DOCSIS 4.0 Network Migration Made Easy

A Technical Paper prepared for SCTE•ISBE by

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1. Introduction

The plethora of new technologies and alternatives has made the task of HFC network migration more challenging than ever! The MSOs are faced with difficult decisions as their strategy executives and HFC network architects try to navigate the future of their HFC networks. The difficulty comes from identifying potential market challenges and addressing those challenges using the right technology in a timely and cost-effective manner.

DOCSIS 4.0 offers various technologies that will enable the delivery of 10 Gbps DS peak rates and 5 Gbps US peak rates. Utilizing the right technology at the right time will be instrumental for the success of the MSOs. This paper attempts to provide the list of available tools in the network migration toolkit and proposes a time-aware methodology for using these tools to yield a cost-effective migration strategy that meets customers traffic demand and addresses competition.

This paper is organized as follows: Section 2 introduces the latest traffic engineering trends and potential COVID-19 impact. Various network migration tools are described in Section 3. Section 4 discusses the decision interactions between some of the migration tools like traditional FDD, FDX & dynamic soft-FDD, and ESD. Time-aware decision process is discussed in Section 5. Section 6 provides an example migration strategy that uses various migration tools. Finally, the paper is concluded in Section 7.

2. Latest Traffic Engineering Trends & Potential COVID-19 Effect

Figure 1 and Figure 2 show the latest busy-hour average subscriber consumption rate (Tavg) for the DS & US directions, respectively, collected from multiple MSOs. These trends, which were captured in the beginning of 2020 and before the COVID-19 pandemic effect has spread, show that Tavg averaged across various MSOs yielded 2.36 Mbps for the DS and 164 kbps for the US. Additionally, the 2020 statistics show that the 3-year DS Tavg CAGR had dropped from 34% to 30% and the US Tavg CAGR had slightly dropped from 22% to 21%.

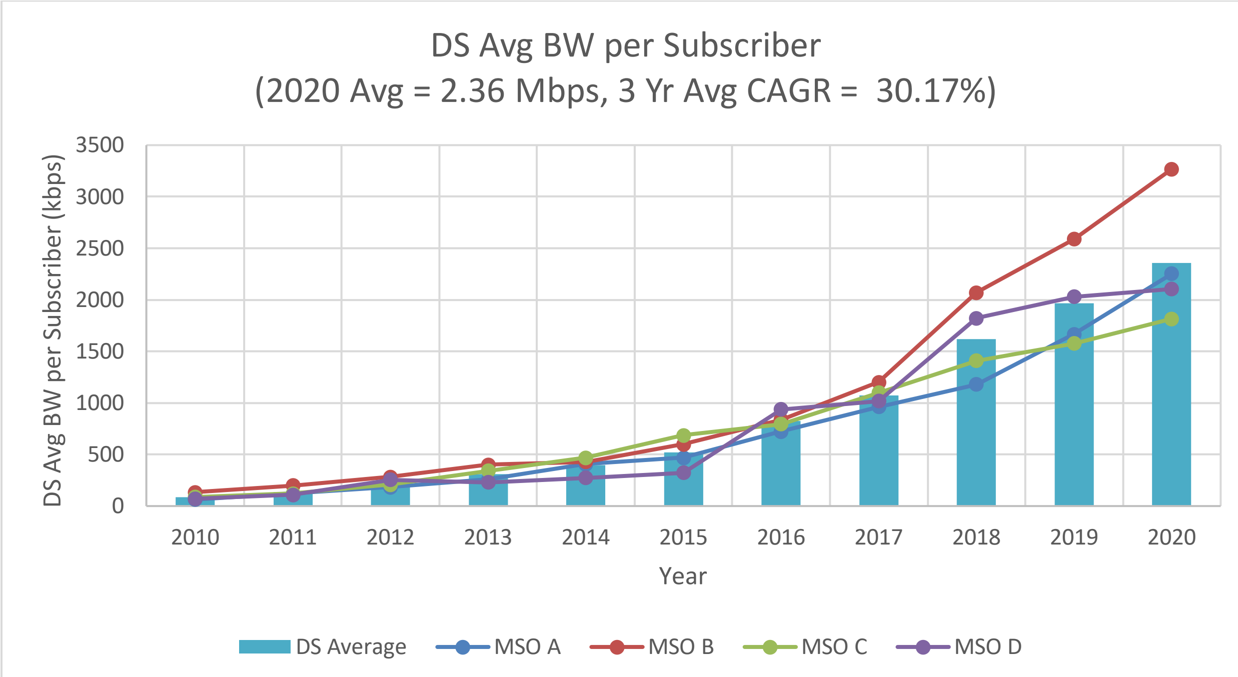

Figure 1 - DS Tavg latest statistics before COVID-19

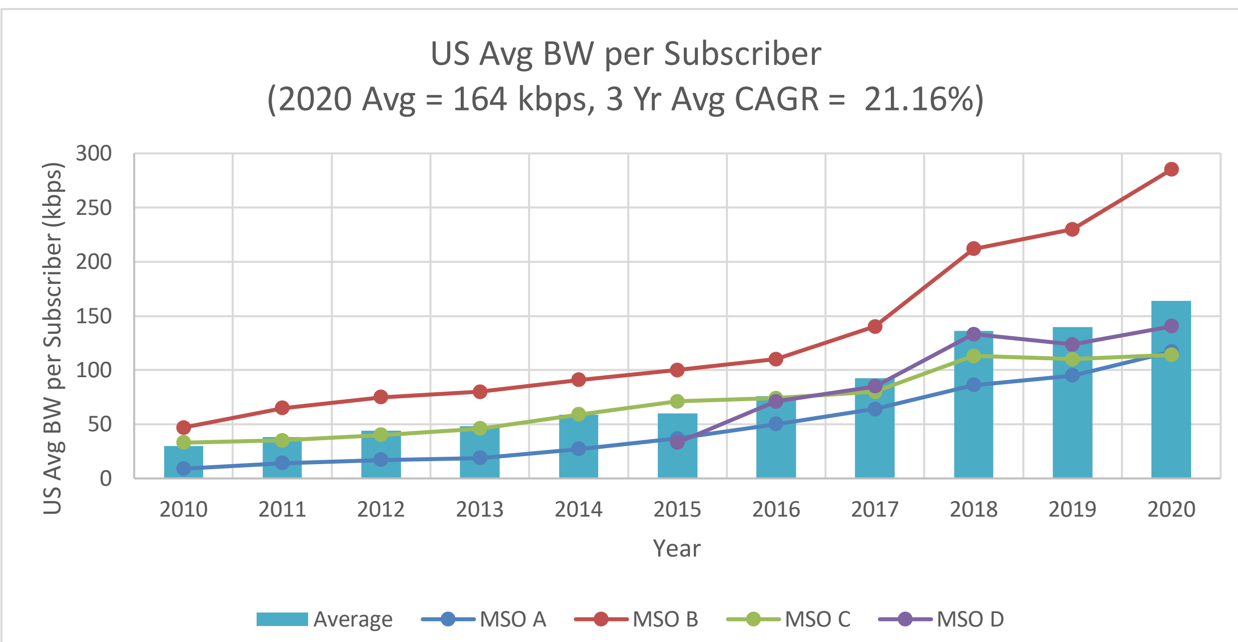

Figure 2 - US Tavg latest statistics before COVID-19

At the outset of the COVID-19 pandemic, the DS and US consumption increased significantly as countries, states, and cities enforced a lockdown to control the disease. With many people at home and the lack of outside activities, increased network consumption was in the form of video streaming, working-from-home, virtual video gatherings, gaming, etc. The increase in the US utilization was about 35% and the increase in the DS utilization was 20%. As some countries, states, and cities started to reduce the limits of the lockdown, the consumption (relative to pre-COVID numbers) has decreased recently (as of July 4, 2020) and currently shows an increase of about 22% for the US and 14% for the DS [NCTA-COVID-19-Tracker-2020]. The US & DS will not likely go back to the original levels because of the "new normal" after COVID-19, where many people will likely continue to work from home. It is probably reasonable to assume that the US will settle to 18% (half of 35%) and the DS will settle to 10% (half of 20%). Therefore, our traffic engineering assumptions for the analyses provided later in this paper assume an US Tavg of 190 kbps (instead of 164 kbps) for 2020 and a DS Tavg of 2.6 Mbps (instead of 2.36 Mbps) for 2020. Note that these percentages represent one-time jump in Tavg due to COVID-19 and are independent from the CAGR percentages discussed in the beginning of this section ,which represent the annual growth in Tavg.

