NETWORK MIGRATION DEMYSTIFIED IN THE DOCSIS 3.1 ERA AND BEYOND

Ayham Al-Banna (ARRIS), Tom Cloonan (ARRIS), Frank O'Keeffe (ARRIS),
Dennis Steiger (nbn)

Abstract

The spectral efficiency of DOCSIS 3.1 networks is analyzed based on real-world measurements from the nbn network. It is shown how DOCSIS 3.1 can reduce the required number of node split operations as well as postponing them. The article proposes a decision tree to select the appropriate technology enablers such that traffic demand is met with minimum cost. DS and US network migration to DOCSIS 3.1 is described. Finally, long term network evolution scenarios are provided.

I. INTRODUCTION

The cable industry has achieved tremendous progress over the past decade in offering high speeds that met customers' demand and defended against competitive threats of speed wars. This journey is nowhere close to an end! As MSOs continue their network evolution, they are currently faced with an interesting time since many options are available to augment their existing HFC networks. For example, Fig. 1 shows multiple potential evolutionary paths that the MSOs can select from. Herein, the network architecture (e.g., I-CCAP/DAA/PON) is plotted against the topology which is presented here as the depth of the fiber in the network (e.g., HFC, FTTLA/FTTC, FTTT, FTTH).

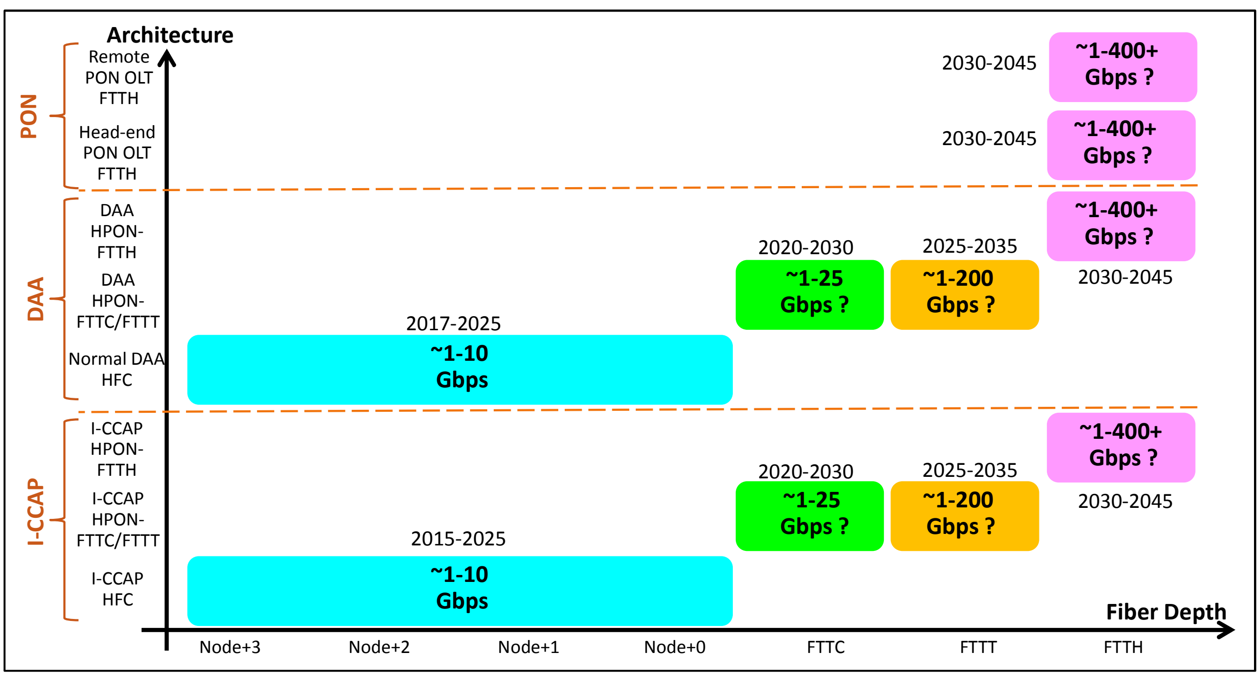

Figure 1. Evolution of cable networks in the next 2-3 decades.

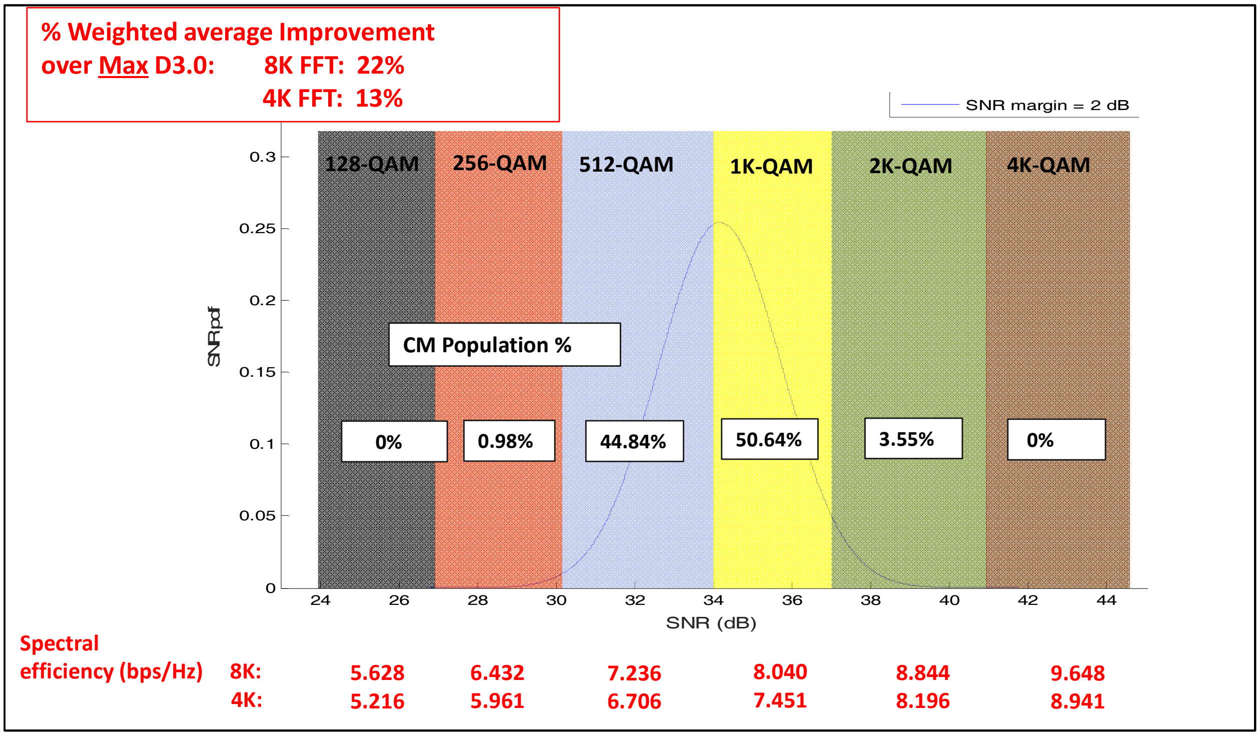

Figure 2. Spectral efficiency of DOCISIS 3.1 signals (pdf is plotted for SNR margin of 2 dB) based on Comcast data [1]

Note that the potential capacities shown in Fig. 1 increase as the fiber depth increases. This is because the analysis assumes that more fiber and less coax will yield less signal attenuation. Moreover, smaller service group sizes leads to less noise especially in the US direction. Both of these factors lead to higher SNR values. For instance, the I-CCAP capacities with HFC networks (N+x to N+0) can offer anywhere between 1 Gbps and 10 Gbps of total capacity depending on the upper edge of the DS spectrum (e.g., 550, 750, 1218, 1794 MHz) assuming that the spectrum is occupied by 402 MHz of broadcast digital video, 16 SC-QAM channels (with 6.33 bps/Hz spectral efficiency [1] [2]), and the rest is filled with DOCSIS 3.1 signals. The spectral efficiency of DOCSIS 3.1 signals is assumed to be ~7.7 bps/Hz based on previous analyses of current MSO plants and assuming an MSO operating margin of 2 dB as shown in Fig. 2 [1] [2]. Observe that the weighted average spectral efficiency of 7.7 bps/Hz is equivalent to an average mix of 512QAM/1KQAM.

For the I-CCAP FTTC capacities of 24 Gbps, the spectrum is assumed to be extended to 3 GHz and DOCSIS 3.1 signals are assumed to fill the whole spectrum with an average of 2K QAM and 0 dB SNR operating margin (8.8 bps/Hz as shown in Fig. 2). For the FTTT option that can offer a total capacity of ~200 Gbps, the spectrum is assumed to be extended to 20 GHz and 4K QAM DOCSIS 3.1 signals are assumed to fill the whole spectrum. The spectral efficiency of those DOCSIS 3.1 signals is assumed to be 9.6 bps/Hz with 0 dB SNR operating margin (see Fig. 2). Observe that the capacities of the DAA architectures in Fig. 1 are assumed to be similar to those of the I-CCAP architecture in this analysis in order to be conservative since the main benefits of moving to distributed access architectures are the saving of power/space in headend and supporting more lambdas with digital optics. While digital optics can lead to higher SNR values and therefore higher capacities [3] [4], those potential capacities cannot be guaranteed due to potential bottle necks in the coax portion which is not affected by the architecture (I-CCAP vs. DAA). The coax portion consists of the following plants pieces: Tap, Drop cable, Home network in subscriber's home, and the Modem (TDHM) [2].

Figure 1 above also showed potential time frames for transitions between different phases of the same architecture or moving from one architecture to another. Those time frames overlap in time because different MSOs may select to transition to a particular alternative at different times. For example, it is shown that the current HFC networks with the normal practice of node splits going to N+0 may live until year 2025. At the same time, the graph shows that some MSOs may choose to move to a FTTC architecture as early as 2020 (until 2030?). Similarly, MSOs may choose to move to FTTT architecture as soon as 2025 (until 2035?). Finally, it is assumed that some MSOs may choose to migrate their networks completely to FTTH as early as 2030. Note that the capacities of all architectures (I-CCAP/DAA/PON) in an FTTH environment in the 2030 time frame are assumed to be similar (~400 Gbps+) because it is assumed that those architectures will leverage similar technologies then.

Different factors can cause MSOs to move from one architecture to another. For instance, moving from centralized (I-CCAP) architecture to distributed architecture (DAA) can provide multiple benefits such as the reduction of the headend space/power requirements and increased number of simultaneous lambdas that can be supported on a single fiber via wavelength division multiplexing. Moving from I-CCAP/DAA to PON architecture permits MSOs to move to a technology (PON) that may be their last-mile technology of the future. Moving from N+x/N+0 to FTTC and FTTC to FTTT permit the MSOs to increase the BW capacity to a service group by making the service group smaller and by reducing the length of lossy coaxial cables as well as extending the spectrum. Alternatively, some MSOs may view OBI-free RFoG) as their long-term last mile technology of the future which can be supported using FTTH architecture.

Given the large combinations of the various network architectures shown in Fig. 1 (I-CCAP/DAA/PON) and different fiber depth topologies, selecting the appropriate architecture/topology transition path is not a trivial task. The challenge at hand is to develop a methodology that utilizes the available technology enablers in selecting the appropriate transition path. These technology enablers include node segmentation, node splitting, DOCSIS 3.1, plant upgrades, spectrum management and reclamation, Selective Subscriber Migration (SSM), extended spectrum DOCSIS, DAA, and others.

Most of the technology enablers listed above are known and understood. However, some enablers like extended-spectrum DOCSIS and selective subscriber migration may need to be explained before being proposed for use in migration strategies. The Extended-spectrum DOCSIS refers to extending the spectrum used in cable networks above and beyond of what DOCSIS 3.1 can support [5] [6]. This can be effective in different network topologies like FTTC and FTTT where no amplifiers or diplexers are present. The coaxial cables can support very high frequencies like 3-6 GHz for rigid cables and 25 GHz for RG-6 drop cables. With extended spectrum DOCSIS, the proposed network topology is illustrated in Fig. 3 for the FTTT case.

