Upgrading the Plant to Satisfy Traffic Demands

The One Touch Approach

A Technical Paper prepared for SCTE•ISBE by

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Introduction

The majority of MSOs outside plant architecture (OSP) consists of N+X. As time goes on the demand for capacity and speed in both upstream and downstream grows. Along with that, the era of symmetrical services is approaching as competitive pressure arises.

Fibre to the premises (FTTP) can help to meet this capacity demand but it is extremely costly. Over the past few years, many innovative alternatives and technologies have been proposed to alleviate this challenge. Full-duplex-DOCSIS (FDX) was one of the developed technologies in response to these demands. Although this concept is revolutionary, it requires the MSO to upgrade the OSP to a passive (N+0) state. This is more cost effective than FTTP, but depending on the operator, area of construction and plant type (aerial or underground), it can be quite costly. Moreover, FDX can be challenging from a technology implementation perspective, as it requires overlapping the downstream and upstream spectrum from 108MHz-684MHz.

Knowing that coaxial cable has 6GHz of useable bandwidth (BW) on average, last year the idea of extending the spectrum from 1.2GHz to 1.8GHz and eventually 3GHz was proposed, which gained a lot of traction in the industry. This can present different approaches to upgrading the OSP, to satisfy the future capacity demands.

In this paper an analysis has been carried out to evaluate the achievable capacity in an extended spectrum network. Capacity estimates have been based on the field measurements taken from the acquired 2.7GHz taps. Furthermore, a cost analysis has been carried out based on capacity estimations in a cascade of N+4.

Based on the analysis demonstrated in this paper, 1.8GHz extended-spectrum-DOCSIS (ESD) can be a great alternative to both N+2 and N+0 FDX. It can provide matching throughputs as N+0 and N+2 FDX, at a lower cost. This allows an MSO to rapidly deploy this technology throughout their existing cascaded plant, in a cost-effective manner.

Content

1. Scope

Historically both upstream (US) and downstream (DS) capacity demands have been growing substantially year-over-year, as we approach the era demonstrated in Figure 1. The year-over-year growth shown in Figure 1, also referred to as Compound Annual Growth Rate (CAGR) is 50%, which is a common and historical rule-of-thumb for DS CAGR. Upstream CAGR has been on average lower than in the DS but is also more volatile

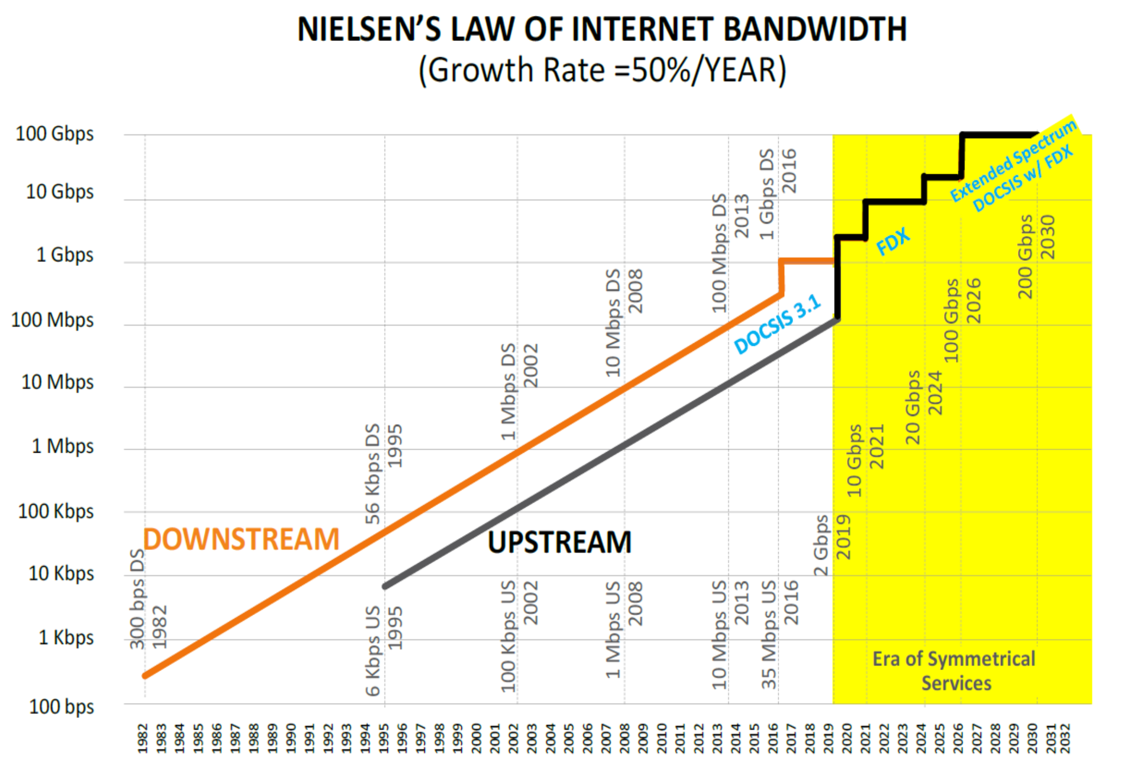

Figure 1 – Nielsen's Law of Internet Bandwidth – Tom Cloonan (Arris)

This can present many challenges for a multi-system-operator (MSO) as the majority of the outside plant (OSP) architecture consists of N+X. On average, Shaw's plant consists of N+4. Since business-as-usual (BAU) node splits don't increase the overall available BW, other strategies must be considered.

In order to quantify the differences between various deployment strategies, the capacities offered by each technology must be evaluated. The categories below have been considered for evaluation:

1. DS and US analysis in a 1.8GHz N+4 ESD plant
2. DS and US analysis in an N+0 FDX plant
3. DS and US analysis in an N+2 FDX plant

In order to estimate the achievable capacity in Scenario 1, a series of acquired 2.7GHz taps were installed in the last span of selected amplifiers. The characterization performance for this test is demonstrated in the analysis section.

The calculated capacities for each scenario can then be compared against the projected demands and the cost of the plant upgrade as it is introduced to satisfy the traffic demands With all cost variables accounted for, this can then be used to create an NPV analysis for each strategy.

In the subsequent sections of this paper, the RF and capacity analysis for each scenario is demonstrated.

2. Analysis

2.1. 1.8GHz Extended Spectrum DOCSIS

Historically MSOs have stretched the spectrum to higher frequencies, from 500MHz to 750MHz, 860MHz, 1GHz and currently 1.2GHz. This can be a challenging task depending on how the OSP was designed. Amplifier spacing and tap span lengths can be a concern when this is put into practice.

Moreover, as the spectrum is stretched higher, coax cable becomes subject to more attenuation, which can be challenging when considering upgrading the plant to 1.8GHz. This is demonstrated Figure 2 below:

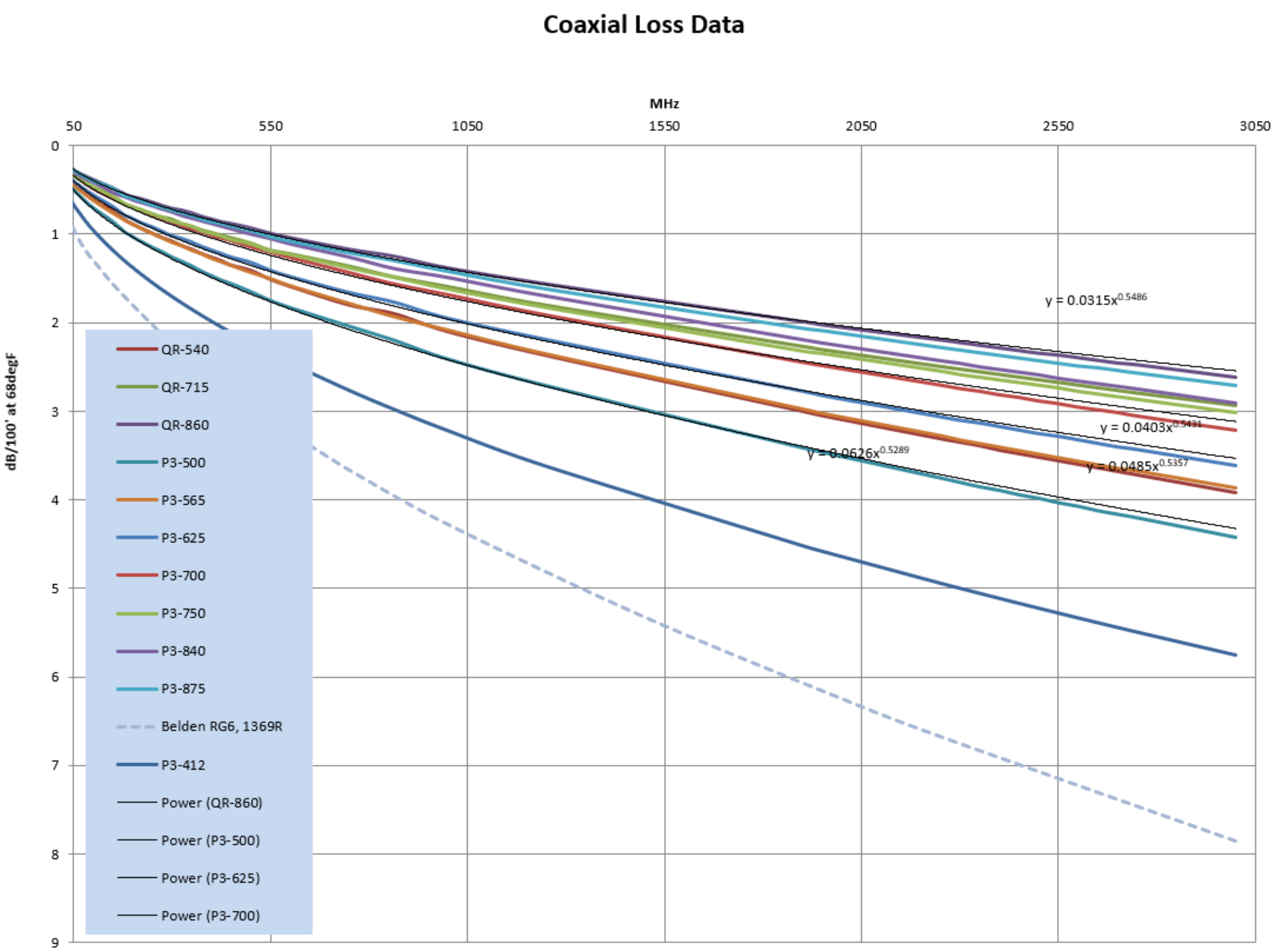

Figure 2 – Coaxial Cable Loss (50MHz – 3GHz)

The following locations were selected to evaluate the feasibility of upgrading the plant to 1.8GHz and eventually 3GHz:

- 412 P3cable with many splices as a result of plant maintenance (see Figure 3)
    - This cable presents us with the most amount of loss in comparison to other cable types at Shaw, as per Figure 2.

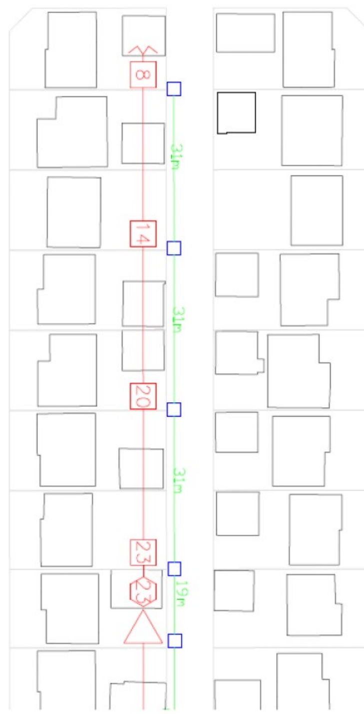

Figure 3 – 412 P3 Test Plant

- 625 P3 cable with the last span tap being ~160m away (see Figure 4)
    - This cable is representative of an average cable type at Shaw with average loss

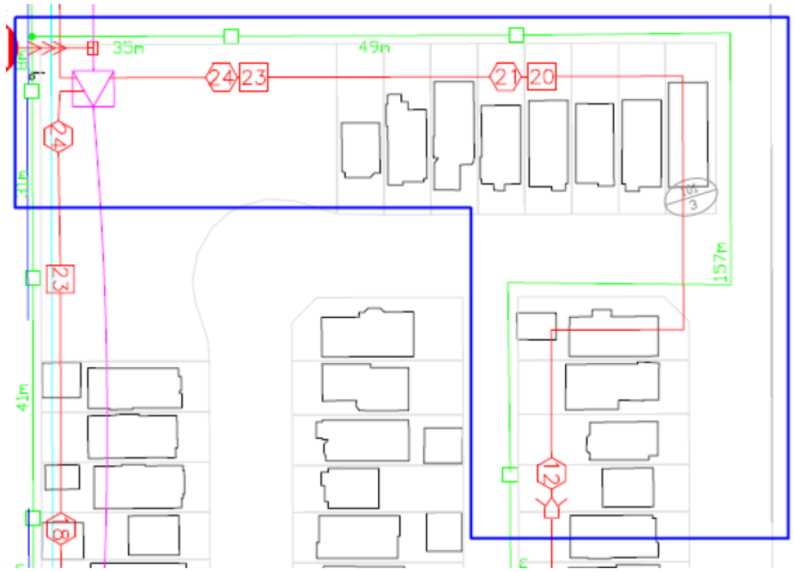

Figure 4 – 625 P3 Test Plant

- 500 QR cable (see Figure 5)
  - Just like the 412 P1 cable, this cable has high loss characteristics

Figure 5 – 500 P3 Test Plant

In each of the selected plant locations, the old taps were replaced with a similar value of 2.7GHz BW in order to have a like-for-like comparison.

