Distributed Gain Architecture

Increased Performance, Decreased Power Draw

A Technical Paper prepared for SCTE•ISBE by

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1. Introduction

As data trends and usage increase, operators are looking for methods to increase the capacity of the network. This is especially the case with upstream. During the COVID-19 pandemic, the need to increase the return-band spectrum bandwidth and throughput became evident. The graph below demonstrates this increase in usage:

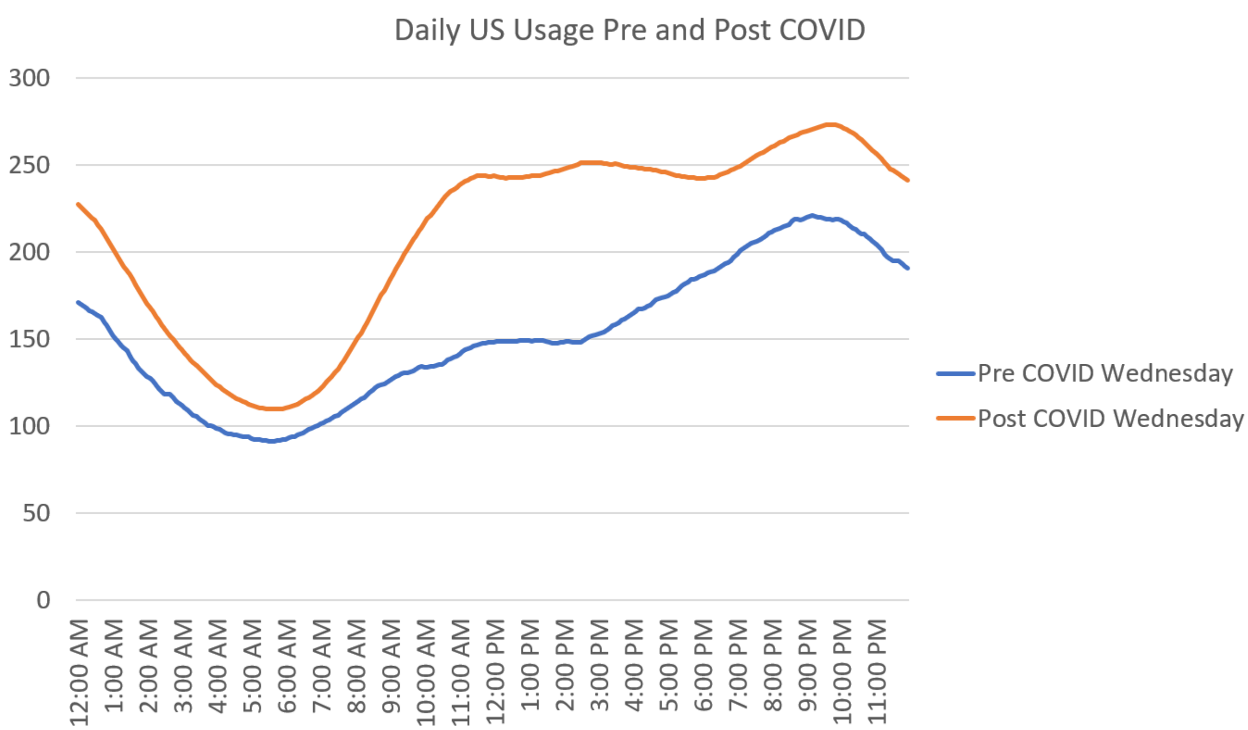

Figure 1 – Upstream Data Trends Pre and Post COVID-19

As a part of upgrading the outside plant (OSP) to 1.8 GHz extended spectrum DOCSIS (ESD) and beyond, to achieve 10 Gbps and more, many operators face the costly prospect of amplifier re-spacing. Given how costly and labour intensive plant re-spacing can be, innovating ideas to overcome this challenge are highly encouraged.

MSOs have traditionally relied on high gain amplifiers to overcome coaxial loss in the access architecture. Traditional amplifiers have served this purpose well, providing 50-60 dBmV of gain, however, they can be power hungry, drawing 60-80 watts each. They can also introduce unwanted distortions in the spectrum, decreasing the signal quality and essentially lowering the achievable throughput in the network.

Distributed gain architecture involves deploying smaller and lower gain amplifiers in selective areas of the network, in conjunction or instead of high gain amplifiers. These amplifiers have a much lower power draw in comparison traditional amplifiers, which can drastically decrease the draw from the existing power supplies, leaving more room for other technologies to be deployed in the access network.

Due to the simplicity of these amplifiers, being single stage with a fixed gain and tilt, they can also be deployed in conjunction with traditional amplifiers. This can boost the end-of-line performance in areas

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that the span loss of the plant cannot be overcome with the available total composite power (TCP) of the traditional amplifiers.

This paper will provide an elaborate study and comparison between a traditional N+2 plant, N+2 plant with booster amplification, and a fully distributed gain versions of the same plant models. An end-of-line performance and power analysis will be provided for each scenario.

2. Technological and Operational Challenges with Extended Spectrum DOCSIS

Prior to the analysis, we must first discuss the challenges that operators face when considering upgrading their access networks to ESD.

In 'traditional' plant, being 750 MHz or even 1 GHz, most MSOs expect 4kQAM to be achievable by each orthogonal frequency division multiplexing (OFDM) carrier deployed, however, the same is not true for 1.8 GHz and beyond. One of the primary reasons for this would be the current spacing that the outside plant is designed to.

2.1. Plant Spacing and Drop-In Upgrades

Most OSP architectures are designed to 550 MHz and 'stretched' to 1 GHz. As a result, most of the radio frequency (RF) power in plant actives, including nodes and amplifiers, has been utilized to overcome the existing span losses. Span loss is defined as the total insertion loss of all the elements in a hybrid-fibre-coax (HFC) span, measured in dB. This includes all the plant passives such as taps, splitters and couplers. Although the span losses today are manageable with the current amplifier gains, they will certainly become a major point of concern when the spectrum is expanded to higher frequencies. As an example, a span loss of 35 dB at 1 GHz in a traditional plant equates to 49 dB at 1.8 GHz.

Plant re-spacing is always an option, however it can be extremely costly and, as a result, operators will rely on the expanded power of amplifier gain chips to overcome span losses.