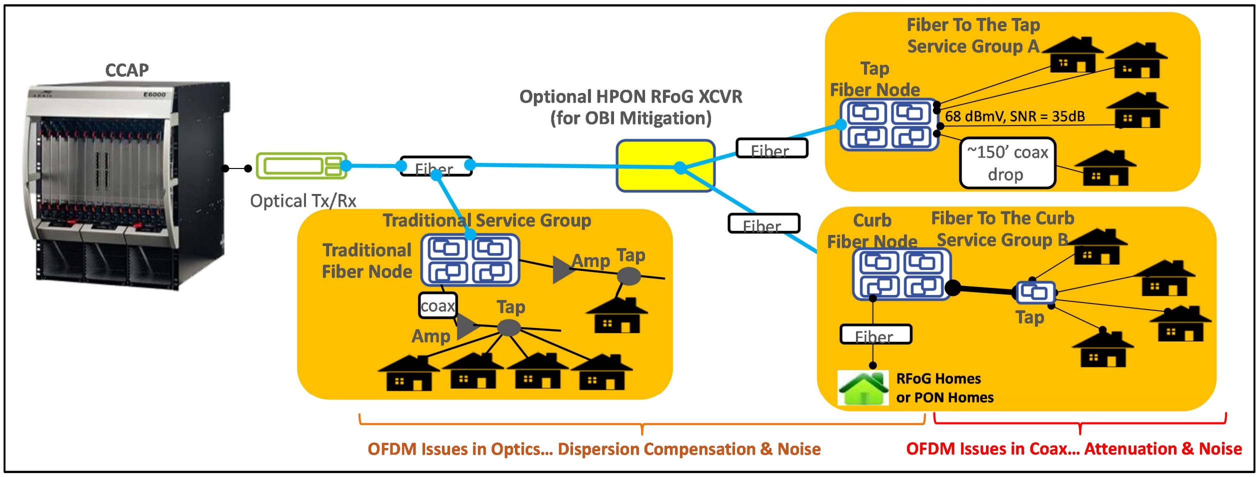

Figure 3. Extended-Spectrum DOCSIS (FTTT & FTTLA examples)

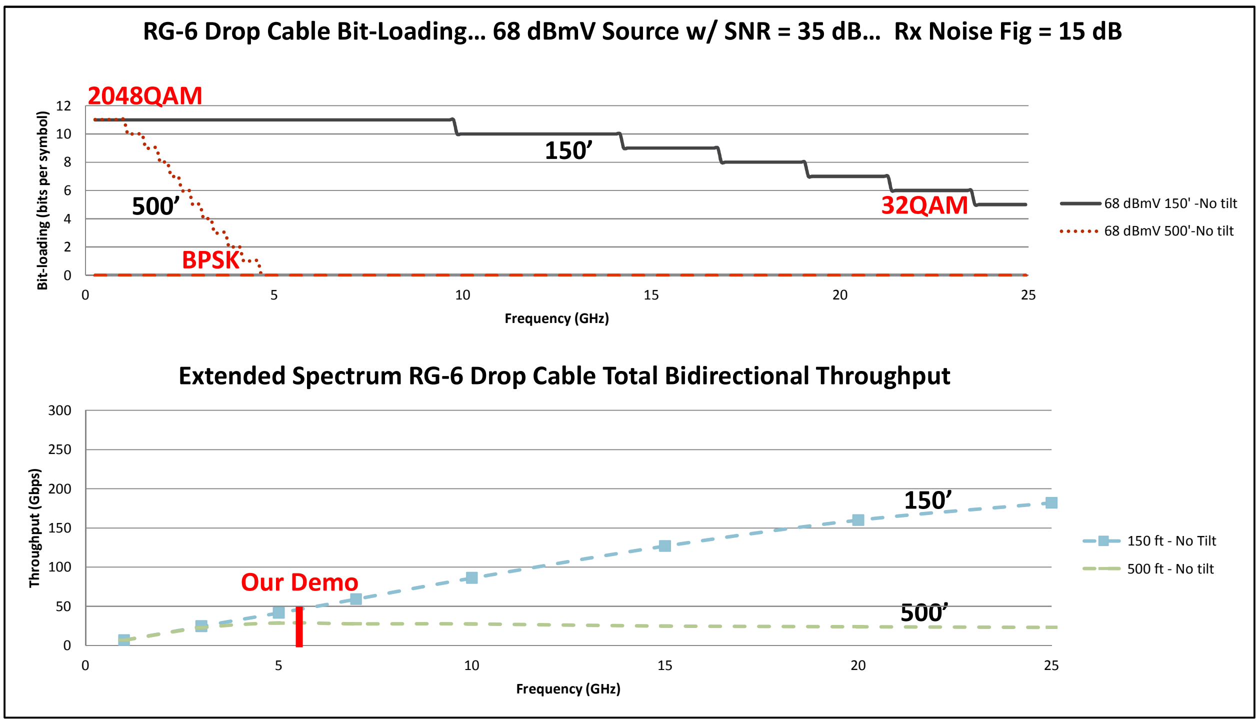

Figure 4. Extended-spectrum DOCSIS for the FTTT case: Modulation order decreases as frequency increases but total system capacity monotonically increases

Extending the spectrum to high frequencies will cause significant signal attenuation which causes a drop in the signal SNR. However, this can be accommodated by using lower order modulations at higher frequencies as shown in Fig. 4. Observe that while the modulation order drops as frequency increases, the total system capacity monotonically increases due to the expansion of the spectrum.

As for the Selective Subscriber Migration technology enabler, it refers to moving subscribers that require high peak rate service (and potentially heavy users) to a different topology like FTTH as shown in Fig. 5 [6]. This process significantly reduces the need to upgrade the network since the majority of the subscribers after the SSM process have moderate peak rates and reasonable consumption that can be accommodated by the existing network for a long period of time.

An example illustrating this concept is shown in Fig. 6, where the average throughput (Tavg) per subscriber in 2015 is assumed to be 600 kbps and the peak rate (Tmax) is 200 Mbps. According to the QoE formula [7] [8], the required capacity to support 500 subscribers is 520 Mbps (assuming k = 1.1). Ten years later (2025), Tavg and Tmax are assumed to be 35 Mbps and 11 Gbps, respectively, assuming 50% ACGR. The number of users is assumed to be 128 in 2025, which has dropped after multiple node splits. In this case, the total required capacity will be 16.6 Gbps. However, if only 1-2% of subscribers require high peak rates and they get moved to a different technology, then Tmax will likely be significantly less (e.g., 5 Gbps instead of 11 Gbps), which in turn drops the total required capacity to 10 Gbps (instead of 16.6 Gbps).

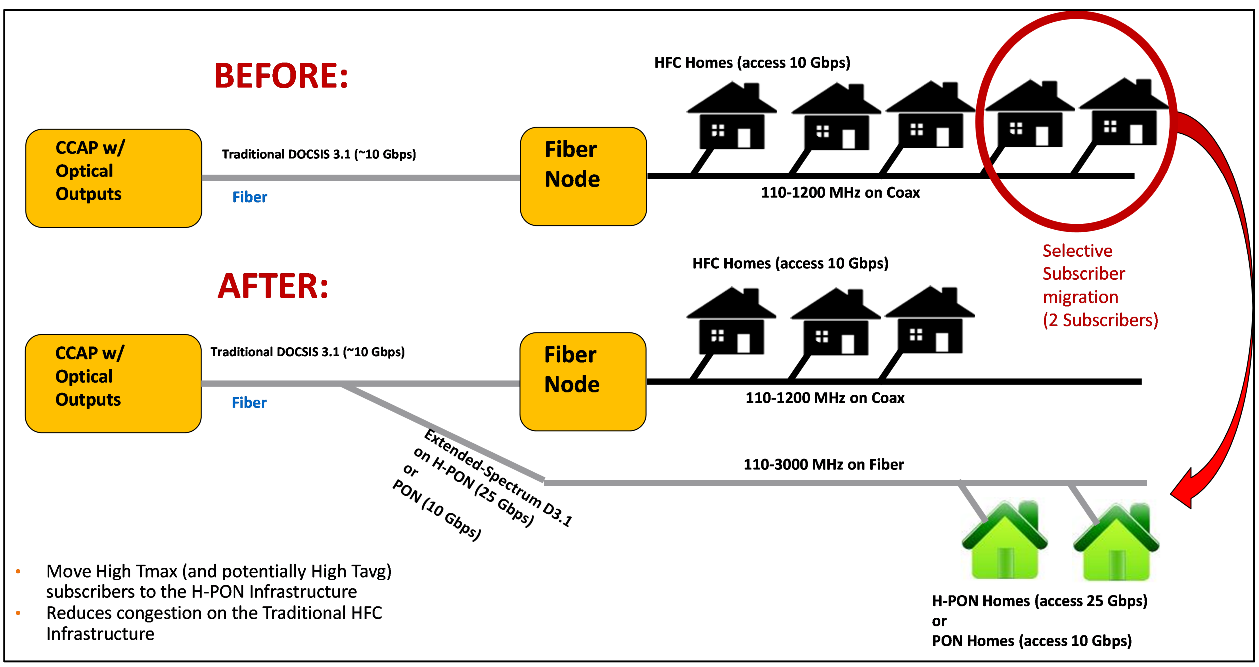

Figure 5. Selective Subscriber Migration
(moving high peak rate users to a different topology like FTTH)

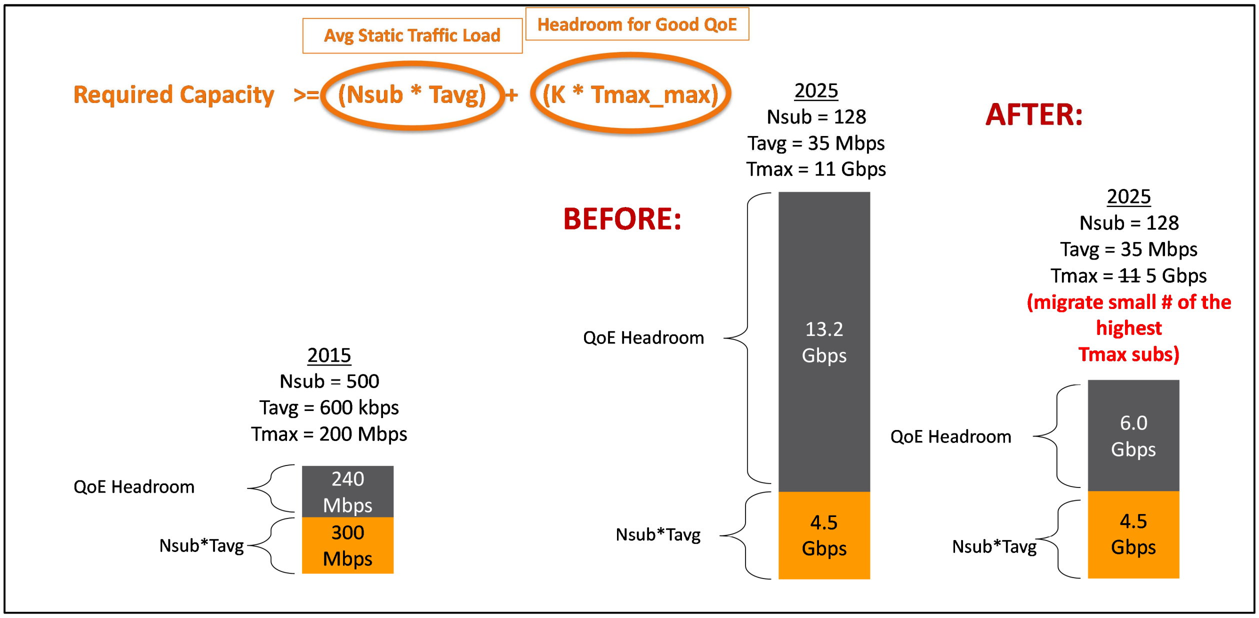

Figure 6. Selective subscriber migration extends the life of the existing network

The purpose of this paper is to develop a gradual network migration strategy that accommodates the traffic demand in a cost-effective manner using the various technology enablers listed above. It is believed that the best way to illustrate this methodology is via relevant and practical examples, which are based on real-world plant measurements and MSOs' particular plans for service offering. The analysis in this paper is based on collaboration between ARRIS and nbn that provided plant measurements as well as example service offering plans to be used in the analysis. While the results could be specific to nbn network, similar methodology can be applied by other MSOs networks through incorporating their own plant measurements and plans for service offering.

The paper is organized as follows: Section II analyses the potential DOCSIS 3.1 spectral efficiency gain based on measurements collected from the nbn network. In section III, traffic engineering and service offering plans are studied to understand how DOCSIS 3.1 can help in extending the life of the network. A methodology to use the different technology enablers for migration strategy is proposed in Section IV. Deployment scenarios specific to DOCSIS 3.1 are found in Section V. Section VI describes different example paths for the long term network migration, and finally, the paper is concluded in Section VII.

II. DOCSIS 3.1 SPECTRAL EFFICIENCY & CAPACITY ANALYSIS

MER measurements were collected and provided by nbn in order to perform the DOCSIS 3.1 analysis provided in this section. The histograms of the collected DS and US MER values are shown in Fig. 7 and Fig. 8, respectively.

