When Does the DOCSIS 3.1 TaFD Feature Increase the Capacity of My Network?

A Technical Paper prepared for SCTE/ISBE by

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Abstract

The traffic engineering benefits of the TaFD feature of OFDMA channels are evaluated for different network scenarios based on real-world assumptions & measurements from a network operator. MSOs are looking at this feature as a potential savior for symmetrical service offering. It will be shown that deploying the TaFD feature may or may not benefit the overall capacities of HFC networks depending on the network assumptions and conditions. The specific conditions will need to be studied and analyzed to decide whether TaFD adds value or not. Migration alternatives are proposed for cases where a symmetrical service offering is desired but TaFD may not help..

1. Introduction

As MSOs start planning the deployment of DOCSIS 3.1 in the US direction to increase US capacities, they wonder whether the DOCSIS 3.1 Time and Frequency Division (TaFD) Multiplexing feature will yield increased network capacities. Part of the challenge is that MSOs are trying to increase their peak rate service offering without increasing the size of the US spectrum due to the prohibitive cost and operational complexity of changing the split across the whole network. Therefore, they look to the TaFD feature as a promising solution to help them address the customer demand and competitors that offer faster services. While previous work [1] showed the advantages of the TaFD when compared to other US scheduling schemes, this article focuses more on analyzing the value of the TaFD feature from a capacity gain viewpoint given real world network scenarios.

The capacity gain that is expected from the DOCSIS 3.1 TaFD feature is a function of many variables. These include, but are not limited to, the following: the service group size, subscribers' traffic engineering statistics, desired peak rate service offering, US spectrum size, OFDMA channel parameters, size and number of SC-QAM channels, TaFD switching overhead, etc. This paper takes the above parameters into consideration as it analyzes any potential capacity gain and improvement in the peak rate service offering as a result of deploying the TaFD feature.

The analysis in this paper is based on multiple scenarios and network conditions provided by a partner network operator (referred to as MSO X for the rest of the paper) as part of a joint collaboration, where a study was performed to evaluate the potential benefits of deploying the TaFD feature. The goal was to provide guidance as to whether deploying the TaFD feature made sense given the network conditions, planned service offering, and subscriber BW usage. Another goal of the study was to provide migration alternatives if/when the TaFD feature does not provide the desired capacity gains.

This paper is organized as follows. Section 2 defines the problem statement and provides the TaFD capacity analysis for multiple scenarios. Alternative migration strategies are provided in Section 3 and Section 4 concludes the paper.

2. TaFD Capacity Analyses

2.1 Problem Statement

The US spectrum configuration in the MSO X network is composed of two QAM64 6.4 MHz channels and two QAM64 3.2 MHz channels as shown in Fig. 1 with a total estimated plant capacity of ~75 Mbps for the whole US Service Group (USSG). The current US peak rate offering for existing DOCSIS 3.0

subscribers is 12 Mbps. The bottom line question is: what is the maximum peak rate (Tmax) that can be offered for the new DOCSIS 3.1 subscribers if the TaFD feature is deployed as shown in Fig. 2? The answer to this question is critical due to the pressure of speed war battles with competition!

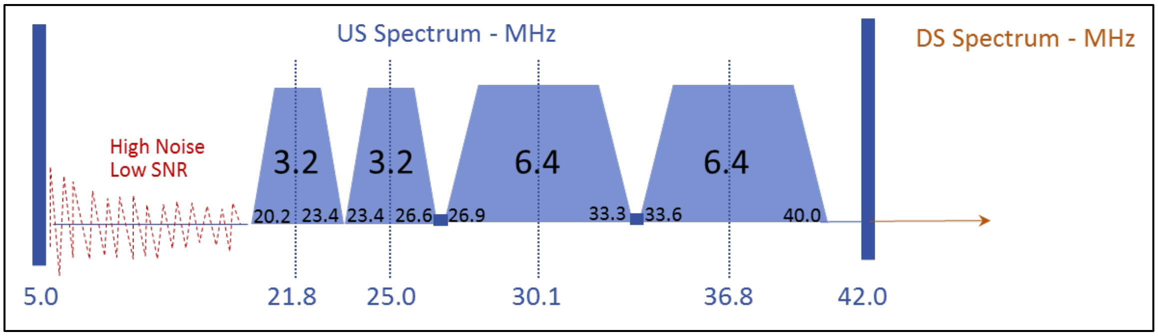

Figure 1 - Existing configuration of the US spectrum with 5-42 MHz plant

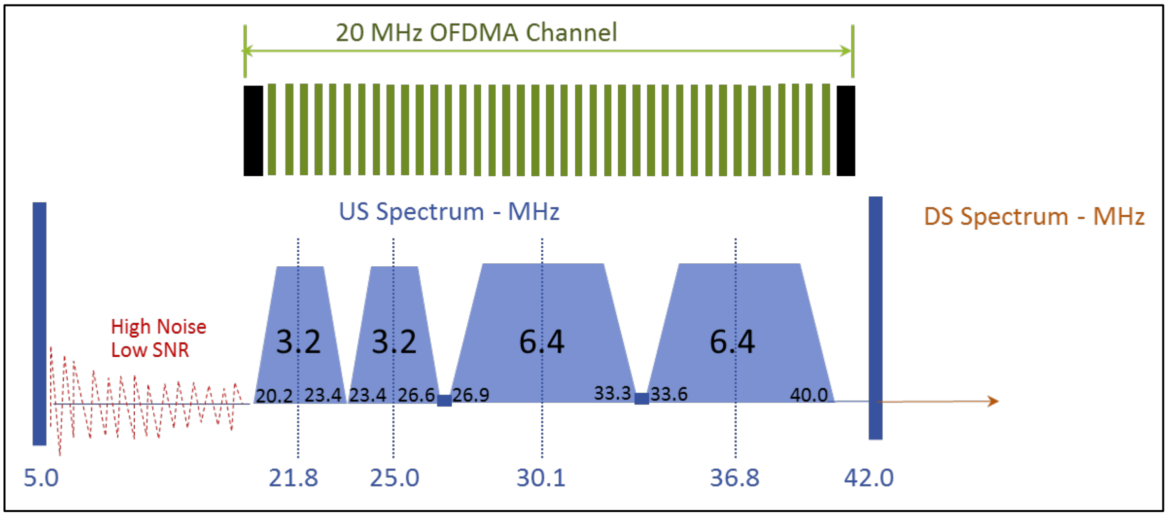

Figure 2 - Deploying the TaFD feature with a 20 MHz OFDMA channel that overlaps with the existing SC-QAM channels in 5-42 MHz plant

As described in the introduction section, the analysis of capacity gain & potential service offering as a result of deploying the TaFD feature is function of many parameters and variables. In the following two subsections, we evaluate two different scenarios (Scenarios A & B) with slightly different assumptions.

2.2 Scenario A Analysis

Scenario A was based on a measured histogram for the USSG BW utilization levels that is shown in Fig. 3. It can be seen that >90% of USSGs have 60% BW utilization or less. Moreover, the histogram of number of subscribers per USSG for the USSGs shown in Fig. 3 is provided in Fig. 4. It can be seen that >90% of USSGs have 180 Subscribers or less. Based on these statistics, the average throughput per subscriber (Tavg) was estimated to be 60%*75 Mbps/180 = 250 kbps.