The test methodology isdescribed below:

2.2. Test Plan

In order to characterize the plant, S parameters have been utilized. A schematic view of S-parameters is shown in Figure 6 below:

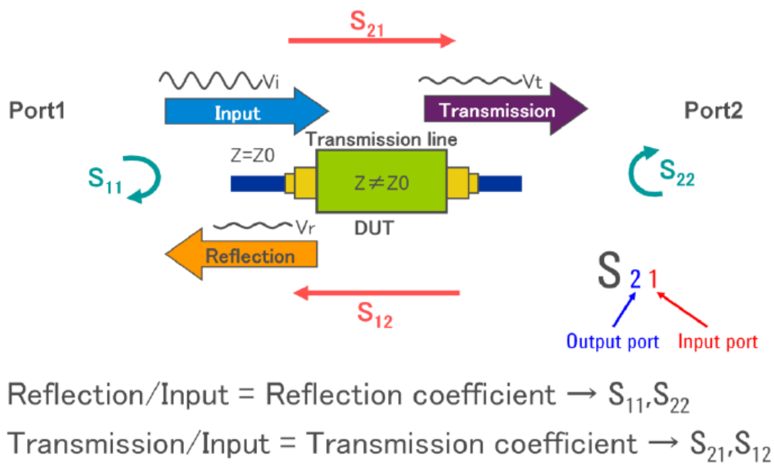

Figure 6 – S Parameters

As shown in the figure above:

$$S_{21} = {}^{V_t}/_{V_i}$$

$$S_{11} = {}^{V_r}/_{V_i}$$

Given that S21 is a unitless parameter, it can be applied to any node or amplifier output power configuration. As an example, cable modem's (CM) receive power (Rx) can be calculated with the following equation:

$$CM\ R_x/_{6MHz} = P_{out}(amp)/_{6MHz} - S_{21}$$

In order to gather data up to 3GHz, the following steps were followed:

- An orthogonal-frequency-division-multiplexing (OFDM) signal was generated at the output of the selected amplifier span location
  - Channel width = 80MHz
  - 50kHz sub-carrier spacing
  - $P_{out} = 56.03dBmV$ per 80MHz channel
- The old taps were swapped like-for-like with the new 2.7GHz taps.
- S21 measurements were taken at each tap location along the span, including a 150ft drop length of RG6 cable
- S11 measurements were also taken in order to characterize the same plant for FDX DOCSIS
- If the signal didn't have enough power to be measured, the source (signal generator) was moved closer to the end of line, to a viable tap location and further measurements were taken

This is demonstrated in Figure 7below:

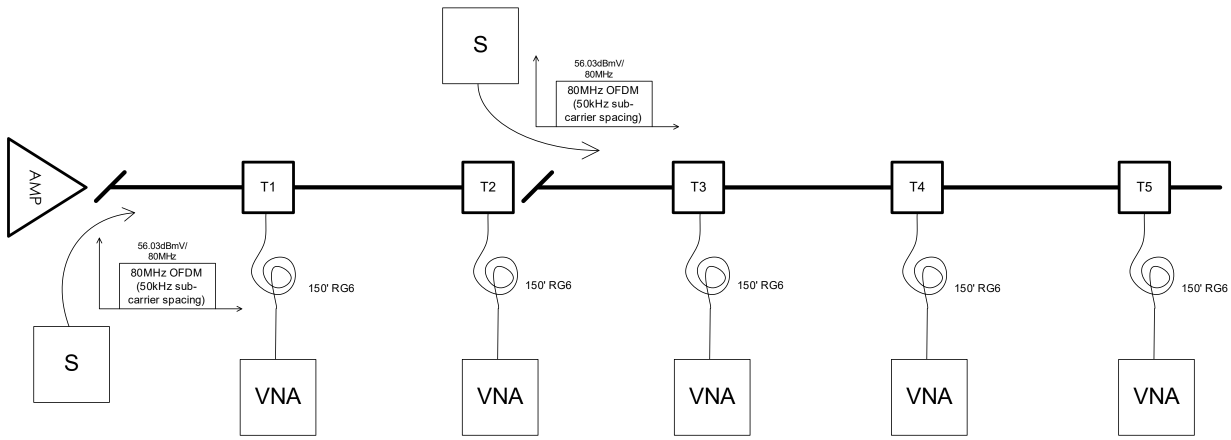

Figure 7 – Test Methodology

2.3. Test Results

2.3.1. TCP for DS and US:

Prior to evaluating the S21 and end-of-line capacity analysis, the output power of the amplifier and the total-composite-power (TCP) shall be discussed. The following assumptions have been considered:

- The TCP of the current amplifier gain chips are 73.8dBmV
- The high output gain chip used in N+0 implementations has TCP = 76.8dBmV
- Amplifier performance (gain, noise and distortion) characteristics of the 1.8GHz actives will be similar and/or comparable to the current 1.2GHz ones

Given that ESD will be deployed in cascaded plant, the focus of this paper will be on cascaded levels and tilt. The current amplifier output levels used are shown in Figure 8 below.

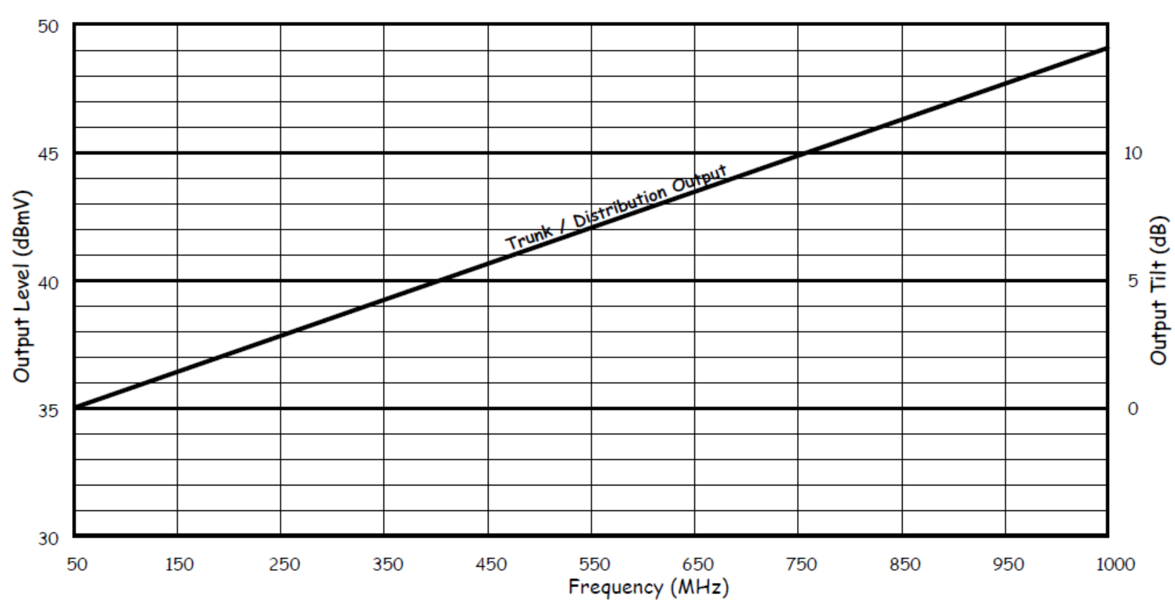

Figure 8 – Current Amplifier Output Power Levels/6MHz (50MHz – 1GHz)

The levels shown above are in analog. To convert them to digital, 6dB has to be deducted from the power level at any given frequency. Note that TCP will be calculated using digital levels. Since these levels are quite conservative and the TCP of the current amplifier gain-chips are 73.8dBmV, the following three power loading and tilt scenarios have been assumed for the deployment of 1.8GHz capable amplifiers:

1. Continuing with the tilt:
    - This results in a 71dBmV TCP (see Figure 9)

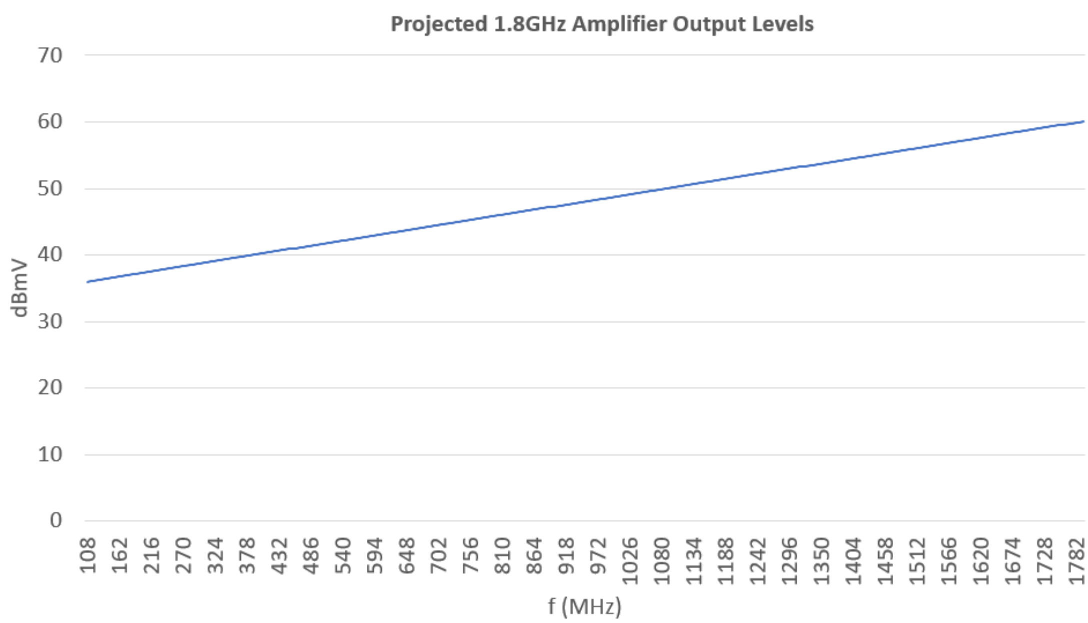

Figure 9 – Projected 1.8GHz Amplifier Output Power Levels/6MHz (108MHz – 1.8GHz)

2. Drop-down at 1GHz (see Figure 10)
    - Tilting the spectrum in the 'legacy' band up to 1GHz, dropping the level by 3dBmV and continuing with the same tilt up to 1.8GHz
    - This results in a 68.5dBmV of TCP

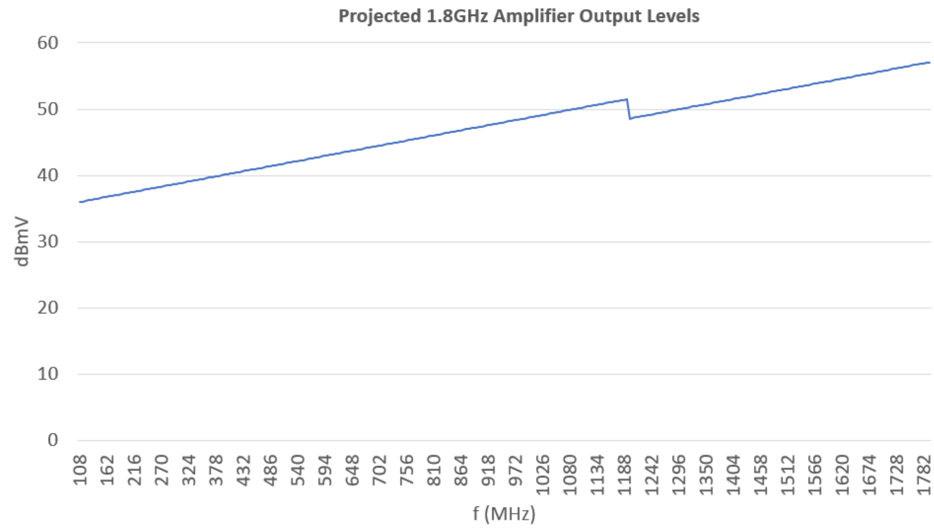

Figure 10 – Projected Drop-Down 1.8GHz Amplifier Output Power Levels/6MHz

3. Flat after 1GHz (see Figure 11)
    - Tilting the spectrum in the 'legacy' band up to 1GHz and continuing with same level from 1GHz to 1.8GHz
    - This results in a 58.5dBmV of TCP

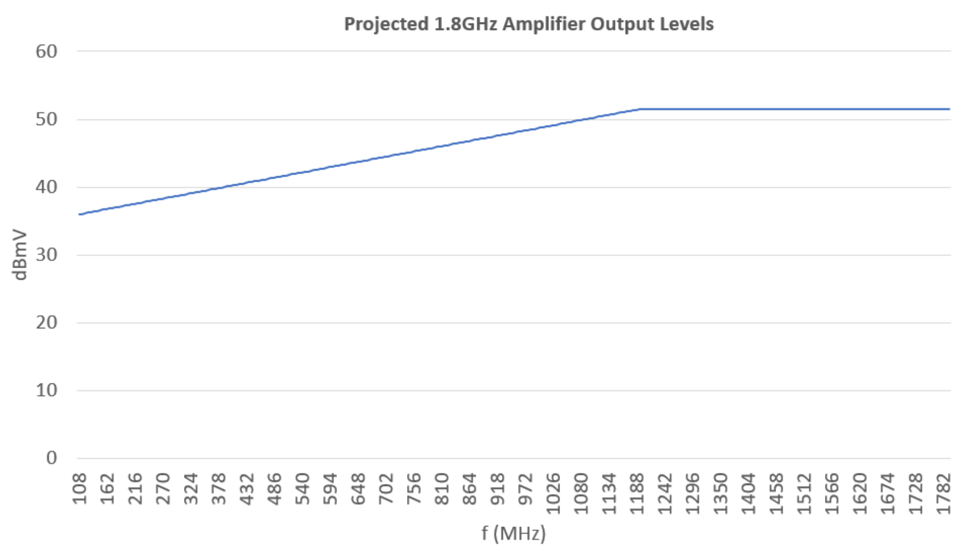

Figure 11 - Projected Flat 1.8GHz Amplifier Output Power Levels/6MHz

For upstream modem transmit levels (MDM Tx), the following has been assumed:

- The modem will have the same transmit capabilities as described in the full-duplex-DOCSIS specifications

- The spectrum is not overlapped

According to the FDX specifications the modem can transmit with a 10dB tilt from 108MHz to 684MHz with a TCP of 64.5dBmV. The following modem transmit levels have been utilized to estimate capacity in the US:

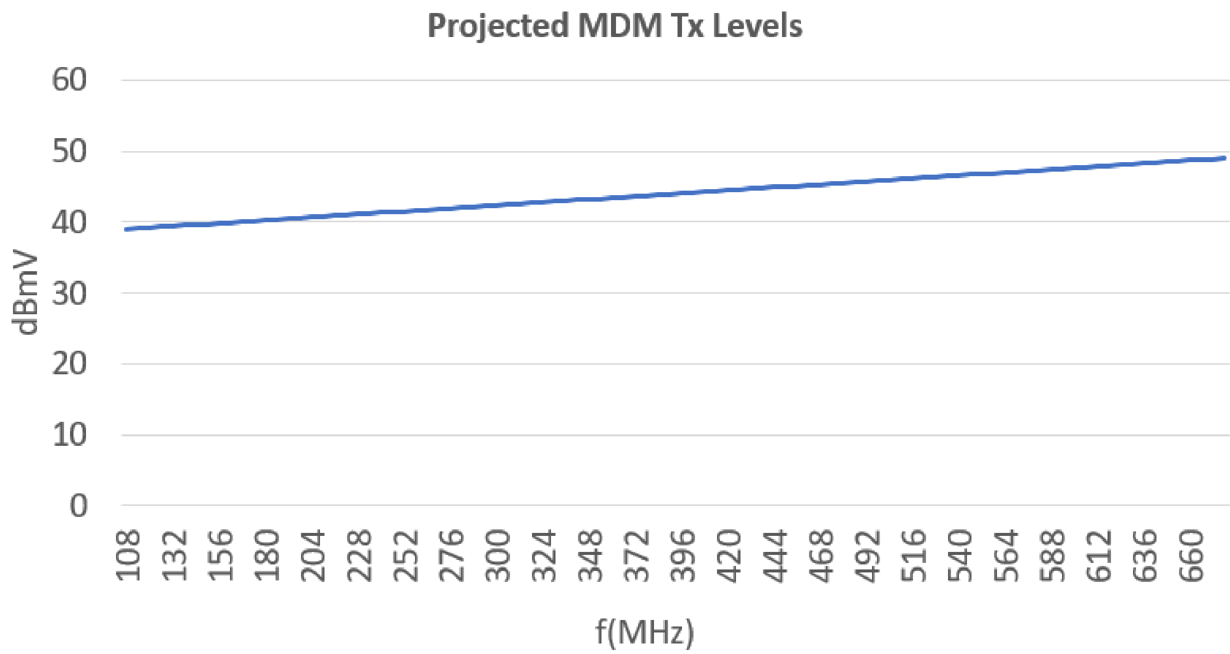

Figure 12 - Projected MDM Transmit Levels/6.4MHz (108MHz – 684MHz)

Although modems in the field will not use the entire 108-684MHz spectrum for upstream burst, upstream capacity has been calculated throughout the entire spectrum.