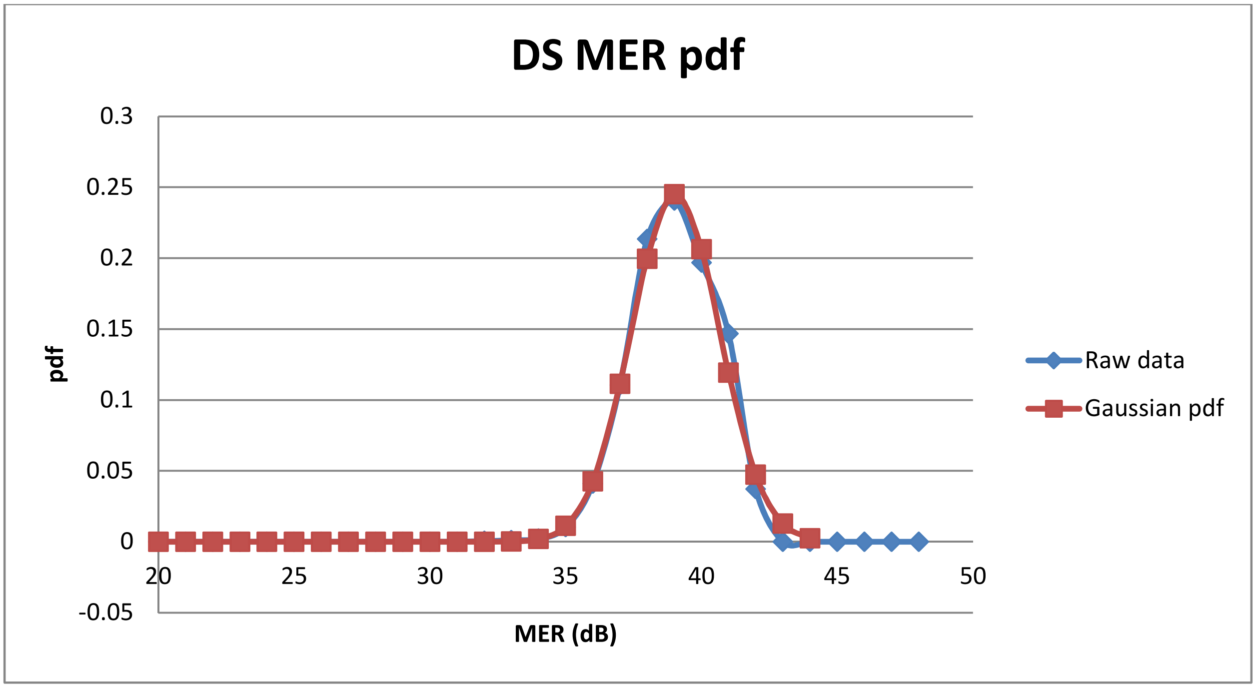

Figure 7. DS MER measurements collected on nbn network

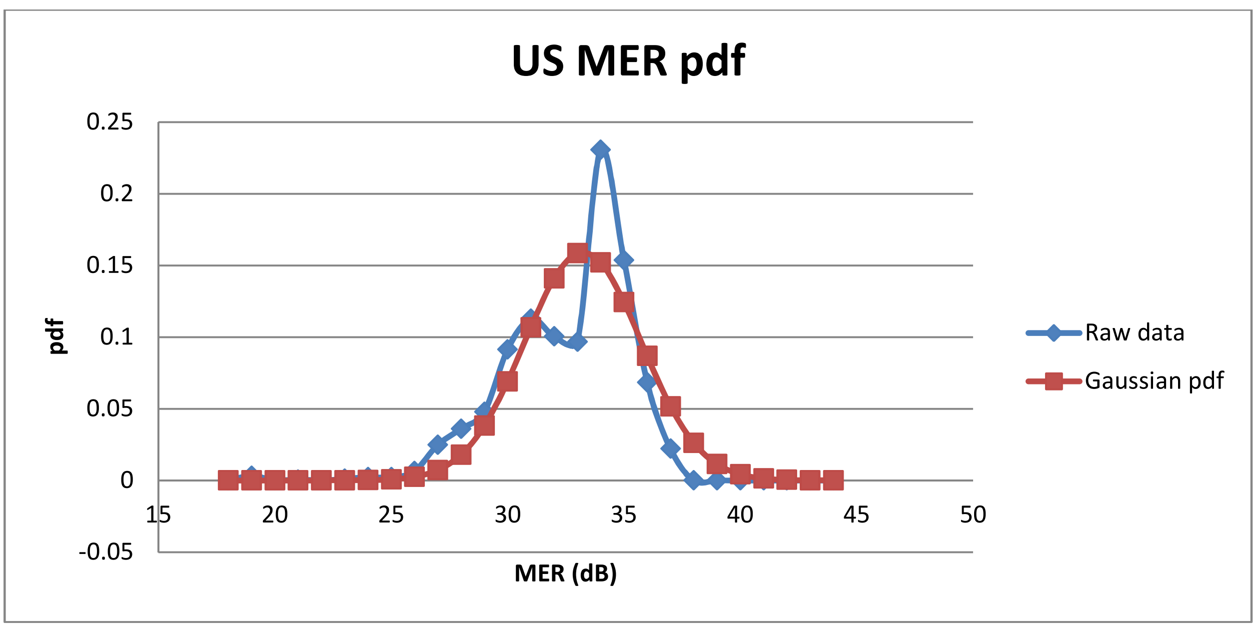

Figure 8. US MER measurements collected on nbn network

The spectral efficiency was analyzed following the same approach that was described in [1] [2] and using the same DOCSIS 3.0 and DOCSIS 3.1 parameters listed there. The DS spectral efficiency analysis for 0 dB and 2 dB MSO SNR operating margins are shown in Fig. 9 and Fig. 10, respectively. The DS spectral efficiency analysis results are summarized in Table 1 and Table 2. Similarly, the US spectral efficiency analysis is shown in Fig. 11 and Fig. 12, and is summarized in Table 3 and°Table°4.

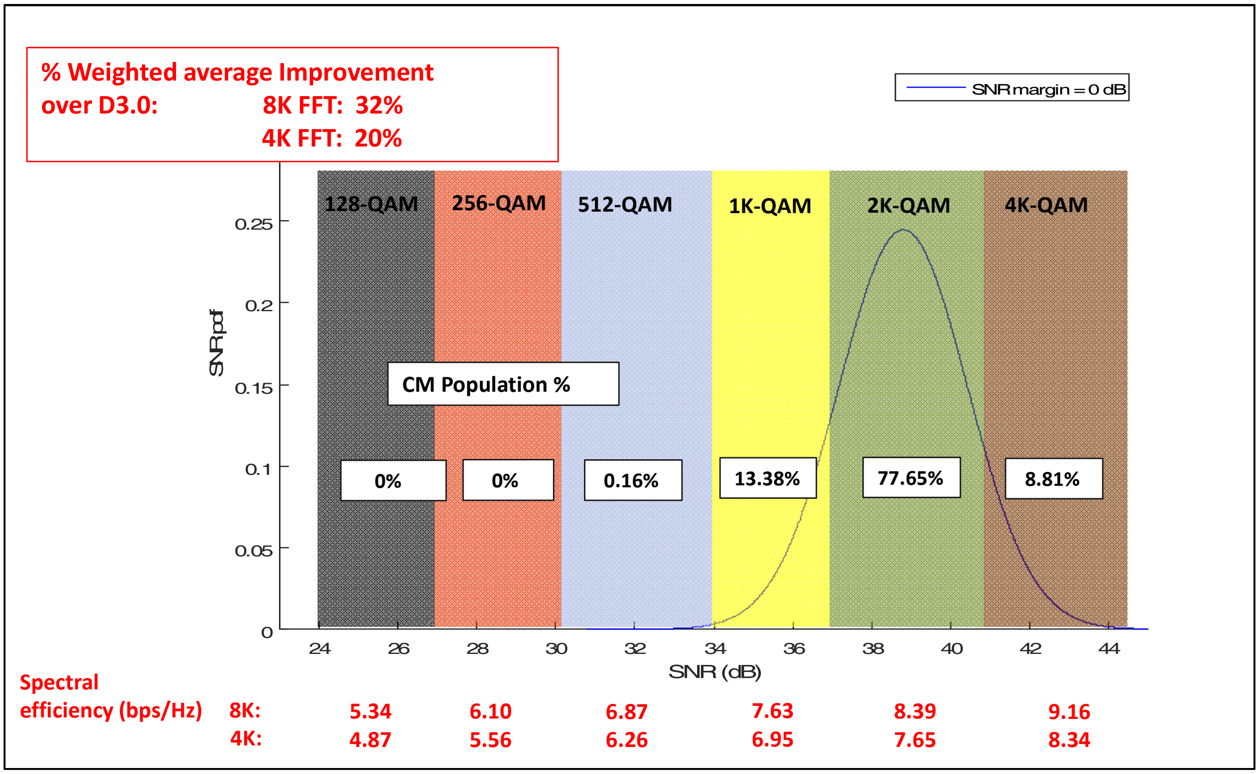

Figure 9. DS DOCSIS 3.1 Spectral efficiency analysis for 0 dB SNR operating margin

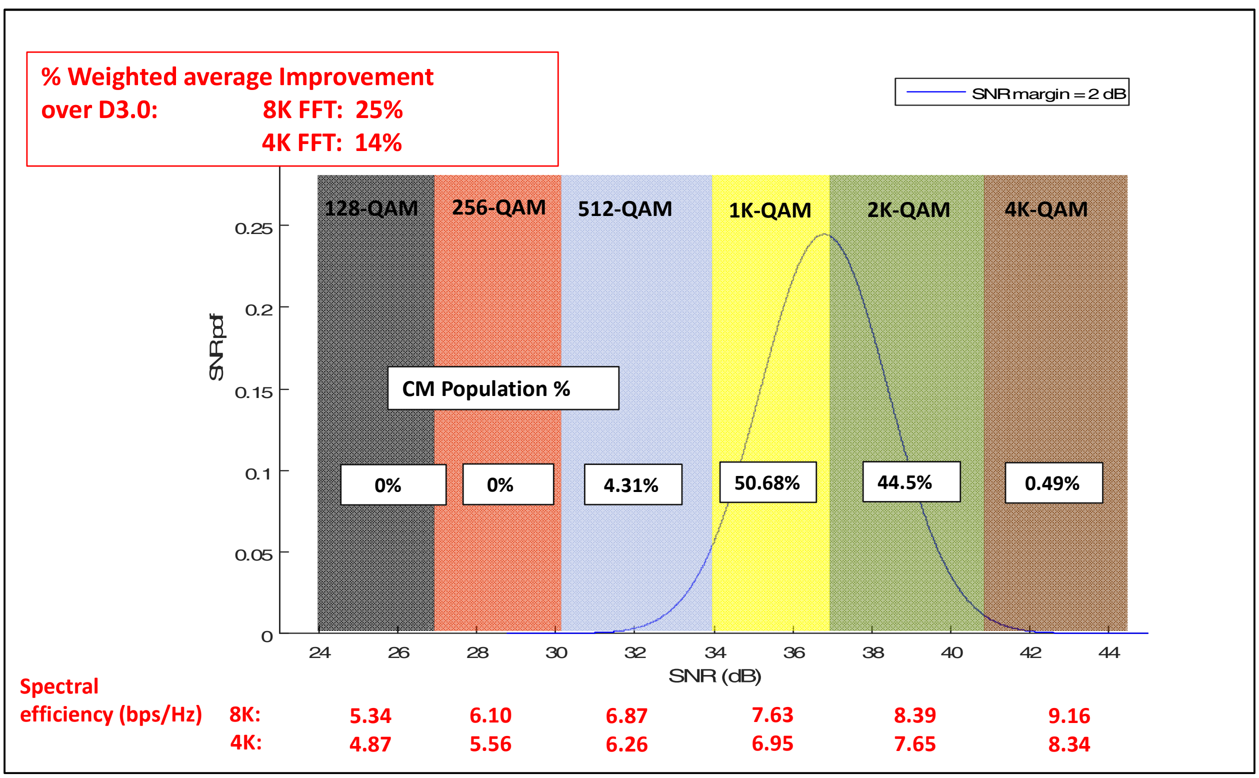

Figure 10. DS DOCSIS 3.1 Spectral efficiency analysis for 2 dB SNR operating margin

Table 1. DS DOCSIS 3.1 Spectral efficiency (bps/Hz) analysis summary

MSO SNR Operating Margin (dB)	4K FFT	8K FFT
0	7.61	8.36
1	7.44	8.16
2	7.24	7.94
3	7.02	7.70

Table 2. DS DOCSIS 3.1 Spectral efficiency gain summary

MSO SNR Operating Margin (dB)	4K FFT	8K FFT
0	20%	32%
1	17%	29%
2	14%	25%
3	11%	22%

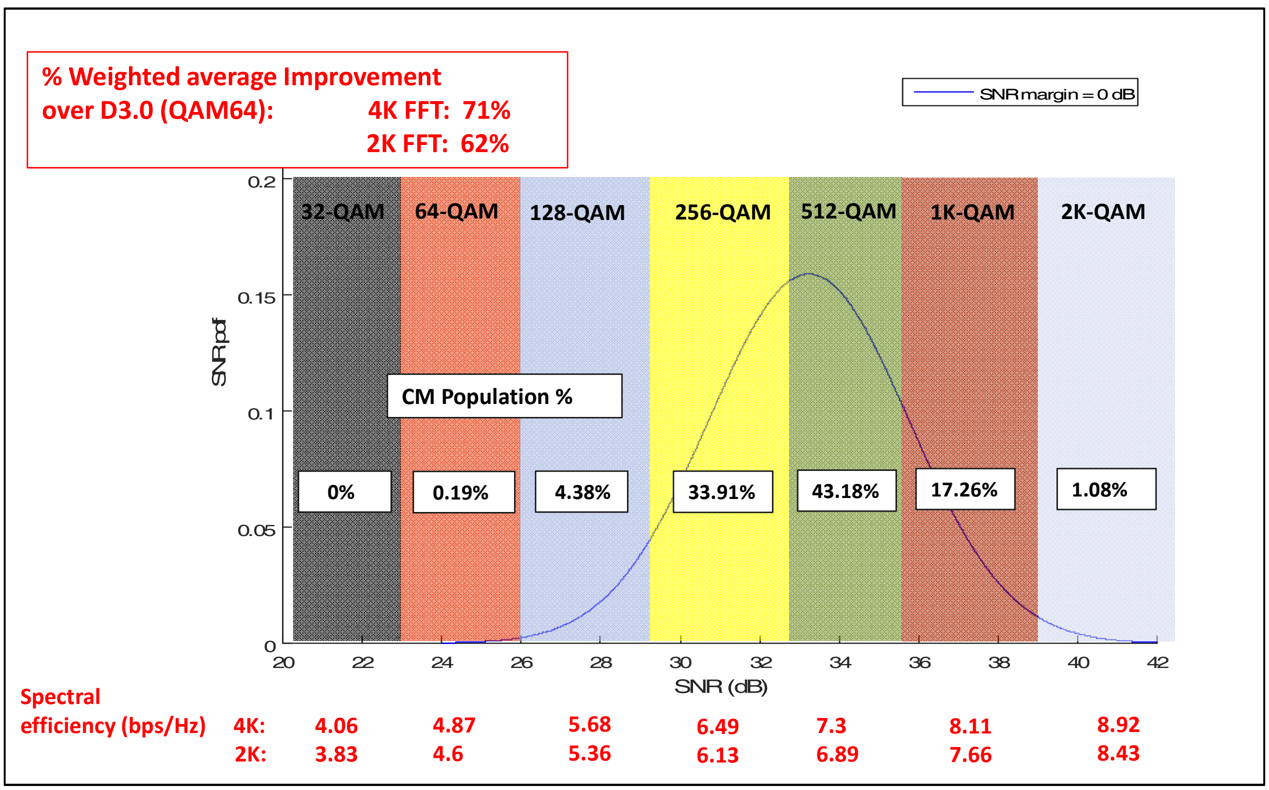

Figure 11. US DOCSIS 3.1 Spectral efficiency analysis for 0 dB SNR operating margin

