however; the above frequencies accurately reflect the assumptions made.

This is where the signal analysis time domain / frequency domain analogy came from: what would these expenses look like if viewed in the 'frequency domain'? Figures 27-31 provide the answer.

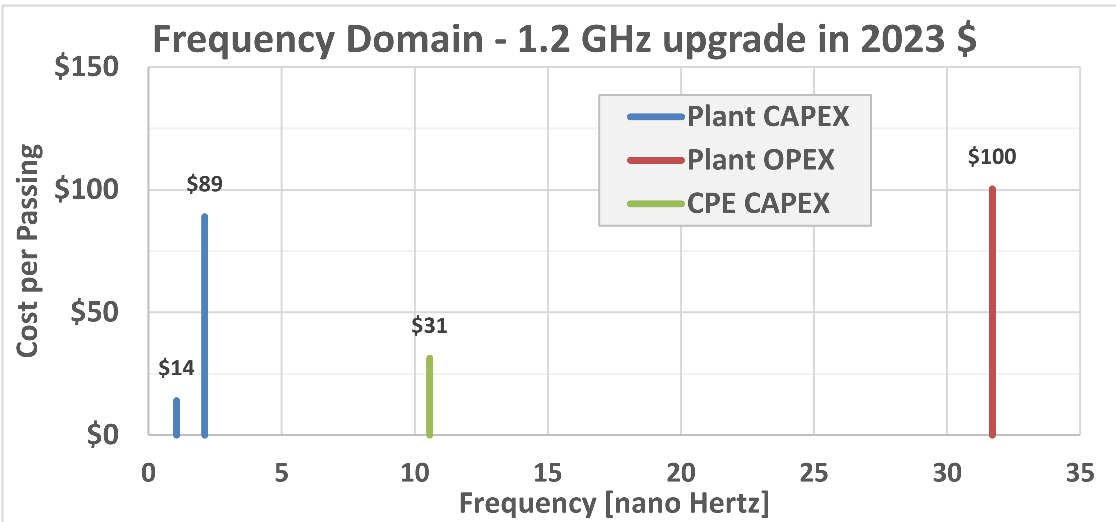

Figure 27: 1.2 GHz high-split upgrade TCO in frequency domain, in '23 dollars

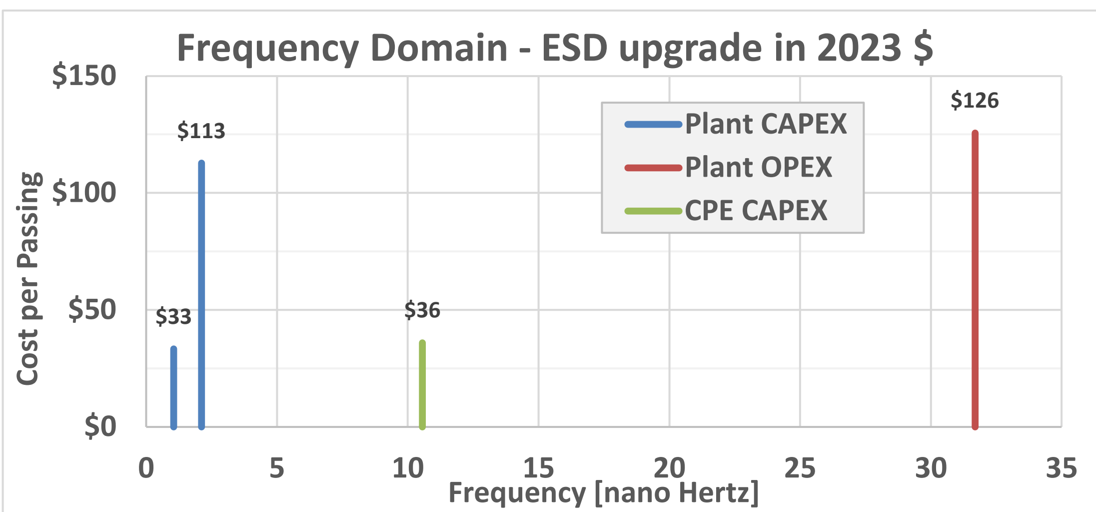

Figure 28: 1.8 GHz ESD upgrade TCO in frequency domain, in '23 dollars

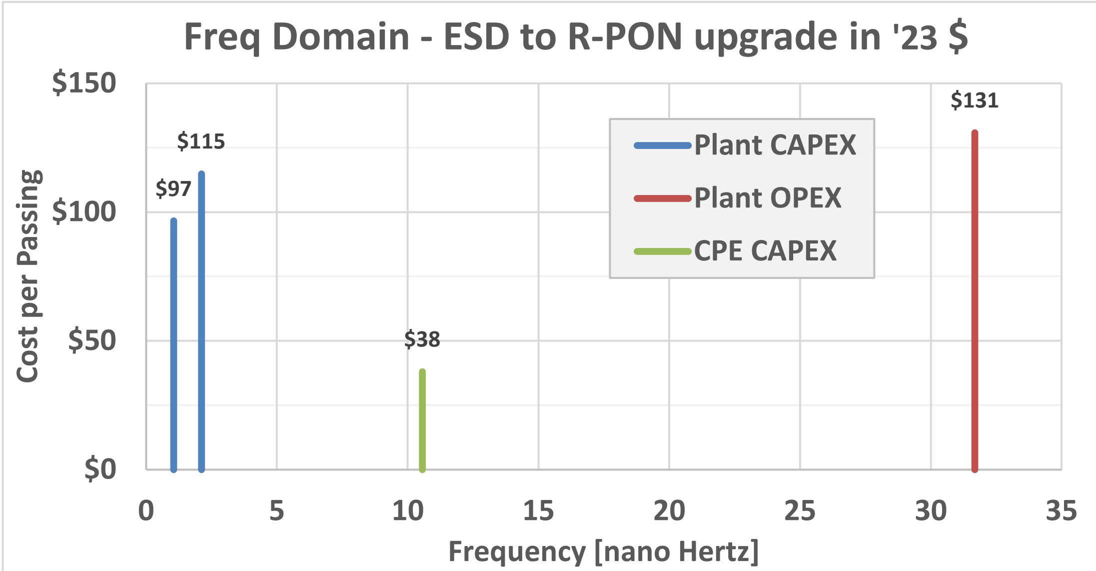

Figure 29: ESD to R-PON upgrade TCO in frequency domain, in '23 dollars

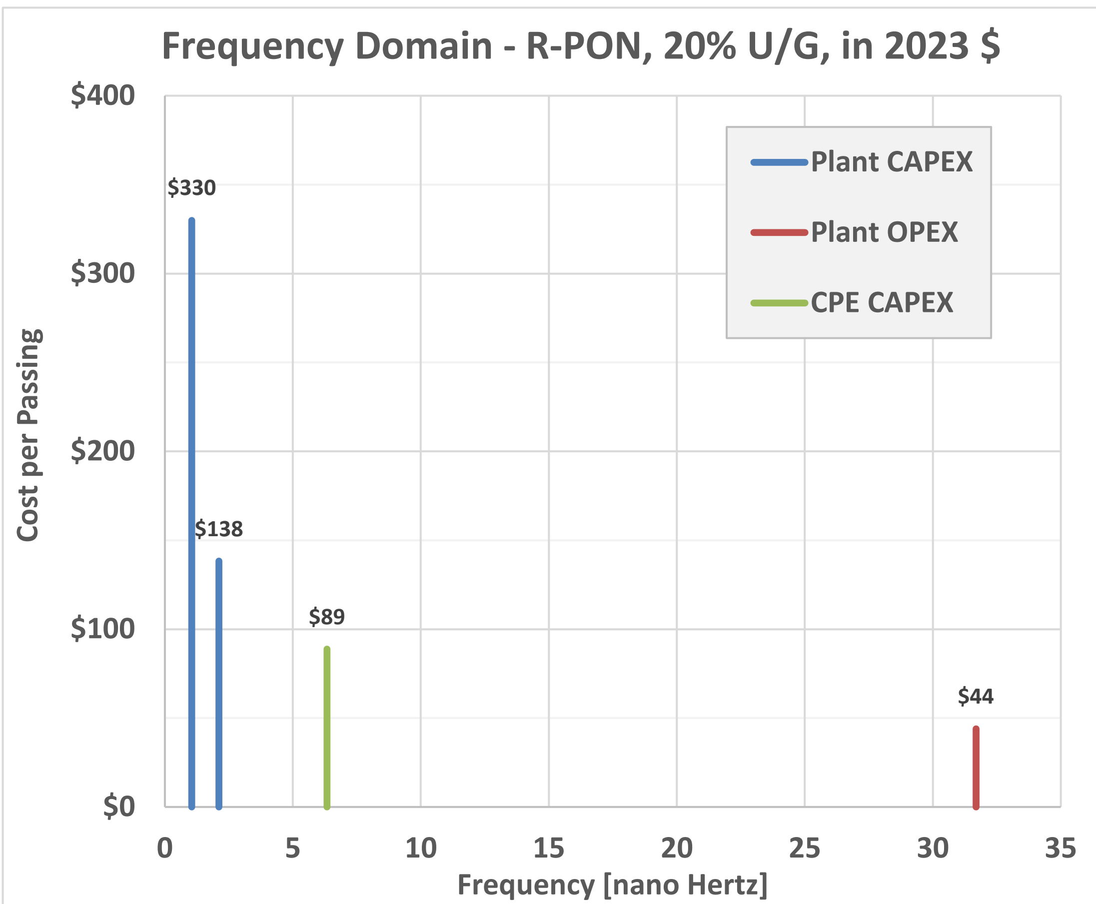

Figure 30: 10G R-PON 20% U/G upgrade TCO in frequency domain, in '23 dollars

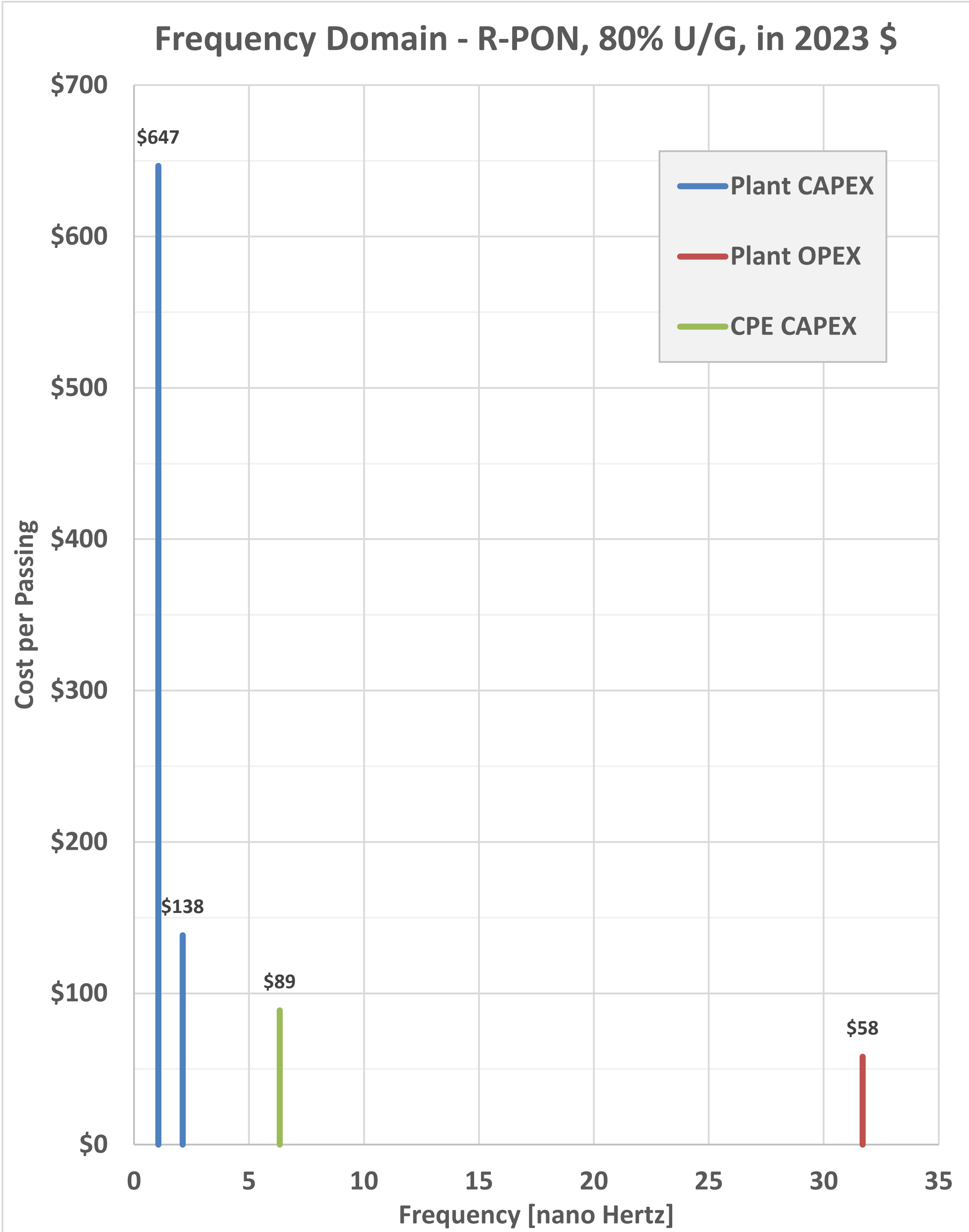

Figure 31: 10G R-PON 80% U/G upgrade TCO in frequency domain, in '23 dollars

Frequency of 'once every year' can be calculated in Hz, which is 1/s, by counting how many seconds there are in an average year (31,557,600), and then taking the inverse; to get 31.7 x 10^{-9} or 31.7 nano Hertz (nHz). That's why the annual OPEX in Figures 27-31 is positioned where it is. Similarly, 30-year periodicity is at ~1 nHz, 15-year at ~2 nHz, 5-year at ~6 nHz, 3-year at ~10 nHz, and so on.

The ~2 nHz dominant CAPEX peaks in Figures 27 and 28 reflect the 15-year cycle of active network elements upgrades (nodes, RF amps, headend optics), while ~1 nHz peaks comprise the 30-year cycle of RF tap replacements and occasional once in 30-year node splits.

The ~2nHz CAPEX peak in Figure 29, ESD to PON upgrade, is an almost exact replica of the same peak of Figure 28, ESD only upgrade, while the ~1 nHz peak captures the once in 30 years fiber overbuild. For the two PON upgrades in Figures 30 and 31, the ~2 nHz peak reflects 15-year cycle of R-OLT refreshes, while the