The assumption for the end-of-line capacity analysis is:

- The modem shall be a point-of-entry (PoE) device, to be installed at the ground block without any splitters
- The limiting factor in achievable modulation order and modulation-error-rate (MER) is the noise floor of the modem and amplifier, if the plant is properly aligned and interference free
- A cascade of four has been assumed for the estimates (N+4)
- A 3dB reduction in signal-to-noise-ratio (SNR) has been included in the estimate, for every doubling of amplifiers. Meaning for a cascade of 4, per assumption above, a 6dB SNR reduction is included as delivered by the network to the modem. This reduction to SNR has been applied to the minimum Rx levels needed at the modem to achieve each modulation order, based on DOCSIS specifications of -15dBmV - +15dBmV per 6MHz at the MDM
- The throughput of each modulation order is based on the theoretical values, not including any overhead, as shown in Table 1 below:

Table 1 – Modulation Orders and Effective Throughputs

Modulation Rate	Effective Throughput (Bits/s/Hz)
256QAM	8
1024QAM	10
4096QAM	12

2.3.2. DS MER Estimations

2.3.2.1. 412 P1 Location

The insertion loss (S21) results for this location are demonstrated in Figure 13 below:

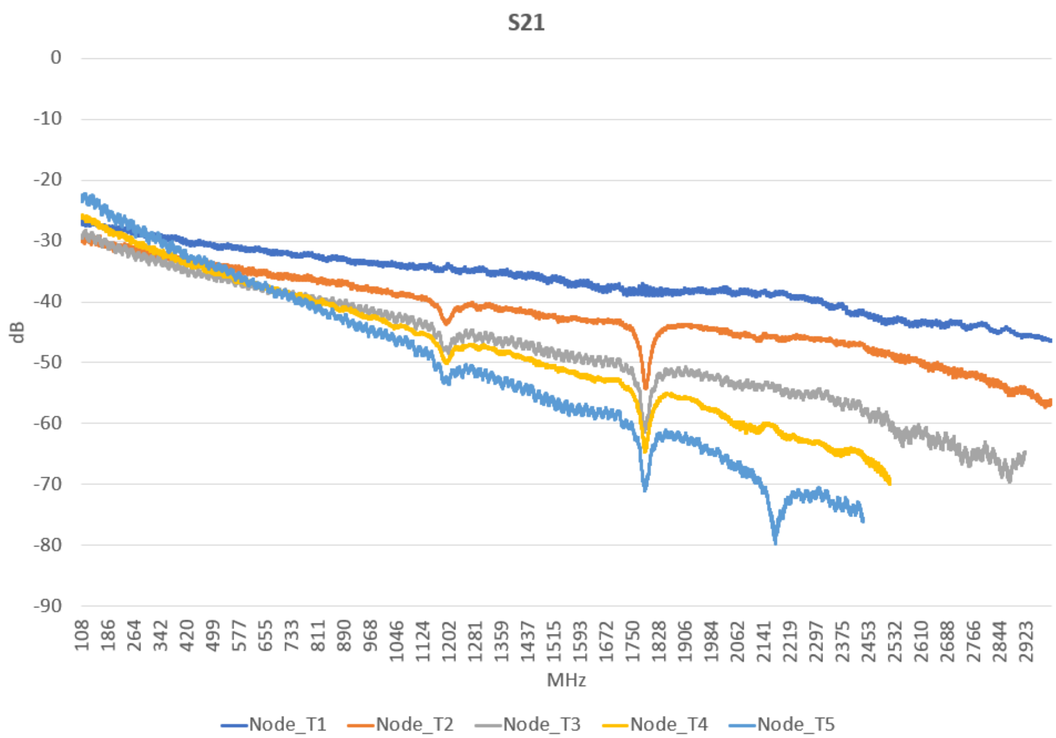

Figure 13 – S21 – 412 P3 Cable Test Plant

From Figure 13,it can be observed that there are "suck outs" present in the spectrum. This can be attributed to a variety of factors, but it is most likely due to the number of coax splices installed in this particular plant in the past ~30 years. A picture of the pedestal where the splices are visible is been shown in Figure 14

Figure 14 – 412 Test Plant Pedestal

This can be alleviated with regular plant maintenance, using a time-domain-reflectometer (TDR). For the purpose of this paper, the calculations have been done on plant, as-is.

Based on the S21 measurement and the 1.8GHz power loading profiles in Figures 9-11, the following modem receive power levels (MDM Rx) can be calculated for each profile.

1. Continuing with the tilt:

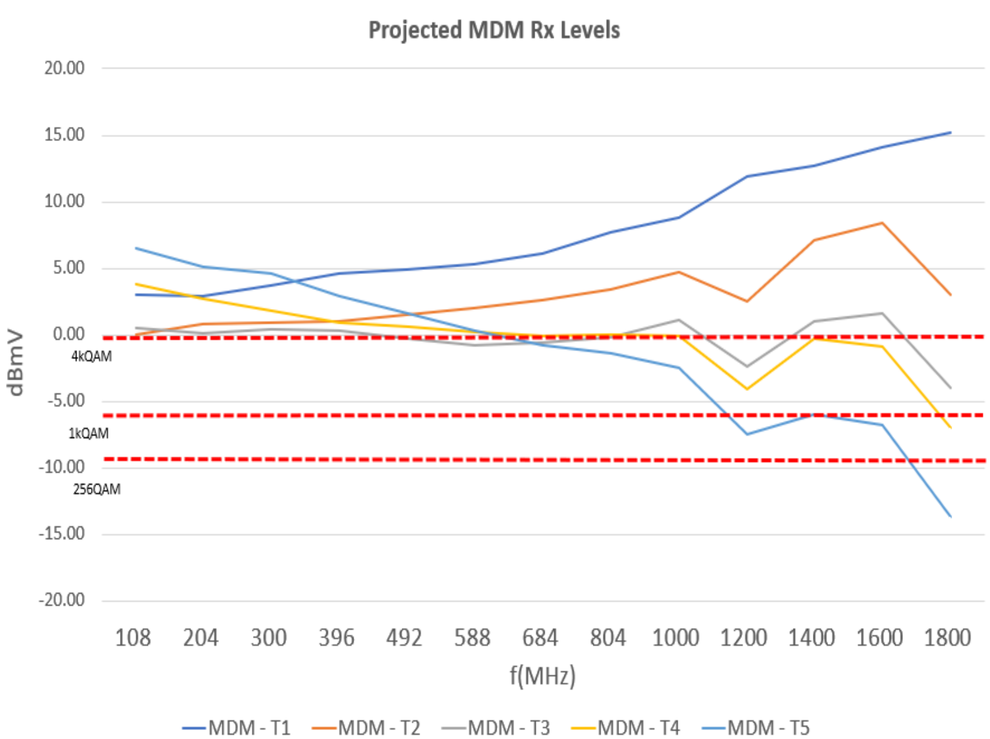

Figure 15 – Projected MDM Rx Levels – Continuing with the Tilt

2. Drop-down at 1GHz:

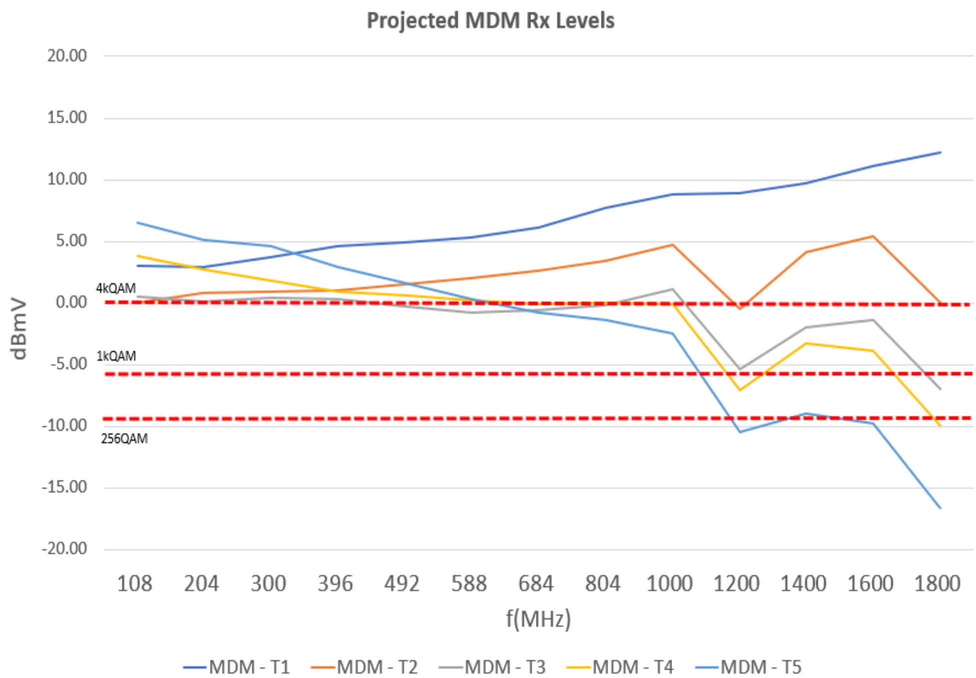

Figure 16 – Projected MDM Rx Level – Drop Down at 1GHz

3. Flat after 1GHz:

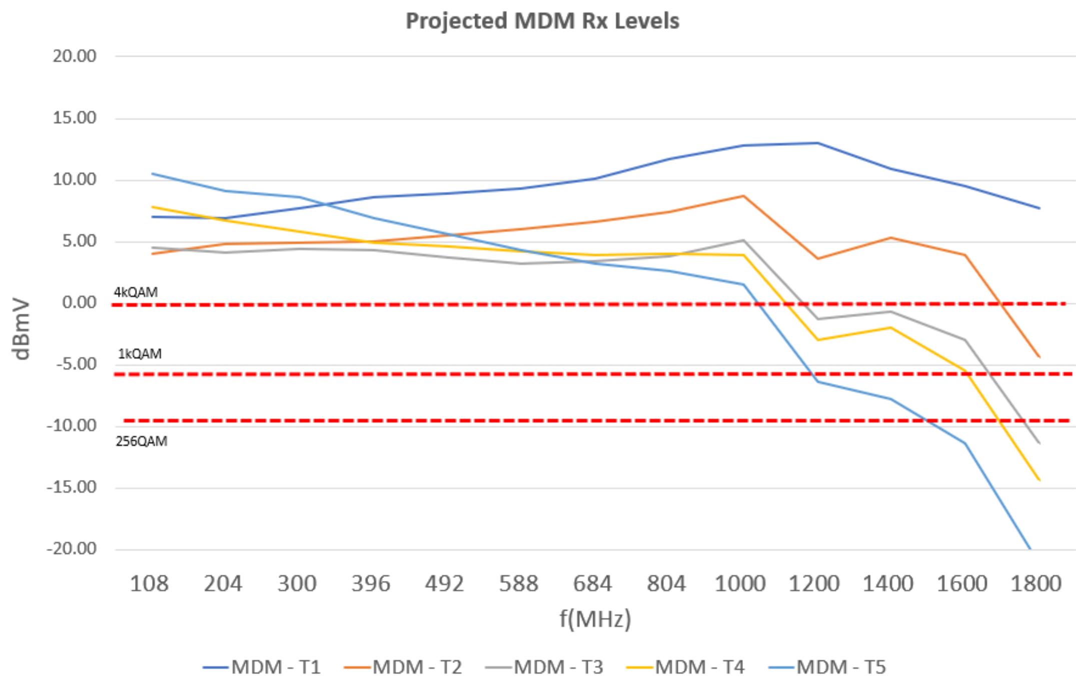

Figure 17 – Projected MDM Rx Levels – Flat after 1GHz

From Figure 15-17 it can be observed that 4kQAM is achievable in the majority of the spectrum across all the taps. Moreover, the only case that 256QAM is not achievable from the figures above is in the flat scenario above ~1.6GHz.

This can be overcome with adjusting the tap values along with using a different drop cable, for example RG11, which should increase the levels by ~2.5dB.