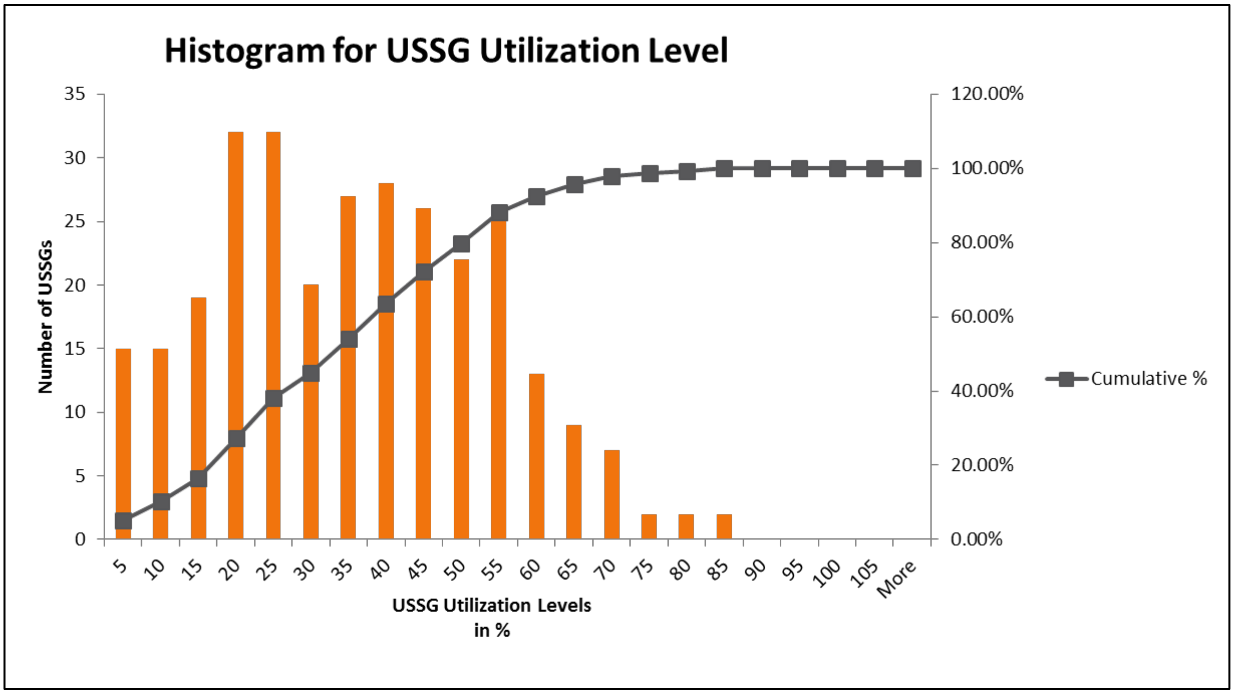

Figure 3 - Histogram of USSG BW utilization levels

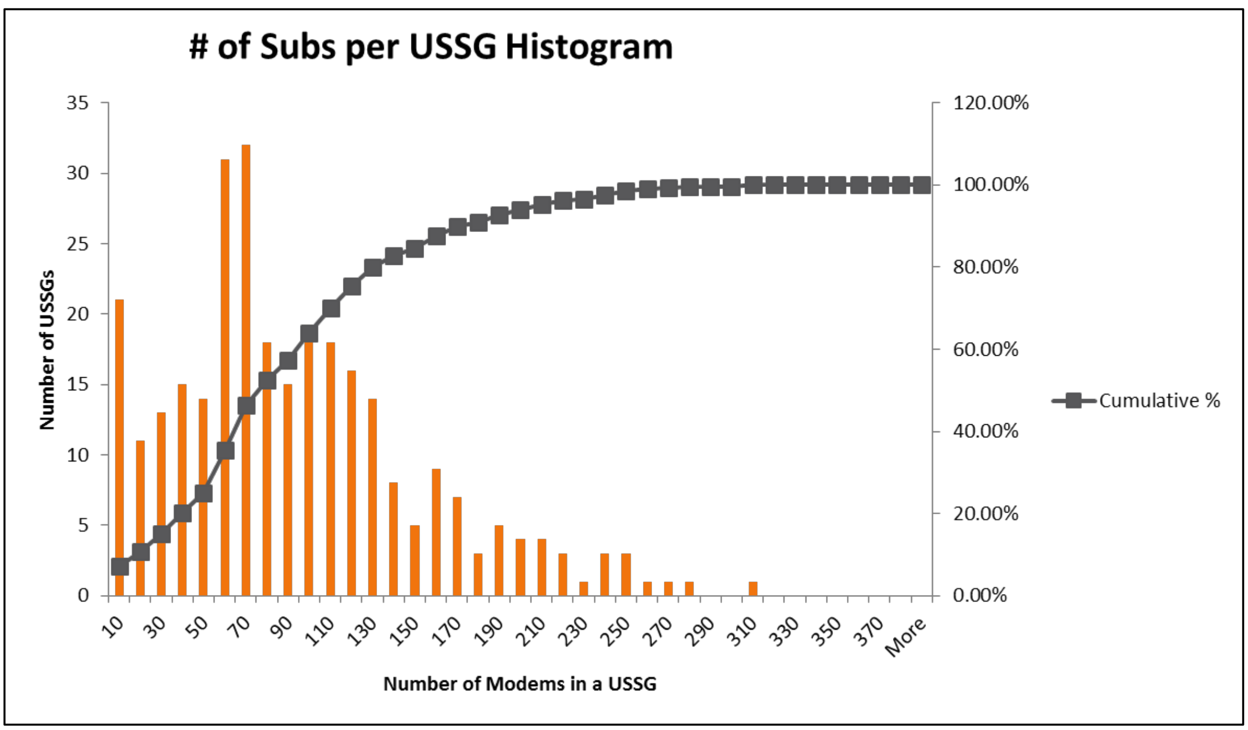

Figure 4 - Histogram of number of subscribers per USSG

In order to estimate the capacity of the OFDMA channel capacity that will provide the TaFD feature, it was also important to obtain some plant measurements. The distribution of US SNR values measured on MSO X plant was as shown in Fig. 5. Although the provided SNR values were the peak SNR values per USSG and number of samples that formed the distribution was not large enough to form a Gaussian-style probability density function (pdf), the histogram (with mean SNR of ~35 dB) still was considered to be usable for the purpose of rough capacity analyses. The estimated OFDMA channel spectral efficiency values for different channel widths is given in Table 1 and assumed the following parameters

- 2K FFT with 50 kHz subcarrier spacing
- Cyclic prefix = 1.875 µsec
- Frame size = 10 OFDMA symbols
- Guard band of 0.5 MHz on each side
- Pilot pattern 2
- Large Codeword size
- MSO SNR margin of 2 dB
- QAM256 modulation order (two modulations order better than QAM64 used with the currently deployed SC-QAM channels that have a spectral efficiency value of 4.15 bps/Hz [2])

Per Table 1, observe that the total capacity of the 20 MHz OFDMA channel, shown in Fig. 2, can be estimated as 20 MHz*5.79 bps/Hz ~ 116 Mbps. Obviously, this value assumes that the OFDMA channel has access to the spectrum 100% of the time and therefore would not take any TaFD switching overhead into consideration.