left-most peak of ~1 nHz captures the rest: fiber overbuild, splitting network, drops buildout – investments that are made just once over the observed period. For all the five cases in Figures 27 -31, CPE capex reflects 3-year cycle for HFC, and the 5-year cycle for PON, while the OPEX shows at the annual-cycle frequency of ~31 nHz and is ~50% lower for the PON upgrades, in comparison to the HFC ones.

3.5.1. Network Upgrade Comparisons – D3.1 vs. ESD vs. FTTP

Comparison among various upgrade approaches seems easier in the frequency domain – in good part because this domain represents 'integral over time,' and in our case expressed in 2023 dollars. Table 2 compares the considered scenarios, by adding up NPV of plant CAPEX, plant OPEX and CPE CAPEX, already shown in the frequency domain plots, to get the comparison in NPV TCO.

Table 2: Network upgrade scenarios compared, in '23 dollars

Upgrade Scenario	1.2 GHz D3.1 HS	1.8 GHz D4.0 ESD	1.8 GHz ESD (w PON overlay'44)	10G R-PON 20% Underground	10G R-PON 80% Underground
Tavg Growth Scenario	Low	Medium	High	High	High
NPV (Plant CAPEX)	$103	$146	$209	$468	$785
NPV (Plant OPEX)	$100	$126	$131	$44	$58
NPV (CPE CAPEX)	$31	$36	$38	$89	$89
NPV TCO (7.5% TVM)	**$235**	**$308**	**$380**	**$601**	**$932**
Total cash outlays over time	*$496*	*$643*	*$971*	*$826*	*$1,176*

While the initial 10G PON CAPEX towers at up to ~10x the cost for the HFC upgrades, the TCO ratios for the 30-year period with OPEX included have dropped to 2x to 3x, for PON upgrade compared to 1.8G ESD upgrade; 2.5x to 4x compared to 1.2G HS I-CCAP upgrade. Time value of money discounting improves the HFC upgrades, given many expenses that are delayed in time. The PON upgrades, however, are heavily front-weighted, even though PON benefits from 50-60% lower OPEX, as compared to the two HFC upgrades.