2.2. Total Composite Power (TCP)

It is generally understood that 1.8 GHz amplifier chips will have ~75 dBmV of total composite power (TCP) available. With that in mind, not all of this power is available for use. As an example, the figure below demonstrates the trade-off between modulation error ratio (MER) and TCP utilized:

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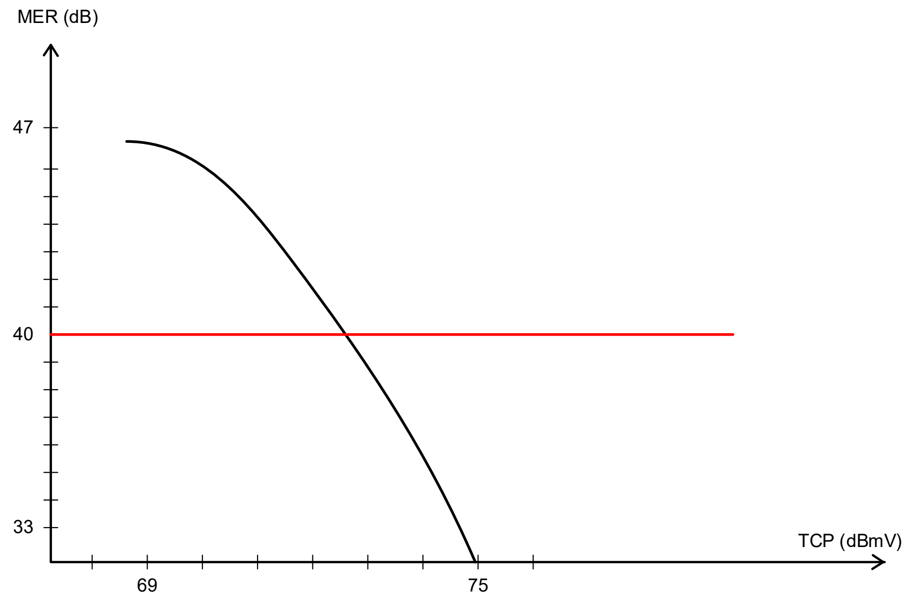

Figure 2 – TCP vs. MER

As a general rule of thumb, 3 dB of back-off is needed to achieve 40+ dB MER, which is typically what operators aim for. Along with that, the internal loss of the active device has to be accounted for, which is usually 2 dB. To summarize, there is a total of 70 dBmV of power to be utilized at the port of each active device. This can be a concern for operators given that 65-68 dBmV of TCP has already been allocated to overcome the span losses in the 'traditional' plant.

2.3. Taps

Taps and passives can be another point of concerns when upgrading the OSP to 1.8 GHz. Traditionally, most operators have relied on face-plate upgrades to expand the spectrum range of plant taps and passives. This is generally accepted as a faster and more cost-effective method to upgrade the available bandwidth of taps.

Unfortunately, this might not be the case with 1.8 GHz upgrades. A face-plate upgrade of the current 1 GHz taps can potentially expand the bandwidth to approximately 1.6 GHz. It should also be noted that this is a best effort.

This can be a concern given the uncertainty of the maximum available bandwidth in the plant. As a result, it is generally accepted that taps and passives have to be swapped out for 1.8 GHz version. Given that the entire housing of the tap has to be swapped out as a part of this effort, most of the taps being developed will have housings that can support up to 3 GHz with future face-plate upgrades, future proofing the plant for 3 GHz upgrades.

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3. Cascaded Plant Design Challenges

HFC architectures can be divided into two categories:

- Passive plant (N+0): where no amplifiers are used after the node
- Cascaded plant (N+X): where amplifiers are used to boost the signal multiple times to the end-of-line

When designing an N+0 plant, the main point of concern is the output performance of the node. Assuming that we are operating in a distributed access architecture (DAA) plant, the primary drivers for the plant quality would be the MER of the DAA device. Since no amplifiers are used to boost the signal, no noise or distortion is added to the primary signal being generated by the DAA device.

On the contrary, when designing an N+X plant, the following can be of concern:

- Amplifier noise contribution
- Amplifier distortion contribution

Note: In order to calculate the overall system carrier to noise ratio (C/N) a starting C/N has to be assumed. Due to the continued development in this area, no starting C/N has been assumed from the RF source (RPD or RMD). Instead, the cascaded amplifier network's contribution to the system C/N has been calculated in this paper. Once a starting C/N is determined at the output of the node, the overall system C/N can be calculated.

3.1. Noise

Designing a cascaded system for optimal carrier to noise is always a big priority for an operator. One of the biggest contributors in system design is the receive power (Rx Power) at the amplifier, given that it is one of the primary drivers for the overall system C/N.

The equation below calculates the C/N of a single amplifier:

$$C/_N\,(dB) = \; C_i(dBmV) + 57.4 - NF(dB)$$

Where:

- C_i: input signal
- NF: Noise figure of the amplifier

Note: the number 57.4 is the thermal noise power in dBmV for 6 MHz QAM carriers.

The equation above shows the significance of the Rx power versus noise figure of the amplifier, in overall system design.

The overall system C/N for amplifiers operating at different output levels can be derived from the following equation:

$$C/_{N_{total}}\,(dB) = \; -10log\left\{10^{\frac{-C/_{N1}}{10}} + \; 10^{\frac{-C/_{N2}}{10}} + \cdots + \; 10^{\frac{-C/_{Nn}}{10}}\right\}$$

Where, $C_{/N_x}$ is the carrier to noise of each amplifier calculated independently.

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When cascading identical amplifiers operating at the same output level, the following approximation is typically used:

$$C/N_{total}\,(dB) = C/N_x - 10log_n$$

Where:

- C/N_x: the carrier to noise of a single amplifier
- n: the number of identical amplifiers in cascade.

3.2. Distortion

The buildup of distortions in a cascaded plant is less predictable than noise. Knowing that almost all carriers deployed in the spectrum in the future will be digital, the distortion products can be summed into carrier to intermodulation noise (CIN), which will increase the noise level that should be considered in the system C/N. Due to lack of availability of data in this realm, CIN was not considered in this paper but it is something that needs to be studied extensively, discussed in section 12.

Since distributed gain amplifiers have very low distortion characteristics, due to the low gain and simplicity of these amplifiers, and the fact that distortions for traditional amplifiers are highly unpredictable, composite second order distortion (CSO), composite triple beat (CTB) and subsequently CIN have been nullified in the calculations for end-of-line performance.

3.3. Designing a Noise-Limited System

For optimal performance, operators design systems that are unity gain. This means that the loss between two amplifiers is equal to the gain of each amplifier. If the loss is less than the gain, output power needs to be increased and as a result, distortions will accumulate. In contrast, if the loss is greater than the gain, then the input power will be too low to the input of the amplifier, degrading the C/N of the system.

Due to the difficulties that come with designing a system that is both noise and distortion limited, removing one of those parameters will be optimal. Given that noise performance of amplifiers is far more straight-forward in comparison to distortion, designing a noise-limited system is an attractive idea.

Since distortions are highly dependent on output power TCP, designing a noise-limited system can be achieved by reducing the output power out of the node/amplifiers and making sure the signal is received at the next amplifier at a high enough level for acceptable C/N in spite of the amplifier's noise figure (NF).

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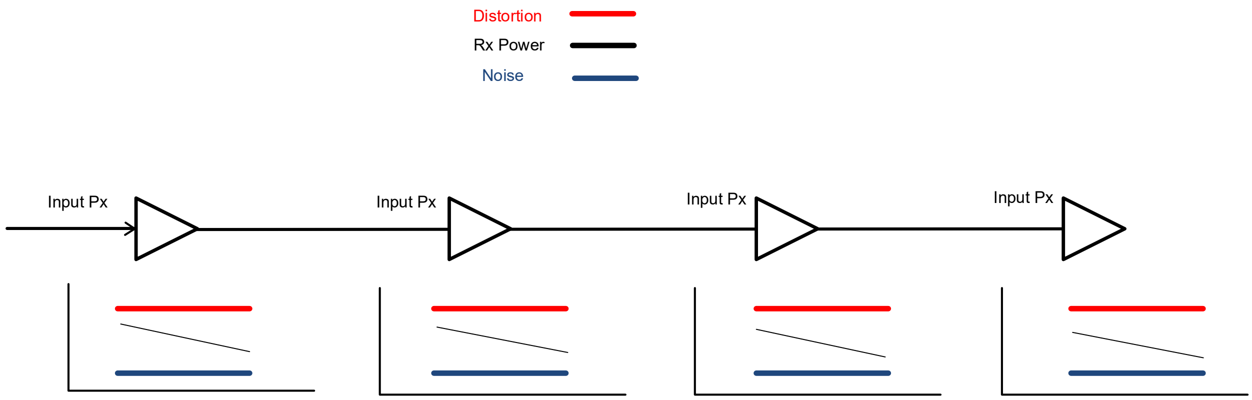

Figure 3 – Signal Level Balanced Between Noise and Distortion

4. Plant Models

In order to encompass most of the HFC architectures deployed, the below plant models and assumptions were considered for this analysis.