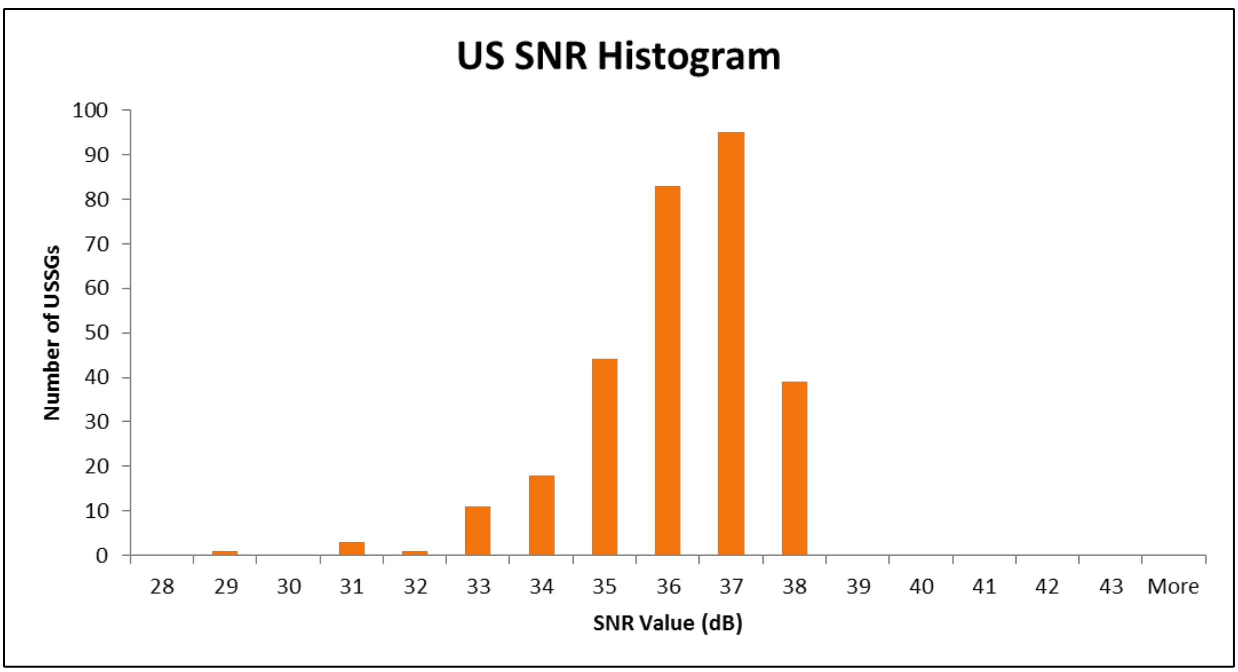

Figure 5 - Histogram of peak US SNR values per USSG

Table 1 - Spectral efficiency of the US OFDMA channel

OFDMA Channel (MHz)	10	20	40	60	80	96
Spectral Efficiency (bps/Hz) at PHY Level	5.40	5.79	5.98	6.04	6.08	6.09

In order to proceed with the TaFD analysis, the following assumptions are made:

- 5-42 MHz plant with total usable spectrum of 20 MHz
- TaFD spectrum is 19.2 MHz (overlapping spectrum between SC-QAM and OFDMA). OFDMA can use 0.8 MHz of spectrum that is not overlapped with SC-QAM
- D3.0 spectral efficiency (PHY) = 4.15 bps/Hz [2]
- D3.1 spectral efficiency (PHY) per Table 1
- Tavg is equal for SC-QAM and OFDMA subs = 250 kbps (calculated previously)
- Currently offered Tmax for SC-QAM = 12 Mbps. The SC-QAM subs will continue to be offered a Tmax of 12 Mbps
- Tavg for the OFDMA subscriber is equal to Tavg for a SC-QAM subscriber
- Total number of subscribers (Nsub) = 180
- TaFD switching and scheduler inefficiency overhead = 20%. This includes overhead due to guard time, guard bands, and scheduling inefficiencies
- MAC overhead = 5%
- ARRIS QoE Formula is used to estimate the needed capacity as shown in Fig. 6:
  - Needed Capacity = Nsub*Tavg + 1.2*Tmax

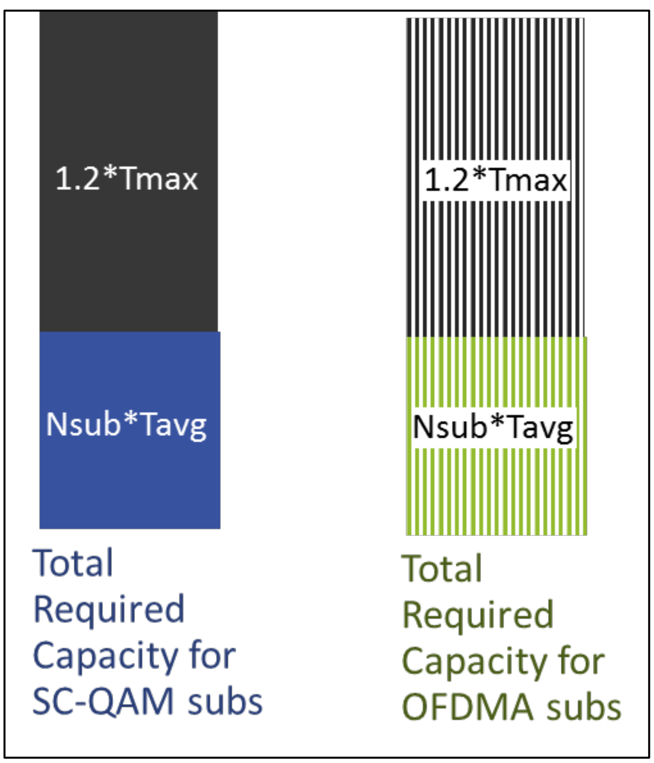

Figure 6 - ARRIS QoE formula used to estimate the needed capacity

Given the above assumptions, the total usable plant capacity using the TaFD feature in a 5-42 MHz plant as a function of the percentage of deployed DOCSIS 3.1 CMs is shown in Fig. 7. This total capacity takes the TaFD switching overhead into consideration and therefore it can be observed that the total capacity of the plant drops, when a small percentage of DOCSIS 3.1 CMs get deployed, due to the 20% TaFD switching overhead assumption. The corresponding peak rates that can be offered to DOCSIS 3.1 subscribers as a result of deploying DOCSIS 3.1 and the TaFD feature are shown in Fig. 8. The results in Fig. 8 includes various cases where bonding between SC-QAM and OFDMA channels is supported or not. There are a few key points to note from these results:

- 25 Mbps can be offered using SC-QAM-only channels.
- Tmax service beyond 25 Mbps for DOCSIS 3.1 subscribers cannot be offered using 5-42 MHz spectrum without utilizing the channel bonding feature in addition to the TaFD feature.
- With bonding enabled, at least 55% of subscribers need to be D3.1 subscribers in order to offer higher than 25 Mbps service.