Perhaps the most interesting result is the middle column – the ESD to R-PON migration. Traditionally, operators may ask why should they invest in ESD now if they must jump to FTTP in the future? Looking at the total cash outlays, in nominal dollars, in the last row of table 2, notice that this option comes in at $971/HP while the equivalent 10G R-PON is at $826/HP. However, factoring in the time value of money results in the ESD to PON migration scenario TCO of only $380/HP in '23 dollars, while the R-PON option is $601/HP. That is almost 60% more cost for R-PON only in '23 dollars. So, if an operator chooses the ESD path in '23, the downside risk, if consumption were to follow the high growth rate, is very manageable and would costs significantly less than R-PON.

In summary, the PON upgrades still cost the operator double, triple, or even quadruple the amount of '23 dollars invested in the plant. But is this difference significant or immaterial to operators' budgets today? To answer this question, the next section compares these cost outlays to operators' existing business-as-usual CAPEX rates.

4. MSO Perspective – Current CAPEX vs. Upgrade TCO

Stepping back for a second, let's look at some key MSO's current capital expenditures to see how these various upgrades fit into their business-as-usual spending. Four USA cable operators: Comcast [CMCSA – cable segment only], Charter [CHTR], Altice USA [ATUS], and Cable One [CABO] are publicly traded companies and provide a wealth of information in their annual report filings and quarterly earning updates. Figure 32 shows annual amount of capital expenditures of each operator for the years 2019 – 2022. (The amounts for 2019-2021 are actually spent, the 2022 number is based on operators' full-year guidance numbers declared at their 2022 Q1 earnings calls). Comcast Cable and Charter, each with ~60 and ~55 million homes and businesses passed, are shown separately from the two smaller ones: Altice USA and Cable One, with ~9.3 and ~2.7 million home passings, respectively.

So, what, some may say? Well, these numbers on their own maybe don't say much. That is why they're often expressed as a percentage of revenue – and typically > 10% of the revenue, because cable is one capital intense business. Nevertheless, those same annual CAPEX numbers normalized by operators' number of homes and business passed (i.e., passings), are much more informative: Figure 33 shows such a normalization, with a weighted average line also added. Even without the addition of the weighted average line, most of the annual data points fall in the $110-$140 per home or business passed range, with the weighted average coming closely to the $130/year value.

Of the four operators, ATUS has been the most vocal about migrating its customers to FTTP. Note how much higher their CAPEX jumped in 2022 compared to the other three operators.

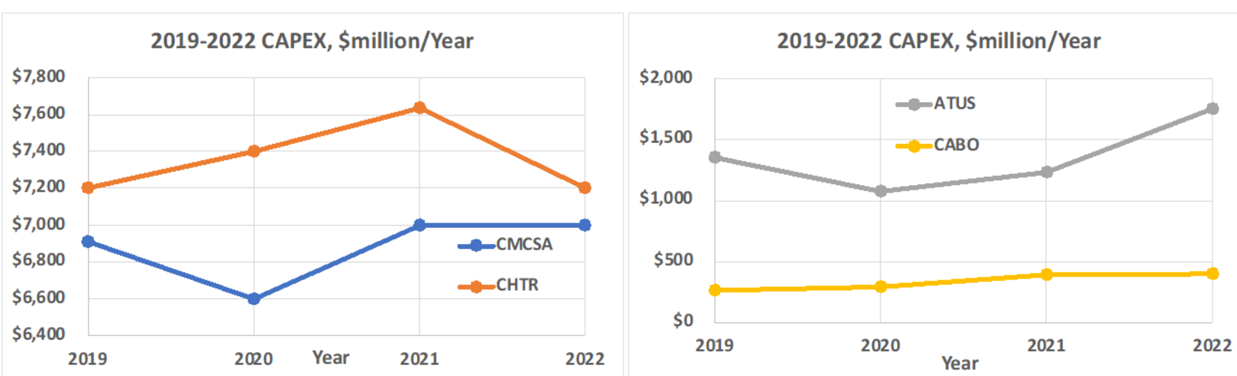

Figure 32: Annual CAPEX for four USA MSOs: Comcast, Charter, Altice USA, Cable One

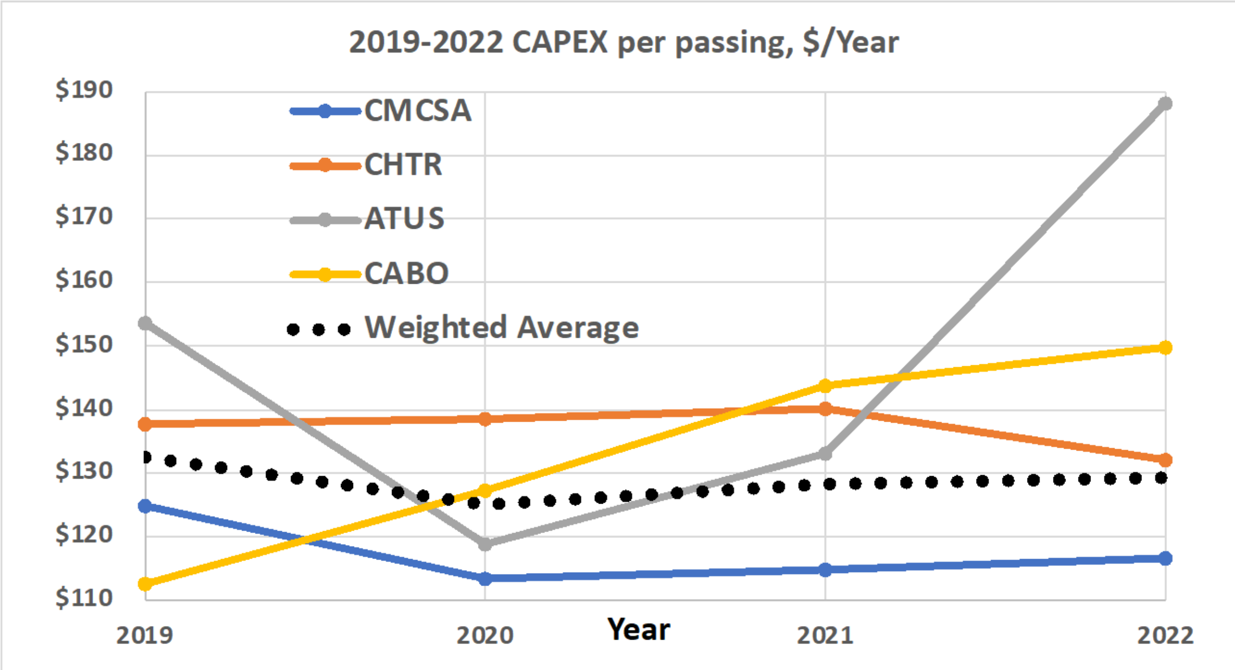

Figure 33: Annual CAPEX for four USA MSOs, Normalized per HP

But what percentage of annual CAPEX is directly related to the network of Figure 11? Charter [CHTR] 1Q22 investors presentation offers a clue – during the year 2021, about 27% of the CAPEX went to 'CPE/Install,' with the other 33% to the network side – for 'Line Extensions' (~23%) and 'Upgrade/Rebuild' (~10%) categories, as shown in Figure 34.

One thus may extrapolate that about 27% + 23% + 10% = 60% of overall operators CAPEX goes into the network, which, multiplied with the values of 'weighted average' from Figure 33 gives ~$77 per-year per-home-passed, of which a slightly larger part (~$42) applies to the plant and the rest (~$35) to the CPE CAPEX. Note that a large portion of the CPE CAPEX applies to set top boxes (STB) and digital video recorders (DVR) for video service inside subscriber's homes. As operators migrate to (Internet Protocol (IP) Video, there will be some reduction in the CPE CAPEX that could be applied to the network CAPEX.