3. Network Migration Tools

This section briefly describes the available tools in the network migration toolbox. These tools can be used to gradually and concurrently migrate along an optimal migration path that extends the useful life-span of today' HFC network while gradually transforming it into the desired end goal as a FTTH network.

3.1. Selective Subscriber Migration

Selective subscriber migration refers to the concept of performing HFC surgical operations, whereby customers demanding very high peak rates are moved to a different platform, such as an overlay FTTH network running a specific flavor of PON. This concept, which was explained in detail in [Spring-Forum-Migration-2016], avoids the need to upgrade the whole network in order to meet the abnormal service levels associated with very small penetration rates. For instance, if only a select number of residential or business customers request symmetrical 10 Gbps service, while the rest of customers are happy with sub 1 Gbps service, then it makes sense to move those few customers to 10G PON (e.g., XGS-PON or 10G-EPON) as opposed to overhauling the whole HFC network. This tool can be used to constrain the goal of HFC network migration to address rates offered by EPON or GPON but not with 10G PON competition. Using this constraint in the decision process will yield an optimal cost-effective competitive migration strategy.

3.2. Node Splits and Node Segmentations

Node splits and node segmentations provide another powerful tool within the HFC network migration toolkit. They can help reduce the number of subscribers per SG, which will lead to less congestion and therefore the ability to support higher peak service rates for a longer time. Recall that the total capacity required by a SG that has Nsub subscribers, each consuming an average busy hour rate of Tavg, and requesting a peak rate service of Tmax, is given by the following formula, where K is a QoE coefficient that is recommended to be between 1-1.2 to provide good QoE:

$$\text{Required SG Capacity} = \text{Nsub}*\text{Tavg} + \text{K}*\text{Tmax}$$

Note that with fixed available capacity, reducing the number of subscribers using a node split will reduce the first term of the above equation, which will enable supporting higher Tmax (within the second term) using the fixed available capacity.

3.3. Digital Video, Switched Digital Video & IPTV

The use of analog video channels comes at a price because they do not use the spectrum very inefficiently. Moving video from analog to digital channels will enable better utilization of the scarce spectrum via more efficient encoding schemes of the digital content. Adding SDV capabilities that only transmit video streams when being viewed can also help reduce spectrum utilization for video services. As time goes on, reducing the number of digital video channels and migrating to IPTV video (which uses more spectrally-efficient DOCSIS 3.1 channels) will provide yet another level of efficient usage of spectrum.

3.4. Split Upgrade

There are multiple US split options supported by the DOCSIS3.1 specifications: sub-split (5-42 MHz in NA and 5-65 MHz in Europe), Mid-split (5-85 MHz), and High-split (5-204 MHz). Supporting US peak rates up to 400 Mbps will require moving from sub-split to mid-split. On the other hand, supporting US peak rates in excess of 1 Gbps will require a move to a high-split architecture.

DOCSIS 4.0 specifications add other ultra-split options with US limits up to 300 MHz, 396 MHz, 492 MHz, and 684 MHz. These splits can be used in a fixed or dynamic manner as will be explained later in this paper.

3.5. Full Duplex DOCSIS

FDX is a technology that is designed to allow the US & DS traffic to share the same spectrum simultaneously. The FDX technology was thoroughly explained in [SCTE-Tec-Soft-FDD-2019]. It is optimized for DAA N+0 network architecture. MSOs who find it expensive to migrate their networks to N+0 will likely need other alternatives. One of those alternatives is to use FDX amplifiers. However, those amplifiers will cause the problem of Interference Group elongation [SCTE-Tec-Soft-FDD-2019], where most of the subscribers become a member of the same interference group (i.e., interfering with each other); therefore true FDX operation in N+x networks may not be feasible.

3.6. Dynamic Soft-FDD

In the previous section, the challenge of running FDX in N+x (x>0) networks was described. A potential solution for that problem is to run the system in Dynamic Soft-FDD mode [SCTE-Tec-Soft-FDD-2019], where the split is changed dynamically to match the traffic demand and hence offering the same benefits as FDX, but with typically larger Interference Groups. In a nutshell, Dynamic Soft-FDD is viewed as the tool that enables FDX operation in cascaded networks. Dynamic Soft-FDD is based on the same modem silicon as FDX and can help avoid replacing taps and passives beyond 1.2 GHz. However, more complex amplifiers will be needed, which may put a limit on the maximum cascade depth that can be supported with Dynamic Soft-FDD. Additionally, operating the Dynamic Soft-FDD plant could be challenging for some MSOs.

3.7. Extended Spectrum DOCSIS

Another tool in the network migration toolbox is ESD, where the DS spectrum is allowed to go beyond 1.2 GHz. DOCSIS 4.0 introduced requirements for 1.8 GHz operation in equipment whose housing supports 3 GHz spectrum. The ESD technology was described in detail in [SCTE-Tec-Soft-FDD-2019] [Spring-Forum-ESD-2016]. While the ESD technology requires changing taps and amplifiers, it works in an FDD mode just like today's networks. The ESD amplifier design can also be challenging due to the high gain requirements needed for operation at high frequencies, where attenuation is significant. Additionally, it should be noted that the limited TCP can be a potential issue with very long plants but not so much with short or medium plants, which make the majority of current HFC networks. Those challenges and potential solutions were discussed in [SCTE-Tec-Soft-FDD-2019].

3.8. Active Taps

As the networks get deeper in fiber deployment, they may eventually get to N+0. Before pulling fiber any deeper, the concept of active taps could be beneficial as taps are transformed into small active devices that support relatively small gain values. This enables continued use of the hardlines with higher modulation orders at higher frequencies, which will yield additional capacities [ANGA-Cable-Migration-2019] [SCTE-Tec-Soft-FDD-2019].

3.9. Fiber To The Tap

FTTT is a natural late-stage step to take before pulling fiber to the home, whether active taps were used or not as an intermediate step. FTTT enables the use of existing drop cables that can support frequencies up to 25+ GHz, which translates to data rates of more than 200 Gbps [Spring-Forum-ESD-2016]. In fact, when FTTT is used, the coaxial cable network becomes a point-to-point network which will enable ESD operation to be used in combination with FDX operation (without undergoing the current complexities of FDX that are faced with the current multi-point-to-single-point HFC networks).