These conclusions do not present the TaFD feature as an attractive transition technology because a large percentage of DOCSIS 3.1 subscribers need to be deployed in order for the feature to start adding value above what SC-QAM can offer alone.

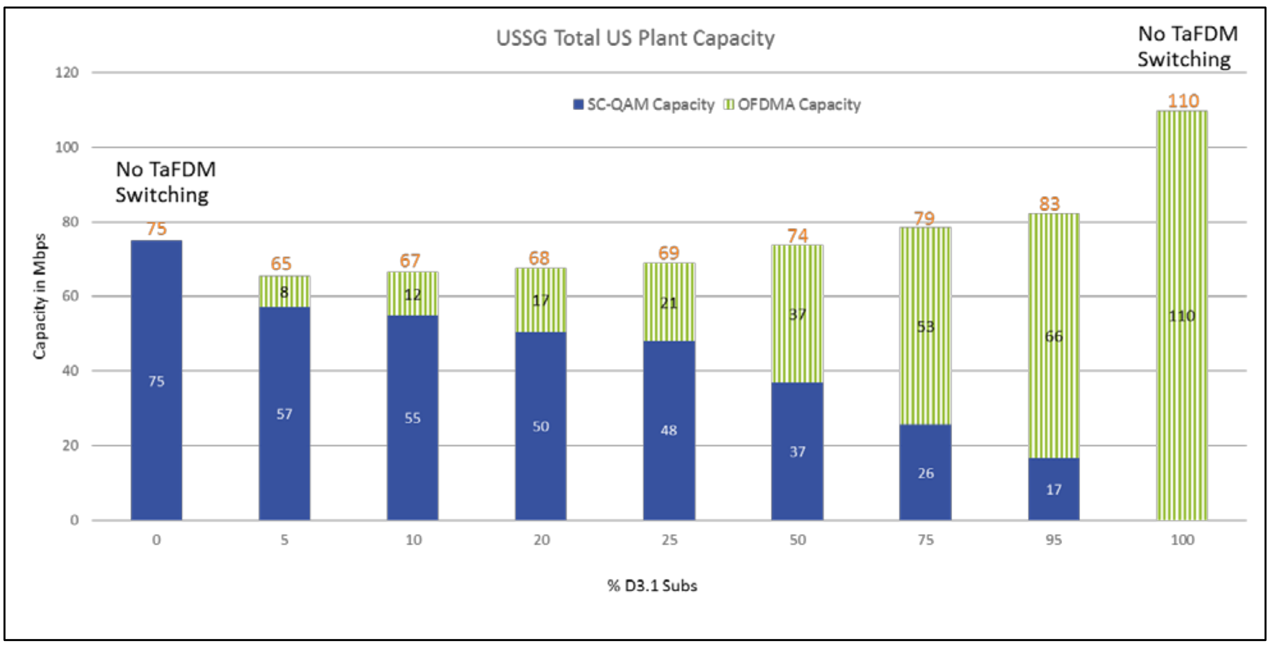

Figure 7 - Total usable plant capacity with TaFD in 5-42 MHz plant for Scenario A

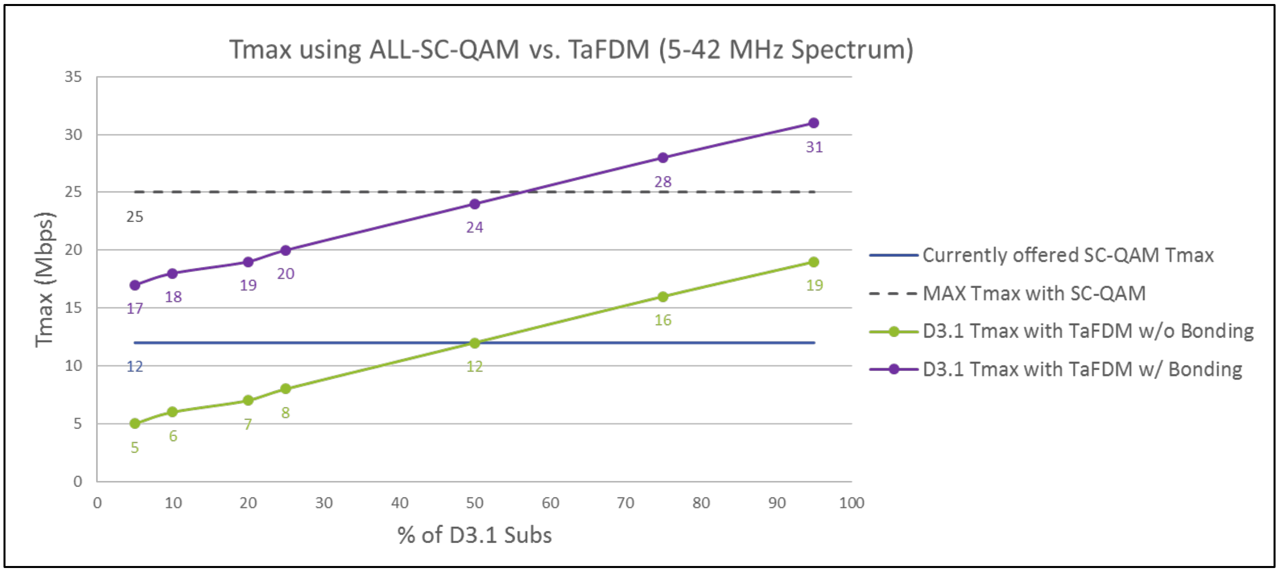

Figure 8 - Peak rates offered to DOCSIS 3.1 subscribers with TaFD in 5-42 MHz plant - Scenario A

The above results make the reader wonder why the TaFD had marginal benefits in 5-42 MHz plants with scenario A. This can actually be attributed to the following:

- OFDMA is less efficient with small channel widths
  - 20 MHz is just about one fifth of the maximum channel size of 96 MHz defined in the DOCSIS 3.1 PHY specifications. [3]
  - Most existing subscribers are DOCSIS 3.0 subs. This leaves little room for spectrum access for OFDMA subscribers.
  - Not only is the OFDMA channel width small, but it also time-shares the spectrum with SC-QAMs resulting additional reduction in throughput.
  - As the number of DOCSIS 3.1 subs increases (and number of SC-QAM subs decreases), the OFDMA performance slightly improves.
- TaFD Switching overhead is significant compared to the gained capacity
  - Switching between OFDMA and SC-QAM channels requires guard time and/or guard bands. [1]
- There is a slight capacity gain from using OFDMA but….
  - The benefit of this gain is marginalized by the switching overhead.
  - Reducing the switching overhead with optimized implementation can increase the value of the TaFD feature.