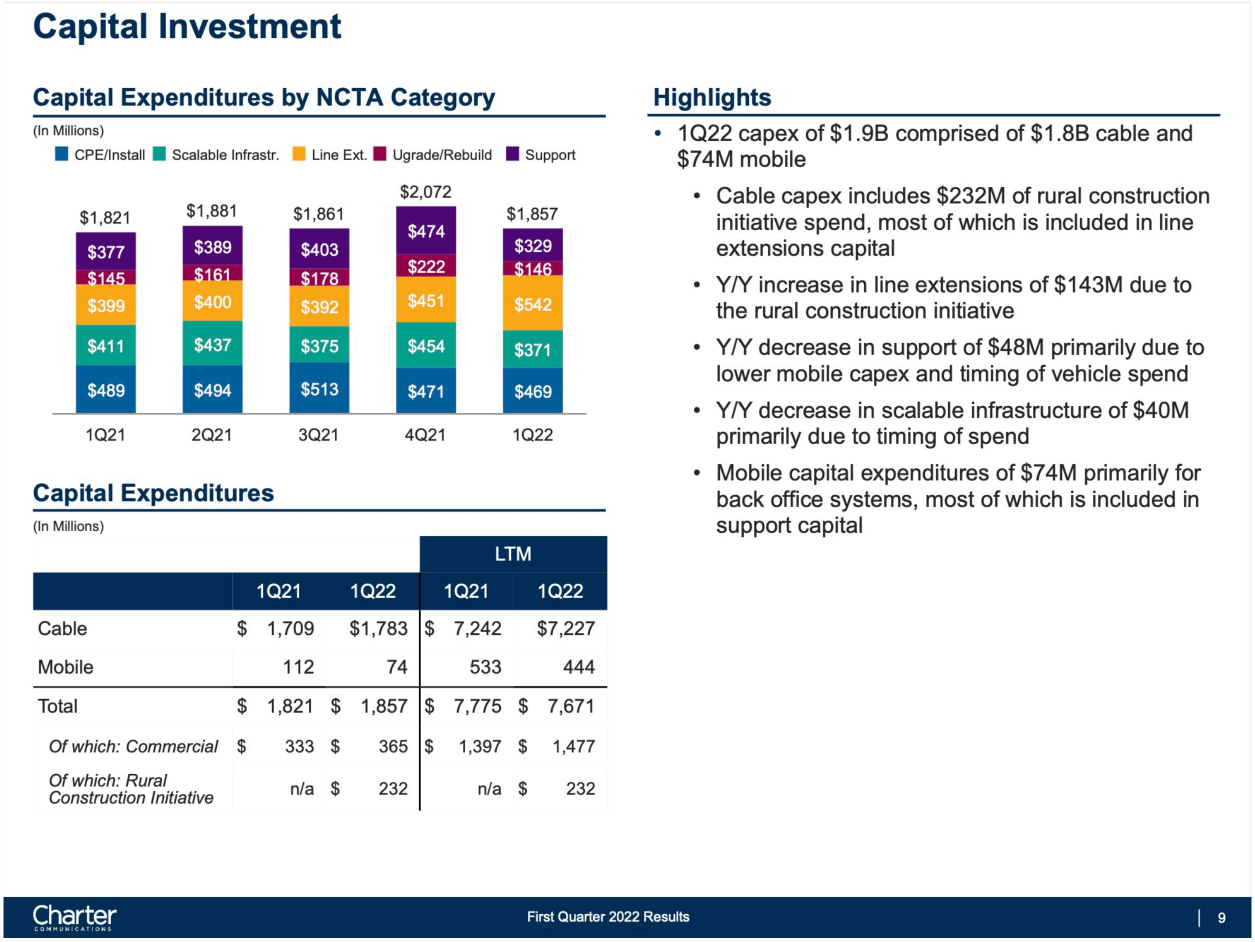

Figure 34: CAPEX by category, from Charter's 1Q22 financial results

As a first sanity check, let's look at $~50 per HP per year for network CAPEX, expanded every 30 years, with a 7.5% discount rate. This results in $590 NPV TCO values expressed in 2023 dollars. Thus, compared to the values in Table 2, if CAPEX were to continue at the rates shown above, any of the HFC upgrade paths could be afforded. A fiber upgrade may be possible if the plant is mostly above ground. Otherwise, a significant increase in CAPEX over 30-years is needed if there is significant underground plant.

Now consider that the operator has roughly $25/HP to $30/HP per year available for these major network upgrades. It turns out that the operator could upgrade all systems to 1.2 GHz over three years; or upgrade all systems to ESD over a 4- to 5-year window. This seems very reasonable. A hybrid of mainly HFC upgrades, plus a careful mix of the FTTP PON ones, where necessary, is another possibility. The necessity is primarily driven by competitors' actions.

If the operators stay at $25/HP to $30/HP per year for the FTTP upgrades, these will need to get spread over 20 to 30-year window, and this would likely not fix the BW problems in a timely manner. If the operator bumps the network CAPEX investments up to $80/HP to $100/HP range (e.g., similar to what ATUS may have done), then FTTP upgrade path would take 5- to 6-years for mostly aerial plant and 8- to 10- years for mostly underground plant. And this doesn't include any HFC upgrades in the interim to remain competitive and provide required capacity to maintain existing QoE.

Caveat Emptor (buyer beware) warning is in order here – above statement are valid, provided all of the assumptions made above are valid.

5. Variations / sensitivity analysis

"One should not make predictions, especially about the future" is a quip variously attributed to Samuel Goldwyn of Metro-Goldwyn-Mayer fame, [Goldwyn], Yogi Berra of baseball-playing philosopher fame [Yogi], and to Niels Bohr, Nobel-prize-winning quantum physicist [Bohr]. Taking these esteemed gentlemen's advice to heart, this section is more about the range of possibilities rather than some precise foretelling of how the networks shall evolve – because only time will tell.

5.1.1. HFC Sensitivity analysis

Thus, rather than provide predictions, Monte-Carlo analysis of Figure 35 and Figure 36 show a range of possible outcomes for TCO of the two HFC upgrades. The graphs show a range and probability of outcomes, based on a certain set of assumptions specified. These 'frequency views' are formed after a run of 100,000 trials is completed.

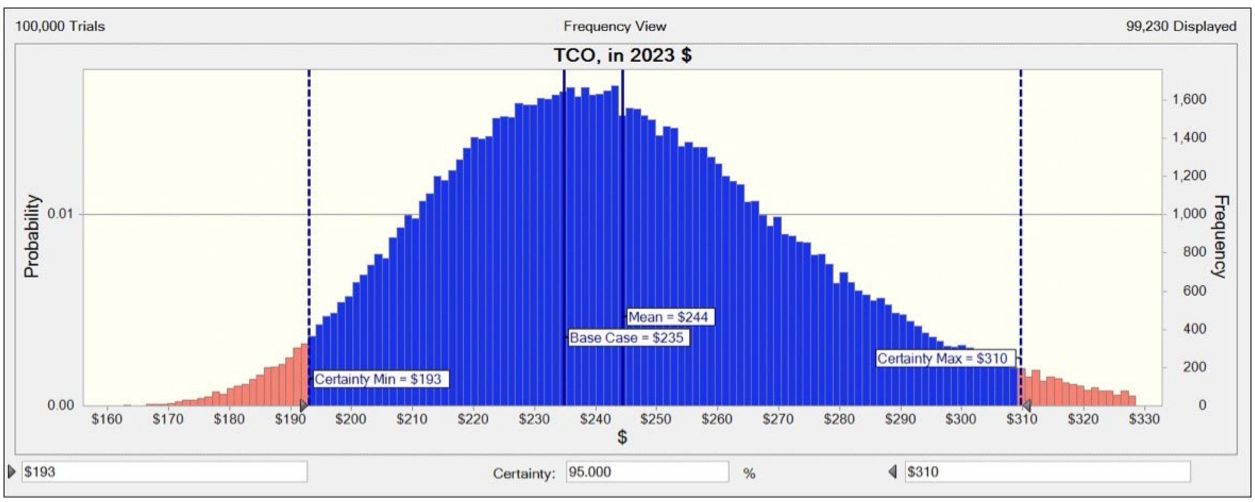

Figure 35: TCO Sensitivy for 1.2 GHz High-Split upgrade – 100,000 trials Monte-Carlo run

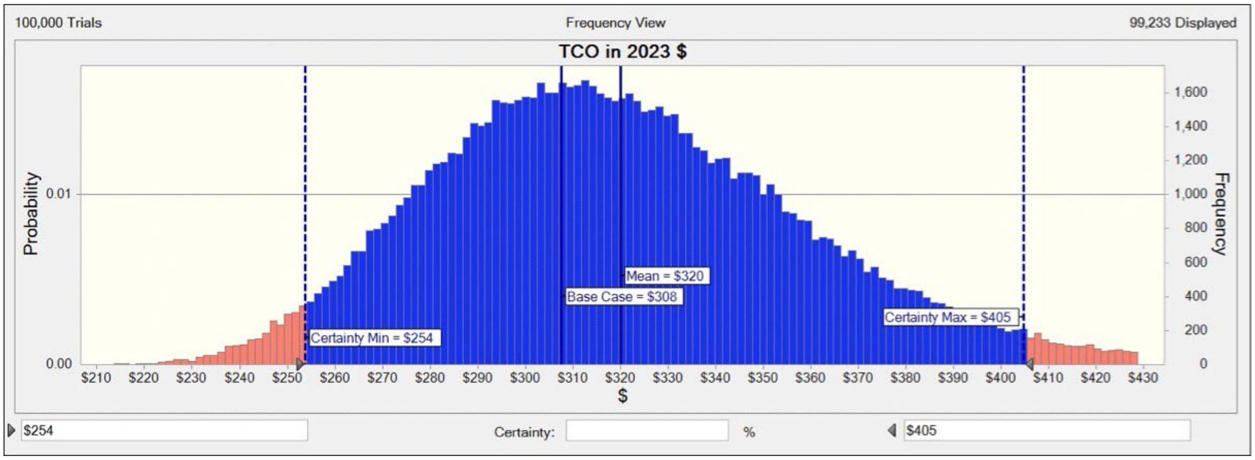

Figure 36: TCO Sensitivy for 1.8 GHz ESD upgrade – 100,000 trials Monte-Carlo run

Rather than discuss a single value under certain assumptions, as done in the previous section, these charts offer a range of outcomes, given certain ranges of assumed variables. Thus, a 95% confidence interval for 1.2 GHz high-split I-CCAP upgrade is $193-$310, vs. $254-$405 for the 1.8 GHz ultra-high-split ESD upgrade. Note that the high end of both 95% confidence intervals is ~30% higher than the base case.