4. Interactions of Traditional FDD, FDX & Dynamic Soft-FDD, and ESD

It can be confusing to think of multiple interrelated tools at the same time. In order to address this challenge, a decision tree was developed for N+x networks as shown in Figure 3. Observe that the decision tree considers multiple interrelated network migration tools including traditional FDD with DOCSIS 3.0 splits, DOCSIS 3.1/DOCSIS4.0 split change, Dynamic Soft-FDD, and ESD. In this context, recall that Dynamic Soft-FDD is the FDX flavor for N+x networks.

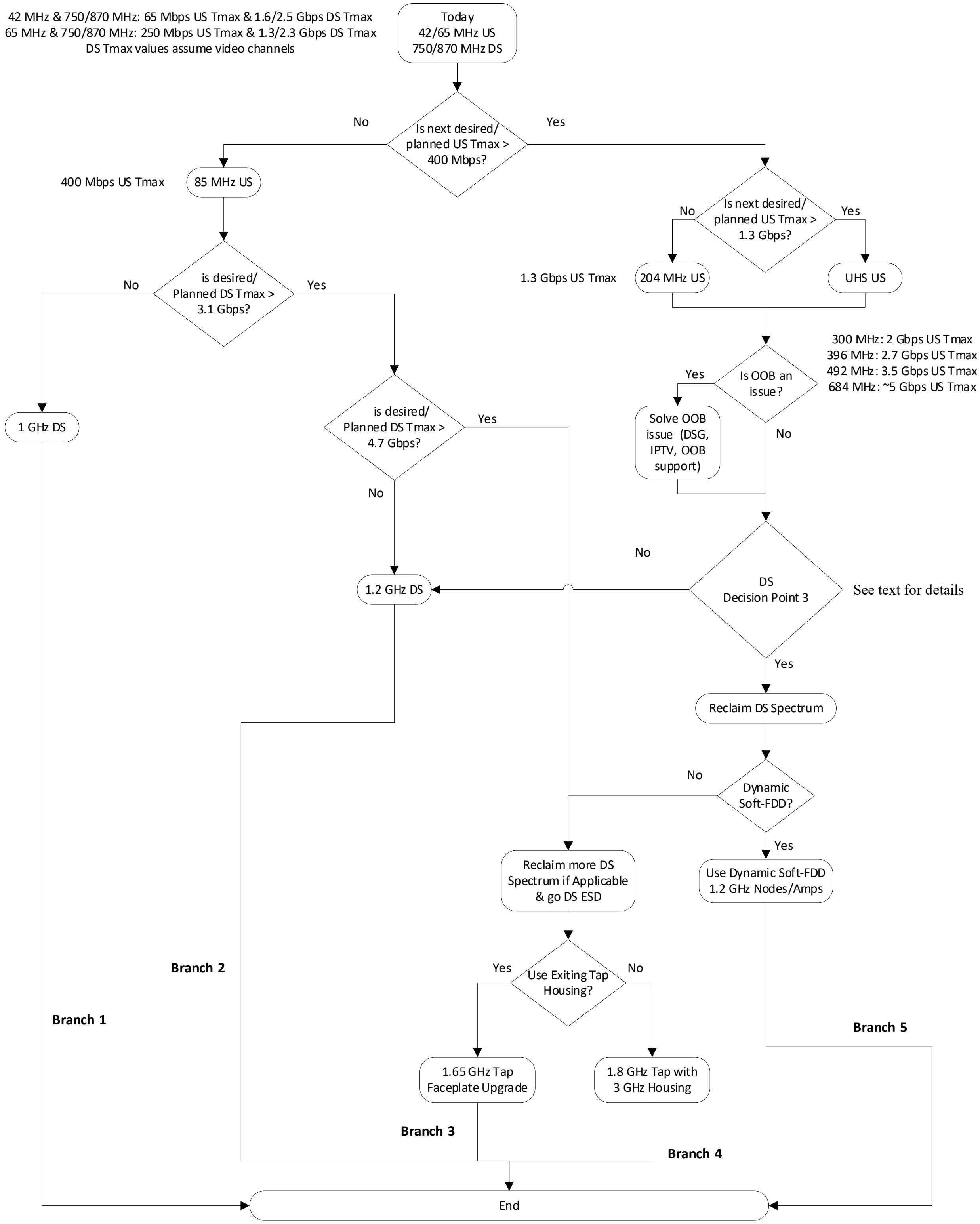

Figure 3 - Decision tree combining multiple interrelated network migration tools: traditional FDD with DOCSIS 3.0 splits, DOCSIS 3.1/DOCSIS4.0 split change, Dynamic Soft-FDD, and ESD

The 'DS Decision Point 3' in Figure 3 contains a list of decision questions, depending on the chosen US split, as follows:

Case (Split)
- Case A: 204 MHz Split
  - is desired/Planned DS Tmax > 3.6 Gbps?
- Case B: 300 MHz Split
  - is desired/Planned DS Tmax > 2.7 Gbps?
- Case C: 396 MHz Split
  - is desired/Planned DS Tmax > 1.7 Gbps?
- Case D: 492 MHz Split
  - is desired/Planned DS Tmax > 900 Mbps?
- Case E: 684 MHz Split
  - is desired/Planned DS Tmax > 0 Gbps?

It can be observed from the above decision point case statement that 1.2 GHz systems cannot support DS Tmax values more than 900 Mbps if the US split is 492 MHz or higher. Note that the 1.65 GHz Tap faceplate upgrade option refers to reusing existing taps housings by only replacing the faceplate with a new faceplate that supports higher frequencies, which can help in reducing the labor costs.

The assumptions that were used to calculate the Tmax numbers in the decision tree are as follows:
- **Traffic Engineering**
  - K = 1
  - Nsub = 250
  - US Tavg = 0.19 Mbps (0.164 Mbps with added step increase of 18% due to COVID-19)
  - DS Tavg = 2.6 Mbps (2.36 Mbps with added step increase of 10% due to COVID-19)
- **US**
  - # of 6.4 MHz SC-QAM channels = 4
  - SC-QAM spectral efficiency = 4.15 bps/Hz
  - OFDMA spectral efficiency = 7.5 bps/Hz
  - US spectrum start frequency = 15 MHz
- **DS**
  - # of 6 MHz SC-QAM channels = 20
  - SC-QAM spectral efficiency = 6.33 bps/Hz
  - OFDM spectral efficiency = 7.8 bps/Hz
  - Video: 66 Digital channels

Clearly, it should be noted that similar decision trees can easily be created for a different set of assumptions.

Note that analyses used in developing the decision tree assumed a SG size of 250 subscribers and 66 digital video channels, which can be argued to be good representative values of today's HFC networks. Table 1 provides the Tmax values that can be supported over today's HFC networks assuming no modifications. On the other hand, Table 2 provides the Tmax values that can be supported over a modified network using the different migration branches that were illustrated in Figure 3, which are:
1. Branch 1: 85 MHz US with 1 GHz DS
2. Branch 2: 1.2 GHz DS (with different US splits)
3. Branch 3: 1.6 GHz DS using tap faceplate upgrade (~ESD with different US splits)
4. Branch 4: 1.8 GHz DS using new ESD taps (ESD with different US splits)

5. Branch 5: 1.2 GHz Dynamic Soft-FDD

Table 1 - US & DS Tmax values that can be supported with today's networks (different configurations)

US Split (MHz)	Top of DS Spectrum (MHz)	US Tmax (Mbps)	DS Tmax (Gbps)
42	750	60	1.5
42	870	60	2.5
42	1002	60	3.5
65	750	250	1.3
65	870	250	2.2
65	1002	250	3.2

Table 2 - US & DS Tmax values that can be supported via different migration paths (with Digital video)

US Split (MHz)	US Tmax (Gbps)	DS Start Frequency (MHz)	Branch 1 FDD 1.0 GHz DS Tmax (Gbps)	Branch 2 FDD 1.2 GHz DS Tmax (Gbps)	Branch 3 FDD 1.65 GHz DS Tmax (Gbps)	Branch 4 FDD 1.8 GHz DS Tmax (Gbps)	Branch 5 Dyn. Soft-FDD 1.2 GHz DS Tmax (Gbps)
85	0.4	108	3.1	4.7	NA	NA	4.7
204	1.3	258	NA	3.6	6.9	8.1	4.7
300	2.0	372	NA	2.7	6.1	7.2	4.7
396	2.7	492	NA	1.7	5.1	6.2	4.7
492	3.5	606	NA	0.9	4.2	5.4	4.7
684	5.0	834	NA	0	2.5	3.6	4.7

It should be noted that the above decision tree must be used along with other tools like selective subscriber migration, node splits, migrating to IPTV, etc. This wholistic approach to the decision-making process yields an optimal migration path from complexity and cost point views. In particular, the table above contains technology options that are either costly or not available today, which should be taken into consideration as the MSOs plan a stepping-stone migration process.