One of the transition plans of MSO X was to move to an US mid-split of 5-85 MHz and increase the number of SC-QAM channels as shown in Fig. 9. Therefore, a similar analysis was performed for the 5-85 MHz split option and the results are shown in Fig. 10. Note that the analysis considered multiple options, where one option assumed that the number of SC-QAM channels is as described in MSO X's transition plan in Fig. 9 deployed together with an OFDMA channel that overlaps with those SC-QAM channels via the TaFD feature. The other option is a reduced number of SC-QAM channels (to the minimum that is needed to accommodate DOCSIS 3.0 subscribers). In the latter option, when the number of SC-QAM channels is reduced, the reclaimed spectrum is given back to the OFDMA channel, which does not overlap with the SC-QAM channels, and therefore does not use the TaFD feature. This is essentially a Frequency Division (FD) operation, where different channels occupy different parts of the spectrum.

The analysis results show that the system performance when reducing the number of SC-QAM channels to the absolute minimum that is needed to accommodate DOCSIS 3.1 subscribers and using OFDMA channels in other parts of the spectrum outperforms the option where the number of SC-QAM channels is increased and the TaFD feature is utilized. In particular, the results show that in 5-85 MHz plant, the offered Tmax with the FD option (FD operation between OFDMA and reduced number of SC-QAM channels) can be as high as 213 Mbps with 5% of the subscribers being DOCSIS 3.1 subs. This Tmax value is more than the Tmax of 184 Mbps that can be offered with the TaFD option (using TaFD & bonding between an OFDMA channel that overlaps with large number of SC-QAM channels) with 5% of the subscribers being DOCSIS 3.1 subs. Similarly, with 95% of the subs being DOCSIS 3.1 subs, Tmax value for the FD option is 227 Mbps compared to 200 Mbps with the TaFD option.

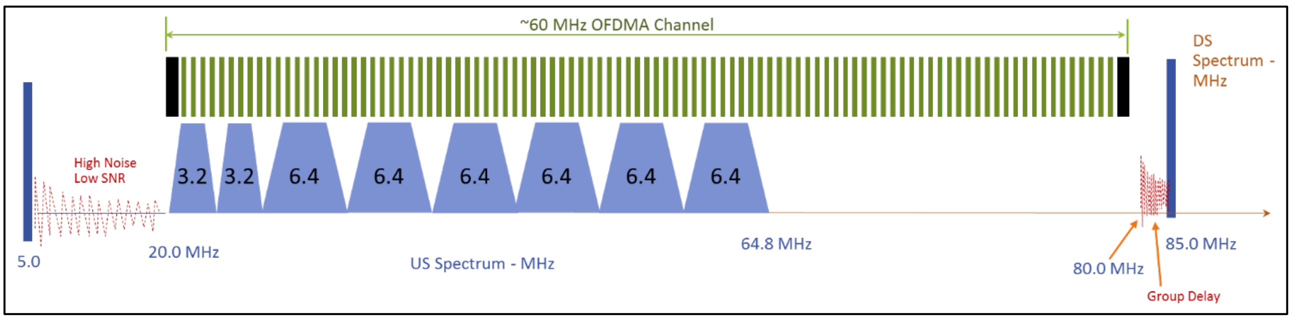

Figure 9 - MSO X original plan to move to 5-85 MHz plan and increase the number of SC-QAM channels– Scenario A

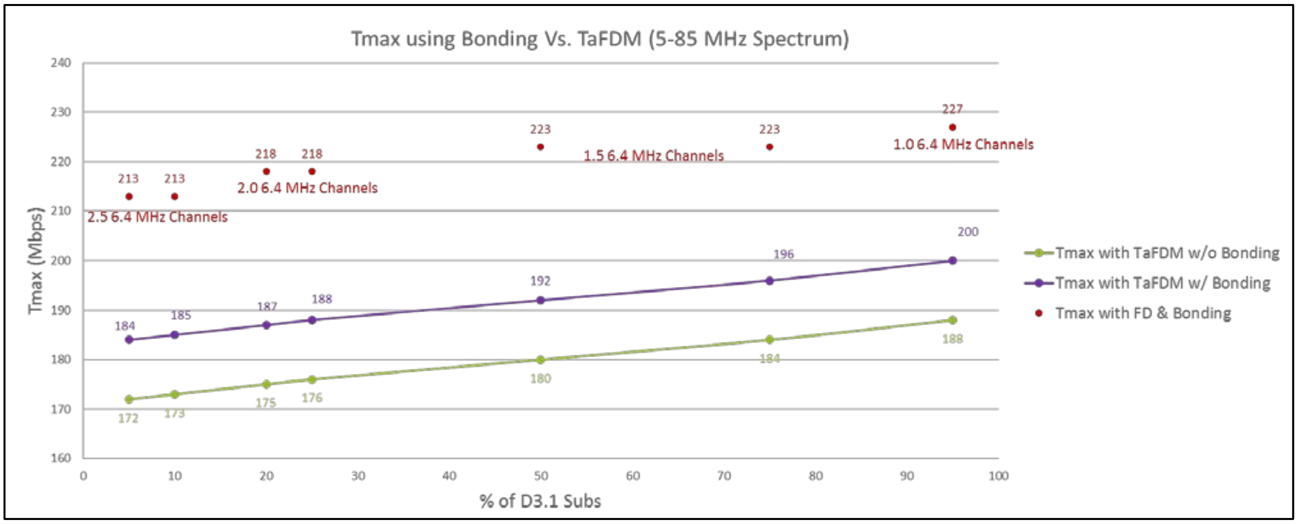

Figure 10 - Peak rates offered to DOCSIS 3.1 subscribers with TaFD in 5-85 MHz plant - Scenario A

Given the above analysis for scenario A, it can be concluded that it is more efficient to stick to SC-QAM technology in 5-42 MHz plants when the percentage of DOCSIS3.1 subs is small (less than ~50%) given the fact that a Tmax value of up to 25 Mbps can be offered using SC-QAM only. It can also be concluded that offering higher Tmax values (for symmetrical services) in scenario A will likely require a migration to 5-85 MHz spectrum and deployment of DOCSIS 3.1. In this case, it is better to use frequency division operation between an OFDMA channel and a small number of SC-QAM channels, which will yield Tmax values as high as 213 Mbps with initial deployments.

2.3 Scenario B Analysis

Scenario B analysis will show that the conclusions can differ depending on the analysis assumptions. The spectrum configuration of scenario B is shown in Fig. 11. Only a few parameters/assumptions were changed from scenario A to create scenario B as shown in Table 2. All other parameters are kept the same including the total number of subscribers per USSG of 180 subs. Note that scenario B assumes that the ODMA channel starts at 13 MHz (not 5 MHz) due to the noisy conditions and potential existence of multiple Out Of Band (OOB) signals in that part of the spectrum (5-13 MHz).