To better understand the model's sensitivity to various assumptions, Figure 37 and Figure 38 display "Tornado charts", for the two HFC upgrade cases: 1.2 GHz high-split I-CCAP and 1.8 GHz ultra-high-split ESD. The Tornado chart ranks each variable's impact from most on the top to least on the bottom. The HFC upgrades are the most sensitive to the number of passings per node, followed closely by the discount rate assumed. Other variables had noticeably less impact and ranked as: cost of kWh of power, number of amplifiers in the network, and so on.

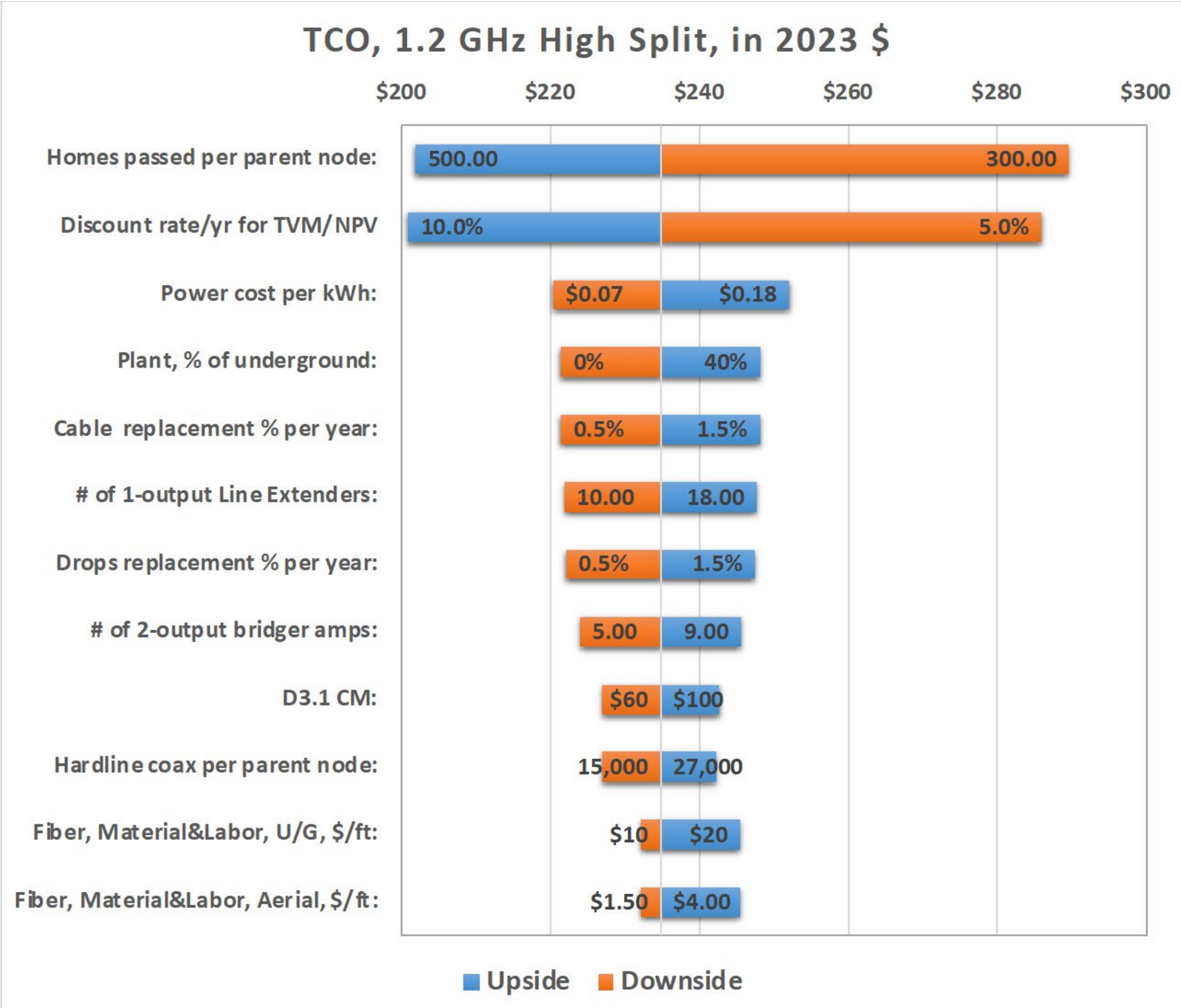

Figure 37: Sensitivity Tornado chart – 1.2 GHz high-split

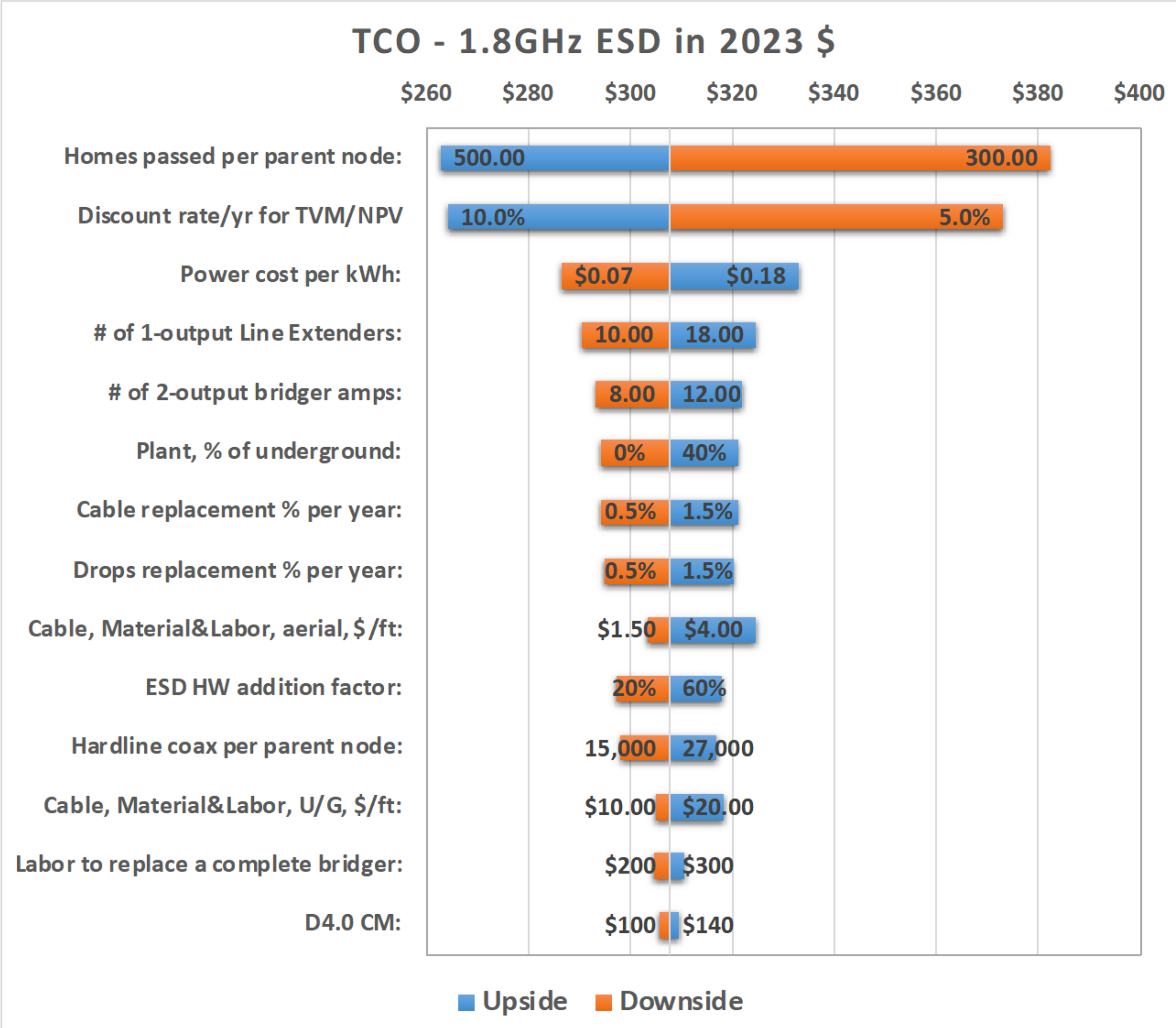

Figure 38: Sensitivity Tornado chart – 1.8 GHz ESD

5.1.2. R-PON Sensitivity Analysis

10G PON cases have charts of their own: Figure 39 displays the distribution and range for the TCO of 10G R-PON upgrade with 20% underground plant. Its 95% confidence interval spans $512-$817; under various assumption ranges, as shown in the sensitivity Tornado chart of Figure 41. To no surprise, the % of underground plant had the biggest impact on sensitivity. The high end of the 95% confidence interval is ~36% higher than the baseline. This shows that FTTP upgrades have more sensitivity in their cost analysis than their HFC counterparts.