5. Time-Aware Decision Making

A key missing aspect from the decision tree and the other tools described in the previous section is the time dimension of the decision. Specifically, the busy hour per subscriber consumption rate (i.e., Tavg) continues to grow as time goes on, which in turn reduces the Tmax values that can be supported given a particular network architecture. Also, the SG size (Nsub) decreases as more node splits are undertaken, which leads to higher Tmax values. However, these two terms are multiplied by each other in the QoE formula so the net effect may not be obvious unless simulations are performed. Another aspect that changes with time is the migration of digital video channels to IPTV which leads to more efficient video delivery and that yields support for higher Tmax values. This section introduces the time-awareness aspect into the decision process.

In order to take the above time-affected tools into consideration, the analysis in this section uses the latest traffic CAGR numbers presented in section 2 (i.e., US CAGR of 21% and DS CAGR of 30%). Also, the impact of node splits over time is studied by analyzing the effect of moving to smaller SG sizes (i.e., reducing the SG size from 250 to 125 and then to 64). Finally, moving video delivery from 66 digital channels to IPTV is also simulated to understand the effect of this move on the life of the network. Finally, multiple curves are illustrated to show the impact of changing the US split and moving the DS top end to 1.65 GHz or 1.8 GHz.

The Time-aware simulation assumptions are as follows:

- **Traffic Engineering**
  - K = 1
  - Nsub = 250 subscribers (Penetration ratio of data subscribers 50%)
  - US Tavg = 0.19 Mbps (0.164 Mbps with added step increase of 18% due to COVID-19) in 2020
  - US CAGR = 21%
  - DS Tavg = 2.6 Mbps (2.36 Mbps with added step increase of 10% due to COVID-19) in 2020
  - DS CAGR = 30%
- **US**
  - # of 6.4 MHz SC-QAM channels = 4
  - SC-QAM spectral efficiency = 4.15 bps/Hz
  - OFDMA spectral efficiency = 7.5 bps/Hz
  - US spectrum start frequency = 15 MHz
- **DS**
  - # of 6 MHz SC-QAM channels = 20
  - SC-QAM spectral efficiency = 6.33 bps/Hz
  - OFDM spectral efficiency = 7.8 bps/Hz
  - Video options: 66 Digital channels, or IPTV
- **IPTV Video**
  - Penetration ratio of video subscribers = 30%
  - Unicast only
  - HD MPEG4 bit rate = 5 Mbps
  - UHD/4K bit rate = 17 Mbps

- 90% HD / 10% UHD mix
- 5% VOD

The results of the analyses are shown in Figure 4 - Figure 9. The first three figures assume digital video channels and study the effect of node splits by varying the SG size from 250, to 125, and finally to 64. Similarly, the last three figures change the SG size but assuming IPTV video delivery instead of digital video channels.

Understanding how to interpret the curves can be best illustrated using an example. For instance, in Figure 4, curves with no markers show the highest peak service rate (Tmax) that can be supported in the US direction for different US split options. On the other hand, curves with markers indicate the highest DS Tmax that can be supported for different configurations (particular US split combined with DS spectrum limit).

Let's assume that the MSO would like to offer symmetrical 1 Gbps service, it can be seen from the Figure 4 that high-split (i.e., 204 MHz US split) can support US Tmax of 1 Gbps until about 2031 – this can be observed from the non-marker gray curve that corresponds to 'US Tmax: 204 MHz US Split'. Using the same approach, it can be seen that a 204 MHz US with 1.2 GHz DS system can offer a DS Tmax value of 1 Gbps beyond 2026 – this can be observed from the circle-marker dark blue curve that corresponds to 'DS Tmax: 204 MHz Split with 1.2 GHz DS'.

The effect of a node split that divides the SG size in half (from 250 to 125), can be observed in Figure 5, where it can be seen that high-split can offer US Tmax of 1 Gbps to about 2034 and high-split 1.2 GHz DS system can offer a DS Tmax value of 1 Gbps about 2029. Also, observe how a move to IPTV can further extend the lifespan of the network. For example, for a SG of 125, a move to IPTV will enable a high-split network with 1.2 GHz DS to support DS Tmax value of 1 Gbps to about 2031 as can be observed in Figure 8.