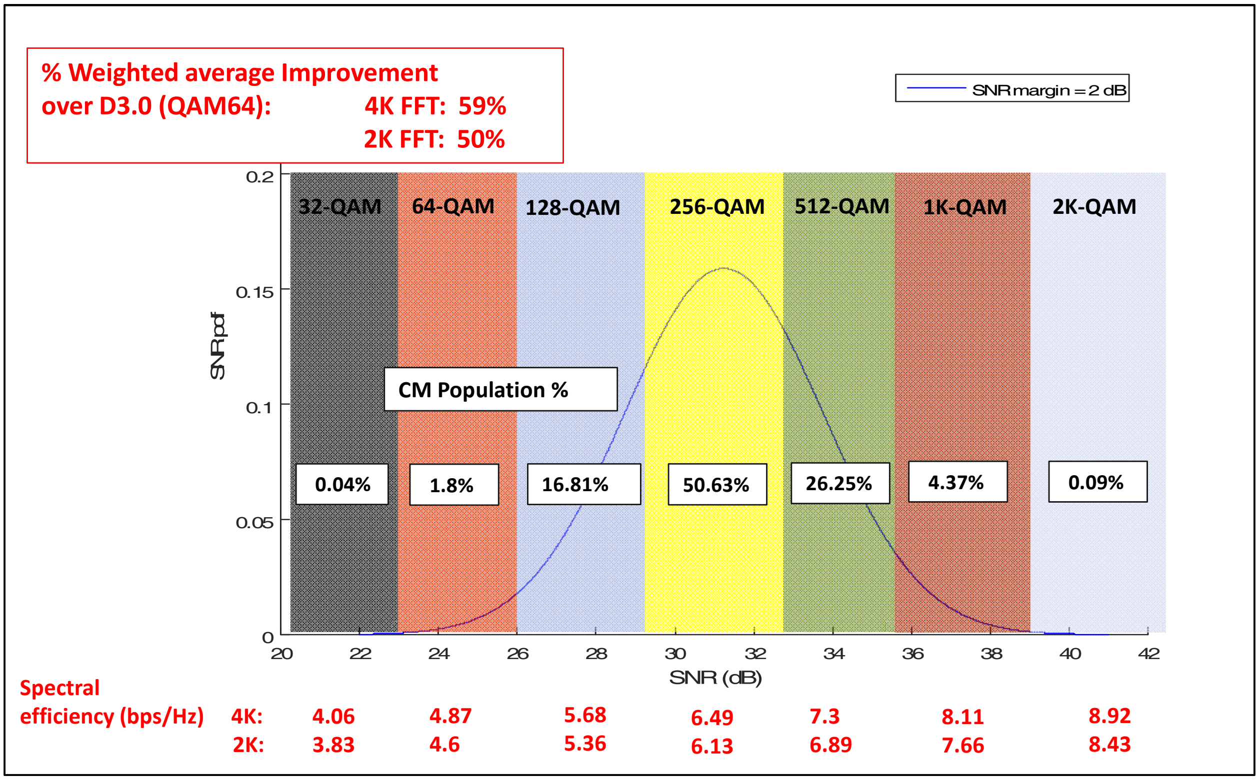

Figure 12. US DOCSIS 3.1 Spectral efficiency analysis for 2 dB SNR operating margin

Table 3. US DOCSIS 3.1 Spectral efficiency (bps/Hz) analysis summary

MSO SNR Operating Margin (dB)	2K FFT	4K FFT
0	6.71	7.11
1	6.48	6.86
2	6.24	6.61
3	6.01	6.36

Table 4. US DOCSIS 3.1 Spectral efficiency gain summary

MSO SNR Operating Margin (dB)	2K FFT	4K FFT
0	62%	71%
1	56%	65%
2	50%	59%
3	45%	53%

DS Capacity analysis was also performed to estimate the rough potential gain that DOCSIS 3.1 can offer. The nbn network is acquiring their infrastructure from two different operators (Optus and Telstra). Once nbn gets a specific network portion, they will offer their DOCSIS services in a coexistence phase with the old operator. This coexistence phase lasts for 18 months were both companies have to share the network infrastructure. Therefore, nbn will not have full access to the spectrum during the coexistence phase. The last coexistence phase will end in 2020. Note that coexistence phase implies that the available spectrum for nbn is limited. While this spectral restriction is particular to nbn network, lack of spectrum is an issue for MSOs in general due to many reasons including analog video channels, legacy DOCSIS channels, regulatory constraints, etc. Therefore, the analysis is applicable to other MSOs. The DS capacity analysis was done for both Optus and Telstra cases and is shown in Table 5. The DS capacities in Table 5 represent the estimated DOCSIS 3.0 and DOCSIS 3.1 capacities that can fit within the available spectrum for nbn assuming a DS DOCSIS 3.0 spectral efficiency of 6.33 bps/Hz and 7.94 bps/Hz spectral efficiency for DOCSIS 3.1 (assuming 2 dB MSO SNR operating margin and 8K FFT. Refer to Table 1 for details).

As for US capacities, similar analysis was performed with 4.15 bps/Hz DOCIS 3.0 spectral efficiency and 6.61 bps/Hz DOCSIS 3.1 spectral efficiency assuming 2 dB MSO SNR operating margin and 4K FFT size (refer to Table 3 for details). For the Optus case, during the coexistence phase, the available spectrum for nbn is 28.7 MHz where a large portion of it is in the noisy part of the spectrum leaving clean spectrum only enough for 3 6.4 MHz DOCSIS 3.0 channels. In the DOCSIS 3.1 case, it is assumed that the OFDMA signal is able to operate and utilize the whole 28.7 MHz spectrum. After coexistence, it is assumed that nbn can run up to 7 6.4 MHz DOCSIS channels in the 5-65 MHz for DOCSIS 3.0 but OFDMA is able to fully utilize the 60 MHz with DOCSIS 3.1. Similar assumptions are used for the Telstra case except for the coexistence phase where the available spectrum is 34.4 MHz where nbn can use 3 6.4 MHz and 1 3.2 MHz DOCSIS channels (instead of 3 6.4 MHz channels in the Optus case) due to access to larger portion of the spectrum during coexistence. The results are summarized in Table 6.

Table 5. DS Capacity gains offered by DOCSIS 3.1

DS Spectrum	D3.0 Gbps	D3.1 Gbps	Gain %
Optus Case			
Co-existence 134 – 198 MHz [8 8 MHz channels]	0.41	0.51	25.4
Post Co-existence [32 8 MHz channels]	1.62	2.03	
Telstra Case			
Co-existence (291-355) + (498-562) MHz [16 8 MHz channels]	0.81	1.02	25.4
Post Co-existence (291-419) + (434-562) MHz [32 8 MHz channels]	1.62	2.03	

Table 6. US Capacity gains offered by DOCSIS 3.1

US Spectrum	D3.0 Gbps	D3.1 Gbps	Gain %
Optus Case			
Co-existence 43 – 63 MHz	0.08	0.19	138
Post Co-existence 5 – 65 MHz	0.19	0.40	113
Telstra Case			
Co-existence 5 - 39.4 MHz	0.09	0.23	145
Post Co-existence 5 – 65 MHz	0.19	0.40	113

III. HOW CAN DOCSIS 3.1 HELP?

In order to show how DOCSIS 3.1 can help in the transition for MSOs, we consider the nbn application. While the numerical results in this section could only be applicable to nbn, the methodology is applicable to any MSO network in general. nbn is faced with several challenges as they acquire new infrastructure from the other operators. These challenges include large number of HHP per node, which could be as high as 1580 in the Optus network. Other challenges are also attributed to the lack of spectrum due to the limited access to the spectrum during the coexistence period, when both nbn and other operator have to share the available spectrum. Finally, the subscriber demand continues to grow!

In order to satisfy the traffic demand generated by the large number of HHP per node via the limited available spectrum, node splits is considered as a potential solution. However, performing large number of node split operations can be challenging for multiple reasons including cost which is affected by the number of nodes that increases exponentially after each node split operation. Another challenge is the availability of large number of trained workers that can perform the required number of node splits operations within the required time frame such that the traffic demand is met. It should be noted that the node split operation can only help in cases where the capacity of the network is not enough to support the average throughput of the users during busy hour. This is because the node split operation reduces the number of subscribers per service group.

On the other hand, node splits cannot help when the network capacity is not enough to support very high peak rates (Tmax), which is significantly higher than the average subscriber rate during busy hour (Tavg). To illustrate this point, consider a hypothetical scenario where a network has two subscribers with DS Tmax of 200 Mbps and DS network capacity of only 150 Mbps; performing a node split that yields one user per service group will not help because the network capacity of 150 Mbps is still not adequate to support a single user with Tmax of 200 Mbps. Note that deploying DOCSIS 3.1 can use the limited spectrum more efficiently and therefore increase the network capacity in a given spectrum portion, which can be helpful in meeting the demand during busy hour as well as offering high peak rates.

This section presents some traffic engineering analyses and shows how DOCSIS 3.1 can be used to delay and reduce the required number of node split operations as well as avoiding them altogether in some cases. This can be very beneficial especially during the coexistence phase that was referenced above when the available spectrum is very limited.

The traffic engineering analyses are based on input from nbn which was obtained via collecting subscriber statistics and providing nbn's vision regarding potential tier speeds that need to be supported in the next few years. The traffic engineering assumptions are listed in Table 7 for both Optus and Telstra networks. Note that the parameters and plans are mostly the same for both networks except for the number of HHP per node which will affect the results significantly. Table 8 provides the take rate assumptions as well as the calculated number of subscribers which were used in the analysis.

Table 7. Traffic engineering assumptions

Details	Parameters	Optus	Telstra
Downstream Maximum Throughput in 2015	DS Tmax (Mbps)	100	100
Downstream Average Throughput in 2015	DS Tavg (Mbps)	0.3	0.3
Upstream Maximum Throughput in 2015	US Tmax (Mbps)	40	40
Upstream average Throughput in 2015	US Tavg (Mbps)	0.06	0.06
Downstream Compound Annual Growth Rate for Tmax	DS CAGR for Tmax	0%	0%
Upstream Compound Annual Growth Rate for Tmax	US CAGR for Tmax	0%	0%
Downstream Compound Annual Growth Rate for Tavg	DS CAGR for Tavg	23%	23%
Upstream Compound Annual Growth Rate for Tavg	US CAGR for Tavg	23%	23%
Household passed per node	HHP	1580	850

Table 8. Projected take rates and corresponding numbers of subscribers

YEAR	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
Take rate	0.1	0.15	0.35	0.54	0.66	0.74	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75
Number of users Telstra	85	127.5	297.5	459	561	629	637.5	637.5	637.5	637.5	637.5	637.5	637.5	637.5	637.5	637.5
Number of Users Optus	158	237	553	853.2	1043	1169	1185	1185	1185	1185	1185	1185	1185	1185	1185	1185

The total system capacity required to support the number of subscribers with the specified Tmax and measured Tavg values is calculated via the QoE formula that was described earlier and provided here again for convenience [7] [8]

C = (Nsub x Tavg) + (K x Tmax),

where

- C -Required bandwidth capacity for a particular service group
- Nsub -Number of subscriber in the service group
- Tmax -Highest peak rate offered to subscribers
- Tavg -Average busy hour per subscriber bandwidth consumption
- K -QoE factor (assumed to be 1.1 for the analysis)

Observe that the first part of the formula compensates for the average traffic load whereas the second part relates to the headroom needed to support the peak rate such that good QoE service is provided to all subscribers. The required DS and US capacities for the Optus network are shown in Fig. 13 and Fig. 14, respectively. The available network capacity corresponding to different phases (refer to Table 5) are also illustrated on figures. For convenience, the available DS capacity numbers from Table 5 are provided here: the DS D3.0 capacity during coexistence phase is 0.41 Gbps, the DS D3.1 capacity during coexistence phase is 0.51 Gbps, and the DS D3.1 capacity after coexistence phase is 2.03 Gbps. Similarly, the US network capacity numbers are obtained from Table 6, where the US D3.0 capacity is 0.08 Gbps during coexistence phase, the US D3.1 capacity during coexistence phase is 0.19 Gbps, and the US D3.1 capacity after coexistence phase is 0.4 Gbps.