Note: Trunk spans are defined as spans that are untapped. Distribution spans are tapped. Both trunk and distribution span losses include all other passive elements' insertion losses, such as splitters and couplers.

Assumptions:

- Modem:
  - Point of entry (PoE) device
- Drop:
  - Cable: RG6
  - Length: 150 feet
- Number of taps in each span:
  - 5
- Distribution span losses at 1GHz:
  - Typical plant: 35 dB
  - Stretched plant: 37 dB
- Trunk span losses at 1 GHz:
  - Typical plant: 32 dB
  - Stretched plant: 35 dB

The figure below summarizes the parameters above:

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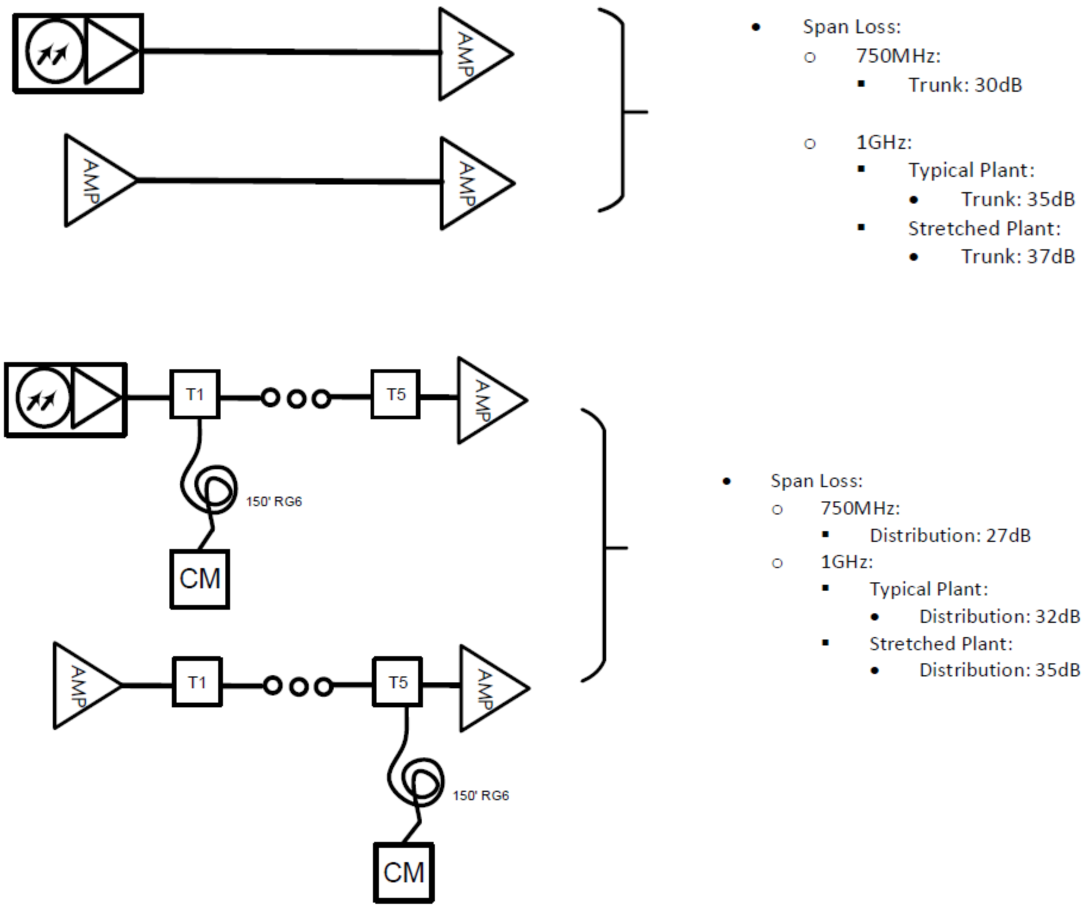

Figure 4 – Plant Models

Taking the span loss parameters above into consideration, the following plant models have been created for the analysis.

Note that the area of focus for this paper is in the last two spans of the N+2 plant, where the amplifiers are installed. The first span, between the node and the first amplifier has not been analyzed for performance. Instead the focus is on the input to the first amplifier since that will be the baseline for the system C/N.

Throughout this paper, each plant type will be referred to by its respective distance:

- **135’ plant**: 135 feet between each plant element
- **190’ plant**: 190 feet between each plant element
- **204’ plant**: 204 feet between each plant element

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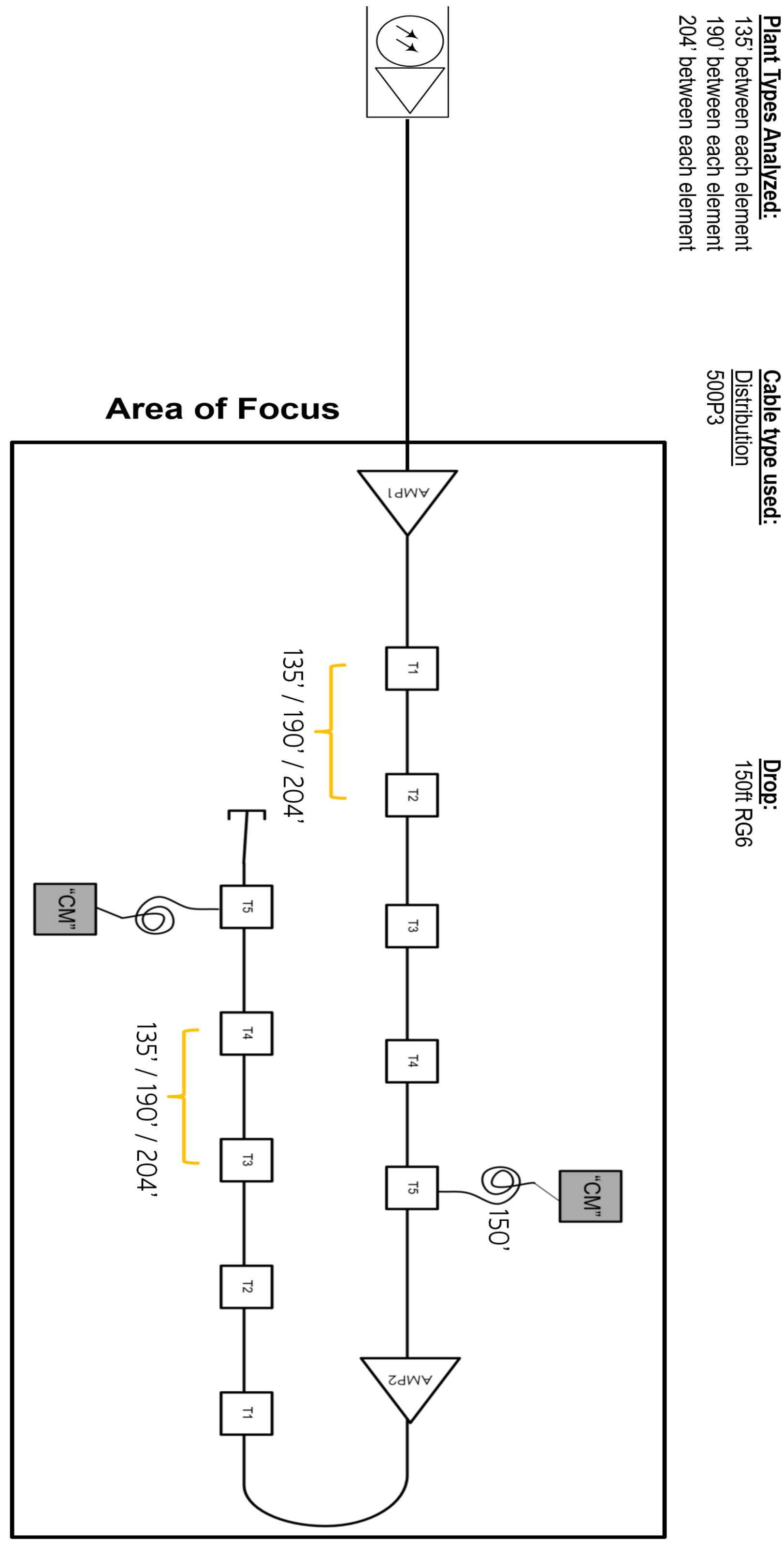