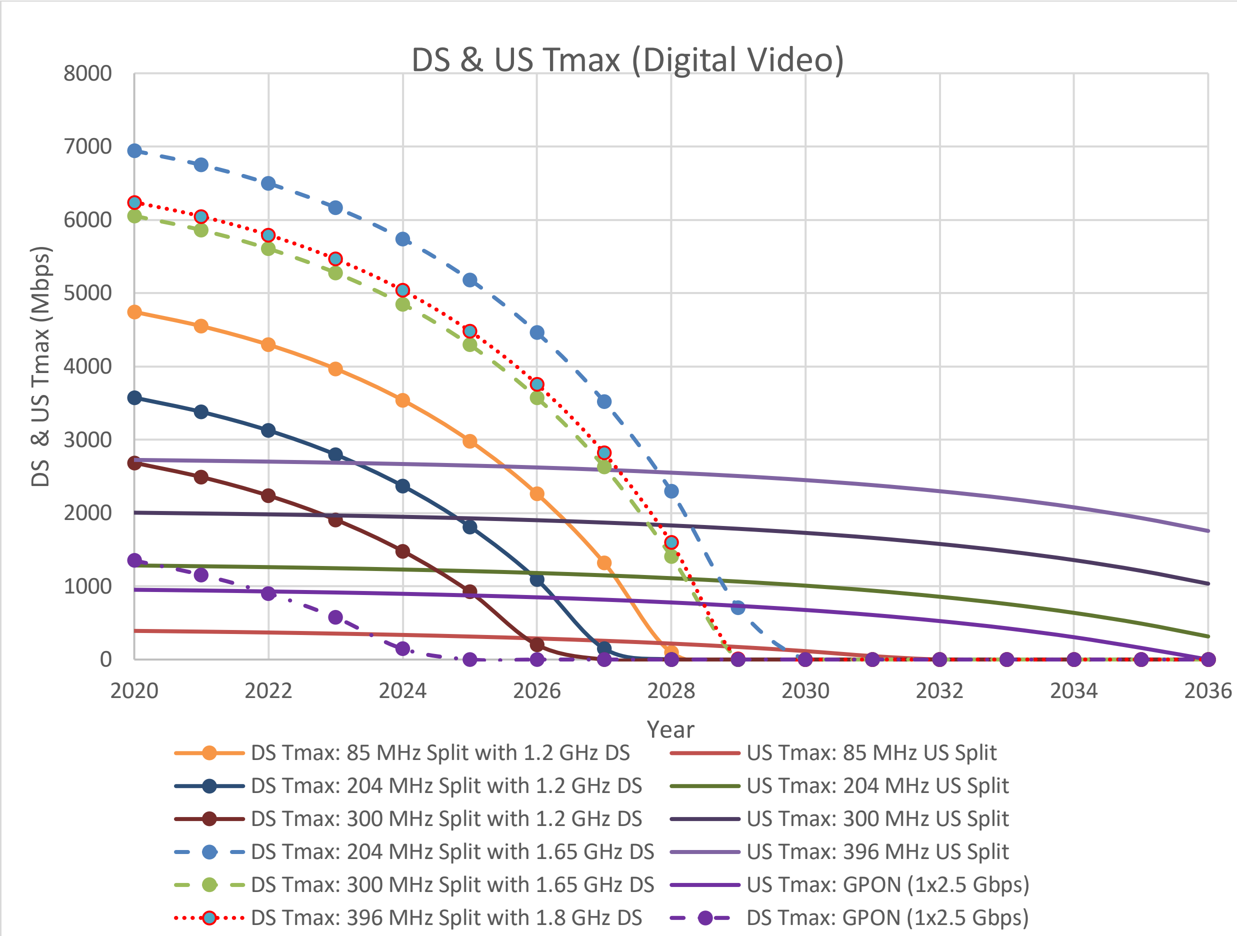

Figure 4 - US & DS Tmax values that can be offered over time for various split options and DS spectrum sizes. (SG size = 250, 66 Digital video channels)

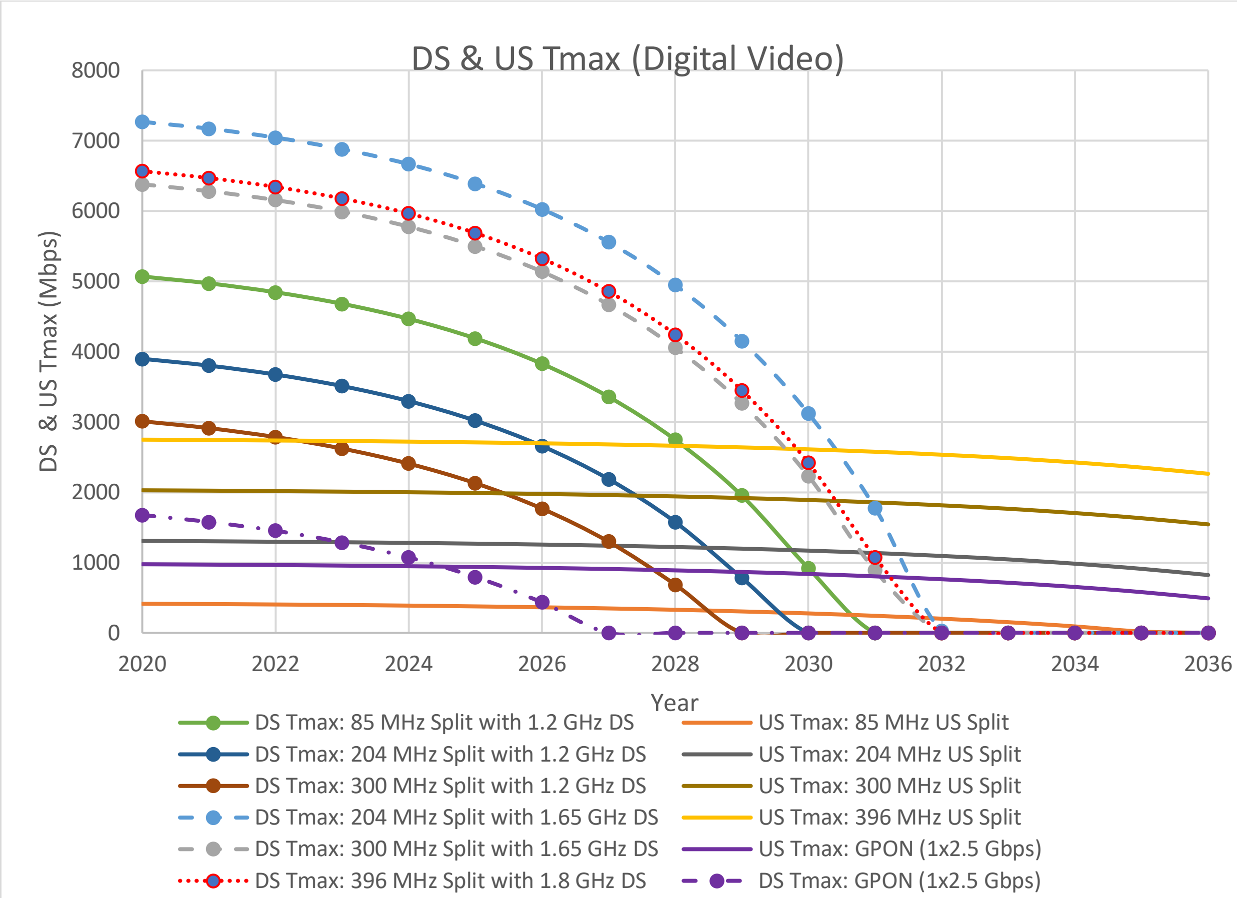

Figure 5 - US & DS Tmax values that can be offered over time for various split options and DS spectrum sizes. (SG size = 125, 66 Digital video channels)