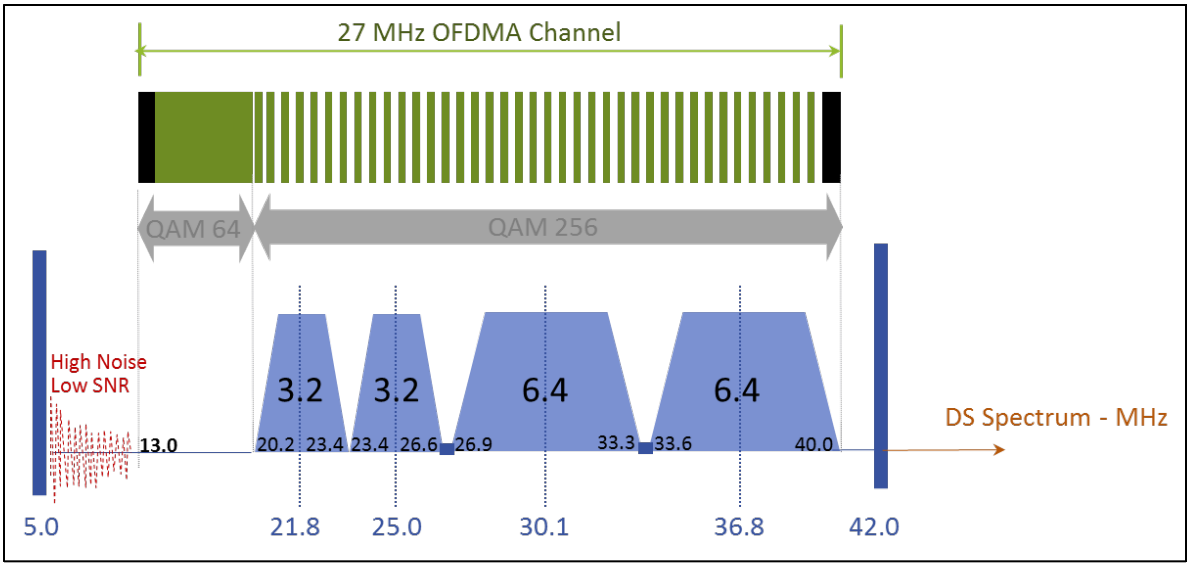

Figure 11 - Spectrum configuration for scenario B with 5-42 MHz plant

Table 2 - Parameters assumed differently for scenarios A & B

Scenario A	Scenario B
Tavg = 250 kbps per sub	Tavg = 84 kbps per sub
US spectrum from 20 to 40 MHz	US spectrum from 13 to 40 MHz
4 US QAM64 SC-QAM channels (2X3.2 + 2X6.4 MHz) between 20 and 40 MHz. OFDMA starts at 20 MHz	4 US QAM64 SC-QAM channels (2X3.2 + 2X6.4 MHz) between 20 and 40 MHz. OFDMA starts at 13 MHz with variable bit loading (QAM64 in 13-20 MHz, QAM256 otherwise)
No DOCSIS channels below 20 MHz	QAM64 for OFDMA channel between 13 and 20 MHz

The results of the analysis for scenario B in 5-42 MHz plant are shown in Fig. 12, which shows the total net capacity of the plant after TaFD switching overhead is taken into consideration. Note that the OFDMA-only capacity refers to the capacity gained from non-overlapping spectrum between 13 and 20 MHz. It can be observed that the US capacity for the 5-42 MHz plant increased to 107 Mbps when 5% of the subscribers are DOCSIS 3.1 subs. This increase in capacity represents a gain of about 43% when compared to plant original capacity of 75 Mbps. Similarly, the US capacity for the plant is increased by 85% when all subscribers are DOCSIS 3.1 subscribers.

The corresponding peak rates for Fig. 12 are shown in Fig. 13. It can be observed that 50 Mbps peak rate service can be offered using SC-QAM-only channels. Also, for initial deployments where 5% of the subscribers are DOCSIS 3.1 subs, TaFD with no bonding between SC-QAM and OFDMA channels provides about 28% gain in Tmax (i.e., 64 Mbps). On the other hand, TaFD with bonding between SC-QAM and OFDMA channels provides about 52% gain in Tmax (i.e., 76 Mbps).

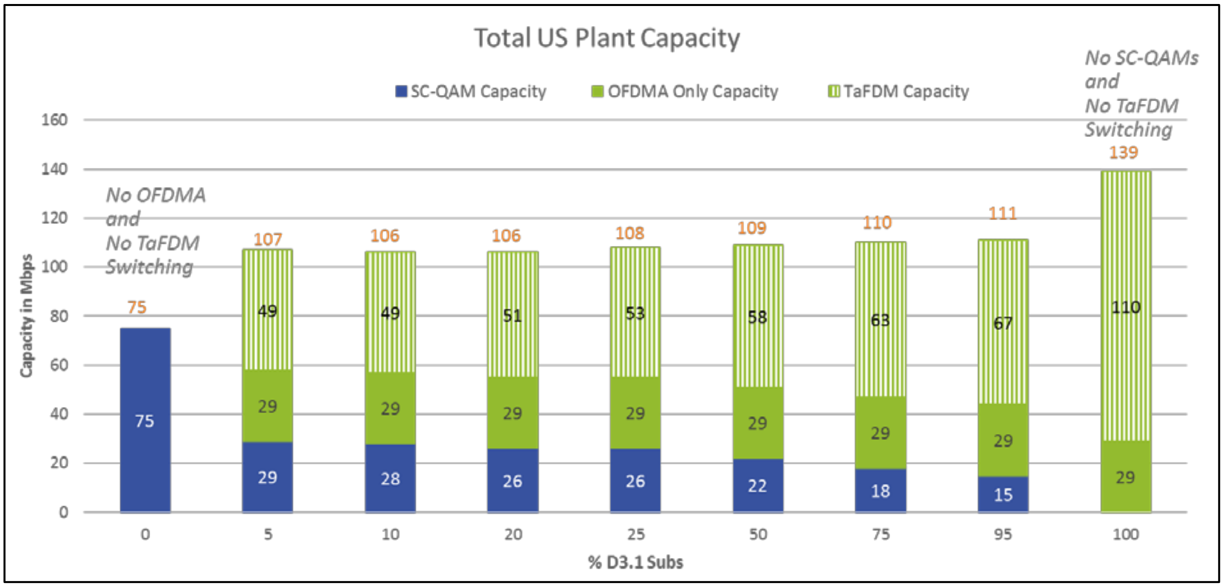

Figure 12 - Total usable plant capacity with TaFD in 5-42 MHz plant for Scenario B