2.3.2.2. 625 P3 Location

The insertion loss (S21) results for this location are demonstrated in Figure 18 below:

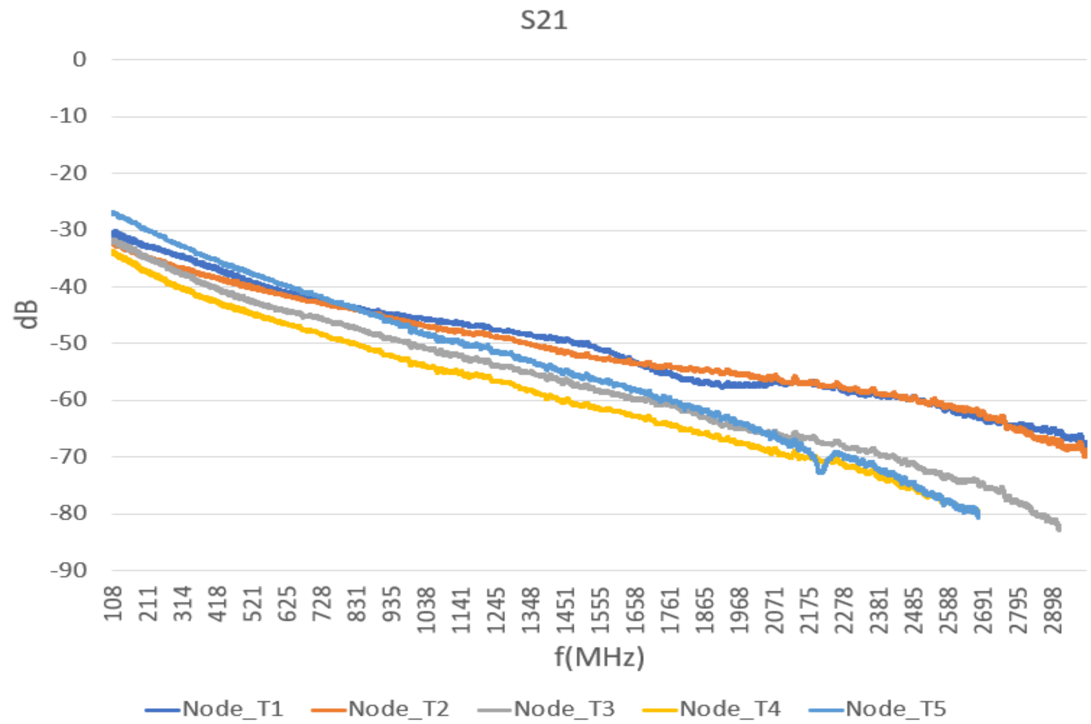

Figure 18 – S21 – 625P3 Test Plant

Based on the S21 measurement and the 1.8GHz power loading profiles in Figures 9-11, the following modem receive power levels (MDM Rx) can be calculated, for each power loading profile:

1. Continuing with the tilt:

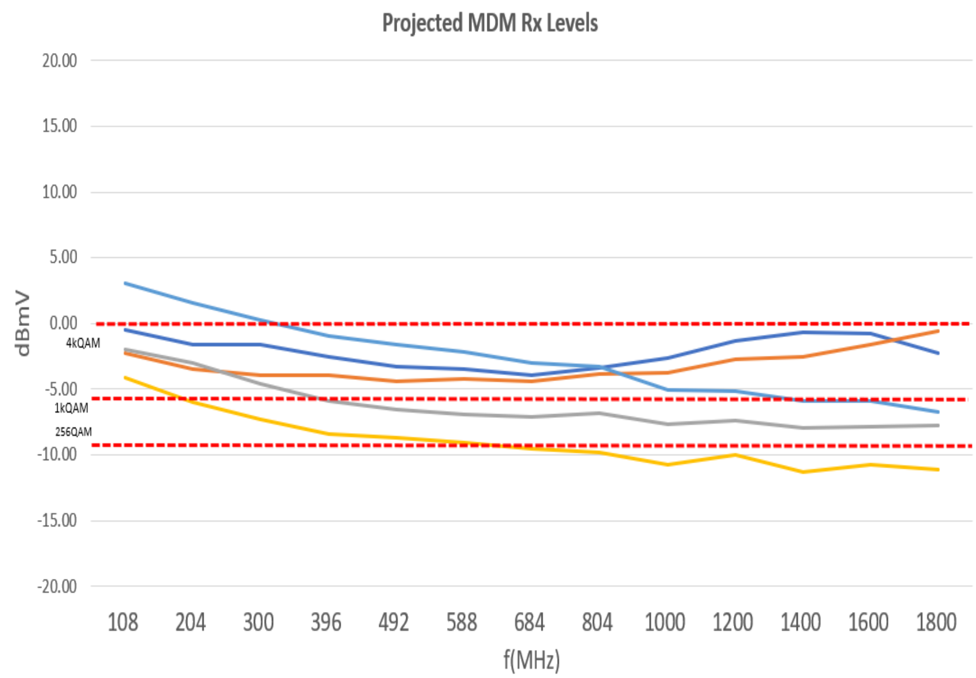

Figure 19 – Projected MDM Rx Levels – Continuing with the Tilt

2. Drop down at 1GHz:

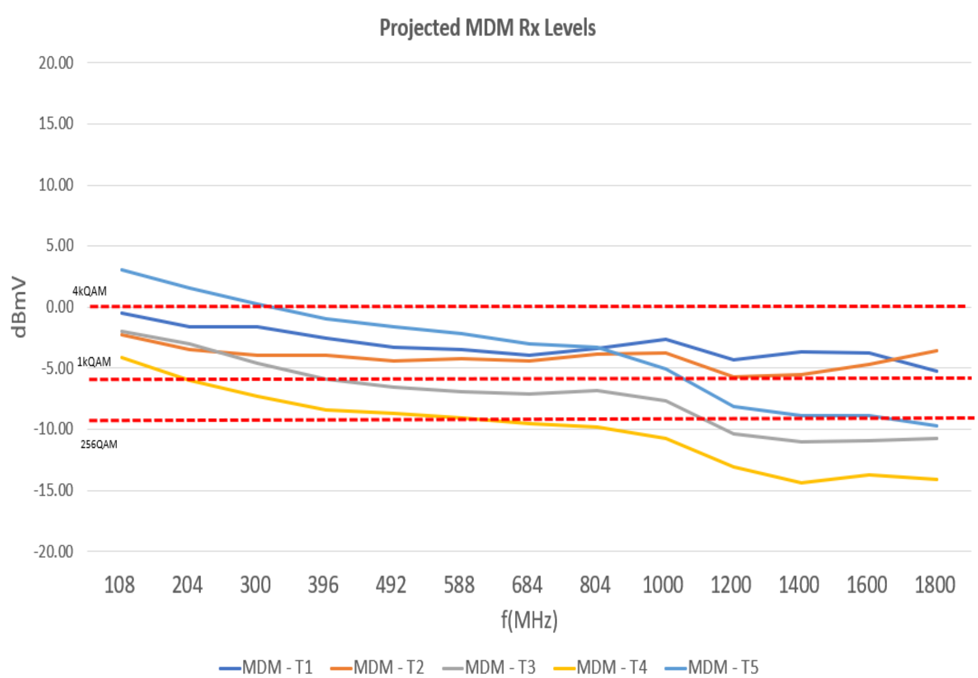

Figure 20 – Projected MDM Rx Levels – Drop Down at 1GHz

3. Flat after 1GHz:

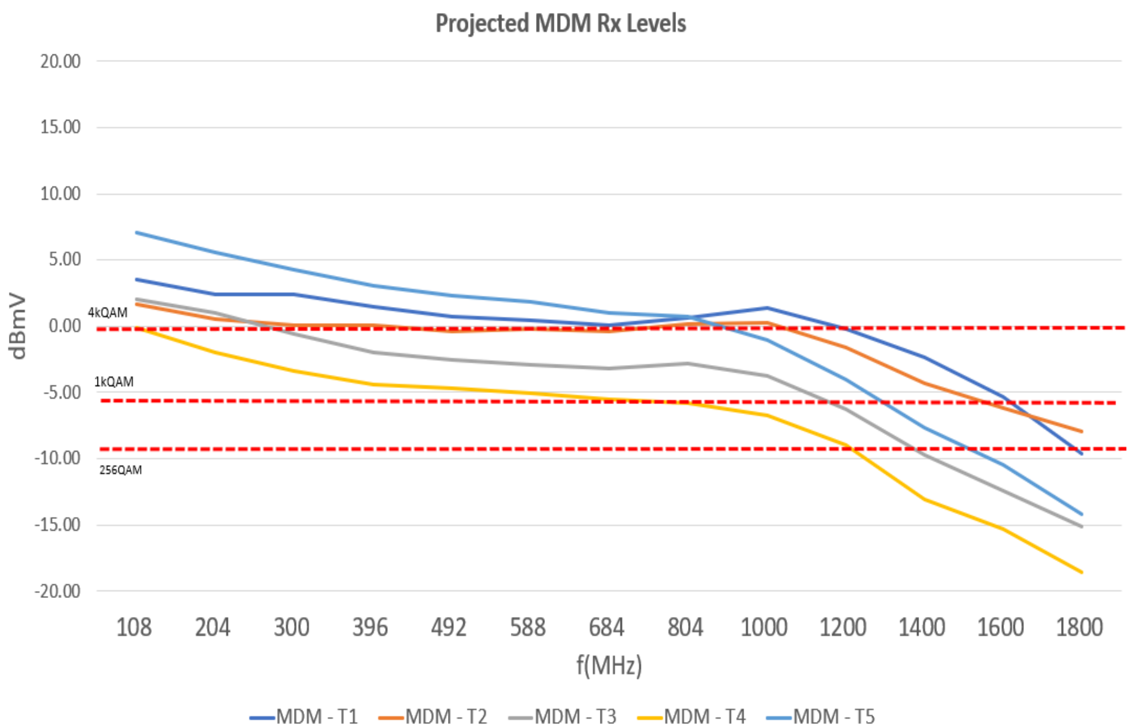

Figure 21 – Projected MDM Rx Levels – Flat after 1GHz

It can be observed that there are certain frequencies where the achievable modulation order is below 256QAM for taps 4 and 5 in the drop-down and flat scenario. This is primarily due to the fact that this plant was not optimized and designed for 1.8GHz. This is visible since tap 5 can achieve a higher order of modulation in comparison to taps 3 and 4. The tap value can play a crucial role in the MDM Rx power which consequently translates to the achievable modulation order. For example, in the case taps 3 and 4, a lower tap value can increase the achievable modulation order at the modem.

2.3.2.3. 500 P3 Location

The insertion loss (S21) results for this location are demonstrated in Figure 22 below:

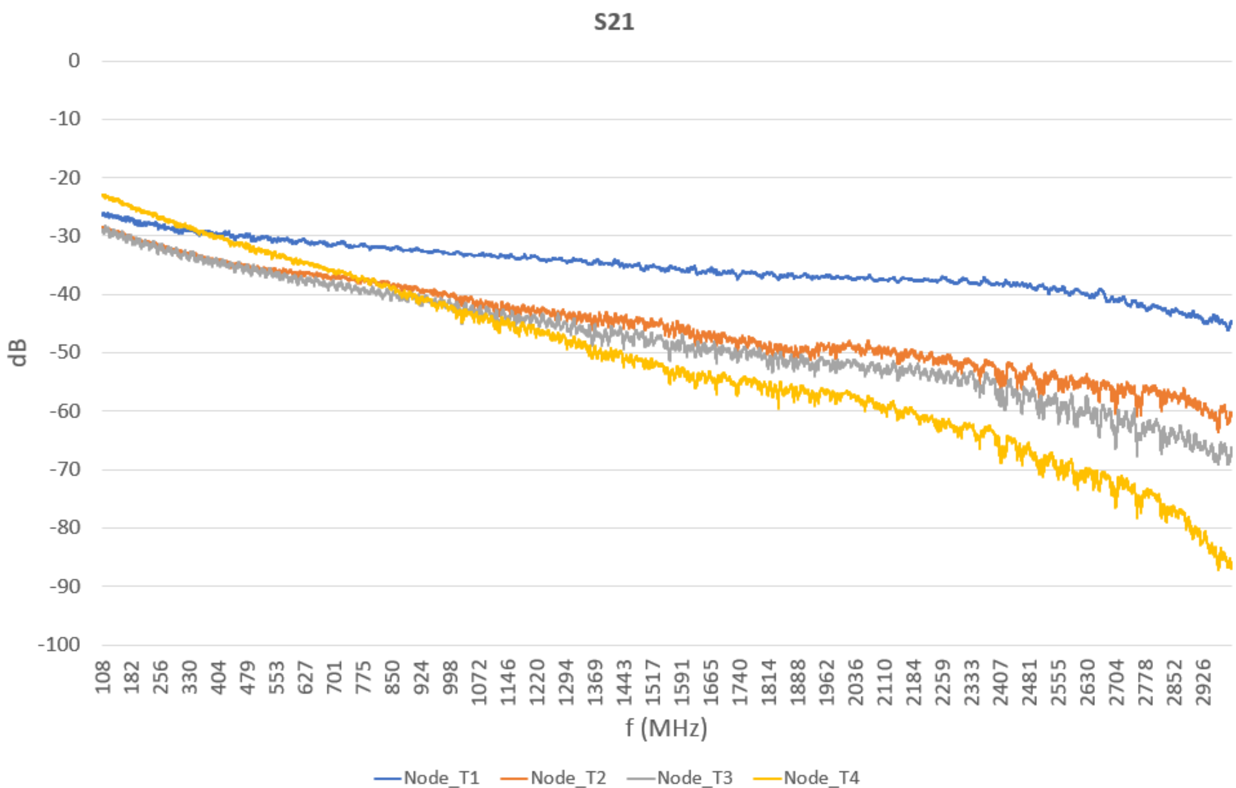

Figure 22 – S21 – 500P3 Test Plant

Based on the S21 measurement and the 1.8GHz power loading profiles in Figure 9-11, the following modem receive power levels (MDM Rx) can be calculated for each profile.:

1. Continuing with the tilt:

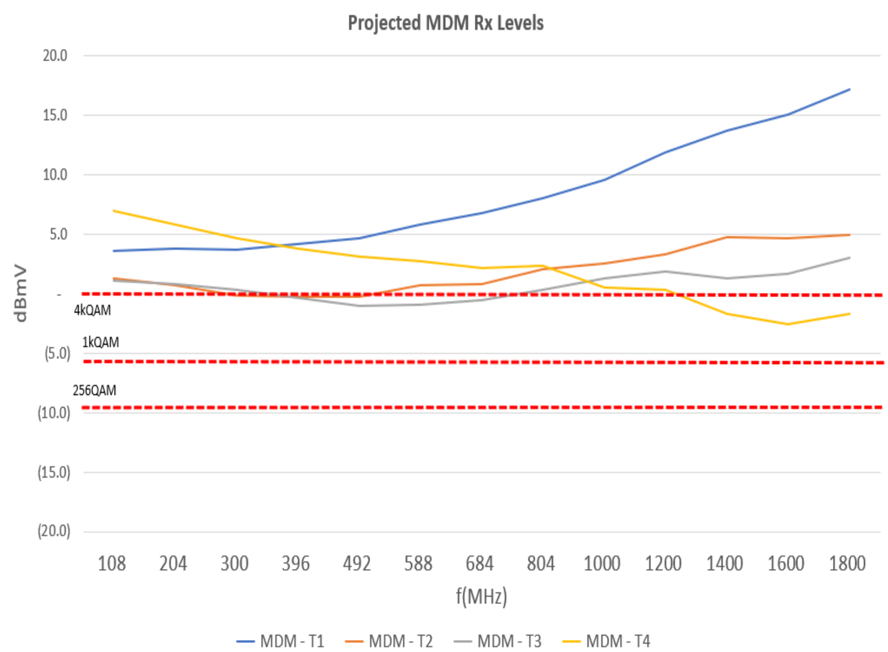

Figure 23 – Projected MDM Rx Levels – Continuing with the Tilt

2. Drop down at 1GHz:

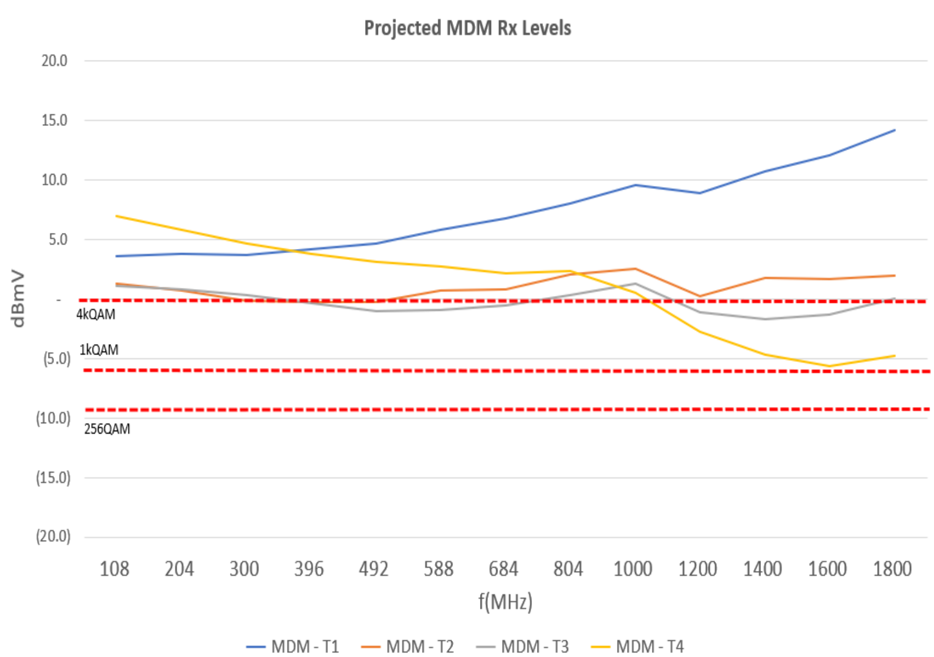

Figure 24 – Projected MDM Rx Levels – Drop Down at 1GHz

3. Flat after 1GHz:

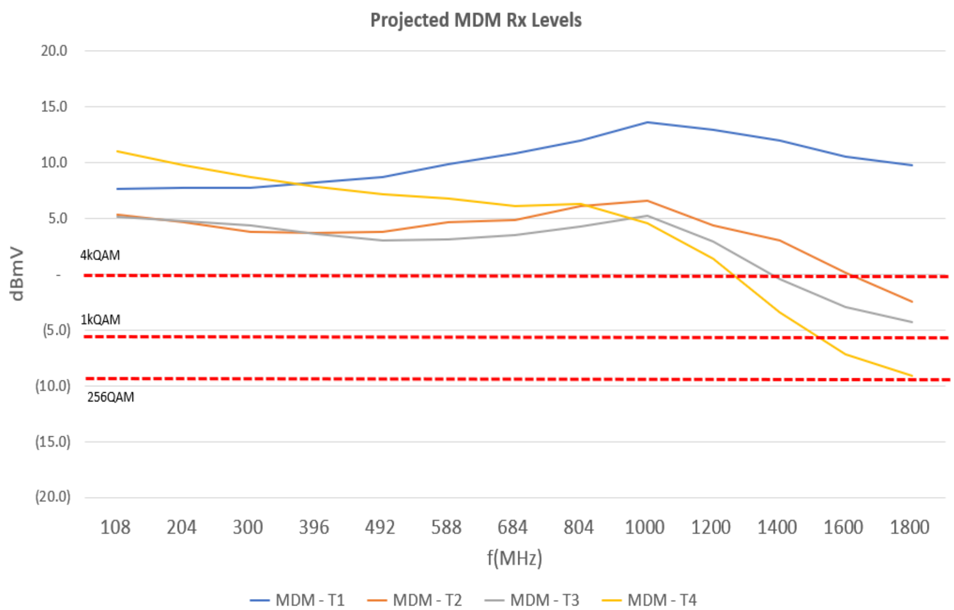

Figure 25 – Projected MDM Rx Levels – Flat after 1GHz

It's visible that although 500 P3 cable suffers more attenuation in comparison to newer cable types, 4kQAM is achievable in almost all cases, regardless of the tilt scenario.

2.3.1. Cascaded Deployment

Given that this technology will be deployed in existing cascaded plant, input levels to the next amplifier in cascade can be a concern. In order to substantiate this the following was performed:

- Mathematically remove the insertion loss of the final self-terminating tap along with 150' of RG6 drop cable
- Mathematically insert the insertion loss of a non-self-terminating tap at the end of line
- Mathematically insert the insertion loss if 100' of 412 cable
    - Given that 412 cable has the highest attenuation in the tested scenarios, as per figure 2, this was kept consistent amongst all test scenarios

Two commonly available classes of amplifiers in the industry today are the Mini-Bridger (MB) and the Line Extender (LE). Typical characteristics of each amplifier type are outlined below:

- Mini-bridger (MB):
    - 42dB of gain
    - 9dB of noise figure
- Line-extender (LE):
    - 34dB of gain
    - 10dB of noise figure

It should be noted that that the same TCP and amplifier output levels as section 2.3.1 has been applied. Below the results have been outlined:

2.3.1.1. 412P3 Location

The results for each power loading profile in Figures 9-11are demonstrated in Figures 26-28 below:

Note that all levels are shown in analog/6MHz.

1. Continuing with the tilt:

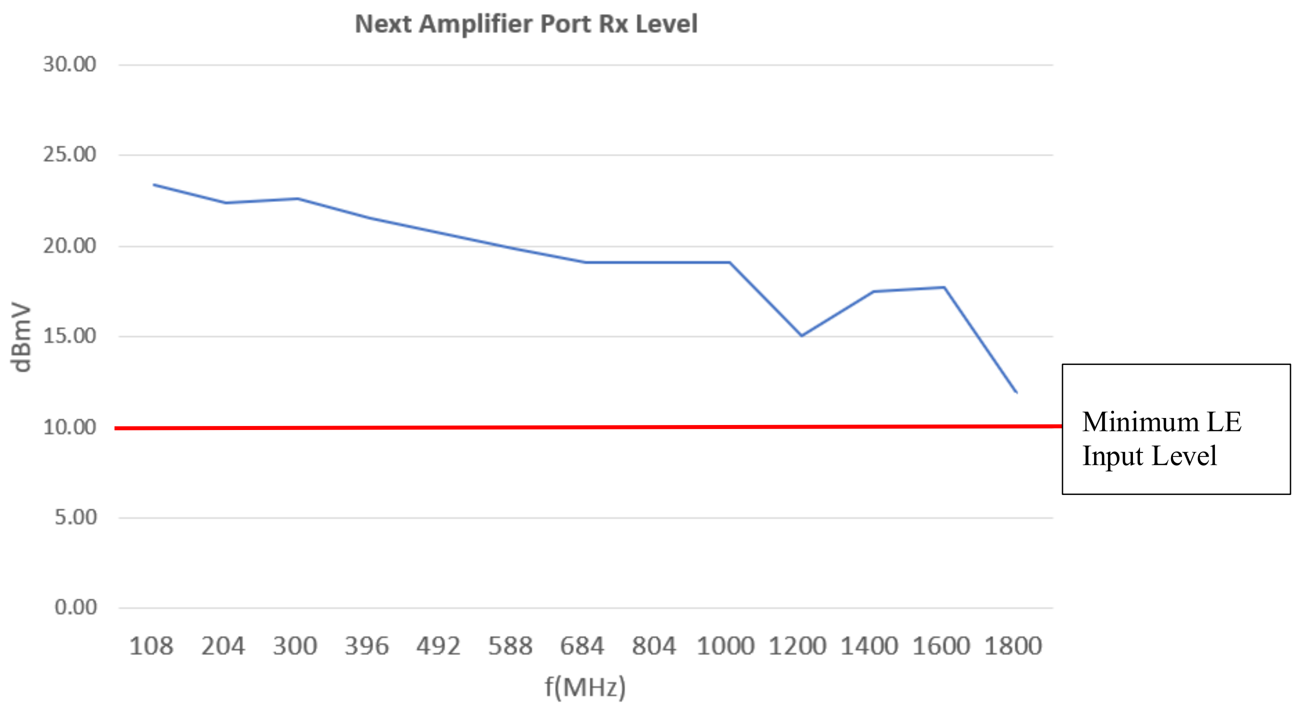

Figure 26 – Projected Amplifier Input Port Rx Levels – Continuing with the Tilt

2. Drop down at 1GHz:

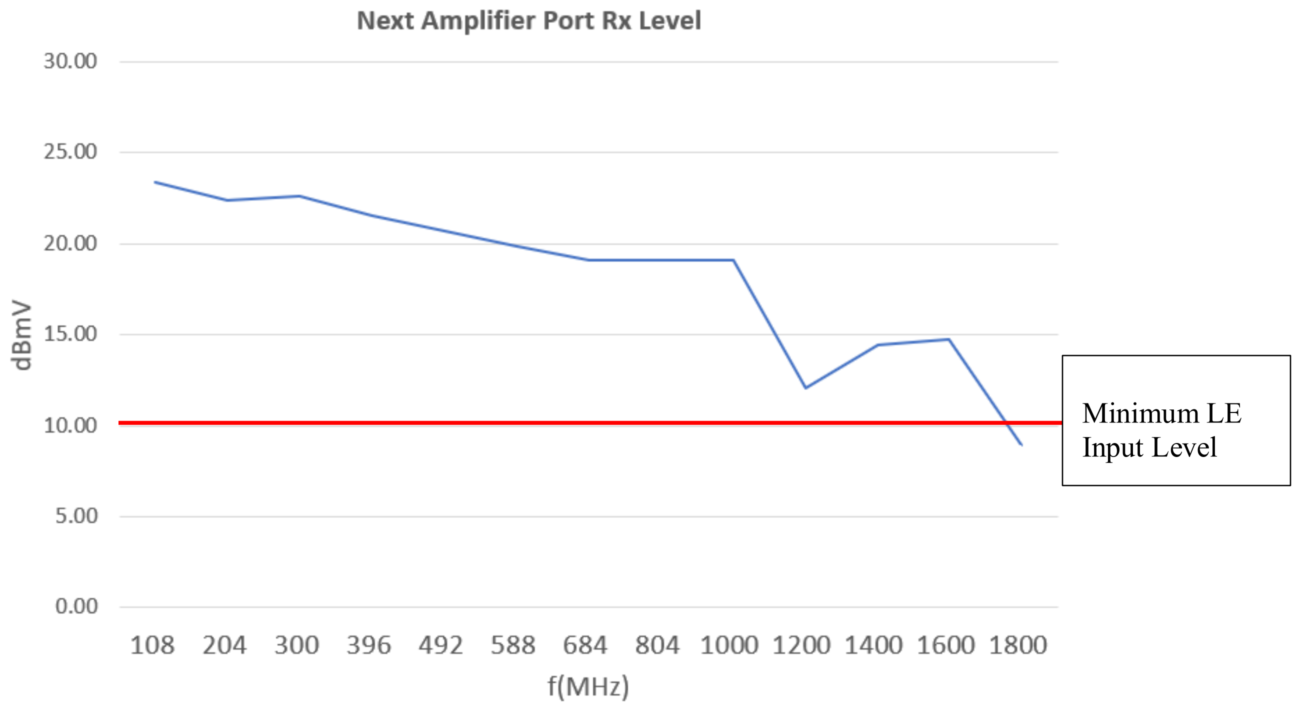

Figure 27 – Projected Amplifier Input Port Rx Levels – Drop Down at 1GHz

3. Flat after 1GHz:

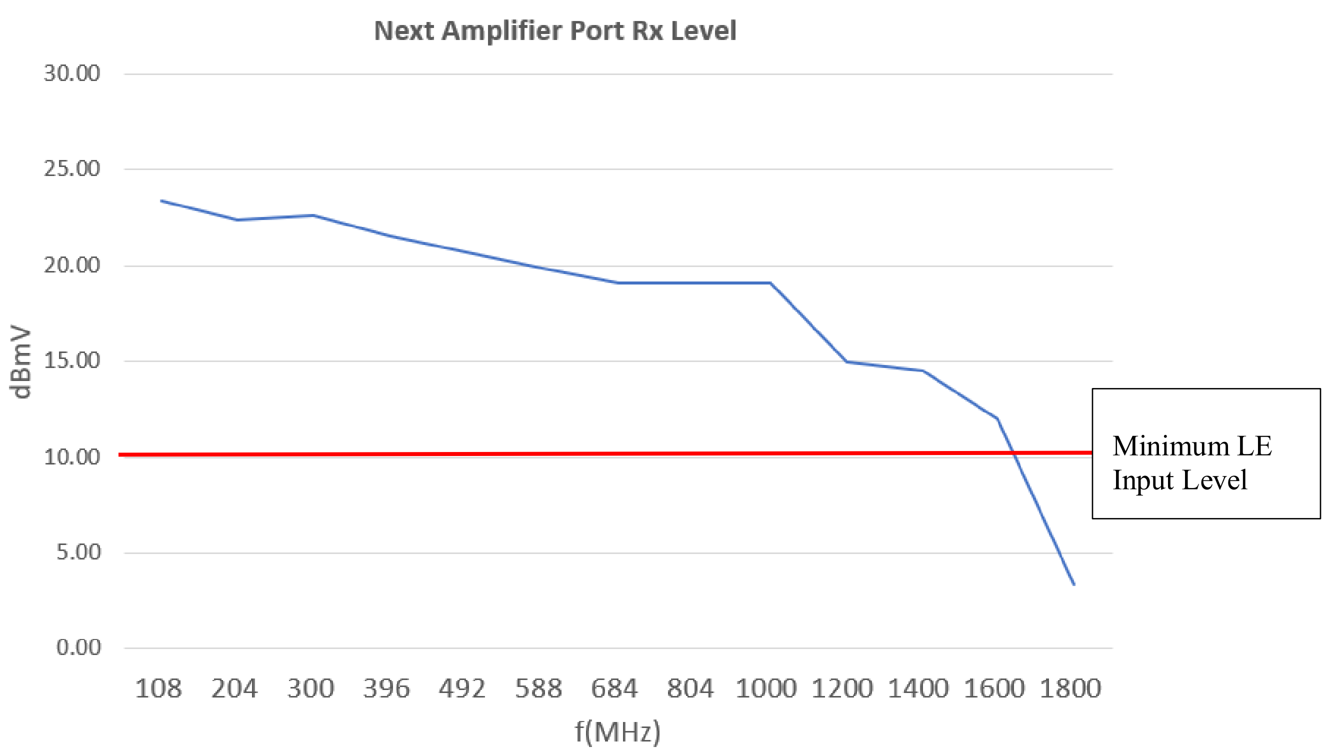

Figure 28 – Projected Amplifier Input Port Rx Levels – Flat after 1GHz

The results above indicate that the 'flat tilt' scenario will not have sufficient level at the amplifier port. This means that the operator will either have to sacrifice the performance of that spectrum (1600MHz – 1800MHz) or they will have to deploy a different tilt scenario (continue with the tilt or drop-down), assuming that the TCP of the currently deployed amplifiers have not be exhausted.