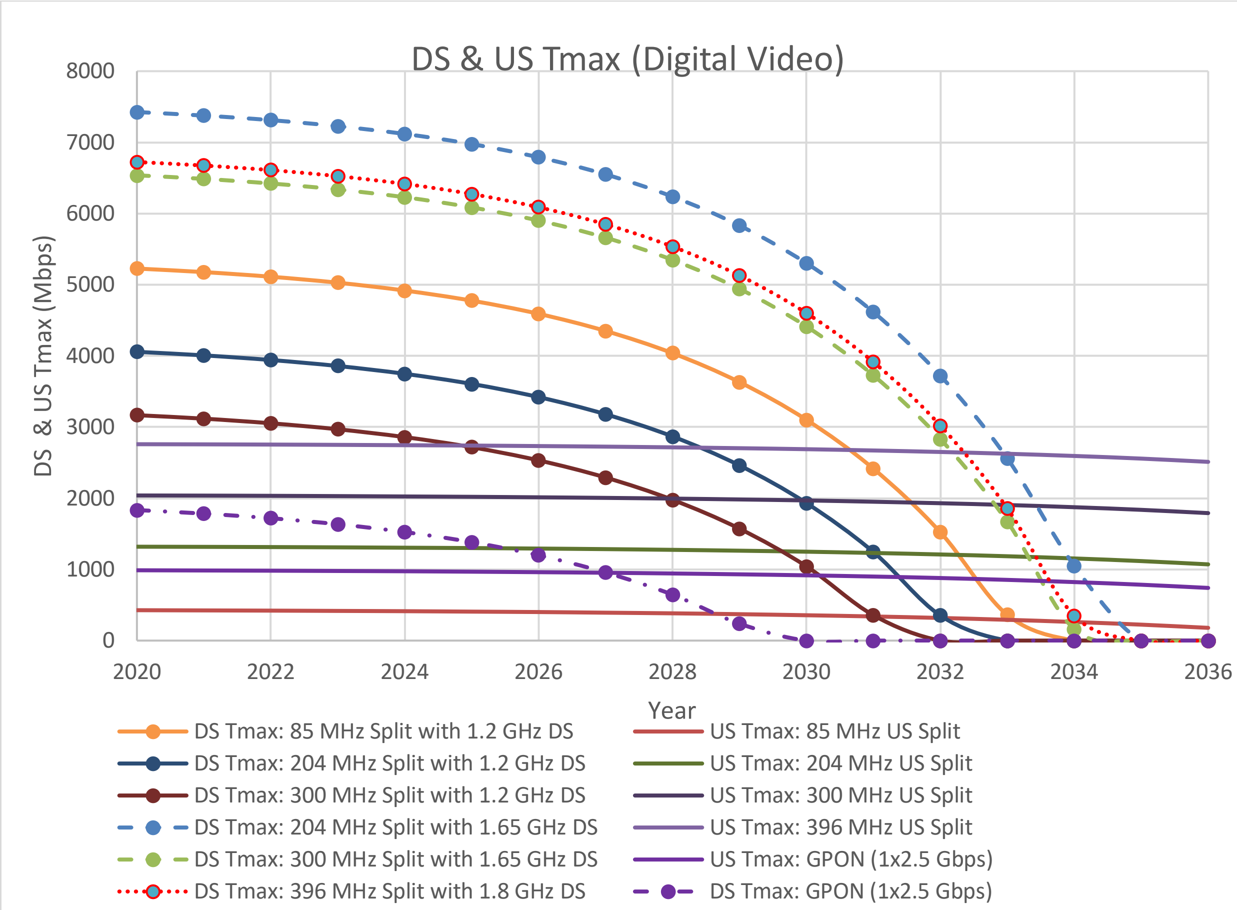

Figure 6 - US & DS Tmax values that can be offered over time for various split options and DS spectrum sizes. (SG size = 64, 66 Digital video channels)

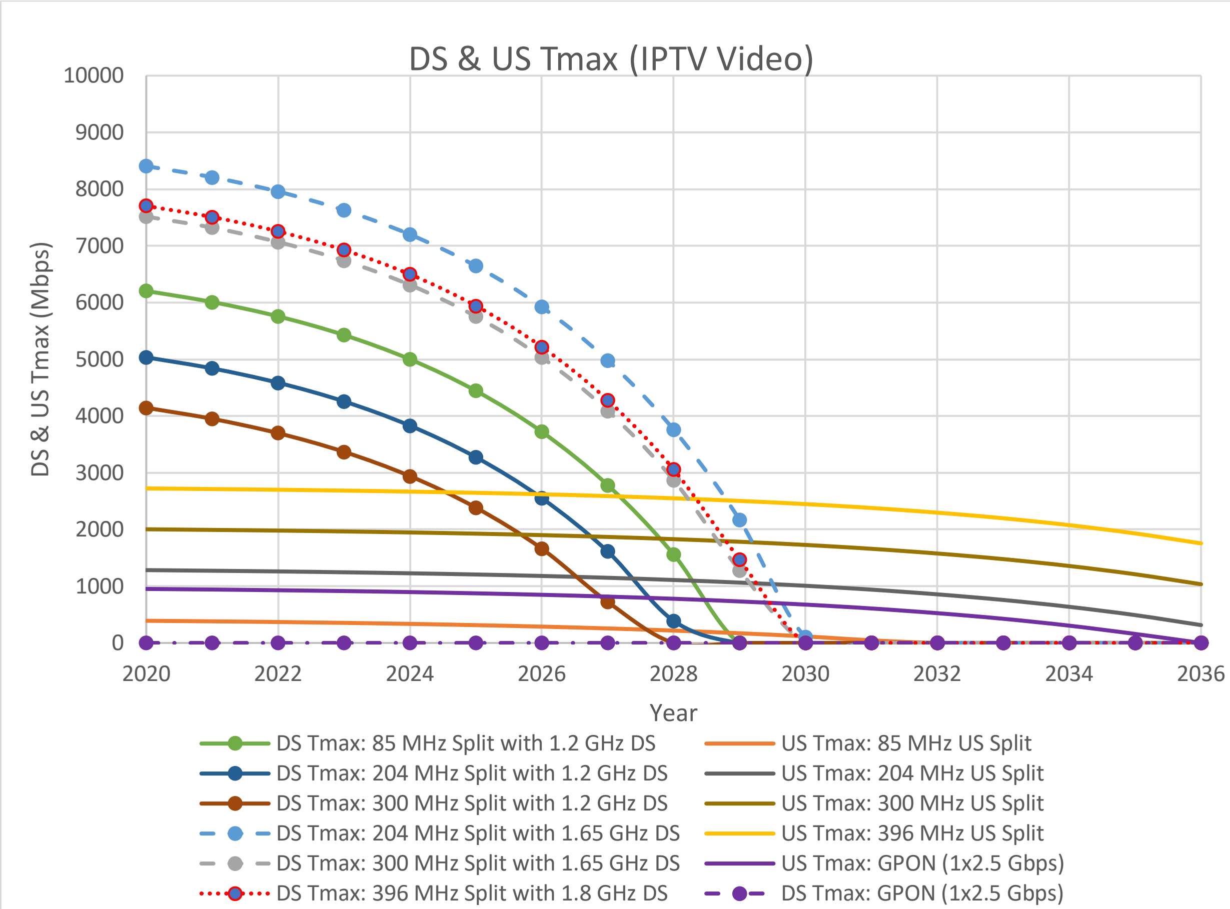

Figure 7 - US & DS Tmax values that can be offered over time for various split options and DS spectrum sizes. (<u>SG size = 250, IPTV video channels</u>)