Figure 40 displays the distribution and range for the TCO of 10G R-PON upgrade with 80% underground plant. Its 95% confidence interval spans $782-$1,370 under various assumption ranges, as shown in the sensitivity Tornado chart of figure 42Figure 41. Because the % of underground plant is already very high, the cost of fiber material & labor had the biggest impact on its sensitivity. The high end of the 95% confidence interval is almost 50% higher than the baseline, showing even more variability. This shows that the higher the % of underground plant, then the higher FTTP sensitivity becomes.

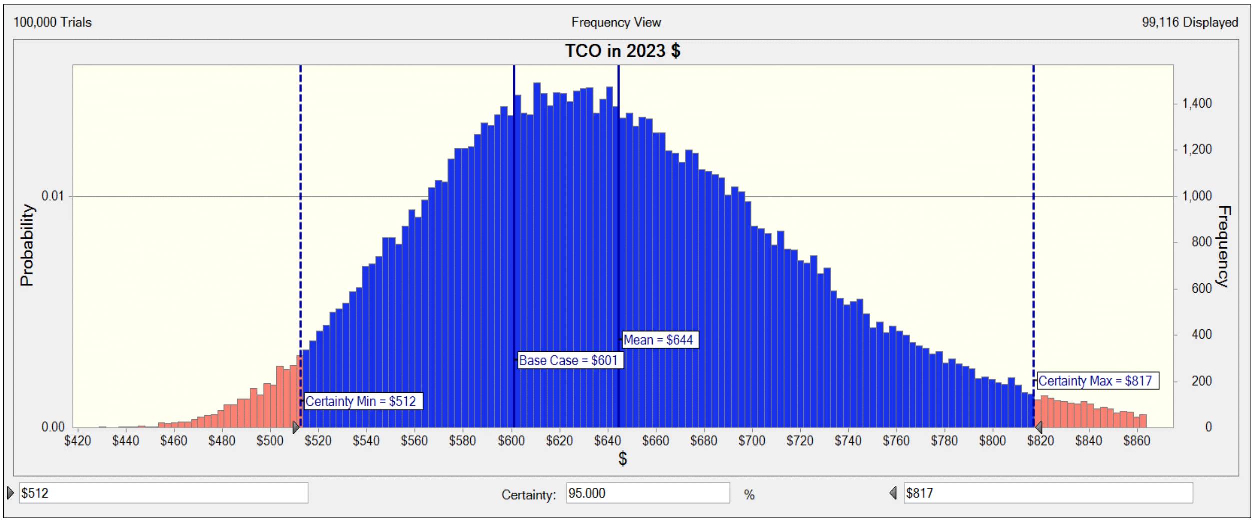

Figure 39: TCO Sensitivy for R-PON 20% U/G upgrade – 100K trials Monte-Carlo runs

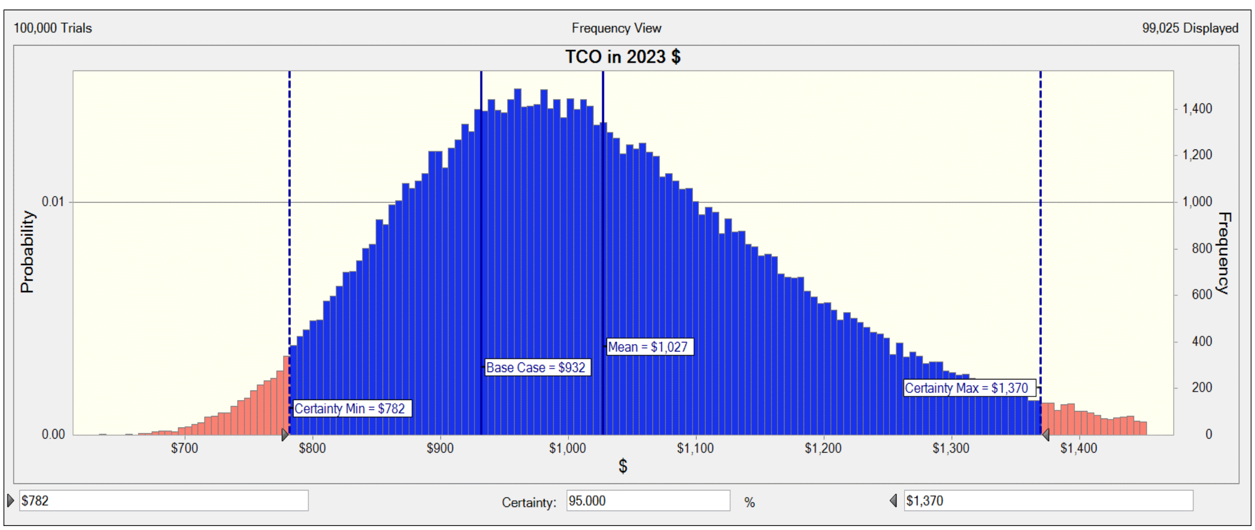

Figure 40: TCO Sensitivy for R-PON 80% U/G upgrade – 100K trials Monte-Carlo runs

Order of variables affecting the TCO of PON upgrade differ from those of the HFC upgrades – understandably so – the cost of running new fiber is highly sensitive to the % of the plant that's underground, as opposed to aerial. Plant length is closely behind, as is fiber installation cost. Interestingly, the discount rate does not affect the outcome as prominently here as it does for the HFC upgrades. This can be explained by HFC annual costs fairly evenly distributed in time, and thus benefiting or not from a high/low discount rate, while the PON costs are mainly upfront and as such don't get much of a benefit if the discount rate is high.