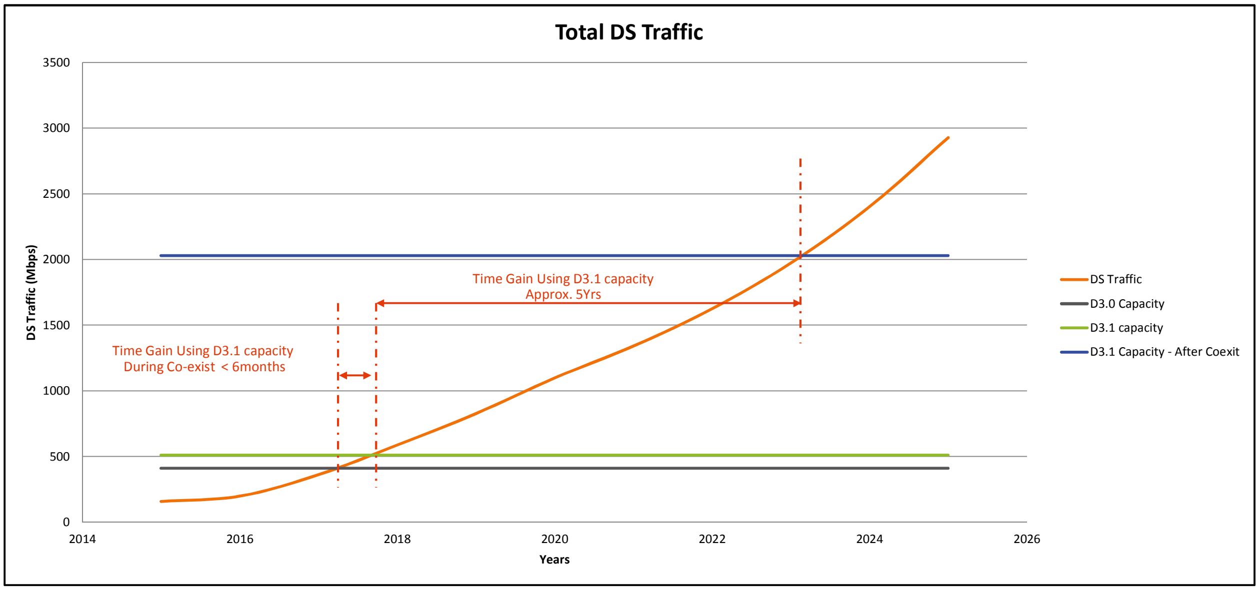

Figure 13. DS traffic demand and network capacity alternatives for Optus networks

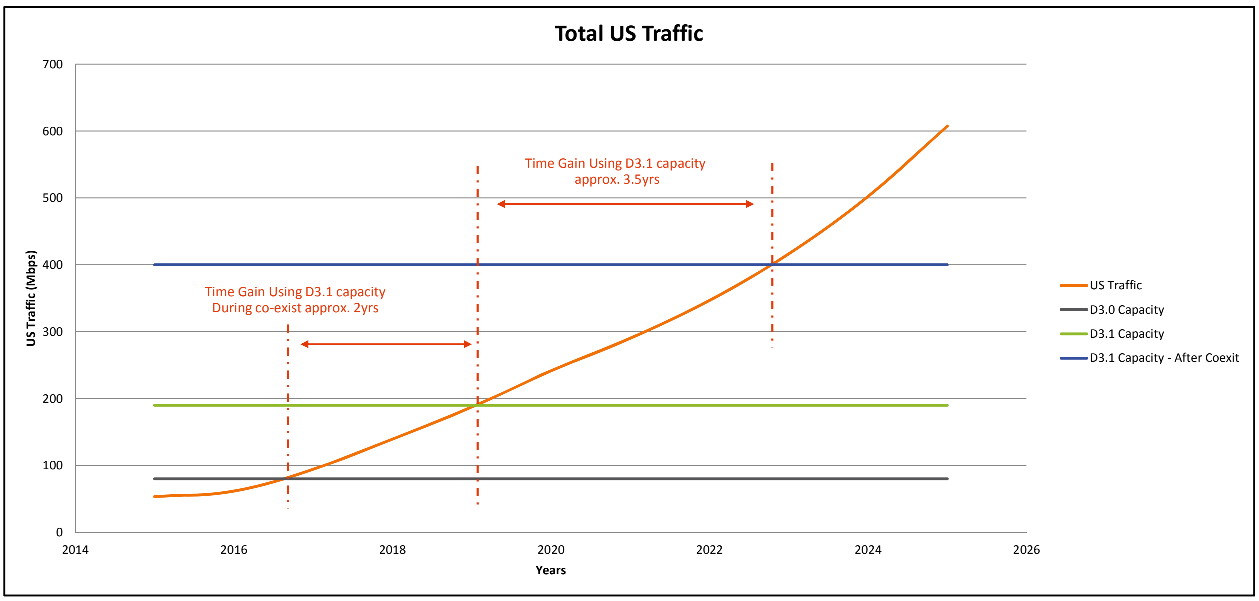

Figure 14. US traffic demand and network capacity alternatives for Optus networks

The results in Fig. 13 show the network capacity when DOCSIS 3.0 is deployed will be exhausted in 2017. Moreover, during the coexistence phase in 2017 to 2018 time frame, deploying DOCSIS 3.1 delays the need to perform node splits by 6 months. Although this may not look significant, it is definitely beneficial given that the coexistence phase lasts only for 18 months. The analysis in Fig. 13 suggests that it is important to start the coexistence phase early for as many nodes as possible to capitalize on the low amounts of DS traffic and which will lead to an early finish of the coexistence phase leading to more available spectrum which translates to significant DS capacities using DOCSIS 3.1. In this case, the amount of additional capacity that DOCSIS 3.1 can offer when full access to the spectrum is available is significantly higher than the capacity that DOCSIS 3.1 can offer with the limited spectrum during the coexistence phase. The difference is worth approximately 5 years!

As for the US, the findings in Fig. 14 suggest that the US traffic demand may trigger a node split in 2016 (i.e., earlier than the DS) if DOCSIS 3.0 is used. However, if DOCSIS 3.1 is used, the US traffic would present less pressure to perform node splits than the DS did. In particular, deploying DOCSIS 3.1 in the US can delay the need for node splits by about 2 years which is beyond the coexistence phase. After the coexistence phase, more spectrum is available and therefore the available US capacity using DOCSIS 3.1 is significant (i.e., worth an additional 3.5 years after the end of coexistence phase).

Similar analysis was performed for the Telstra network and the required DS and US capacity results are shown in in Fig. 15 and Fig. 16, respectively. Observe that the network capacity numbers for the DS and US were obtained from Table 5 and Table 6 as was done earlier with the Optus analysis. Note that the pressure to perform node splits in the Telstra network is significantly less than that in the Optus case because of smaller number of HHP per node.

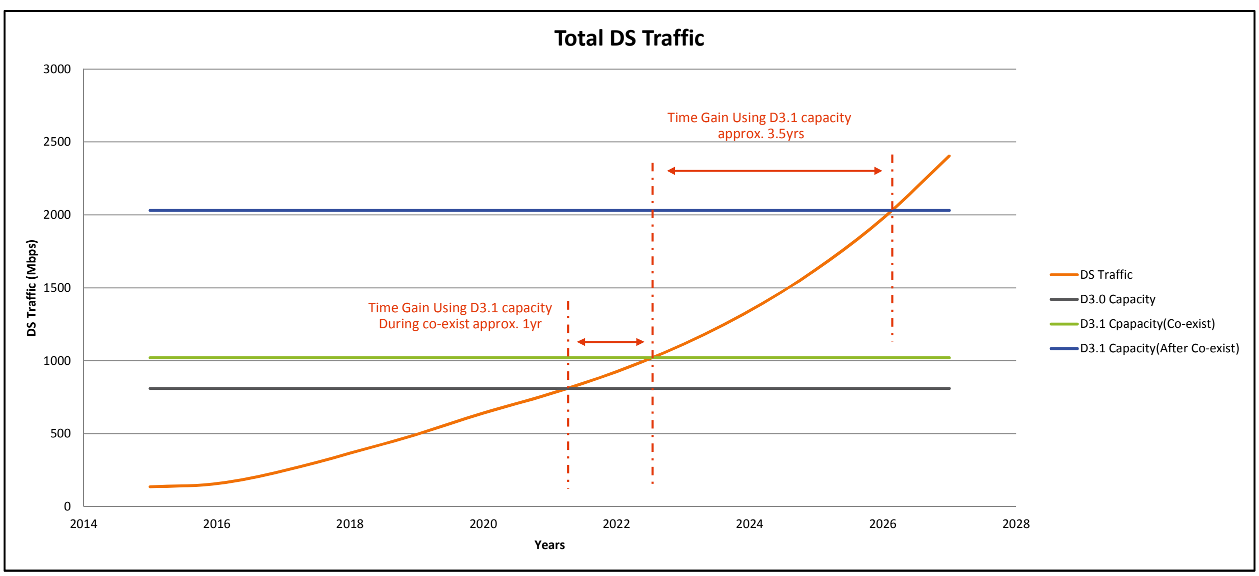

Figure 15. DS traffic demand and network capacity alternatives for Telstra networks

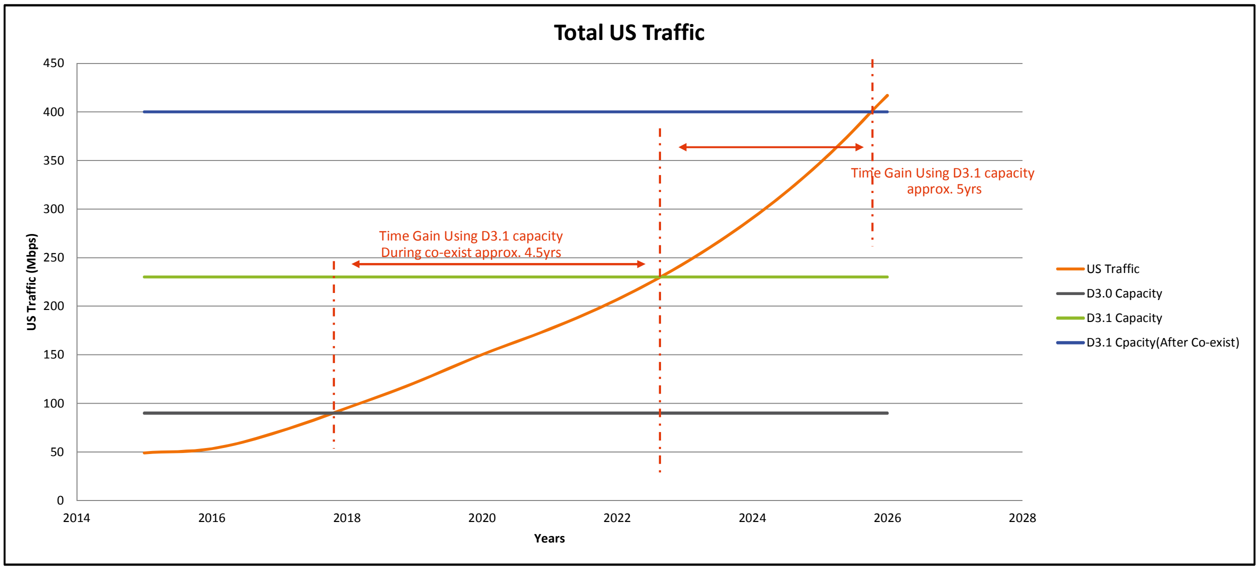

Figure 16. US traffic demand and network capacity alternatives for Telstra networks

<u>HHP Sensitivity Analysis</u>

While Optus and Telstra networks had only one difference in the analysis assumptions which was the HHP per node parameter, they had very different results in terms of the value of DOCSIS 3.1 in regard to the number and timing of node splits operations. Therefore, more analyses were performed corresponding to different HHP per node scenarios, where same assumptions as before were used for the other parameters. The DS and US results are illustrated in Fig. 17 and Fig. 18, respectively. Observe that these figures also contain the throughput curves corresponding to the Optus and Telstra networks.