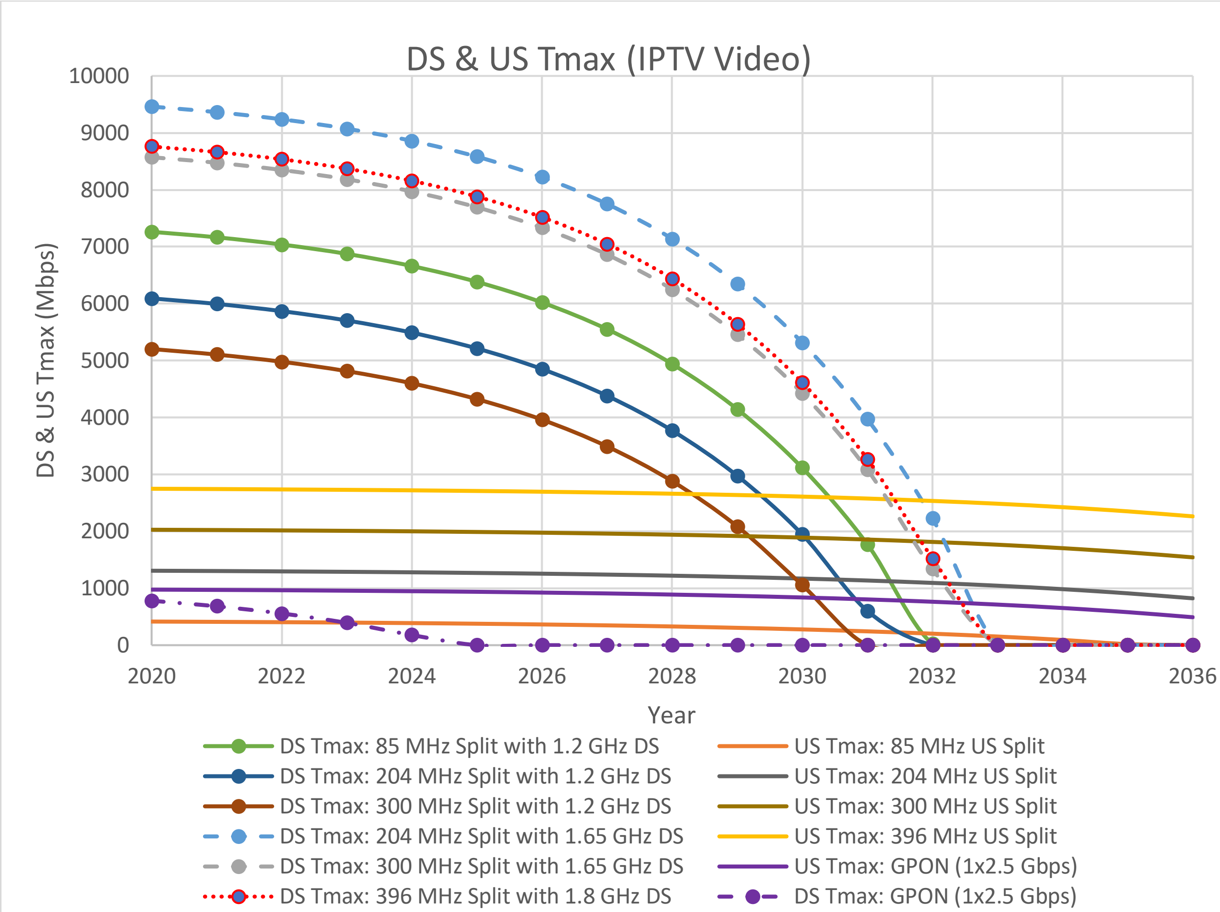

Figure 8 - US & DS Tmax values that can be offered over time for various split options and DS spectrum sizes. (<u>SG size = 125, IPTV video channels</u>)

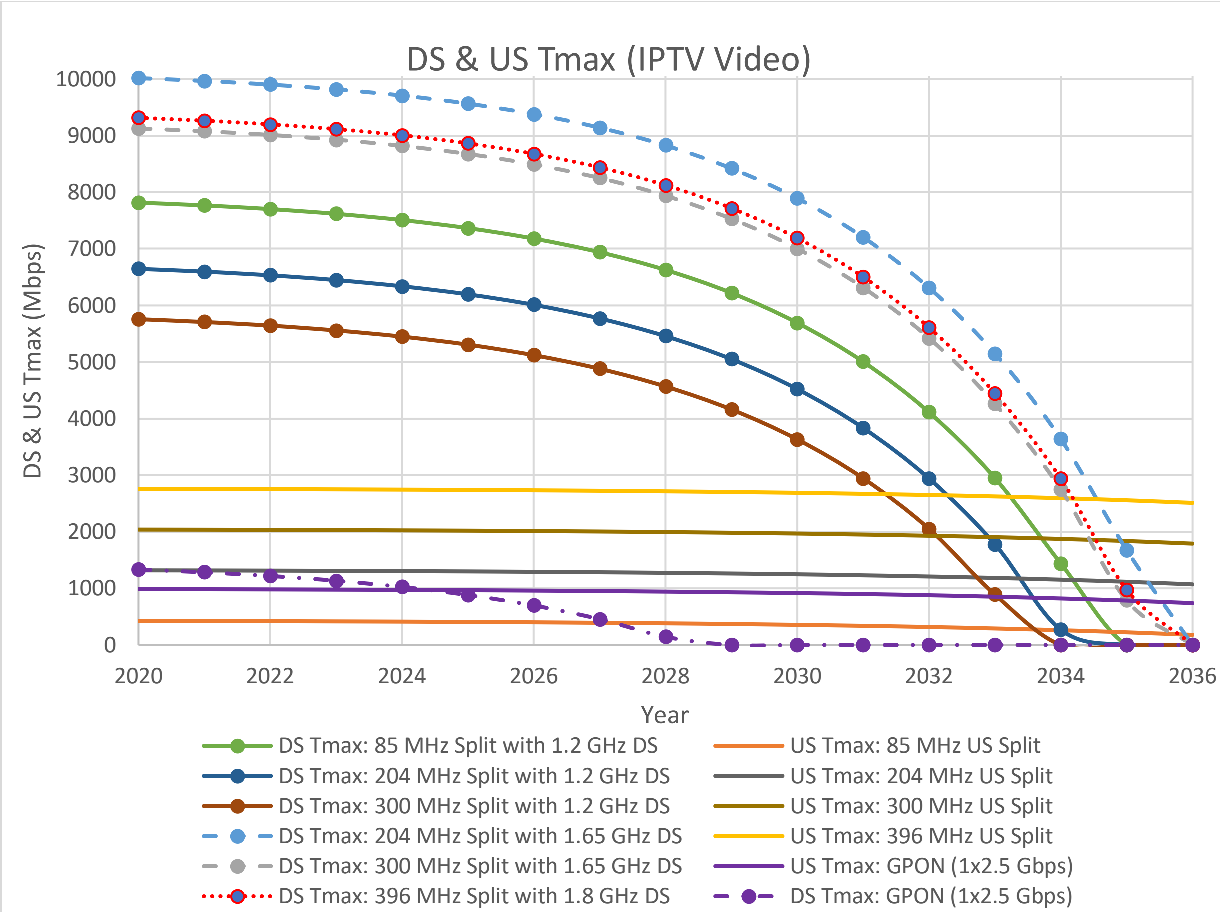

Figure 9 - US & DS Tmax values that can be offered over time for various split options and DS spectrum sizes. (SG size = 64, IPTV video channels)

Observe that the above figures do not propose a specific set of US or DS Tmax values that the MSOs should offer. An MSO with envisioned support for a particular Tmax value (depending on their specific demand and competition) can use the curves to estimate the lifespan of their network given that envisioned Tmax value.

Besides indicating the Tmax capabilities resulting from US split changes, node splits, DS spectrum size changes, and video delivery strategy changes, the above family of curves can also be used concurrently with other tools like the selective subscriber migration tool. For example, looking at Figure 4 which assumes digital video and SG size of 250 subscribers, it can be noticed that high-split with 1.2 GHz DS network cannot support DS Tmax values of 5 Gbps. However, if selective subscriber migration is used, where the few subscribers requiring 5 Gbps service are moved to another platform (like 10G PON over FTTH), then the rest of the subscribers on the network will need less demanding DS Tmax values like, say 1 Gbps, and therefore the same network with no modification will be able to support a DS service rate of 1 Gbps to 256 subscribers until 2026.

Finally, it should be noted that Figure 4 - Figure 9 include Tmax curves that can be supported using the 1x2.5Gbps GPON platform. For the digital video scenarios, it is assumed that video is transported via a separate wavelength and therefore all of the GPON capacity is available for data. On the other hand, the IPTV scenarios assume that IP video traffic is sent over the PON technology along with data and therefore both video and data share the total available capacity, which leads to reduced Tmax values. It can be seen from Figure 4 - Figure 9 that HFC networks can compete very well against GPON using the available migration tools. This observation can lead us to argue that it is wise to limit the competition scope of HFC networks to only compete against EPON/GPON and use selective subscriber migration for customers who require service rates that are comparable to those offered by 10G PON, when the percentage of subscriber requiring those rates is small. This can be a smart move that yields a cost-effective migration strategy, where HFC networks can live for a long life while meeting the demand and addressing non 10G PON competition.