Figure 5 – Analyzed Plant Types

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4.1. Traditional Node and Amplifier Outputs

Assuming 70 dBmV of TCP is available at the port of each active device, the following two options can be considered for extending the spectrum to 1.8 GHz:

1. Change the output tilt in a way to make it more 'flat'
2. Introduce a step-down at a certain frequency, typically 1 GHz

Given the sensitivity of 'legacy' devices in the plant to RF level fluctuations, option 1 is typically avoided. Instead option 2 is typically considered by most operators in traditional plant design.

With that in mind, along with knowing that the majority of TCP is allocated on the higher portion of the spectrum (in this case 1.8 GHz), the following power spectral density (PSD) outputs have been assumed for traditional node and amplifier outputs:

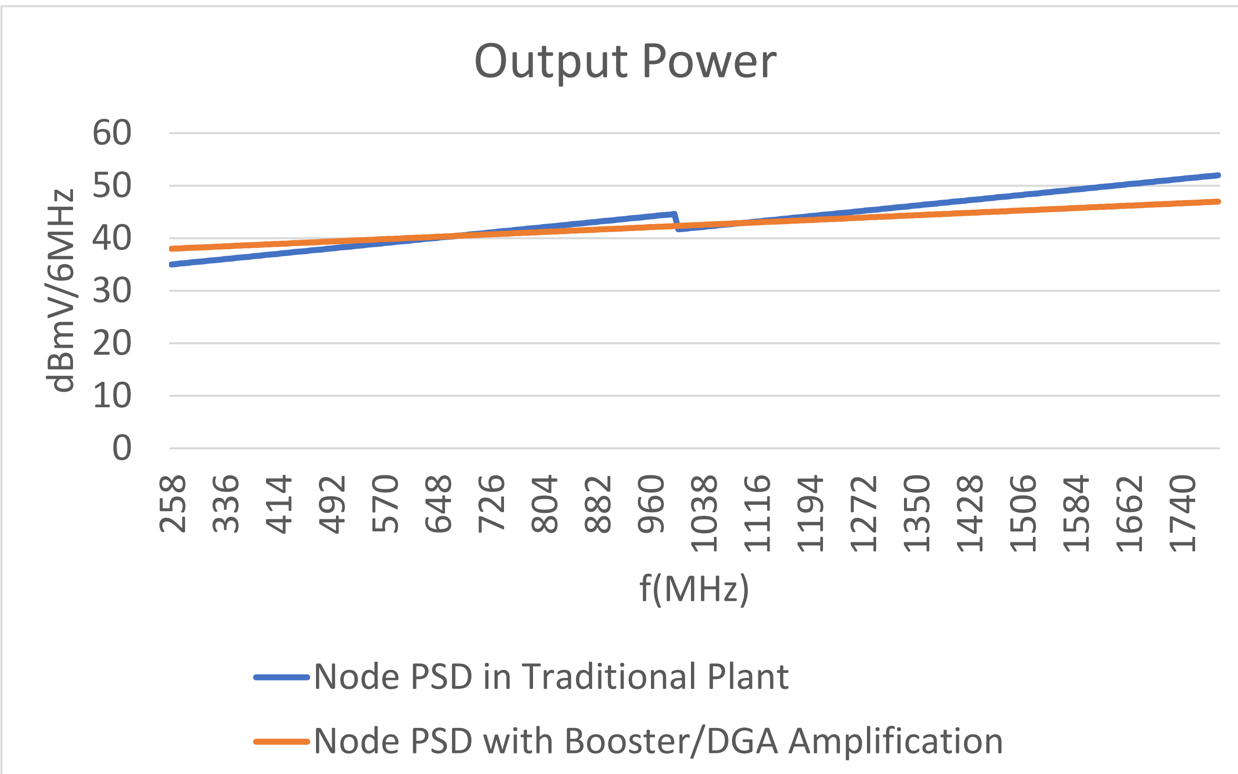

Figure 6 – Node and Amplifier Output PSD

It can be seen from the figure above that distributed gain architecture (DGA) PSD does not have any step-downs throughout the spectrum, due to the addition of DGA amplifiers along the distribution path.

The raised levels from 258 MHz to 650 MHz should be mentioned in light of the comment above regarding legacy devices. Given that the low end of the spectrum has been raised by only 2.5 dB, the potential impact of this on legacy devices along the distribution path has been deemed insignificant.