2.3.1.2. 625P3 Location

The results for each power loading profile in Figures 9-11 are demonstrated in Figures 29-31 below:

1. Continuing with the tilt:

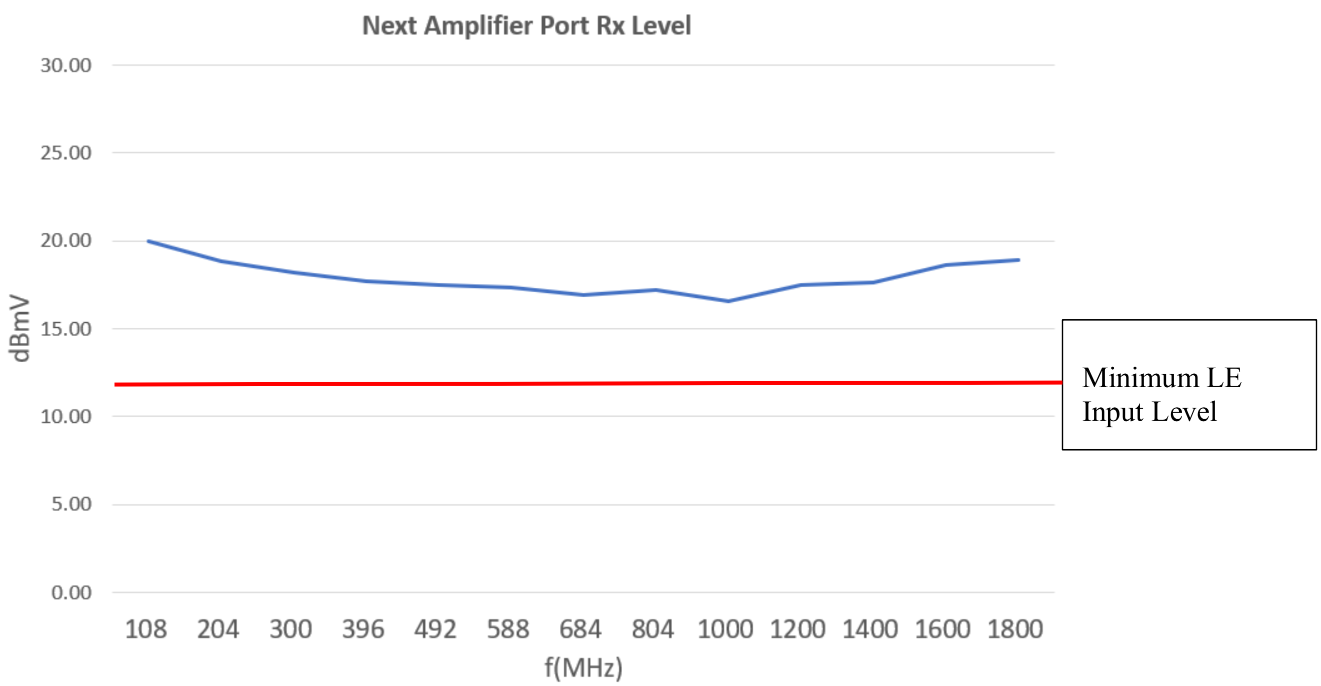

Figure 29 – Projected Amplifier Input Port Rx Levels – Continuing with the Tilt

2. Drop down at 1GHz:

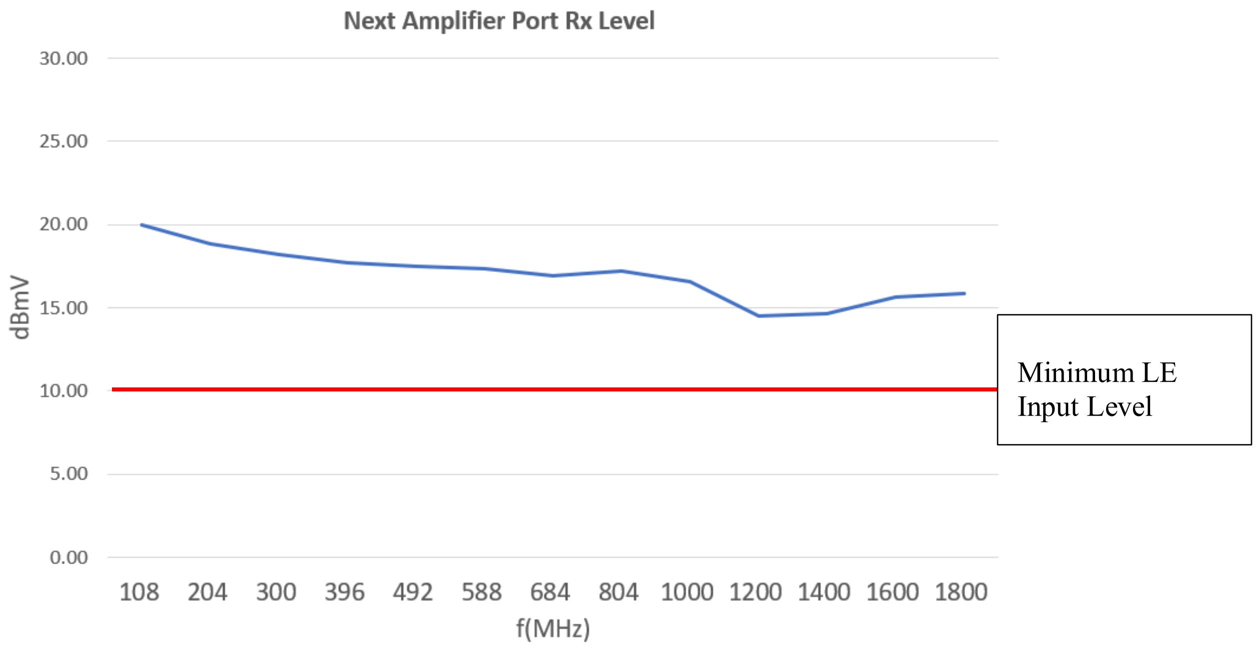

Figure 30 – Projected Amplifier Input Port Rx Levels – Drop Down at 1GHz

3. Flat after 1GHz:

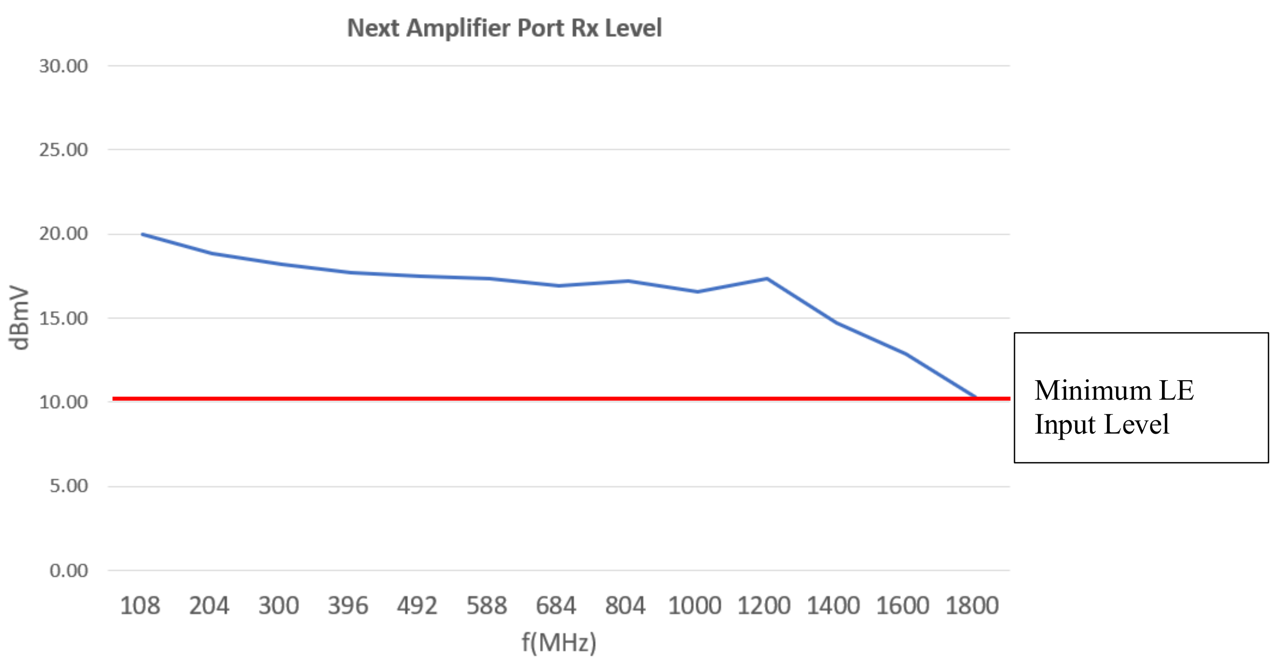

Figure 31 – Projected Amplifier Input Port Rx Levels – Flat after 1GHz

It's visible that in all the output power scenarios, assuming that the current amplifiers' gain and noise characteristics remain the same, the signal can be amplified with enough level to reach the next amplifier in cascade.

2.3.1.3. 500P3 Location

Tthe results for each power loading profile in Figures 9-11are demonstrated in Figures 32-34 below