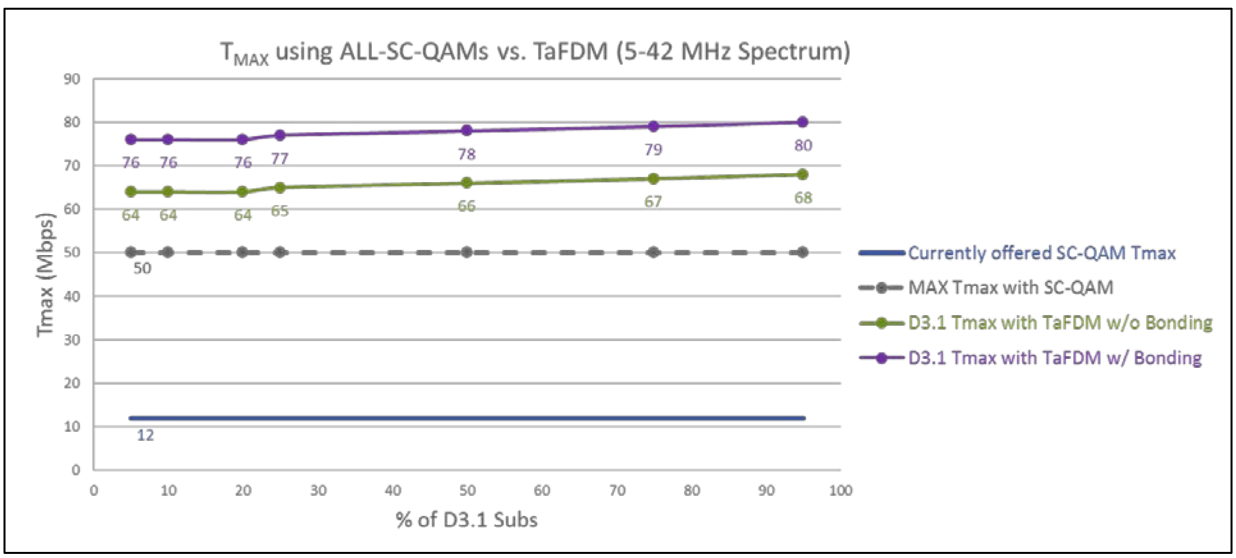

Figure 13 - Peak rates offered to DOCSIS 3.1 subscribers with TaFD in 5-42 MHz plant - Scenario B

TaFD analysis for scenario B with 5-85 MHz mid-split plant was also performed in a similar fashion to what was done for scenario A in the previous section. The 5-85 MHz plant configuration for scenario B is shown in Fig. 14. Similar to what was done earlier, the TaFD analysis considered two options: the FD option and the TaFD option (refer to the previous section for the description of those options).

It can be observed from the analysis results shown in Fig. 15 that the system performance when reducing the number of SC-QAM channels to the absolute minimum that is needed to accommodate DOCSIS 3.1 subscribers and using OFDMA channels in other parts of the spectrum (i.e., FD option) <u>exceeds</u> the system performance where the number of SC-QAM channels is increased and the TaFD feature & bonding is utilized (TaFD option). In particular, the results show that in a 5-85 MHz plant, the offered Tmax with the FD option can be as high as 273 Mbps with 5% of the subscribers being DOCSIS 3.1 subs. This Tmax value is more than the Tmax of 245 Mbps that can be offered with the TaFD option with 5% of the subscribers being DOCSIS 3.1 subs. Similarly, with 95% of the subscribers being DOCSIS 3.1 subs, Tmax value for the first option is 277 Mbps compared to 250 Mbps with the second option.

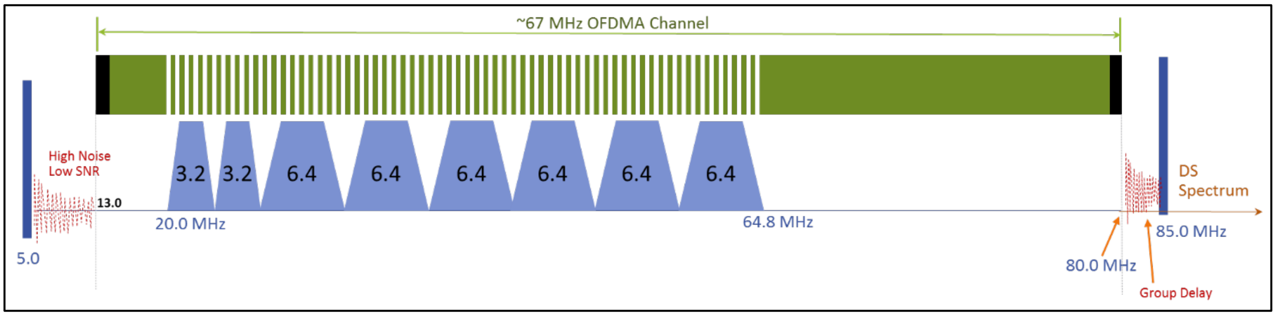

Figure 14 - MSO X original plan to move to 5-85 MHz plan and increase the number of SC-QAM channels – Scenario B

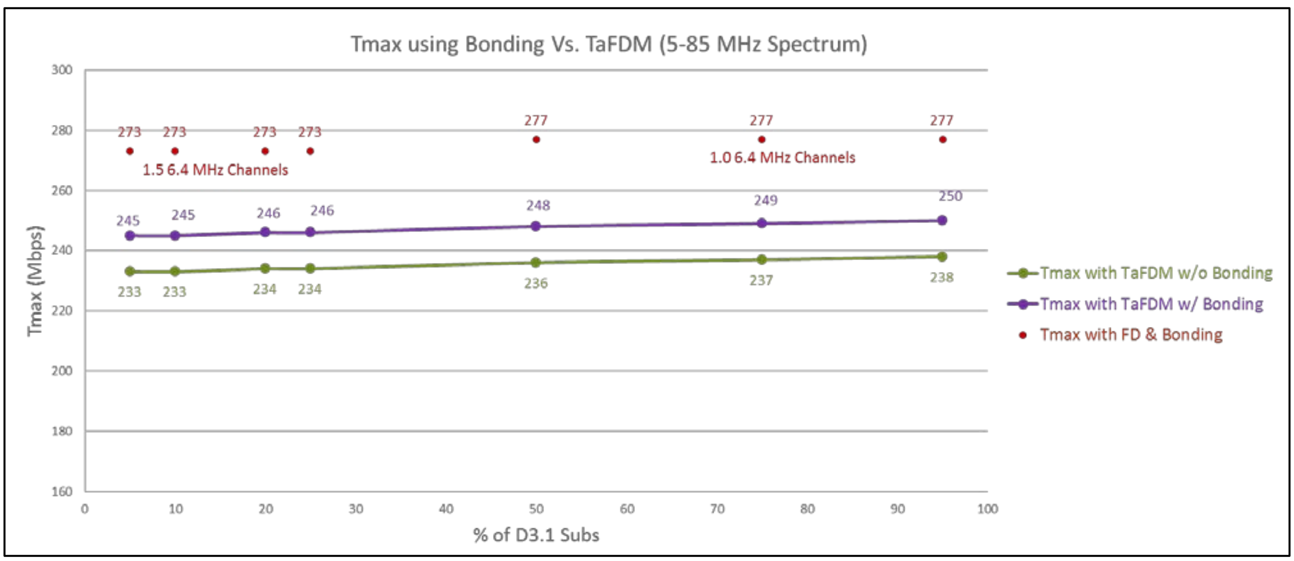

Figure 15 - Peak rates offered to DOCSIS 3.1 customers with TaFD in 5-85 MHz plant - Scenario B

Given the above analysis for scenario B, it can be concluded that moving to DOCSIS 3.1 and utilizing the TaFD feature in 5-42 MHz plant can yield increased plant capacities and peak rate offering. This increase ranged from 28% (64 Mbps via TaFD without bonding) to 52% (76 Mbps via TaFD with bonding) for initial deployment when the percentage of DOCIS 3.1 subs is 5%. Observe that this percentage gain can be deceiving because while the percentage gain could be high (up to 52%), the offered Tmax of 76 Mbps may not be enough for symmetrical services. Therefore, the MSO will have to perform business case analyses to decide whether these achieved Tmax values justify the spending and operational complexity of this feature/scenario. Note that moving to 5-85 MHz split, where the number of SC-QAM channels is reduced to the minimum needed to accommodate DOCSIS 3.0 subs, deployed along with an OFDMA channel via frequency division operation provides the optimal solution to offer symmetrical services. This less operationally complex solution can provide Tmax values up to 273 Mbps, which is 446% gain compared to the 50 Mbps that can be offered via 5-42 MHz plant and SC-QAM only channels and about 11% gain compared to the 245 Mbps that can be offered via 5-85 MHz plant and TaFD/bonding features.