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4.2. Traditional Node and Amplifier Noise Figure (NF)

Depending on the type of amplifier deployed in the OSP and their respective internal splitting, the DS NF of traditional nodes and amplifiers can vary anywhere between 8 dB – 12 dB. In order to set a baseline for system C/N calculations, the following NF has been assumed:

Table 1 – Node and Amplifier NF

Node & Amplifier NF @ Device Port for DS	11 dB

4.3. Modem (MDM) Transmit Power:

The following table has been referenced in the DOCSIS 4.0 specification for modem transmit power (Tx)

Table 2 – MDM Tx Power/1.6 MHz

Upstream Centre Frequency	108 MHz	684 MHz	Spectral tilt (dB)
Upstream Reference PSD (dBmV/1.6MHz)	33	43	10

Converting the numbers above from 1.6 MHz reference PSD to 6.4 MHz equivalent numbers, the modem Tx power can be graphed as:

Table 3 – MDM Tx Power/6.4 MHz

Upstream Centre Frequency	108 MHz	684 MHz	Spectral tilt (dB)
Upstream Reference PSD (dBmV/6.4MHz)	39	49	10

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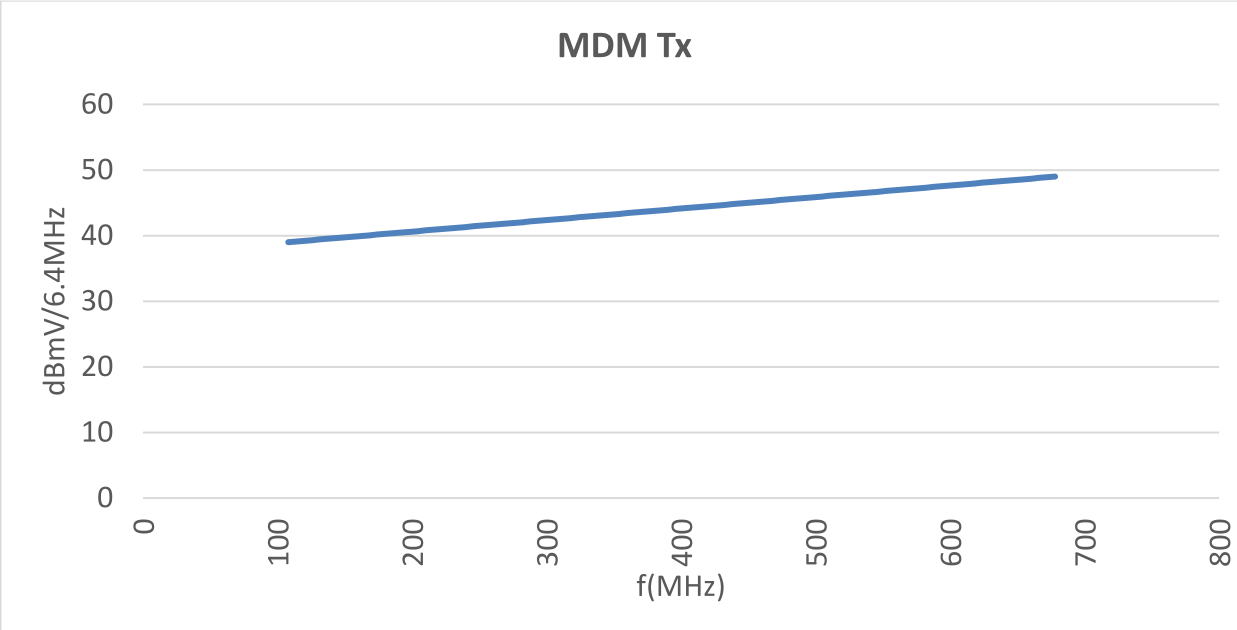

Figure 7 – MDM Ouput Power PSD

4.4. Modulation Order vs. Power and C/N

In order to have a baseline for achievable modulation orders throughout the distribution plant, the below table from the DOCSIS 4.0 PHY specification has been utilized.

Note: although DOCSIS 4.0 modems are able to receive and demodulate signals as low as 16QAM with 16 dB of C/N and -30 dBmV/6 MHz, no values below 256QAM has been considered in this paper since modulation orders lower than 256QAM are typically deemed unacceptable by operators.

Table 4 – MDM Tx Power/6.4 MHz

Constellation	C/N (dB)	Rx Power/6 MHz (dBmV)
4kQAM	44	-6
2kQAM	40	-9
1kQAM	36	-12
512QAM	33	-15
256QAM	30	-18

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5. DGA Amplifier Considerations

In order to implement booster or DGA amplifiers, a baseline for upstream (US) and downstream (DS) gains needs to be set. Given that these amplifiers are single stage with a fixed output, the output performance of the device is highly dependent on the input levels for upstream and downstream. This is defined by noise power ratio (NPR) for the US and carrier to interference noise ratio (CINR), as a function of input TCP.

For the designs carried out in this paper, due to lack of availability on the parameters mentioned above, instead only the US and DS amplifier's noise figure (NF) has been considered in the overall system performance considerations. The NF of booster/DGA amplifiers have been shown in the table below:

Table 5 – DGA Amplifier DS and US NF

DGA/Booster Amplifier NF @ Device Port for US and DS	15 dB

5.1. DS Gain

The following figure has been assumed for the DGA amplifier DS gain:

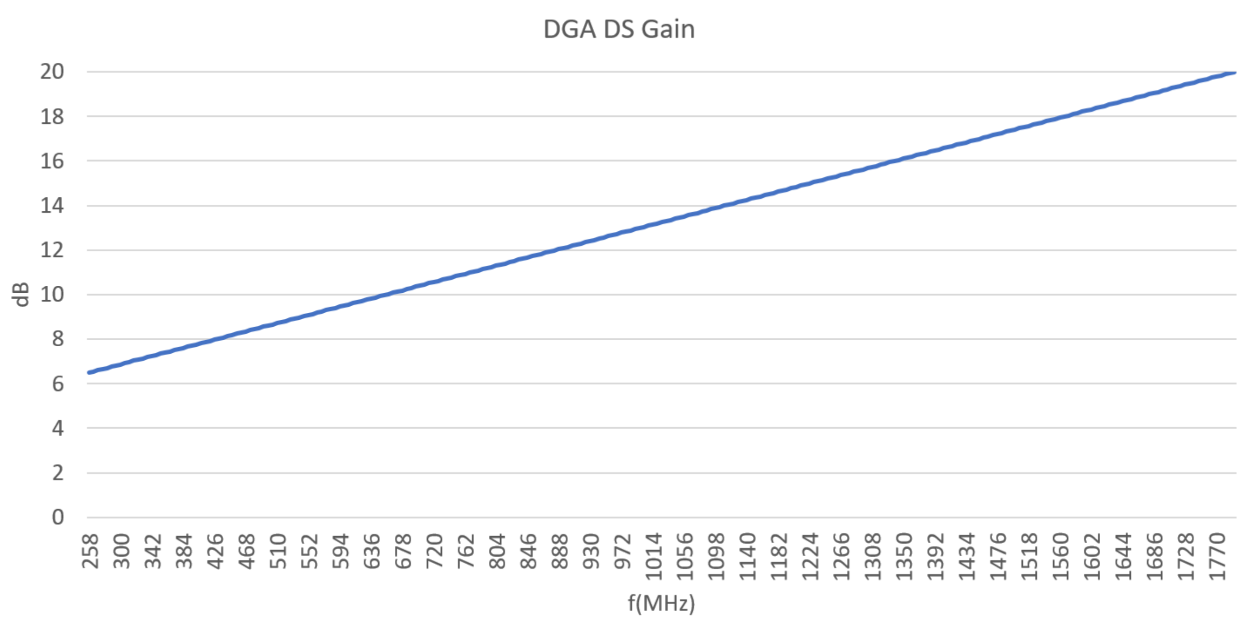

Figure 8 – DGA Amplifier DS Gain

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5.2. US Gain

The following figure has been assumed for the DGA amplifier US gain:

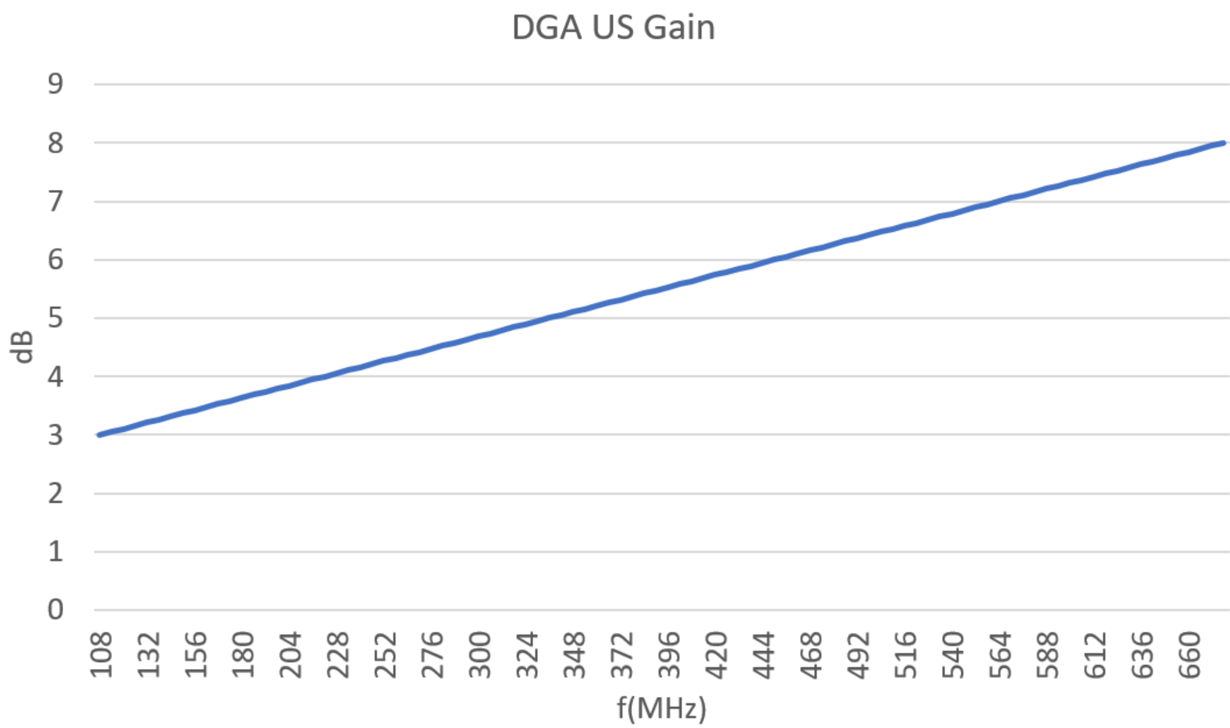

Figure 9 – DGA Amplifier US Gain

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6. Traditional Plant DS Results

The performance results in this section are used as a baseline for comparison. Before discussing the modem receive levels in each plant type, the amplifier contributions to system C/N for each scenario is calculated below.

<u>135' Plant C/N:</u>

Applying the 'traditional PSD' node and amplifier output in section 4.1 to the 135' plant model will result in the following Rx Power at the port of amplifiers:

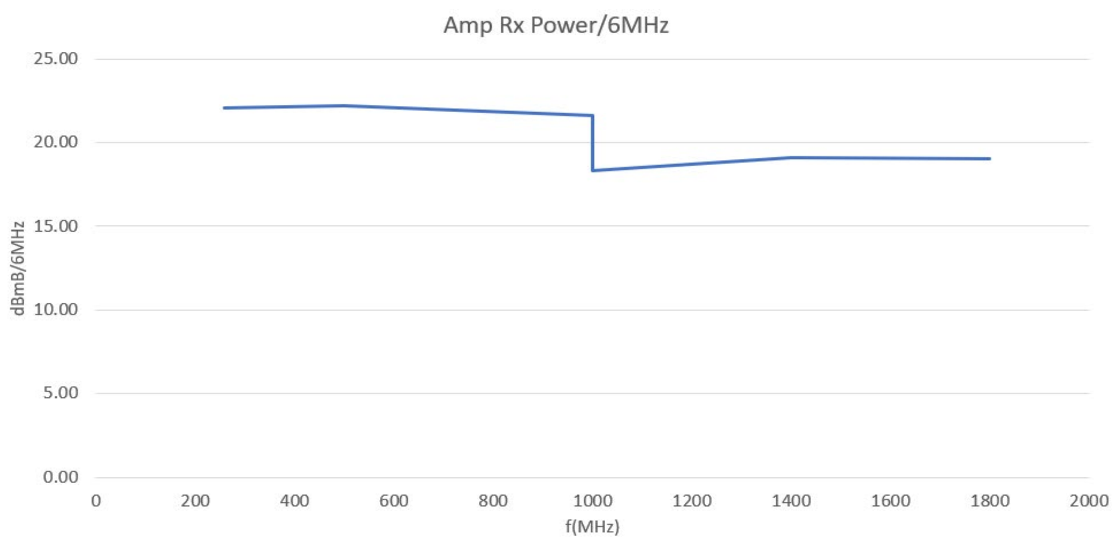

Figure 10 – 135' Amplifer Rx Power @ Amp. Port

From the figure above the C/N contribution of the amplifiers at 1 GHz and 1.8 GHz can be calculated:

Table 6 – 135' Tradtitional Amplifier Contributions to System CNR

N+2 CNR @ 1 GHZ	58.7 dB
N+2 CNR @ 1.8 GHz	59.4 dB

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<u>190' Plant C/N:</u>

Applying the 'traditional PSD' node and amplifier output in section 4.1 to the 190' plant model will result in the following Rx Power at the port of amplifiers:

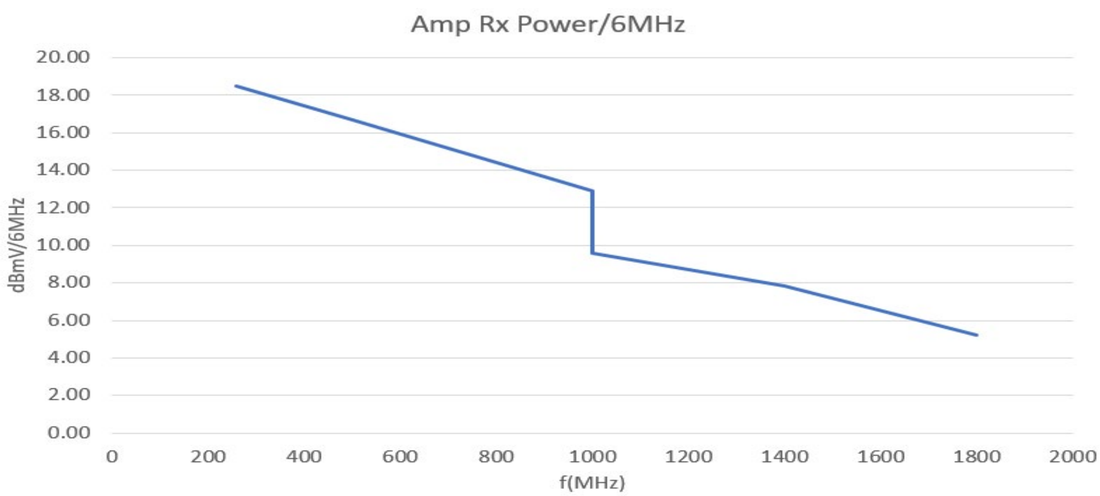

Figure 11 – 190' Amplifer Rx Power @ Amp. Port

From the figure above, the C/N contribution of the amplifiers at 1GHz and 1.8GHz can be calculated:

Table 7 – 190' Traditional Amplifier Contributions to Ststem CNR

N+2 CNR @ 1 GHZ	51.7 dB
N+2 CNR @ 1.8 GHz	48.4 dB

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204 Plant C/N:

Applying the 'traditional PSD' node and amplifier output in section 4.1 to the 204' plant model will result in the following Rx Power at the port of amplifiers:

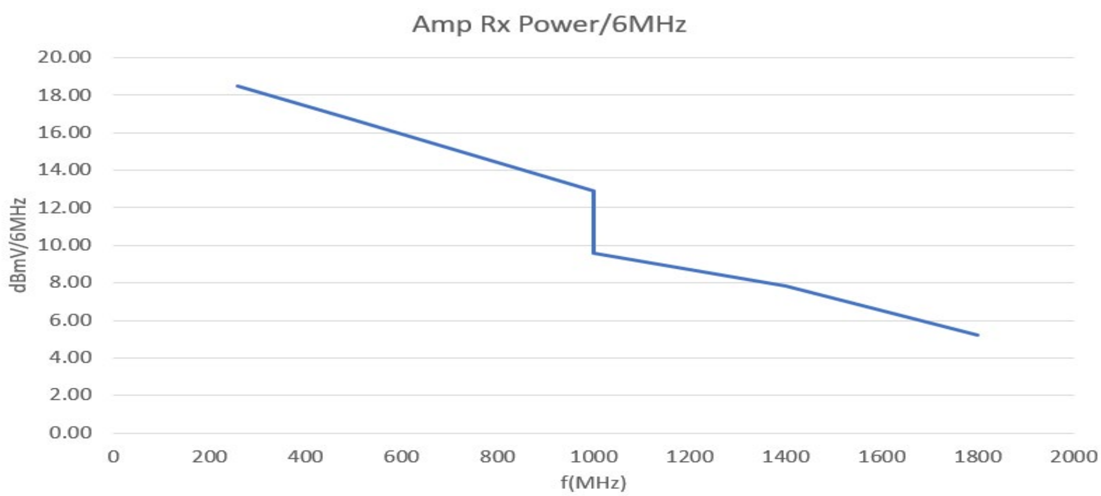

Figure 12 – 204' Amplifer Rx Power @ Amp. Port

From the figure above the C/N contribution of the amplifiers at 1GHz and 1.8GHz can be calculated:

Table 8 – 204' Traditional Amplifier Contributions to System CNR

N+2 CNR @ 1 GHZ	50 dB
N+2 CNR @ 1.8 GHz	45.6 dB

Observation: From the results in Table 7 and 8, we can observe that although the input Rx power into the traditional amplifiers are below 11 dBmV/6 MHz, all the C/N's are above the minimum required for 4kQAM. This is an optimistic assumption for 190' and 204' plant as the distribution network's contribution the system C/N is very close to the numbers in Table 4. As noted in section 3.1, the starting C/N from the node plays a big role in the overall system C/N.

Knowing this and applying the 'traditional PSD' node and amplifier output discussed in section 4.1 to the plant models in section 4.0, will result in the modem receive levels (MDM Rx) below.

Note: as discussed in section 4, all the drops lengths throughout this paper are 150 feet of RG6 which can be considered a worst-case scenario.

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6.1. 135' Plant MDM Rx Powers

The Rx power levels /6 MHz for each modem along the distribution line for the 135' plant has been demonstrated below:

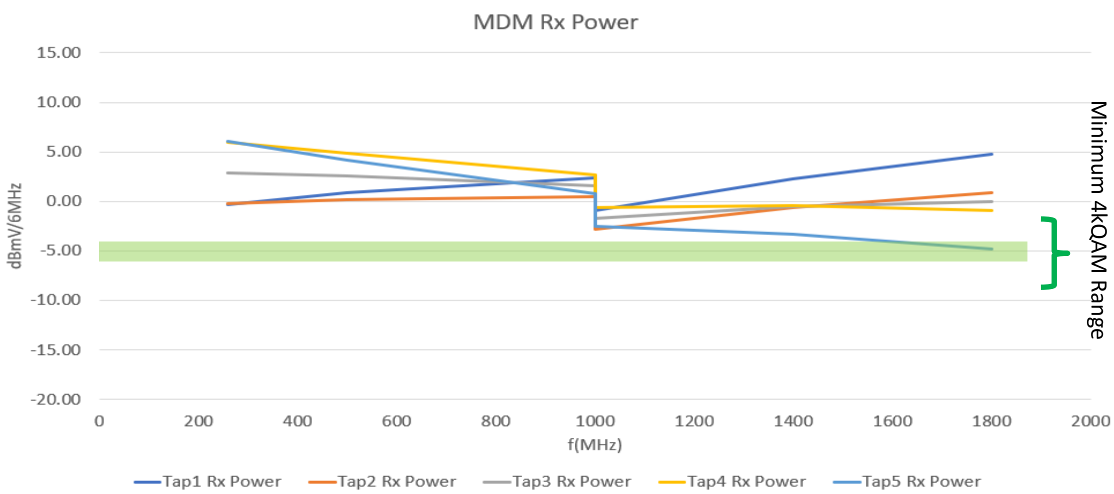

Figure 13 – 135' Span 1 MDM Rx Power/6 MHz

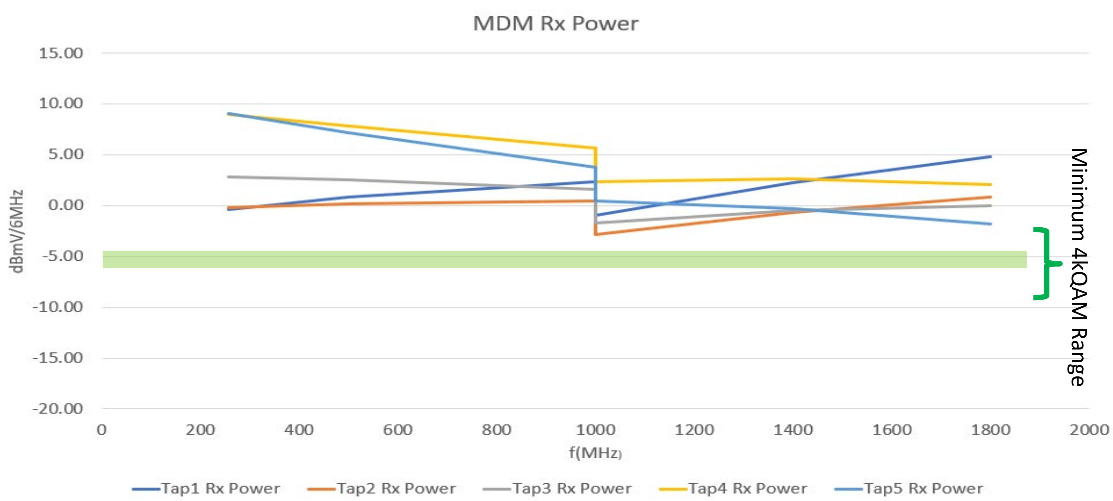

Figure 14 – 135' Span 2 MDM Rx Power/6 MHz

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6.2. 190' Plant MDM Rx Powers