1. Continuing with the tilt:

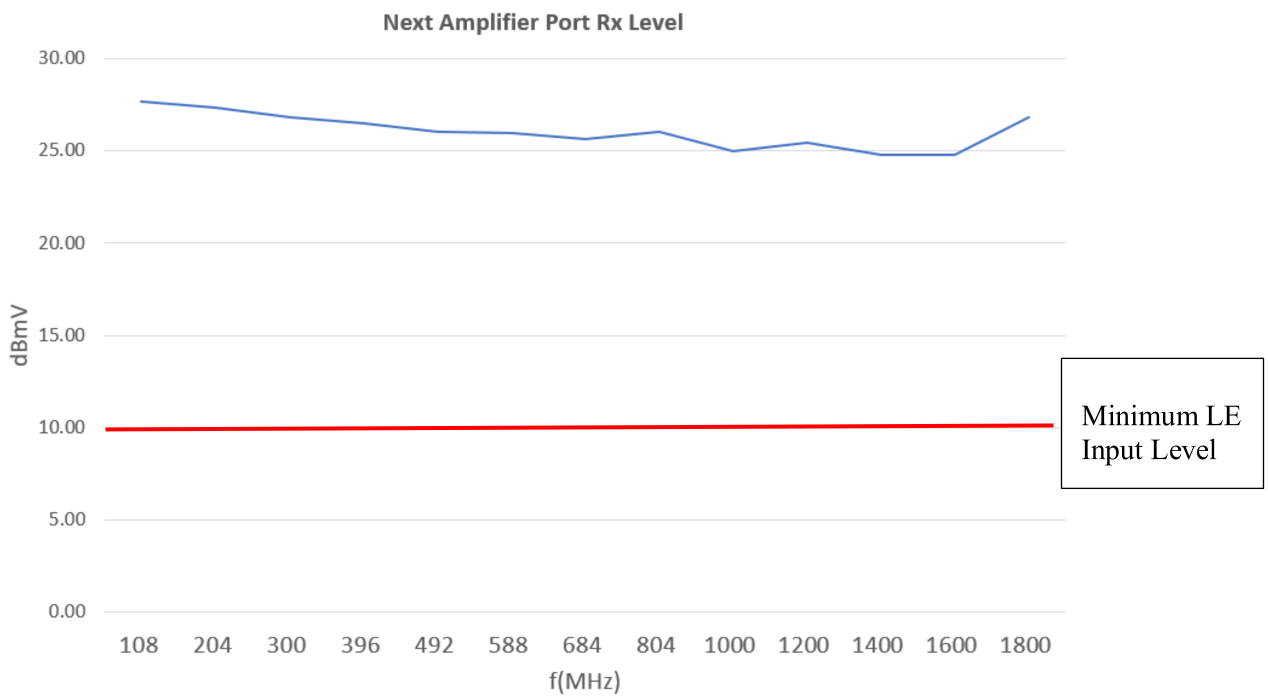

Figure 32 – Projected Amplifier Input Port Rx Levels – Continuing with the Tilt

2. Drop down at 1GHz:

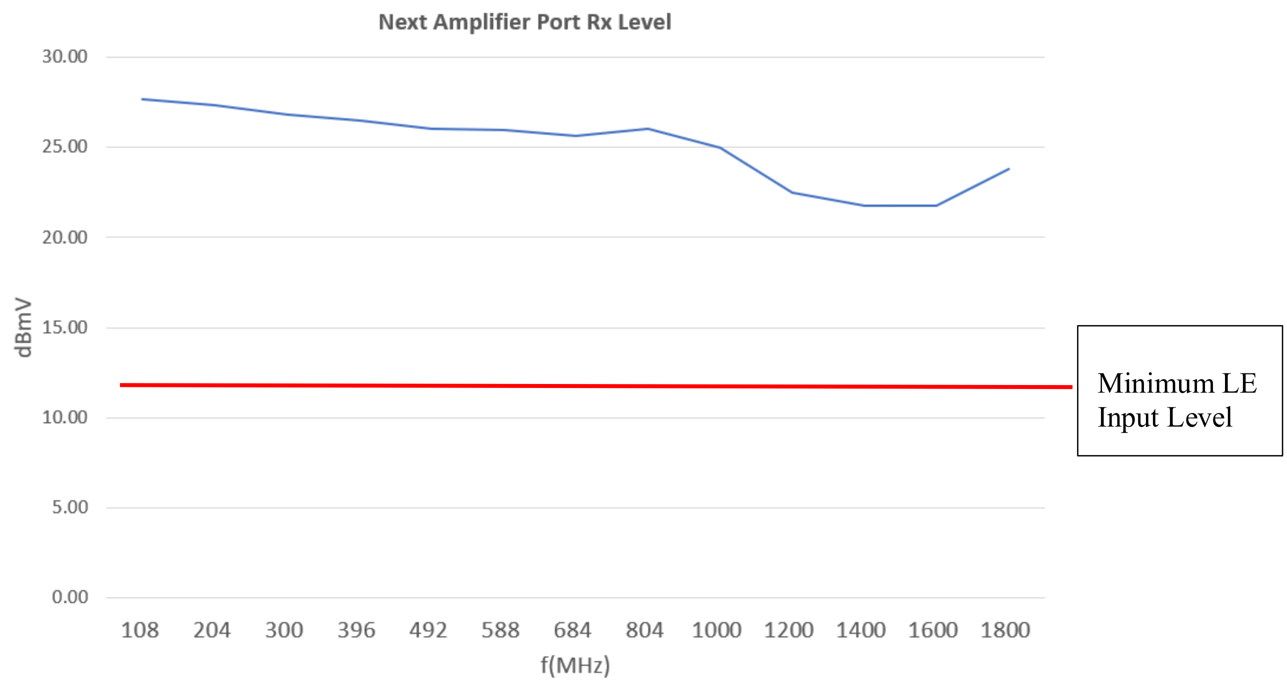

Figure 33 – Projected Amplifier Input Port Rx Levels – Drop Down at 1GHz

3. Flat after 1GHz:

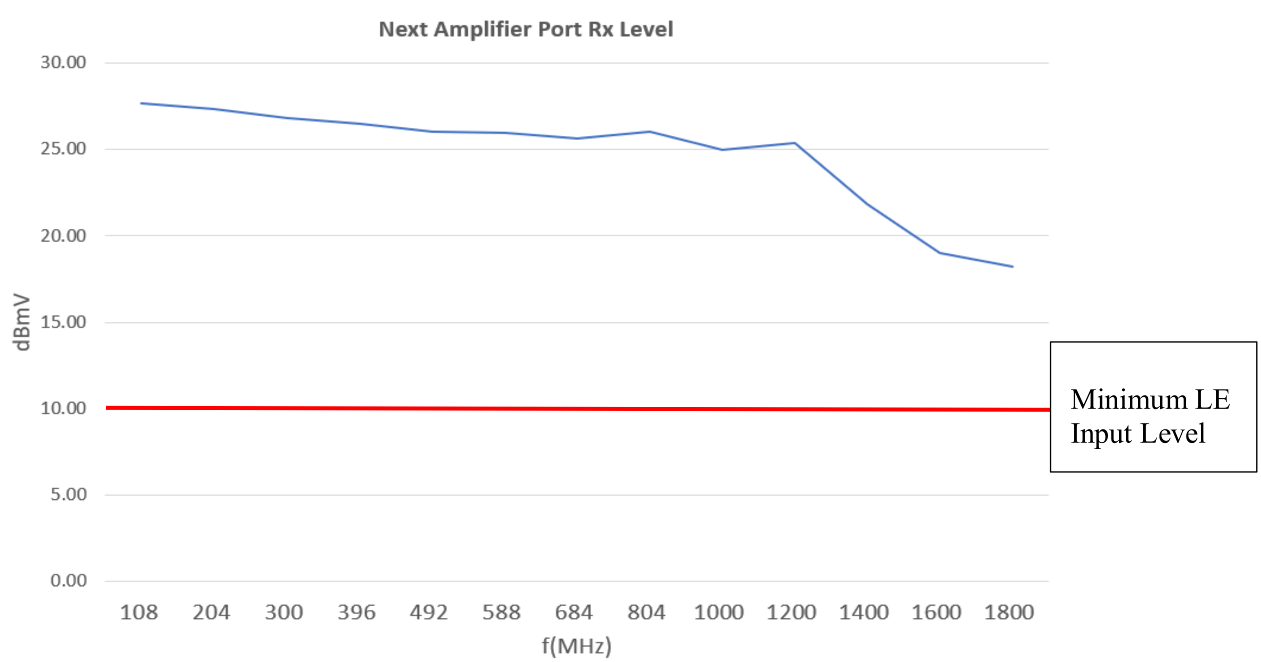

Figure 34 – Projected Amplifier Input Port Rx Levels – Flat after 1GHz

It’s visible that in all the output power scenarios, assuming that the current amplifiers’ gain and noise characteristics remain the same, the signal can be amplified with enough level to reach the next amplifier in cascade.

2.3.2. US MER Estimations

There are various challenges with upstream MER analysis. For downstream the main limitations of MER are receive power levels and the number of amplifiers in cascade. It’s generally accepted to assume 3dB of SNR loss per doubling of amplifiers. That’s not the case for upstream. The main limitation of MER in the upstream is noise funneling, which is hard to model, as this depends on the number of modems that are bursting simultaneously in the US, as well as unpredictable external interference sources that funnel upstream. Moreover, it’s hard to simulate what channels are going to be occupied in the US, depending on where the modem sits in the cascade.

With that in mind, since it’s generally understood that the modems will have the same transmit capabilities in the US as defined in FDX spec, as per Figure 12, the capacity comparison in the US for 1.8GHz ESD and FDX becomes easier.

The receive levels per 6.4MHz at the amplifier port in the return for each cabling scenario in Figures 3-5 are shown in Figure 35 below, assuming that the modem is transmitting throughout the FDX return-band (108MHz – 684MHz), with the tilt shown in Figure 12:

- 412P3 Location

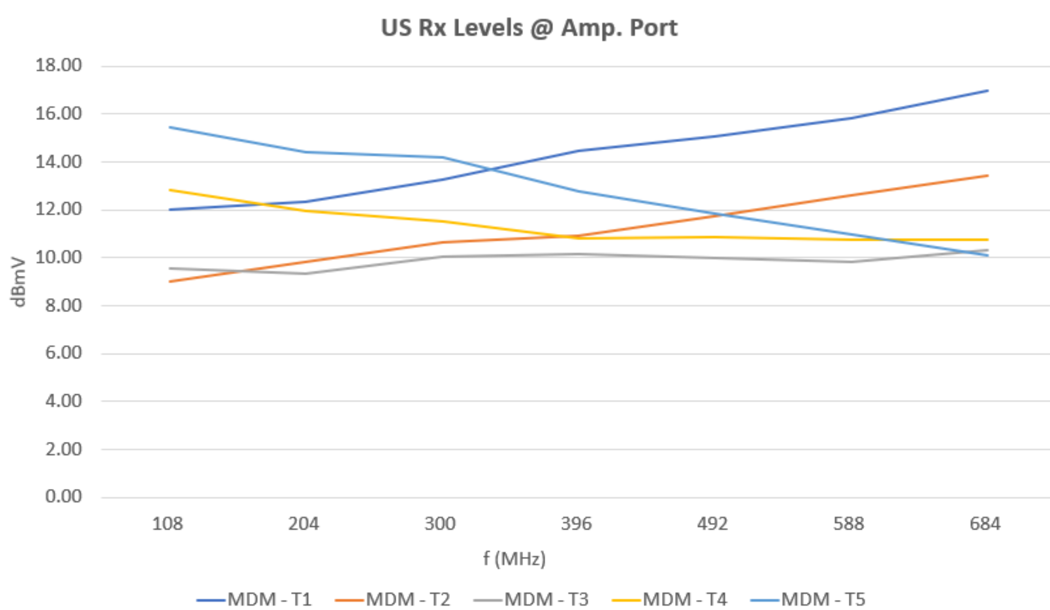

Figure 35 – Projected MDM Rx Levels at the Amplifier Port in the US

- 625P3 Location

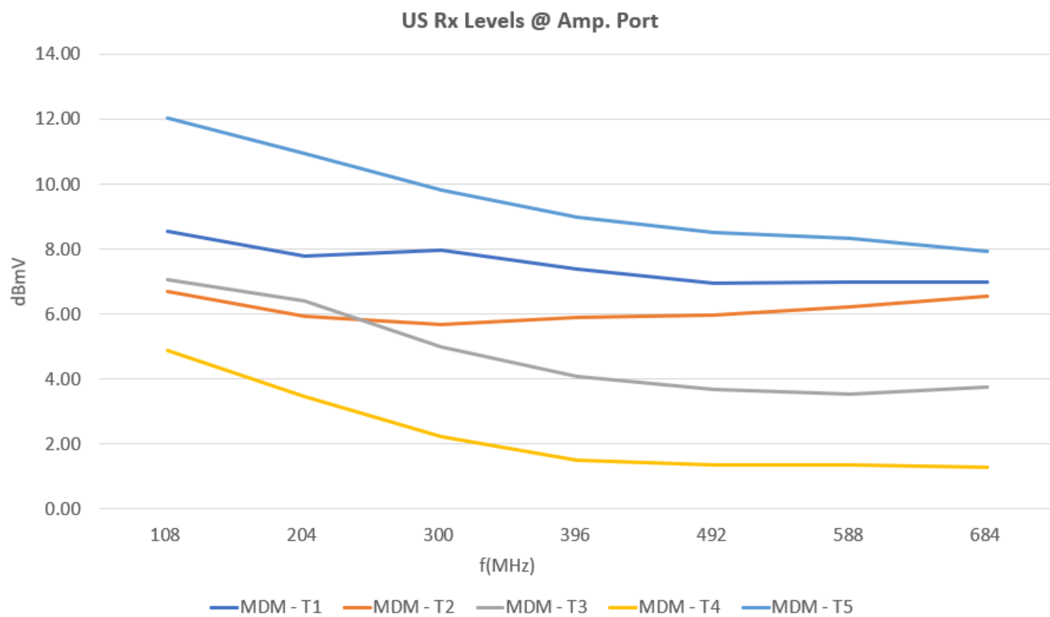

Figure 36 – Projected MDM Rx Levels at the Amplifier Port in the US

- 500P3 Location

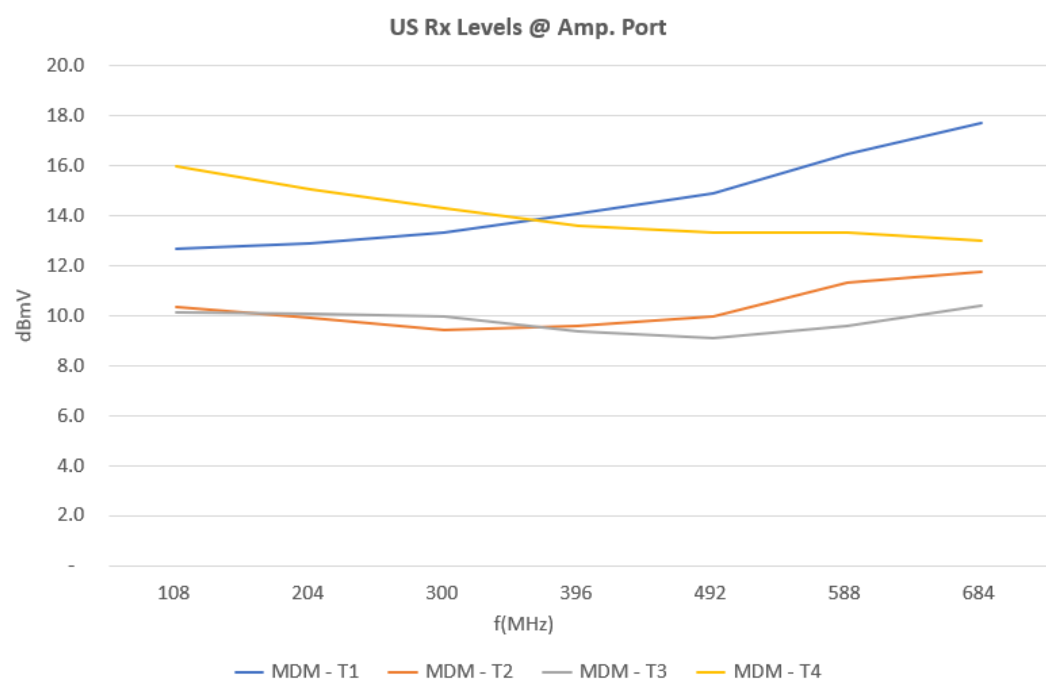

Figure 37 – Projected MDM Rx Levels at the Amplifier Port in the US

2.3.3. *Capacity Analysis*

In order to estimate the achievable capacity in the network, an US/DS split needs to be selected. The following assumptions have been considered for this analysis:

- The spectrum is assumed to be 100% IP / DOCSIS
- A guard band of 20% has been assumed for ESD
- The spectrum evolution has been assumed to be completed in this analysis, such that in both FDX and ESD cases the US has been stretched to 684MHz. The spectrum plans in Figures 38-39 below demonstrate this:

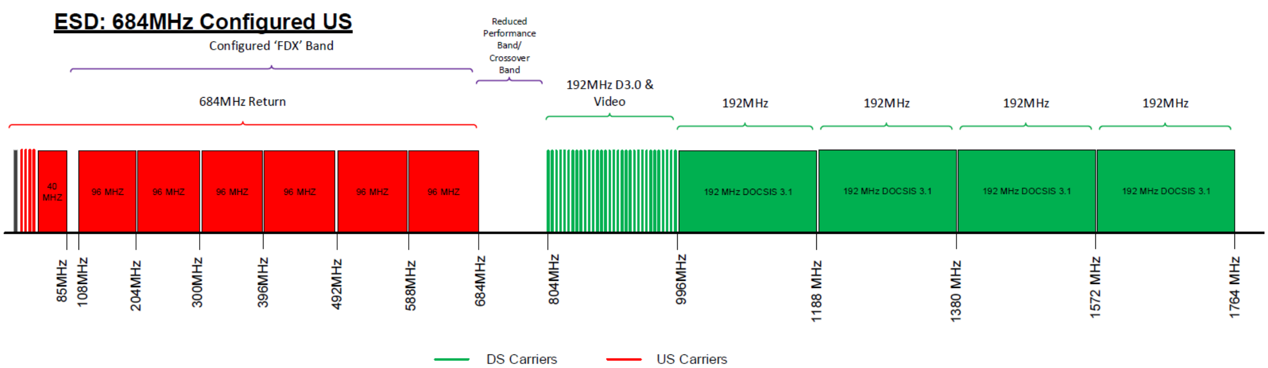

Figure 38 – 1.8GHz ESD Spectrum Plan

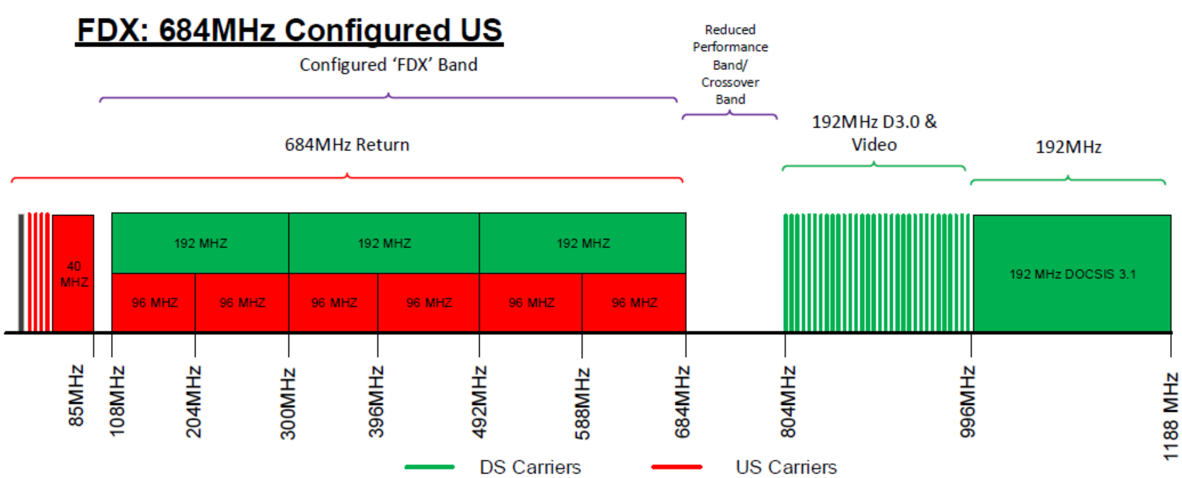

Figure 39 – FDX Spectrum Plan

- Given the data in section 2.3.2 and 2.3.3 an average of 1kQAM for the plant has been assumed for US up to 684MHz and DS up to 1.5GHz. A conservative modulation order of 256QAM has been assumed between 1.4GHz and 1.8GHz.
- For FDX, without available performance of technology under development, the following has conservatively been assumed
  - For N+0,1kQAM is used for both US and DS
  - For N+2,256QAM is used in the US and 512QAM is used in the DS

Based on the assumptions above and figures 38 and 39, the following table and bar chart can be produced:

Table 2 – Capacity Comparisons Table

Architecture	DS Throughput (Gbps)	US Throughput (Gbps)
1.8GHz Dynamic FDD	8	6.3
N+0 FDX	8.8	6.3
N+2 FDX	6.5	3.8

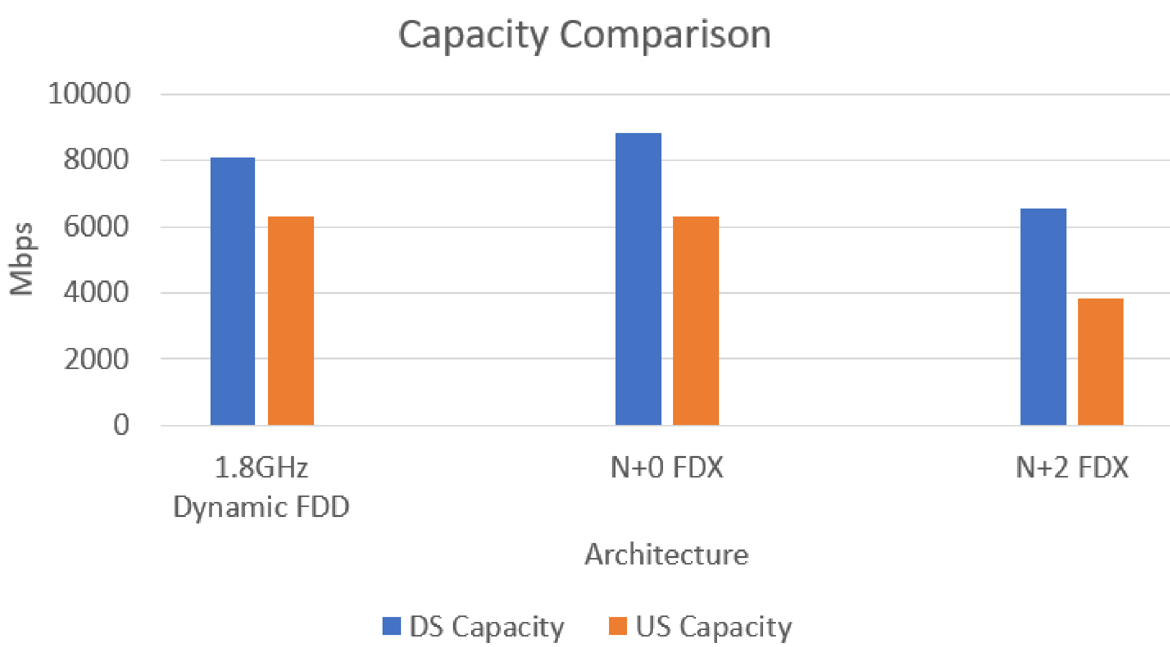

Figure 40 – Capacity Comparisons – Bar Graph

2.4. Cost Analysis

Assuming that N+X FDX amplifiers are developed, the following figures have been produced to visualize the comparisons between 1.8GHz ESD, N+2 FDX and N+0 FDX:

<u>Note:</u> The figures below are produced based on Shaw's experience performing fibre-extensions, as a part of node splits and drop-in upgrades, as a part of mid-split upgrades in the plant. Depending on each MSO's location and cost for construction and/or fibre-extension costs, these results may vary. The following have also been included in this analysis:

- ESD cost analysis:
    - No firbe extensions
    - Drop-in upgrades at existing node, amplifiers and tap locations
- N+2 FDX:
    - Fibre-extensions to existing amplifier locations such that no cascade length is larger than 2 after the installed nodes
    - Drop-in upgrades at existing node, amplifiers and tap locations
- N+0 FDX:
    - Fibre-extensions to existing amplifier locations such that no amplification is required after the installed nodes
    - Drop-in upgrades at existing tap locations

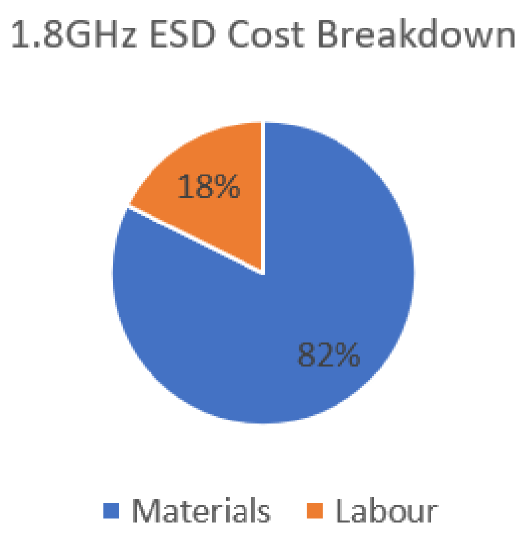

Figure 41 – 1.8GHz ESD Upgrade Cost – Materials vs Labour

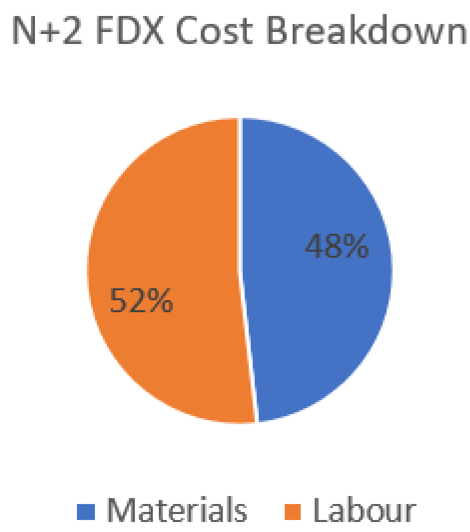

Figure 42 – N+2 FDX Upgrade Cost – Materials vs Labour

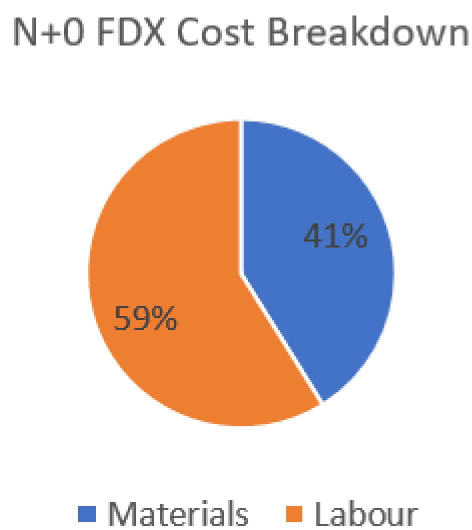

Figure 43 – N+0 FDX Upgrade Cost – Materials vs Labour

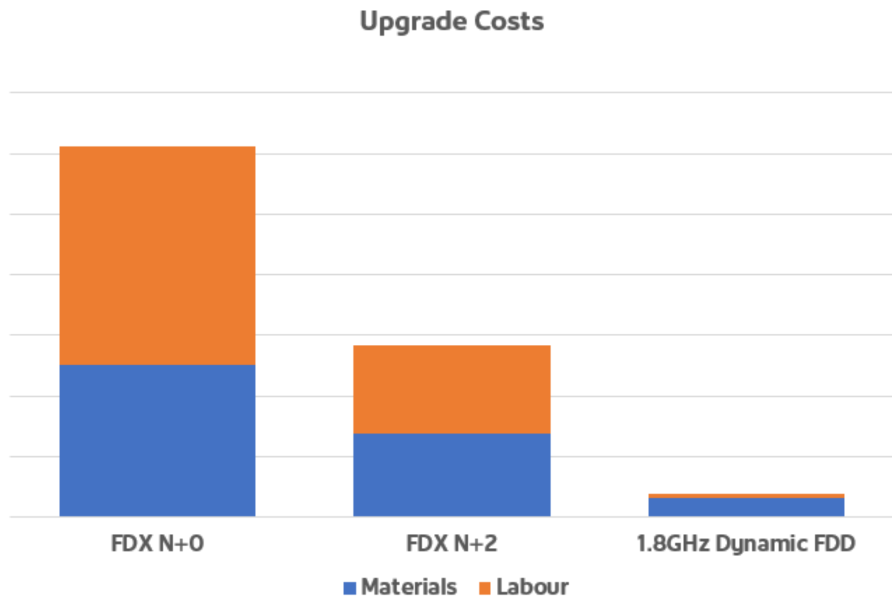

Figure 44 – Upgrade Costs – Materials vs Labour

2.5. CM's

Although this paper has mainly focused on the analysis of various access architectures and costs associated with them, it is worth noting how the CMs fit in the full story. FDX modems will have the most flexibility and they can be deployed in any architecture, including 1.8GHz ESD, given that the echo-canceller (EC) can be utilized as a 'dynamic' di-plex filter. This will have an impact on the cost of the modem.

Di-plexed modems don't have the same dynamic capability as FDX modems but they do potentially provide faster time to market along with lesser cost.

Given that MSOs may have different deployment strategies for their access networks, both modems mentioned above can potentially be deployed. This means that if they same silicon is developed, accommodating FDX with 1.8GHz of spectrum (DOCSIS 4.0), each operator can determine how the silicon can be implemented in their modems, which can potentially reduce price of the silicon and the modems.

Conclusion

As per the data outlined in this paper, 1.8GHz ESD is a viable option for the access network. As demonstrated in the plant measurements taken and the analytics carried out, it is reasonable to expect high modulation orders such as 4kQAM and/or 1kQAM from the existing plant. The results of the analysis identified distance as the most significant factor in loss and therefore achievable MER.

Based on the capacity analysis demonstrated in this paper, the following can be concluded:

- **OSP**
  1.8GHz ESD equipment (amplifiers, taps and passives) provides the lowest projected initial implementation cost for roughly equivalent total capacity as N+0 FDX. Although N+0 FDX can match and potentially surpass this capacity, it doesn't utilize the full RF capacity potential of the current coaxial cable in the plant as much. Upgrading the current HFC actives to extract that capacity is a viable possibility with DOCSIS 4.0 ESD. For some operators, this also provides for a more evolutionary approach, and more similar to MSO upgrades of the past, for increasing the available bandwidth in the network.
  Echo-cancellation technology has the potential to reduce the guard band between US and DS, if they were to be implemented in 1.8GHz amplifiers and nodes, maximizing spectral efficiency and flexibility. Industry alignment on this item can potentially drive down cost and decrease the development timelines.

- **CPE and CMTS (RPHY)**
  FDX based silicon with echo-cancellation technology provide the most flexibility since the equipment can be deployed in any architecture. Given that customer premise equipment can be a challenge to change or remove in the future, this silicon can remove that burden.
  Industry alignment on this topic would drive down costs, making this a more viable option.

Abbreviations

bps	access point
BW	bandwidth
dB	decibel
dBmV	decibels relative to one millivolt
DOCSIS	data over cable service specification
DS	downstream
ESD	extended-spectrum-DOCSIS
HFC	hybrid fiber-coax
FDX	full-duplex-DOCSIS
FTTP	fibre to the premises
GHz	giga hertz
Hz	hertz
ISBE	International Society of Broadband Experts
LE	line extender
MB	mini bridger
MDM	modem
MER	modulation error rate
MSO	multiple system operator
PoE	point of entry device
QAM	quadrature amplitude modulation
Rx	receive power
SCTE	Society of Cable Telecommunications Engineers
SNR	signal to noise ratio
Tx	transmit power