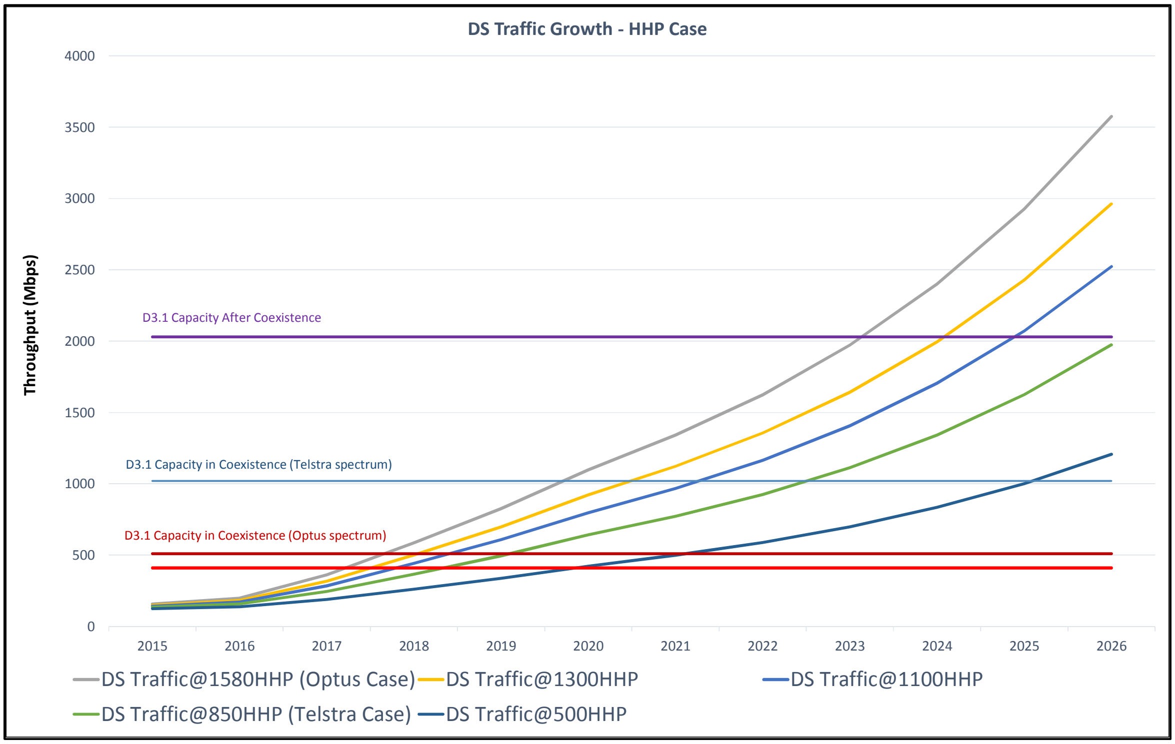

Figure 17. HHP per node sensitivity analysis for DS capacity

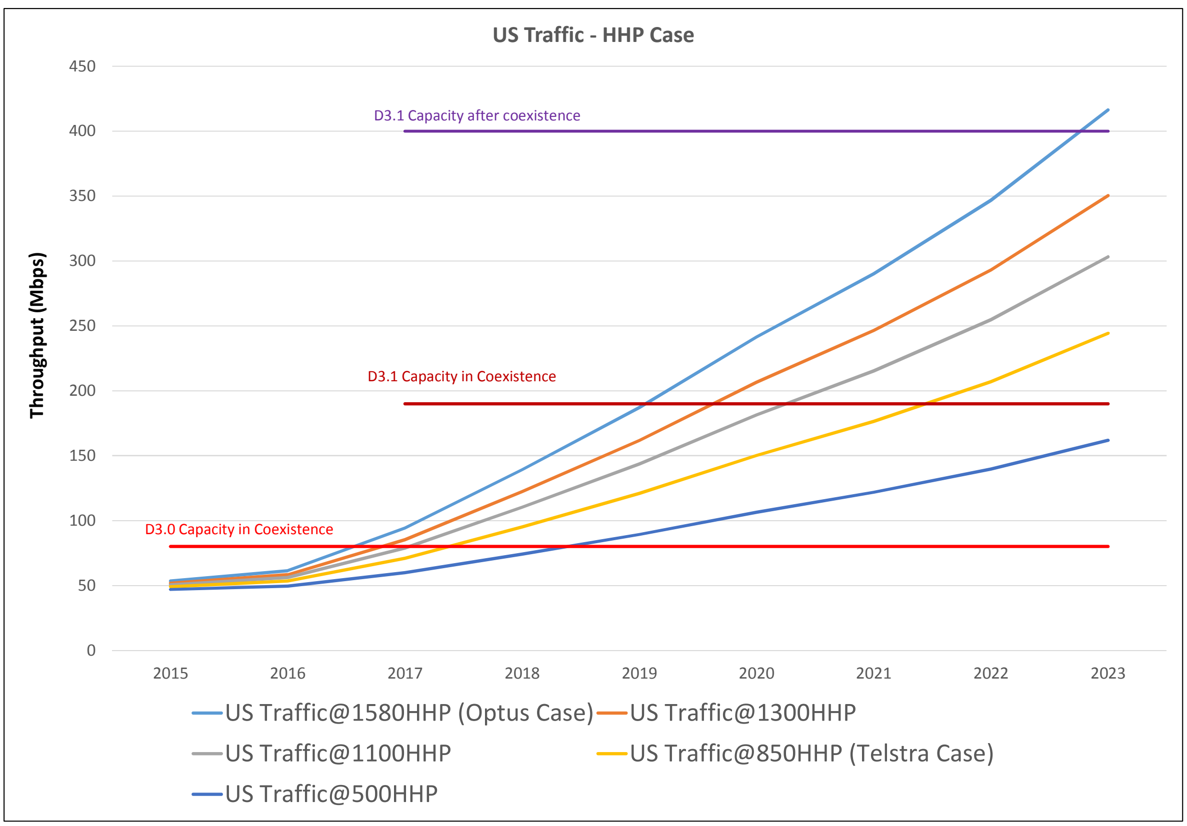

Figure 18. HHP per node sensitivity analysis for US capacity

The analysis that was presented thus far in this section assumed a CAGR of 0% for the DS and US Tmax. In other words, it is assumed that the highest DS and US peak rates will stay at 100 Mbps and 40 Mbps, respectively, for a few years. This may appear to be an unrealistic assumption. However, if the selective subscriber migration strategy is used to accommodate the highest tier subscribers, most other subscribers will likely stay satisfied with the peak rates specified above. Also, the analysis was mostly concerning the near future where studying the effect of DOCSIS 3.1 in reducing the required number of node splits is critical and therefore those rates appeared adequate to nbn for the next few years. Having said this, the analyses presented above were regenerated using 25% CAGR for both US and DS and the results are shown in Fig. 19 and Fig. 20, respectively.

It should be noted that the analysis approach described here can be used for any assumption made by the MSOs. It is actually very possible that each of the MSOs will have their own set of assumptions that fits their networks, subscribers, service offering plans, etc. Those assumptions can be applied to the methodology presented here in order to estimate the value that DOCSIS 3.1 can bring to their network.

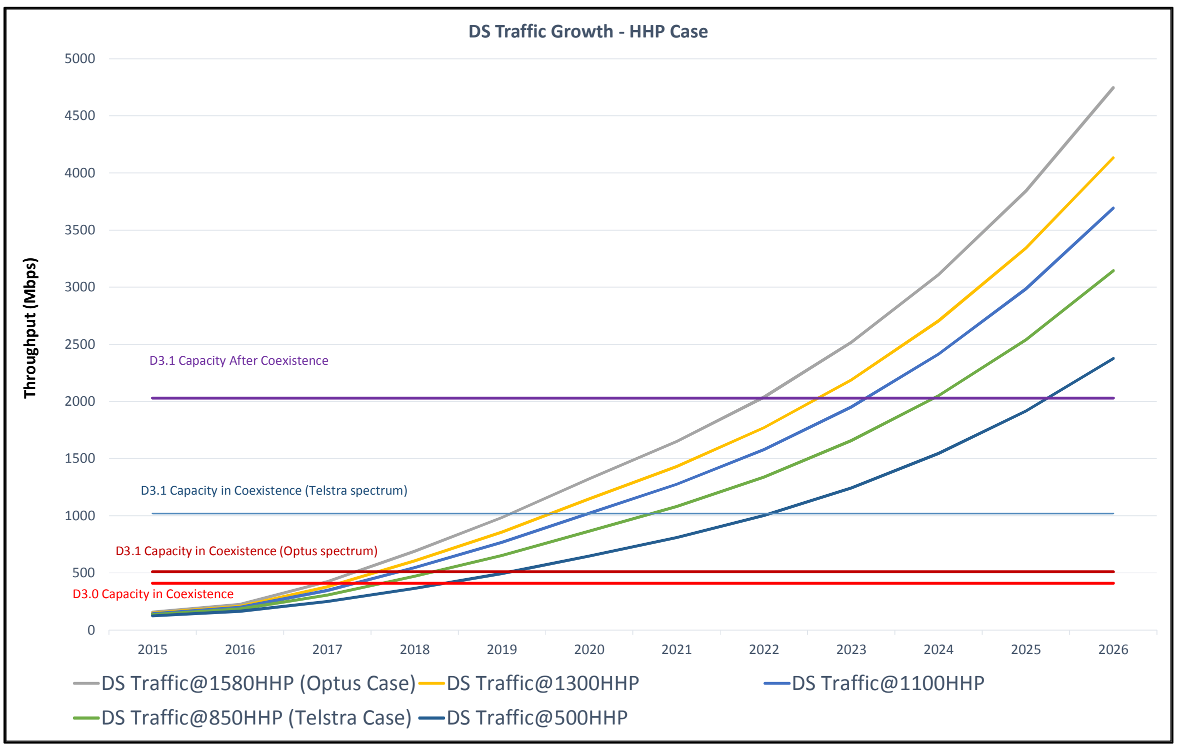

Figure 19. HHP per node sensitivity analysis for DS capacity (DS Tmax CAGR = 25%)

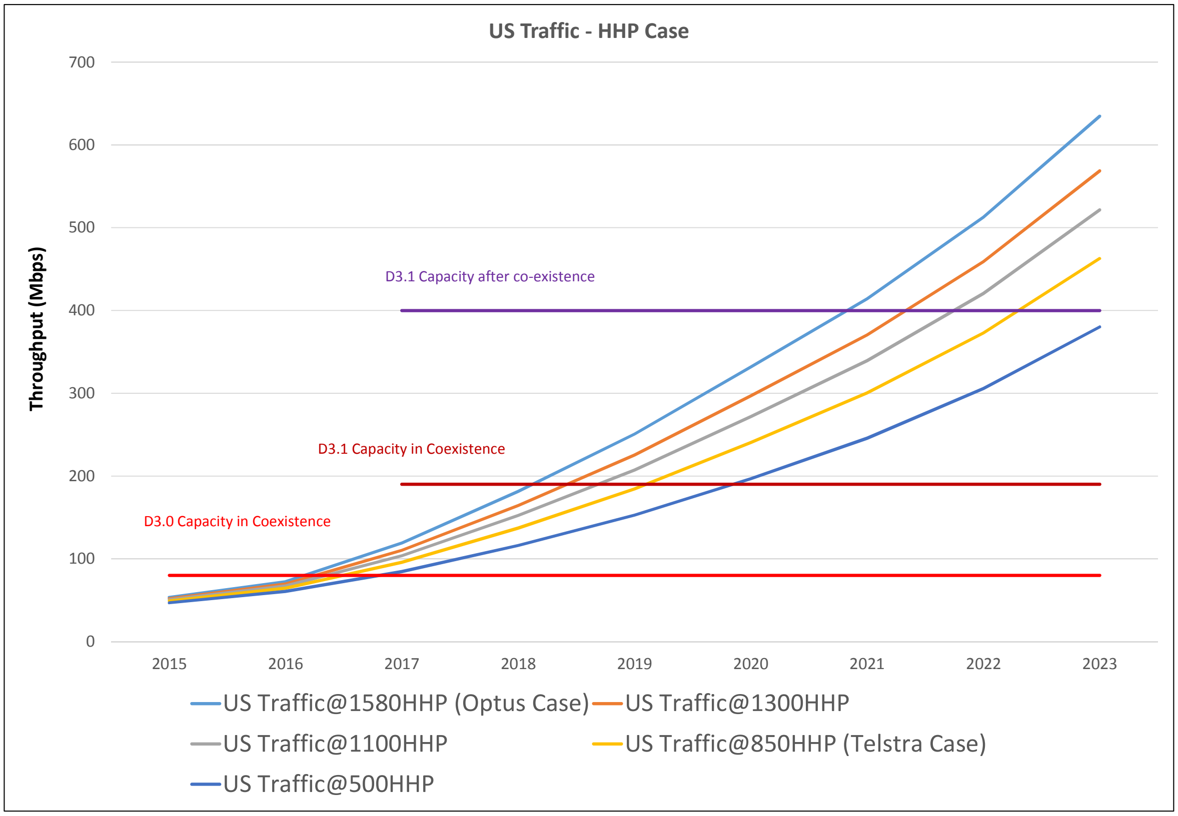

Figure 20. HHP per node sensitivity analysis for US capacity (US Tmax CAGR = 25%)

IV. HOW TO PROCEED WITH NETWORK MIGRATION?

The analysis in the previous section showed that DOCSIS 3.1 is an excellent tool that is available for the MSOs to extend their network capacities, reduce number of required node splits, and meet the offered traffic demand using existing infrastructure. As described in Section I, DOCSIS 3.1 is actually one of many tools that are available for the MSOs to choose from. These tools include node splitting & segmentation, selective subscriber migration, HFC vs. FTTH, RFoG vs. PON for FTTH, DAA vs centralized, etc. The optimal choice depends on the network parameters, offered demand and statistical distribution of subscribers among services, and MSO's restrictions (e.g., logistics/operational/resources constraints, infrastructure, budget, etc.). Therefore, a solution that perfectly works for one MSO may not be optimal for another MSO!

This section proposes a methodology that can be beneficial in selecting the appropriate near term transition path. Later in Section VI of this paper, multiple long term transition examples are described. For the near term transition paths, Fig. 21 illustrates a decision tree that can be considered when making a decision in response to a bandwidth problem. The decision state flow diagram starts when the network available capacity is not enough to meet the desired demand and/or address the competition. When that situation occurs, the decision state flow diagram proposes that the insufficient bandwidth issue is thoroughly understood before taking any actions because there is no one particular solution that fixes all problems. There are different solutions to different problems!

For instance, at high level, the network capacity can be deemed inadequate for two different reasons: The first scenario is when the network capacity is not enough to enable offering the high peak rate (Tmax) service which is required to address competition or to satisfy business customers and super users; The second scenario is when the network capacity not enough to accommodate the traffic demand offered during busy hours (Nsub*Tavg).