3. Migration Alternatives to Offer Symmetrical Services

The results in the two subsections above suggested that moving to 5-85 MHz split is more beneficial than utilizing the TaFD with bonding feature when symmetrical service offering is the goal on mind. The ability to provide symmetrical service offering can only be improved by moving to high-split (5-204 MHz). However, some MSOs cannot sacrifice the DS spectrum for the sake of US spectrum in the near future. Therefore, the 5-85 MHz mid-split option might be a good compromise for those MSOs in the next few years.

Moving to 5-85 MHz option does not have to be done across the whole network at once. The MSO may choose to selectively change the plant to support 5-85 MHz spectrum. This means performing 5-85 MHz surgical split upgrades only in areas where symmetrical service offering is required due to demand or competition. The MSO can then choose to leave the rest of the network unchanged especially if the subscribers are happy and competitors are out of that market.

In an effort to offer symmetrical services in a specific area, once the MSO migrates that part of the plant to 5-85 MHz split, the next step is to allocate just enough spectrum for SC-QAM channels to satisfy legacy customers (the ARRIS QoE formula can be used to do those estimates). Once that is performed, the remaining spectrum may be used for OFDMA and DOCSIS 3.1 may be deployed. Channel bonding between SC-QAM channels and OFDMA can also be used to offer even higher peak rates.

Note that, in addition to the above methodology, the MSO can choose to perform selective subscriber migration to DOCSIS 3.1. In this scheme, the MSO can choose to move heavy (high usage) subscribers and super users (high peak rate subscribers) from legacy channels to DOCSIS 3.1 OFDMA channels. That, in turn, reduces the pressure on SC-QAM channels and therefore the number of those SC-QAM channels can be further reduced leaving more spectrum for the more efficient OFDMA channels. The decision-tree flow diagram of the above technique is shown in Fig. 16.

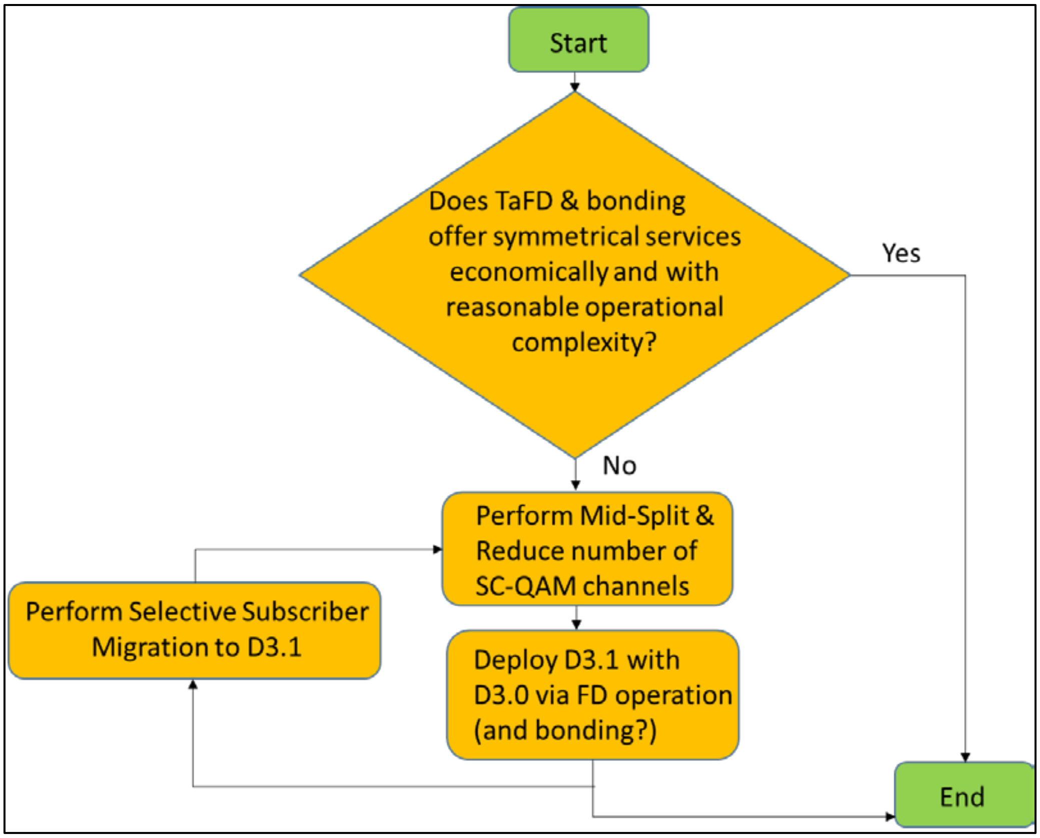

Figure 16 - Decision-tree flow diagram to offer symmetrical services

4. Conclusions

The paper provided traffic engineering analyses for the TaFD feature of OFDMA channels. It was shown that the value added by the TaFD feature depends on the network assumptions. The paper showed that the TaFD feature did not offer any value in some network scenarios but provided benefit in others, especially if used with the channel bonding feature. The MSO will have to perform business case analyses in order to decide whether the benefits & peak rates provided by the TaFD feature are worth the investment or whether investing in other alternatives like mid-split migration in areas where symmetrical service offering is needed. The paper recommended a selective migration to the mid-split option especially when high US peak rate offering for symmetrical services is desired. A decision-tree flow diagram was proposed for the migration process, where selective subscriber migration to DOCSIS 3.1 was proposed to provide an added benefit.

Acknowledgement

The authors would like to thank Sunil Mansharamani of ARRIS for his contributions to this paper.

Abbreviations

BW	Bandwidth
D3.0	DOCSIS 3.0
D3.1	DOCSIS 3.1
DOCSIS	Data Over Cable Service Interface Specifications
FD	Frequency Division
FFT	Fast Fourier Transform
HFC	Hybrid Fiber Coax
kbps	kilobits per second
Mbps	Megabits per second
MSO	Multiple System Operator
Nsub	Number of subscribers
OFDMA	Orthogonal Frequency Division Multiple Access
pdf	probability density function
QAM	Quadrature Amplitude Modulation
QoE	Quality of Experience
SC-QAM	Single Carrier QAM
SNR	Signal to Noise Ratio
TaFD	Time and Frequency Division
Tavg	Average throughput per subscriber during busy hour
Tmax	Peak rate
US	Upstream
USSG	US Service Group

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