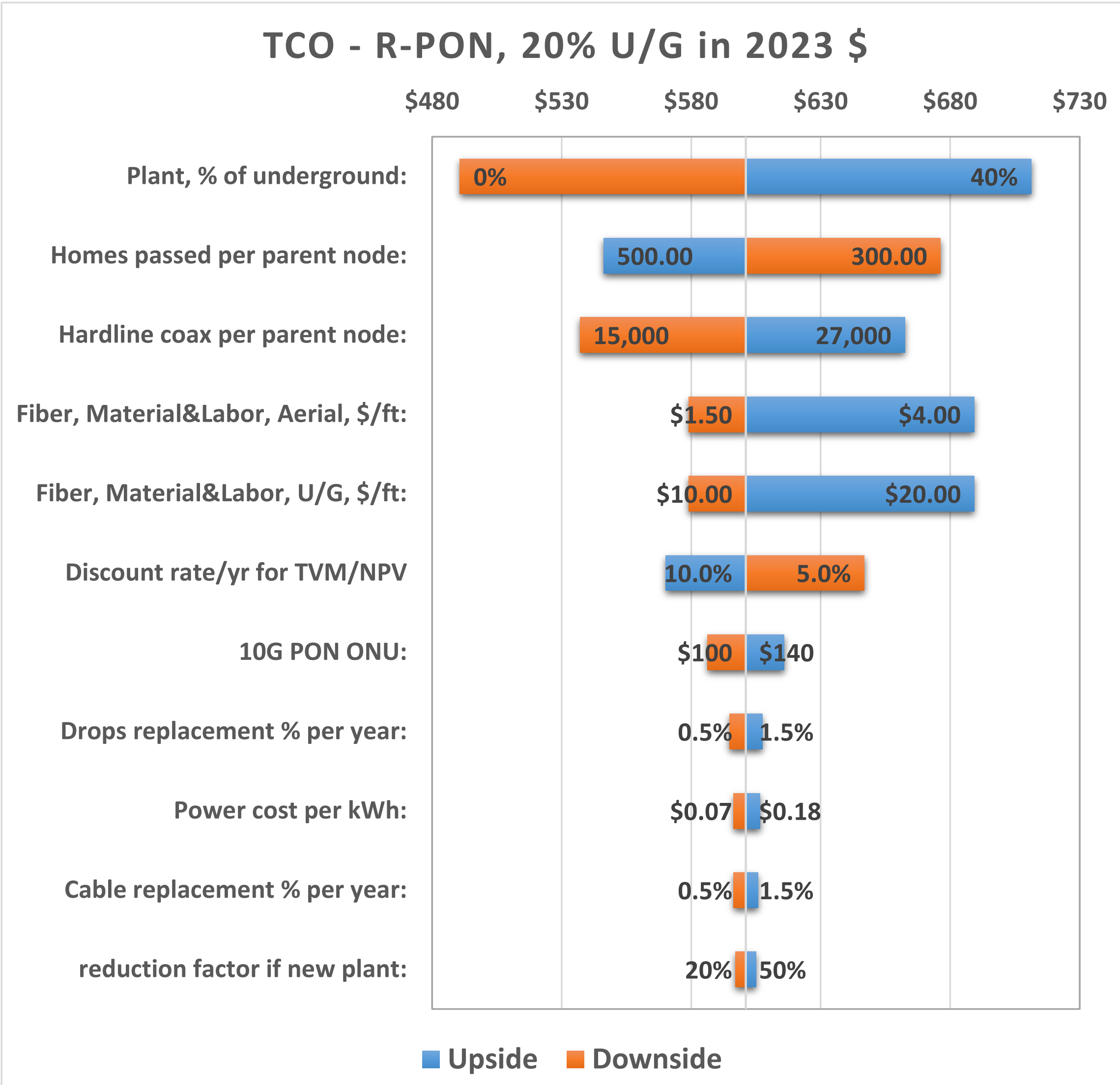

Figure 41: Sensitivity Tornado chart for the 10G R-PON 20% U/G upgrade

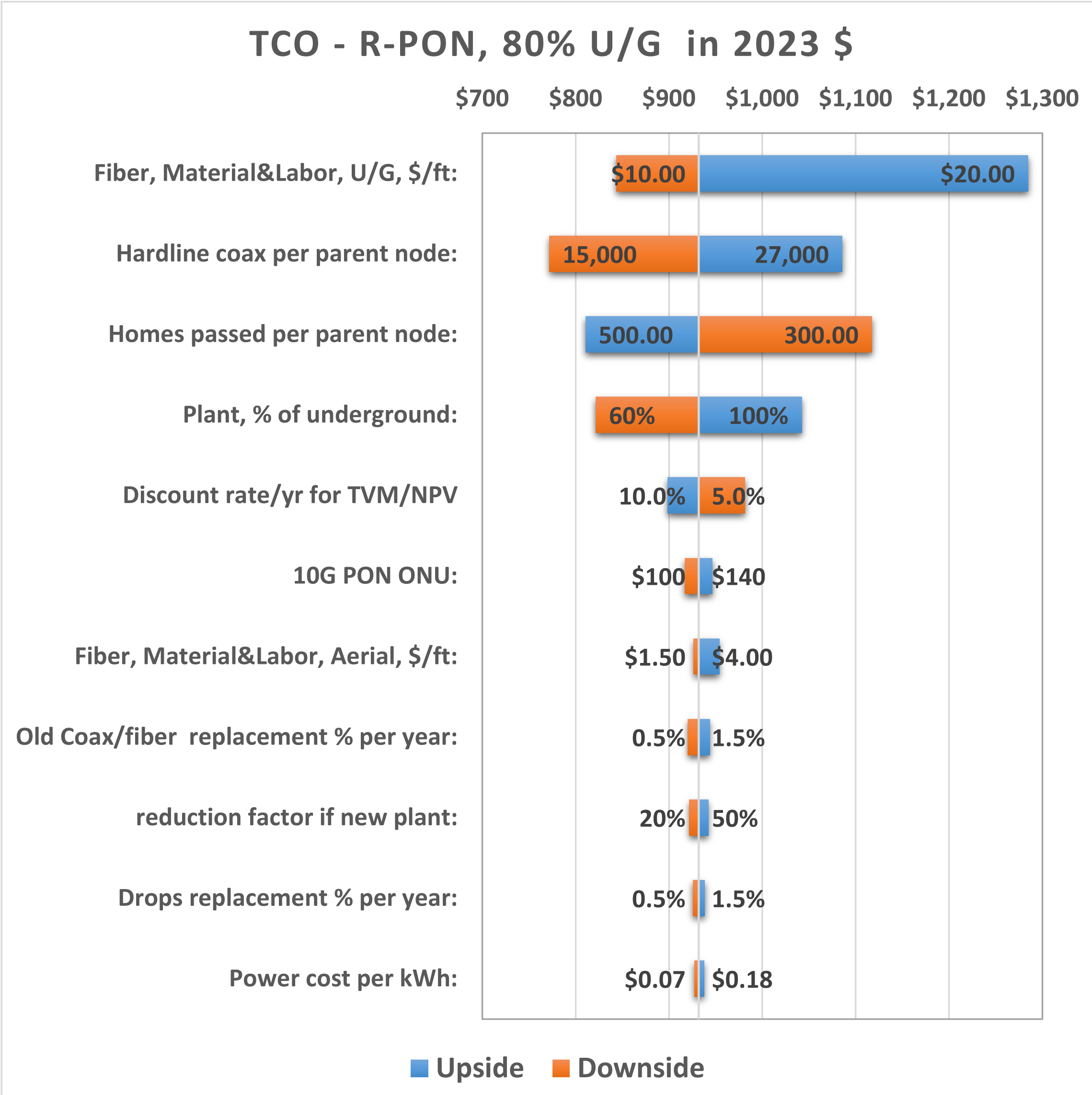

Figure 42: Sensitivity Tornado chart for the 10G R-PON 80% U/G upgrade

5.1.1. ESD to R-PON Sensitivity Analysis

Perhaps the most interesting upgrade path under consideration for the high growth projection is starting with an ESD upgrade in '23 and then to add an R-PON overlay in '44. This had a baseline NPV TCO of $380/HP. The Monte Carlo sensitivity analysis for this scenario is shown in Figure 43. The 95% confidence interval is $307/HP to $533/HP. The top end of this blended upgrade scenario is ~40% higher than the base line.

The Tornado chart is shown in Figure 44. For this case, the discount rate is the most impactful variable followed by HP per parent node. The % of underground plant is a distant third to these inputs, with variation of ~$37 per 20% increase in underground runs. This means that even an 80% underground plant would add just $110 to the NPV TCO of the ESD-to-R-PON upgrade, as compared to adding $331 if PON upgrade were to be done in 2023.