For the first scenario, when the network capacity is not adequate to offer high Tmax values, there are multiple solutions. For instance, DOCSIS 3.1 can be deployed, if not already, to get an instant boost in the network capacity without changing the outside plant. Observe that deploying DOCSIS 3.1 in the DS assumes that spectrum is available for DOCSIS 3.1 and CMTS/CMs that support DOCSIS 3.1 are available. If DOCSIS 3.1 is already deployed and the capacity is still not enough, there are two potential solutions:

1. Selective subscriber migration (via FTTH).

2. Plant upgrades (change split, deeper fiber, new equipment with support for larger spectrum, etc.).

It is important to study the cost as well as the logistic/operational complexity of performing selective subscriber migration vs. plant upgrades. For instance, if the number of business customers/super users is small and the cost/logistics of upgrading their paths to FTTH is manageable, then upgrading those portions of the network selectively and leaving the larger portion of the network untouched could be the best option. This not only allows satisfying business customers/super users by moving them to their own network infrastructure, it also alleviates the traffic and high peak rate service demand on the rest of the network; which in turn elongates the life of the network at minimum cost.

On the other hand, if the MSO decides the number of business customers/super users is large or the likelihood of the penetration percentage for that service is high, then it may makes sense to upgrade the whole network all at once. This case study needs to be performed for every portion of the network where this decision needs to be made because one decision for one portion of the network may not be appropriate for another portion.

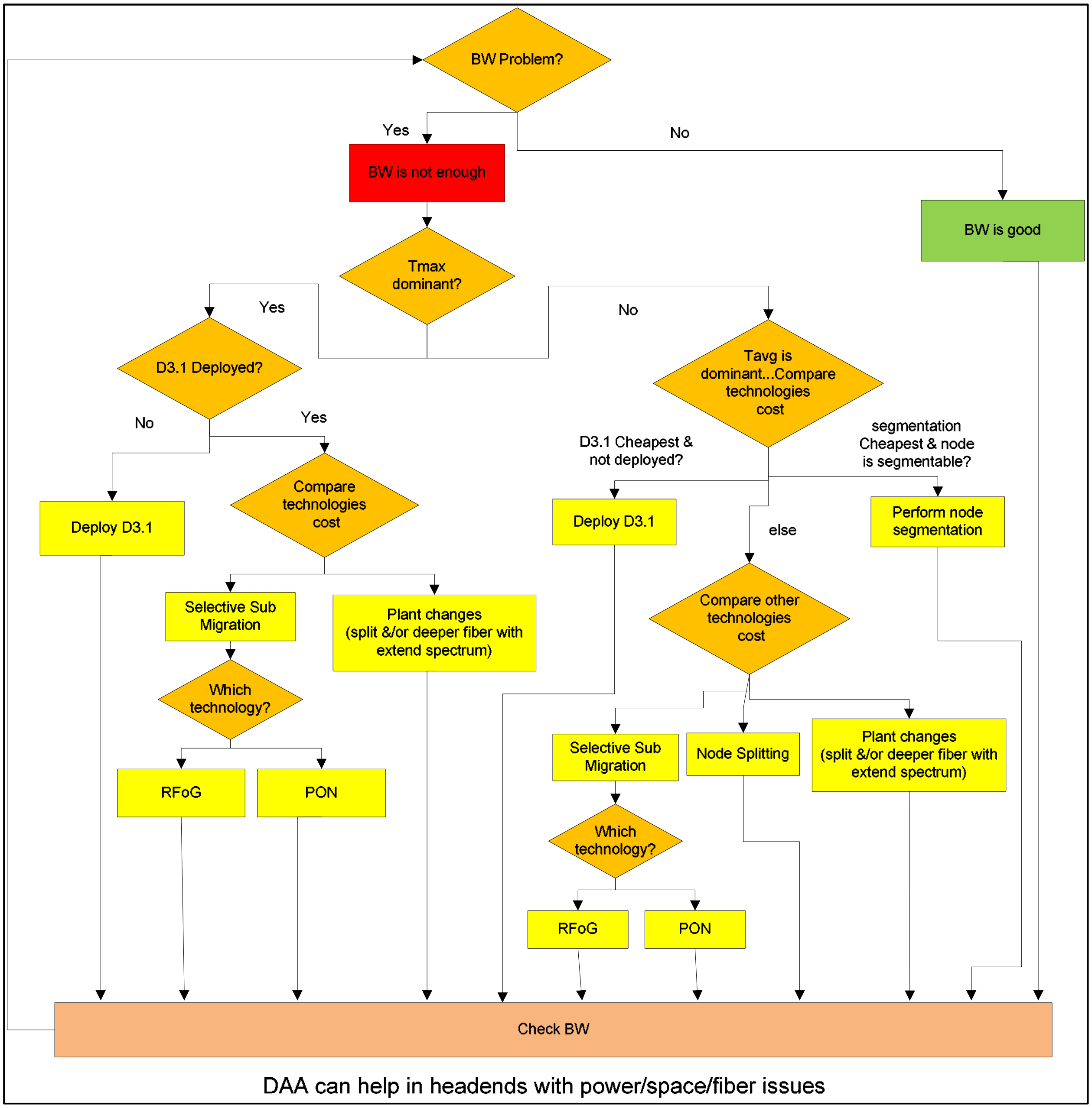

Figure 21. Proposed state flow diagram to make a decision in a response to a bandwidth problem

If the MSO decides that selective subscriber migration is more adequate than full plant upgrade, then there will be two alternatives for signal transmission and resource allocation for the FTTH infrastructure: RFoG and PON. The RFoG approach has multiple benefits such as:

1. There currently exist OBI-free solutions.
2. OBI-free solutions allow for multiple US transmissions and therefore uses the system capacity more efficiently.
3. OBI-free solutions can work with any CMTS and CM without any modification.
4. Works with any DOCSIS version including DOCSIS 3.1.

5. Can support future DOCSIS features like extended spectrum DOCSIS [5] [6] and full duplex DOCSIS [5] [9].

6. Reuses same back-office systems, CMTSs, CMs, and therefore protects the MSO's investment.

While RFoG has many advantages as described above, some MSOs may still select PON as their transition step if they believe it better fits their long term plans. Both approaches have their own pluses and minuses as discussed in other papers [10] [11]. The topic of comparing these technologies against each other is outside the scope of this paper, which mainly focuses on proposing the decision tree.

Regarding the second scenario where the network capacity is not adequate to accommodate the traffic offered during busy hours, different solutions are required. In particular, when that situation occurs, the MSO may have to select from the two options below after studying the cost of deployment and operational implications:

1. Deploying DOCSIS 3.1

2. Node Segmentations

Observe that the two options listed above are relatively cheap because they do not require immediate plant upgrades. DOCSIS 3.1 can offer an instant boost to the network capacity over the existing infrastructure and node segmentation can reduce the number of subscribers per service group and therefore increase the available capacity per subscriber. Note that node segmentation does not require changes to the physical plant if the node design is segmentable.

If the MSO has already deployed DOCSIS 3.1 and segmented the node (if segmentable), and the available capacity is still not adequate, then the MSO can further advance in the decision process and select from one of the following solutions:

1. Node splitting

2. Selective subscriber migration (via FTTH)

3. Plant upgrades (change split, deeper fiber, new equipment with support for larger spectrum, etc.)

All of the above approaches require physical changes to the plant. Therefore, a detailed business case study needs to be performed in order to select the most appropriate option which can offer the longest plant life at minimum cost. Again, part of this process is to decide whether to use RFoG or PON if selective subscriber migration or FTTH infrastructure is chosen as the appropriate solution.

Finally, the decision tree assumed that DAA network architectures can be beneficial in addressing headend power/space issues as well as the limited number of wavelengths that are supported by the AM optics. Since the capacity gain from transitioning to DAA networks can be limited depending on the network parameters and/or the TDHM bottle neck, increasing the network capacity was not assumed to be a key driver for the MSO to move to DAA network architecture.

V. DEPLOYMENT OF DOCSIS 3.1

The previous section provided a proposed decision tree that can be considered when decisions are needed to perform near term transitions to the existing network when the available capacity is not enough. One of the available tools in the decision tree was the deployment of DOCSIS 3.1. This section provides more insight regarding DOCSIS 3.1 deployment due to its importance as multiple MSOs are currently thinking of or have already started migrating to DOCSIS 3.1.

As implied in the previous section, deployment of DOCSIS 3.1 does not have to be done across the whole network at once. It can be done as needed and where needed. Once DOCSIS 3.1 has been selected as the appropriate next step for the node or service area, then it can be deployed gradually as the functionality is verified via lab trials, field trials with friendly customers, and finally using production offering.

The first question that comes to mind when thinking of DOCSIS 3.1 deployment is how to come up with spectrum for DOCSIS 3.1 channels. The answer could be different for the DS and US directions. For the DS, the MSO can reclaim spectrum via:

1. Phasing out analog channels

2. Use IPTV for video delivery

3. Use more efficient encoding schemes for video

4. Use of switched digital video

5. Transfer spectrum between services (e.g., MPEG VoD to DOCSIS)

Beyond spectrum reclamation, other alternatives can be utilized. These include:

1. Turning off some of the legacy SC-QAM channels and assigning the spectrum to DOCSIS 3.1 (especially if heavy and super users are moved to DOCSIS 3.1, i.e., selective subscriber migration to DOCSIS 3.1 is performed).

2. Us of the top part of the spectrum that could be noisy and interference-prone for DOCSIS 3.0 operation but could be usable by DOCSIS 3.1.

3. Use of roll off spectrum which can be utilized by using DOCSIS 3.1 features such as Multiple Modulation Profiles (MMP) and Variable BitLoading (VBL).

The DOCSIS 3.1 DS channel does not have to be 192 MHz wide. It could be smaller [12]. A small portion of the spectrum assigned to DOCSIS 3.1 can still be beneficial because DOCSIS 3.1 CMs can receive bonded traffic over OFDM and legacy SC-QAM channels. As spectrum is secured for DOCSIS 3.1 channels, the MSO can simply add the OFDM channel to the DOCSIS 3.1 CM's Receive Channel Set (RCS) and use the OFDM channel.

If a small number of CMs experience issues in locking to the OFDM channel, those will still be connected to legacy channels and trouble-shooting can be performed without affecting the subscribers' service. If a large number of DOCSIS 3.1 modems experience issues with the OFDM signal, the MSO may choose to turn off that signal all together and get to the bottom of the issue before putting the OFDM channel back in service.

As for the US, several techniques can be utilized to secure spectrum for OFDMA channels. These include:

1. Use of DOCSIS 3.1 Time and Frequency Division (TaFD) multiplexing to share the US spectrum between legacy and OFDMA channels. This feature allows dynamic allocation of US spectrum to SC-QAM and OFDMA as needed. That is, the same part of the spectrum can sometimes be used for SC-QAM and some other times used for OFDMA [13]. This feature can be beneficial when no or little spectrum is available for OFDMA channels.

2. Use of the lower and/or top part of the spectrum that could be noisy and interference-prone for DOCSIS 3.0 operation but could be usable by DOCSIS 3.1 OFDMA channels.

3. Use of roll off spectrum which can be utilized by utilizing DOCSIS 3.1 features such as Multiple Modulation Profiles (MMP) and Variable BitLoading (VBL).

4. Turning off some of the existing legacy SC-QAM channels and assigning the spectrum to DOCSIS 3.1 (especially if heavy and super users are moved to DOCSIS 3.1 OFDMA channel, i.e., selective subscriber migration to DOCSIS 3.1 is performed).

If, for any reason, the CM is not able to range and register on an OFDMA channel, it will likely try SC-QAM channels. Therefore, the CM will probably not be completely offline due to issues with an OFDMA channel. After registration, there are two scenarios:

1. If SC-QAM and OFDMA channels do not overlap and/or the TaFD feature is not available (i.e., they overlap but exclusions within the OFDMA channels are used to accommodate SC-QAM channels), then the traffic from the SC-QAM and OFDMA channels can be bonded together. That is, the Transmit Channel Set (TCS) of the CM will contain OFDMA and SC-QAM channels that are bonded together. In this case, if the OFDMA channel gets impaired, the traffic gets scheduled on the SC-QAM channels (i.e., partial service).

2. If the TaFD feature is used, then a slightly different approach can occur. There are two cases:

   a. The TCS of the CM contains only an OFDMA channel that services the SF of the CM. If the CM experiences issues with the OFDMA channel, it will likely reset and tries to range on the available SC-QAM channels.

   b. The TCS of the CM contains an OFDMA channel plus one or more SC-QAM channels that act as backup to the OFDMA channel in case of a failure. For normal operation, the traffic is scheduled on the OFDMA channel only. If the OFDMA channel gets impaired, then the CMTS schedules grants on the SC-QAM channels. This operation does not require a modem reset. Observe that the CMTS can add more SC-QAM channels via the DBC operation if needed.

VI. LONG TERM NETWORK MIGRATION

As MSOs plan their long term migration, they can take different approaches in reaching their end goal architecture. In particular, they can take one of the following evolution approaches:

1. Gradual evolution

2. Large-step evolution

3. Very large-step evolution

Different scenarios illustrating examples of the various approaches listed above are provided in Fig. 22 to Fig. 25. While only a few examples are shown, many alternatives can be envisioned. This paper encourages a gradual approach for network migration to capitalize on the investment protection and perform upgrades only where and when needed. This methodology was presented via the analyses and decision state flow diagram in Sections III and IV, respectively. Observe that the decision state flow diagram presented earlier can be considered as the MSO takes gradual transition steps leading to the end goal network architecture.