Finally, it should be noted that all of the curves in Figure 4 - Figure 9 will stretch to the right if the CAGR percentages drop.

6. Example Network Migration Strategy

As mentioned earlier, there are many tools available to help the MSOs with their HFC network migration exercise. Some of the near-term tools are:

- Enable more DOCSIS 3.1 OFDMA for the US
- Enable more DOCSIS 3.1 OFDM for the DS
- Node split/segmentation
- Enabling Switched Digital Video
- Increasing Video Compression
- Video BW reclamation by moving to IPTV
- Increasing the US split
- Increasing the DS spectral range
- Selective subscriber migration

An optimal network migration strategy is obtained by applying a comprehensive decision process that considers all the available tools concurrently. The process is repeated every time a decision is to be made. In particular, the optimal decision changes as time moves on. This paper listed various tools that can be used concurrently along with a proposed decision tree and family of time-aware curves to help make the right decision when a migration step is needed.

Based on the above, an example migration strategy is given below:

1. Reframe the goal as ‘constrained’ network migration **{Selective Subscriber Migration}**
    a. The result of constraining the process is avoiding the costs associated with unnecessary ‘network-wide’ upgrades when only a small percentage of the subscribers demand a service requiring such an upgrade. This is accomplished using the Selective Subscriber Migration tool, where a constraint is put on the maximum data rate that should to be supported using the HFC network. Any peak rate exceeding this maximum is to be offered using another platform like PON over FTTH. An example of a chosen max rate to be supported on the HFC network can be 2.5 Gbps. Rates beyond 2.5 Gbps are not carried by the HFC network. That is, HFC is to compete with EPON/GPON but not 10G PON, when the percentage of subscribers requiring rates in excess of 2.5 Gbps is very small. The result is moving the small percentage of subscribers with demand for very high peak rates to a different platform, which in turn relieves the pressure from the existing network and therefore elongating the life of the network by allowing it to serve

the remaining 'normal' subscribers without massive upgrades. Note that when the MSO decides to offer a particular service that requires an upgrade to the majority of their subscribers, then a network-wide upgrade will be appropriate and justifiable.
   b. The next steps in this migration strategy example assume network-wide upgrades, where all super subscribers have already been moved to a different platform.
2. Continue reducing the SG size **{Node splits}**
   a. Node splits and node segmentation will help in reducing the SG size, which will reduce the overall busy hour BW requirements and therefore elongate the life of existing networks.
3. Move to 204 MHz US with 1.2 GHz DS **{High-split/1.2 GHz DS network architecture}**
   a. With DOCSIS 3.1, 204 MHz US enables the offering of 1+ Gbps US peak rates. 1.2 GHz DS adds additional spectrum to accommodate the increased DS traffic demand.
   b. Assuming no node split (i.e., SG size of 250 subscribers), high-split with 1.2 GHz DS can offer symmetrical 1 Gbps until at least 2026 (DS limited). With two nodes splits (i.e., SG of 64 subscribers), the same architecture can offer 1 Gbps symmetrical service until 2031/2032.
4. Continue Reclaiming video BW **{Move video to IPTV}**
   a. Moving video to IPTV can further elongate the life of a high-split 1.2 GHz DS HFC network (with SG size of 64 subs) by two years. That is, it can offer symmetrical 1 Gbps service until 2033/2034.
5. Further Increase the US & DS throughputs **{Move to either ESD or Dynamic Soft-FDD}**
   a. DOCSIS 4.0 ESD specifications enables the US to go up to 684 MHz and the DS to go up to 1.8 GHz. This will yield US and DS peak rates of 5 Gbps and 10 Gbps, respectively. ESD is a fixed-split FDD operation that is easy to manage but it requires the replacement of taps and amplifiers. Amplifiers may be challenged with high gain requirements to accommodate the increased attenuation at higher frequencies. As mentioned earlier, limited TCP values may not a major issue for short and medium HFC plants.
   b. Dynamic Soft-FDD is the FDX flavor for N+x networks. It enables the US to go up to 684 MHz and the DS to continue to be at 1.2 GHz, where the US & DS time-share the 108-684 MHz spectrum. This will yield US and DS peak rates of 5 Gbps and 10 Gbps, respectively. While Dynamic Soft-FDD does not require tap replacements, its operation may be a little more challenging than ESD. Also, due to the potential complexity of the amplifiers, it may only work for small cascades although it has the advantage of using the same FDX CPE silicon.
   c. While ESD & Dynamic Soft-FDD are equivalent from capacities point view, the decision to go one direction versus the other has major implications to the network architecture and its operation.
6. **Active Taps**
   a. Taking the fiber deeper in the network beyond N+0 can be done in stages. In particular, the MSO can choose to maximize the use of existing hardlines by using active taps, which are small active amplification devices, to enable signal delivery at high frequencies over hardlines.
7. **FTTT**
   a. Whether active taps were used or not, before going FTTH, it is beneficial to visit this step to maximize the life of HFC networks by using the existing drop cables that can go beyond 25 GHz. In fact, with FTTT architecture, the HFC network becomes a point-to-point network with only the drop cable between subscriber and the network. This can enable FDX, ESD, or combination of the two.

8. FTTH

a. The desired end goal of HFC networks is to extend the fiber to the home.

7. Conclusions

There are many tools available in the network migration toolbox which will enable the HFC networks to support their customers well into the 2030 decade. These tools include selective subscriber migration, node splits, moving video to IPTV, upgrading the US split, increasing the DS spectrum, dynamic Soft-FDD, active taps, FTTT, and FTTH.

After utilizing the selective subscriber migration concept to constrain the network migration process, the article proposed a decision tree combined with a time-aware decision process to yield an optimal network migration strategy. It was found that the combination of light/medium touch options like moving the US split 204 MHz with 1.2 GHz DS & nodes splits/segmentations can extend the life of the HFC network to 2030 if the desired DS Tmax is 2 Gbps or less. Deploying IPTV will further extend the life of HFC networks. Moreover, this article also showed that Dynamic-Soft-FDD & ESD can both increase the life-span of HFC networks. In the ESD case, going with US splits higher than 396 MHz when the DS is limited to 1.8 GHz is not optimal.

Abbreviations

bps	bit per second
BW	bandwidth
COVID-19	Corona Virus Disease 2019
DAA	distributed access architecture
DOCSIS	data over cable service interface specifications
DS	downstream
DSG	digital set-top gateway
EC	echo cancellation
EPON	Ethernet PON
ESD	extended spectrum DOCSIS
FD	fiber deep
FDD	frequency division duplex
FDX	full duplex DOCSIS
FTTH	fiber to the home
FTTT	fiber to the tap
Gbps	gigabit per second
GW	gateway
HD	High Definition
HFC	hybrid fiber coax
Hz	hertz
IG	interference group
IP	internet protocol
IPTV	Internet Protocol Television
kHz	kilo hertz
Mbps	mega bit per second
MHz	mega hertz
MPEG	Moving Picture Expert Group

MSO	multiple service operator
OFDM	orthogonal frequency division multiplexing
OFDMA	orthogonal frequency division multiple access
OOB	out of band
PON	Passive Optical Network
QAM	quadrature amplitude modulation
QoE	quality of experience
RF	radio frequency
RPHY	remote physical layer or remote PHY
SC-QAM	single-carrier QAM
SG	service group
SLA	service level agreement
STB	set-top box
TCP	total composite power
TG	transmission group
US	upstream
GPON	Gigabit PON
UHD	Ultra High Definition
UHS	Ultra-High Split
VOD	Video on Demand
XGS-PON	10G symmetrical PON defined by ITU

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