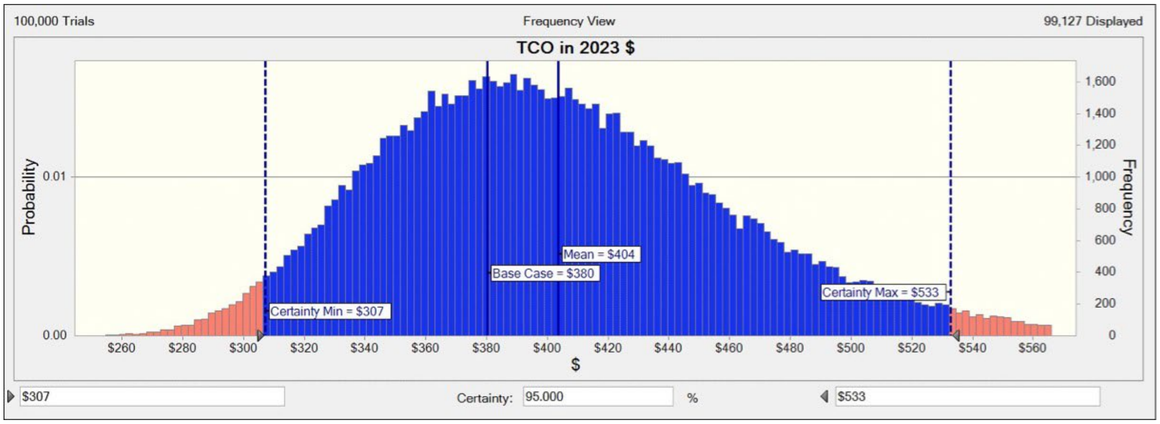

Figure 43: TCO Sensitivy for ESD to R-PON upgrade – 100K trials Monte-Carlo runs

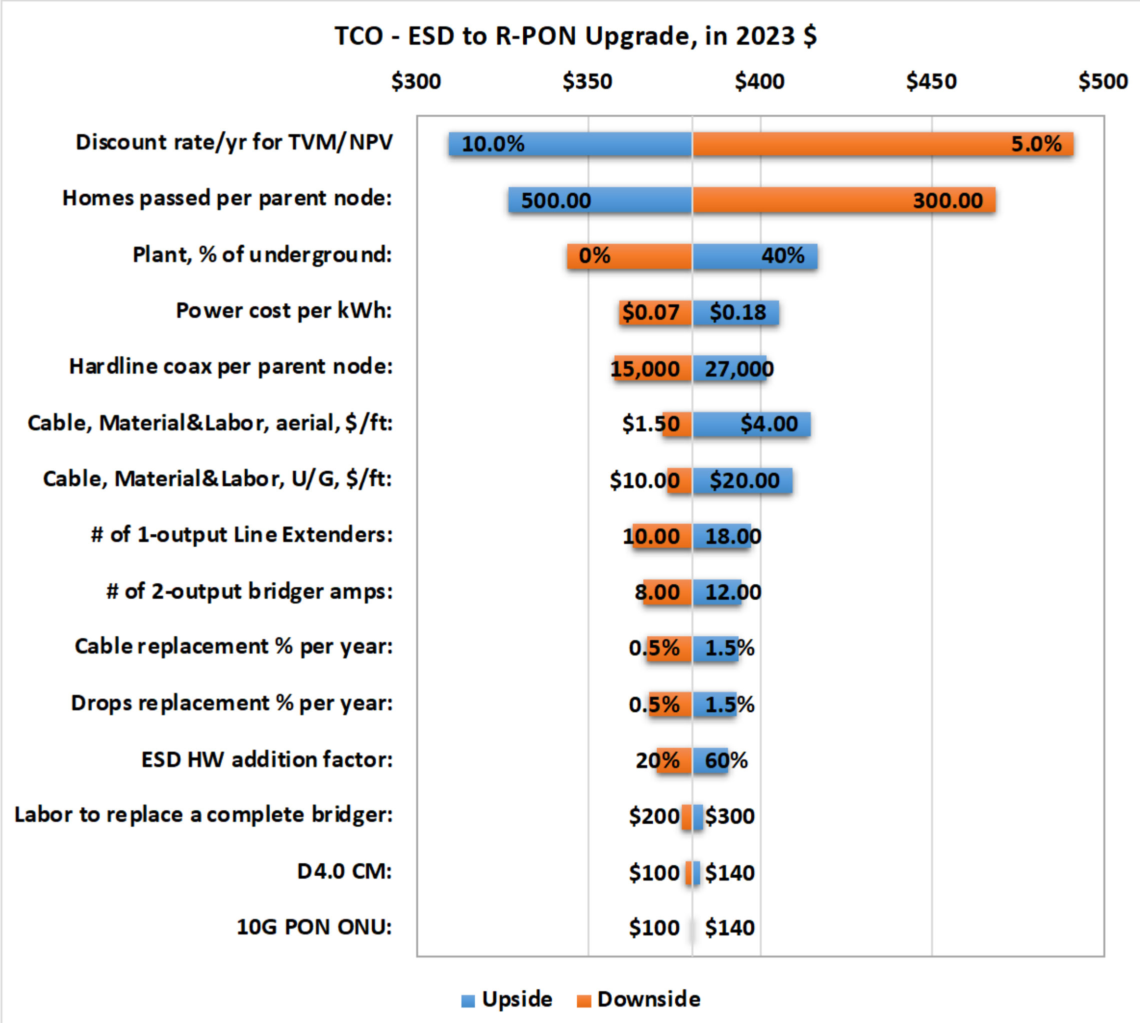

Figure 44: Sensitivity Tornado chart for the ESD to R-PON upgrade

6. Conclusion

Damn the torpedoes – the humankind's inability to predict the future ought not to stop us from trying to envision what a possible range of network upgrade outcomes may look like – that's what this paper is about. Common to all scenarios was the starting point of 400HP, 200 subs per node, with the top tier of 5/1 Gbps DS/US as the common goal.

The 1.8 GHz ESD plant upgrade handled the low to moderate DS Tavg growth projections just fine, through the 30-year window. The moderate case needed two node splits – one in 2038 and the other in 2046. Its TCO/HP came to $308 in '23 dollars. If DS Tavg follows the high growth projection for 20+ years, then a R-PON overlay might be needed to migrate 'heavy' customers to FTTP. This increased the NPV TCO/HP up to $380. This effectively provides a ceiling for the potential NPV TCO based on low to high growth scenarios.

For the low growth DS Tavg projections, the 1.2 GHz high split I-CCAP upgrade held up surprisingly well, with just one node split required in 2049. Its TCO/HP came to $235. For non-competitive markets and/or tight capital budgets, this remains a solid option. However, if DS Tavg follows the moderate to high growth projections, then a switch to ESD or FTTP will be needed during the next decade.

The FTTP PON upgrades are often associated with the high growth scenarios, but cost 2x higher than ESD NPV TCO/HP (i.e., $308 vs. $601) when overbuilding 80% aerial plant; and 3x higher (i.e., $308 vs. $932) for 20% aerial plant (and the rest underground). Along the way, the 10G R-PON original 1:128 splitting group had to be halved twice: once in 2035, and second time in 2042. And if the DS Tavg growth follows the low or moderate projections, then the operator may be spending a lot of excess money it might not need to.

Pushing big spending decisions into the future does provide significant value in today's dollars, as seen in "1.8 GHz ESD upgrade now, overbuild with fiber in 2044" scenario. This scenario benefits from the lower NPV TCO of the ESD route, as well as from the future high capacity of PON, but only implemented if needed. The blended ESD/PON path NPV TCO comes in 37% saving compared to doing PON now, and only at a 23% premium, in 2023 dollars, as compared to staying with ESD for 30 years.

Based on the track record of the publicly traded USA MSOs, the CAPEX dollars are likely to stay available for the lower cost upgrade approaches, provided operators' profitability stays on part. Another option is to use a hybrid approach: a lower-cost HFC upgrades where the market drivers call for it, and the higher cost/higher capacity PON in competitive markets. To conclude, if in doubt, let the market show you the way.

7. Acknowledgements

David Bowler, for expert guidance on finer aspects of 1.8 GHz ESD plant upgrade.

Abbreviations

10G	10 gigabits per second
AR	augmented reality
BW	bandwidth
CAGR	compound annual growth rate
CAPEX	capital expenditures
CATV	community antenna television
CIN	converged interconnect network
CM	cable modem
CMTS	cable modem termination system
COVID	coronavirus disease
CPE	consumer premises equipment
D3.1	DOCSIS 3.1
D4.0	DOCSIS 4.0
DAA	distributed access architecture
DDM	dividend discount model
DFN	distribution fiber network
DOCSIS	data over cable service interface specification
DS	downstream
DWDM	dense wavelength-division multiplexing
ESD	extended spectrum DOCSIS
FTTP	fiber-to-the-premises
HEO	head-end optics
HFC network	hybrid fiber-optic and coaxial cable network
HP	homes-passed
HS	high-split
I-CCAP	integrated converged cable access platform
IP	internet protocol
IPTV	internet protocol television
MAC	media access control
Mbps	megabits per second
MDU	multi dwelling unit
MSO	multiple system operator
nHz	nano Hertz
NPV	net present value
OFDM	orthogonal frequency division multiplexing
OFDMA	orthogonal frequency division multiple access
OLT	optical line terminal
ONT	optical network terminal
ONU	optical network unit
OPEX	operating expenditures
PHY	physical layer
PNM	proactive network maintenance
PON	passive optical network
PV	present value

QAM	quadrature amplitude modulation
QoE	quality of experience
RF	radio frequency
RPD	remote PHY device
RMD	remote MAC/PHY device
ROI	return on investment
R-PON	remote PON
SC-QAM	single carrier quadrature amplitude modulation
SDV	switched digital video
SFP	small form factor pluggable
SFP+	enhanced small form-factor pluggable
SG	service group
SLA	service level agreement
TCO	total cost of ownership
TVM	time value of money
UHS	ultra-high-split
US	upstream
VR	virtual reality
W	Watt

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