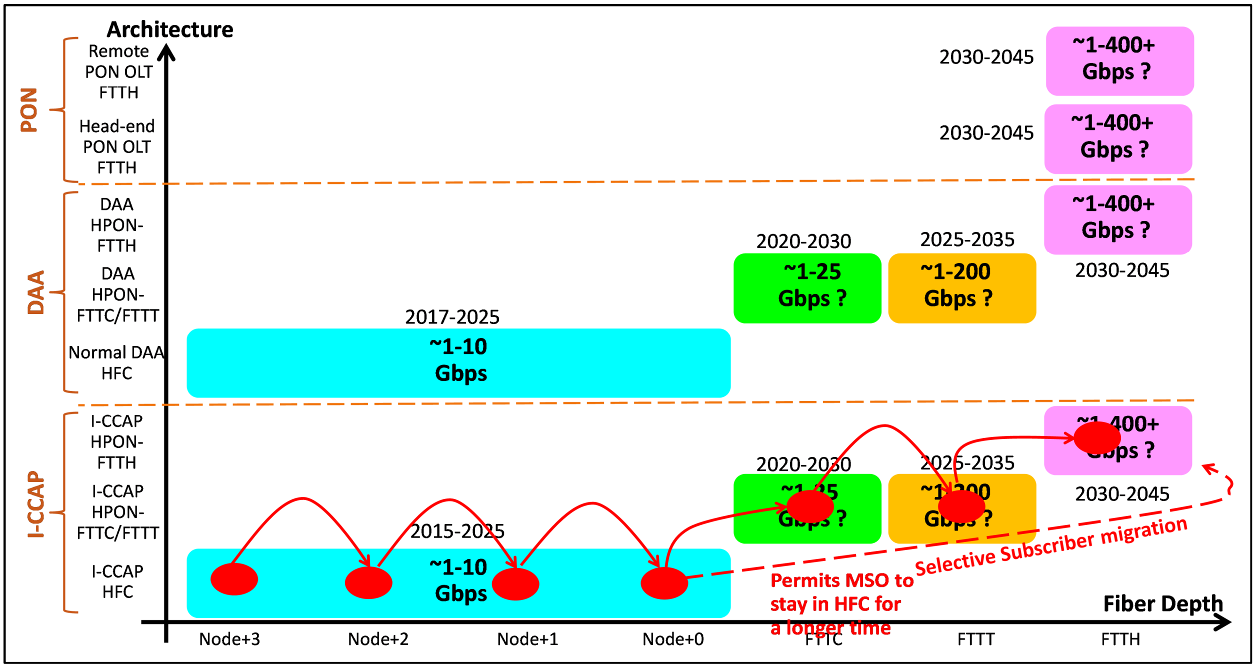

Figure 22. Example of gradual migration strategy – Scenario 1.

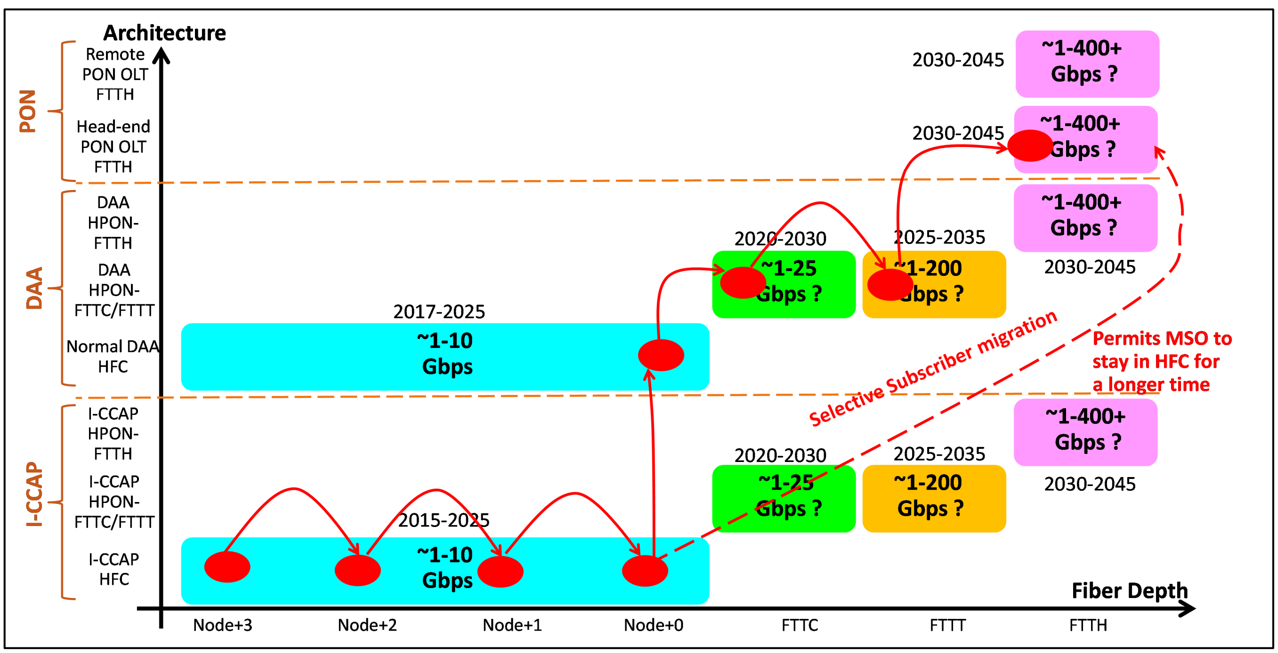

Figure 23. Example of gradual migration strategy – Scenario 2.

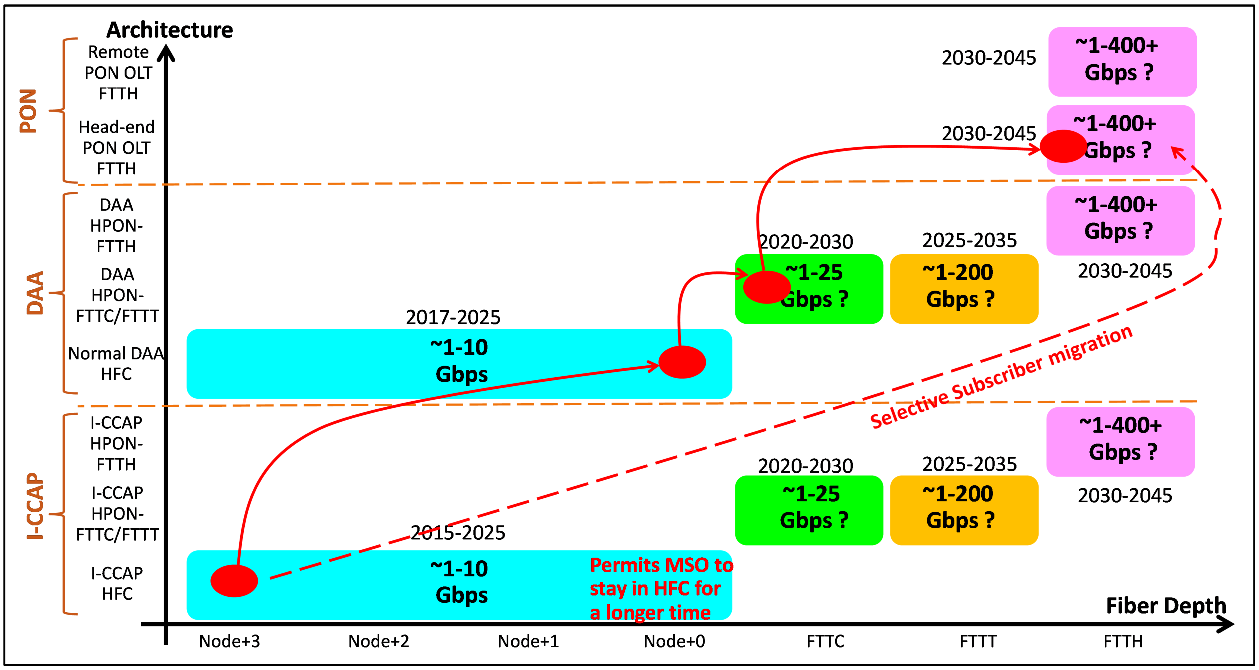

Figure 24. Example of large-step migration strategy.

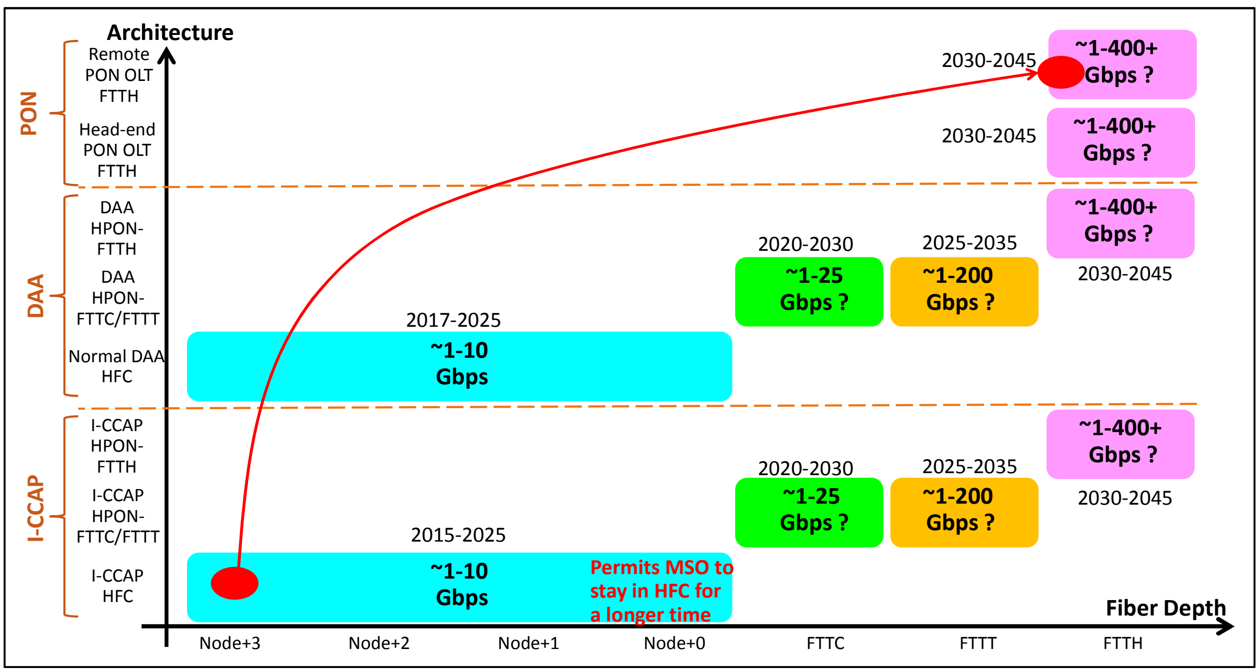

Figure 25. Example of very large-step migration strategy.

VII. CONCLUSIONS

The article analyzed the value of DOCSIS 3.1 in increasing the network capacity and reducing the OPEX costs. Based on real-world scenarios, it was shown that deploying DOCSIS 3.1 can delay node-split operations needed to address inadequate DS capacity by 6 months to 1 year. As for the US, DOCSIS 3.1 deployment can delay node split operations to address inadequate US capacity by 2-4.5 years. The article described different technology enablers including DOCSIS 3.1, node splits/segmentation/selective subscriber migration, plant upgrades, RFoG vs. PON, DAA vs. I-CCAP. A decision tree state flow diagram was proposed to select the appropriate combination of the above technology enablers to form an optimal near term transition path. Finally, the paper described the network migration process to DOCSIS 3.1 in the DS & US directions and also showed different long term network migration scenarios.

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ABBREVIATIONS & ACRONYMS

CAGR	Cumulative Annual Growth Rate
CM	Cable Modem
CMTS	Cable Modem Termination System
DAA	Distributed Access Architecture
DOCSIS	Data Over Cable Service Interface Specifications
DS	Downstream
FTTLA	Fiber To The Last Active
FTTC	Fiber To The Curb
FTTH	Fiber To The Home
FTTT	Fiber To The Tap
HFC	Hybrid Fiber Coax
H-PON	Hybrid PON
I-CCAP	Integrated-Converged Cable Access Platform
IPTV	Internet Protocol Television
MER	Modulation Error Ratio
MMP	Multiple Modulation Profiles
MPEG	Moving Picture Experts Group
MSO	Multiple System Operators
OBI	Optical Beat Interference
OFDM	Orthogonal Frequency Division Multiplexing
OFDMA	Orthogonal Frequency Division Multiple Access
OPEX	Operational Expenses
pdf	Probability density function
PON	Passive Optical Network
QoE	Quality of Experience
RCS	Receive Channel Set
RFoG	Radio Frequency over Glass
SC-QAM	Single Carrier-Quadrature Amplitude Modulation
SNR	Signal to Noise Ratio
SSM	Selective Subscriber Migration
TaFD	Time and Frequency Division Multiplexing
Tavg	Average Throughput per subscriber during busy hour
TCS	Transmit Channel Set
TDHM	Tap, Drop, Home network, Modem
Tmax	Highest peak rate
US	Upstream
VBL	Variable Bit Loading
VoD	Video on Demand