The Rx power levels /6 MHz for each modem along the distribution line for the 190' plant has been demonstrated below:

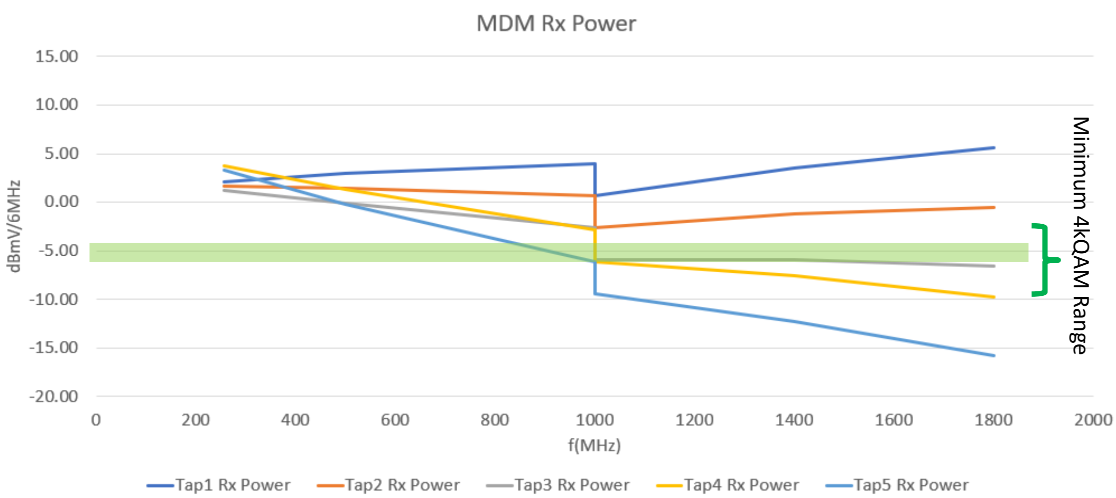

Figure 15 – 190' Span 1 MDM Rx Power/6 MHz

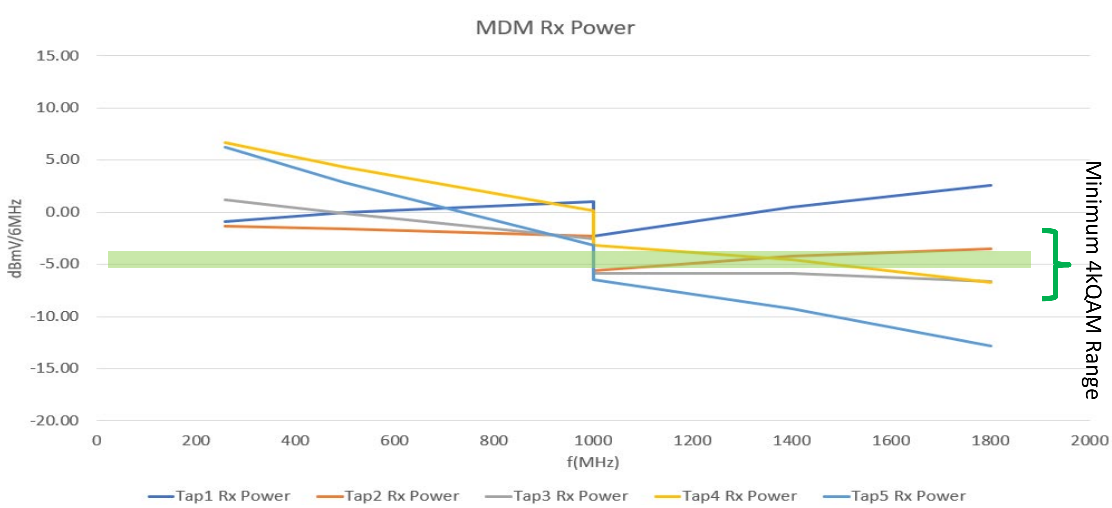

Figure 16 – 190' Span 2 MDM Rx Power/6 MHz

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6.3. 204' Plant MDM Rx Powers

The Rx power levels /6 MHz for each modem along the distribution line for the 204' plant has been demonstrated below:

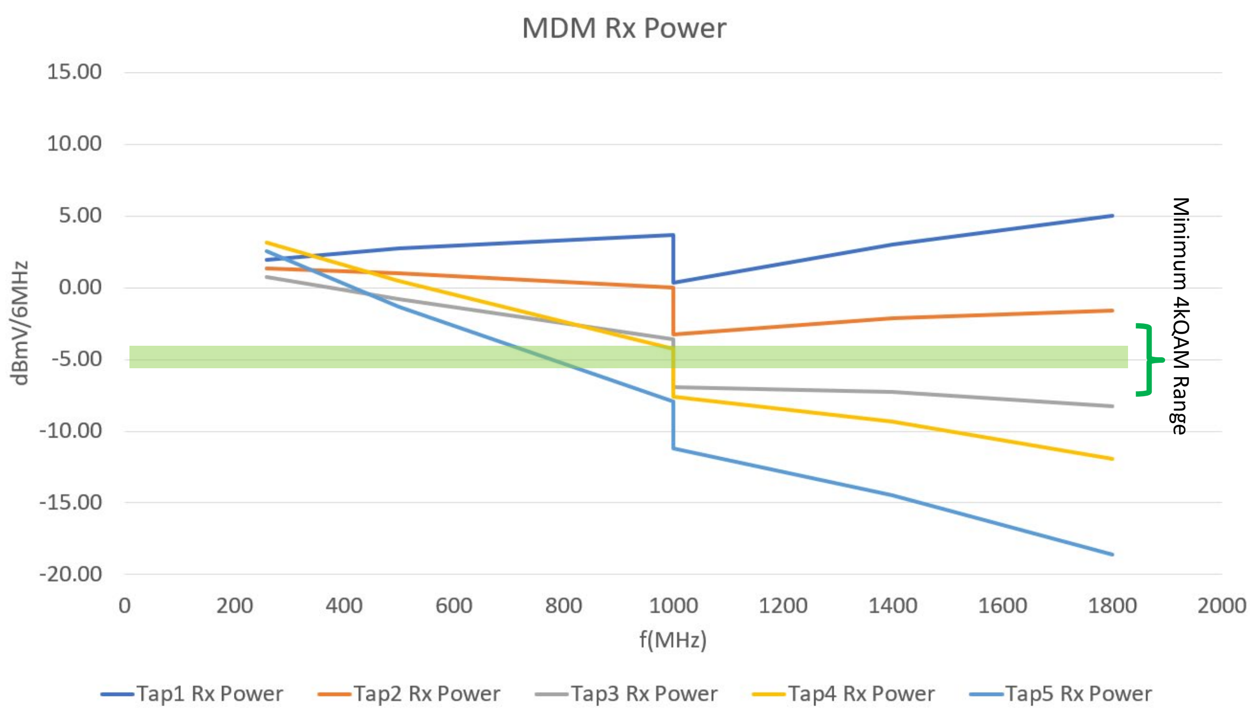

Figure 17 – 204' Span 1 MDM Rx Power/6 MHz

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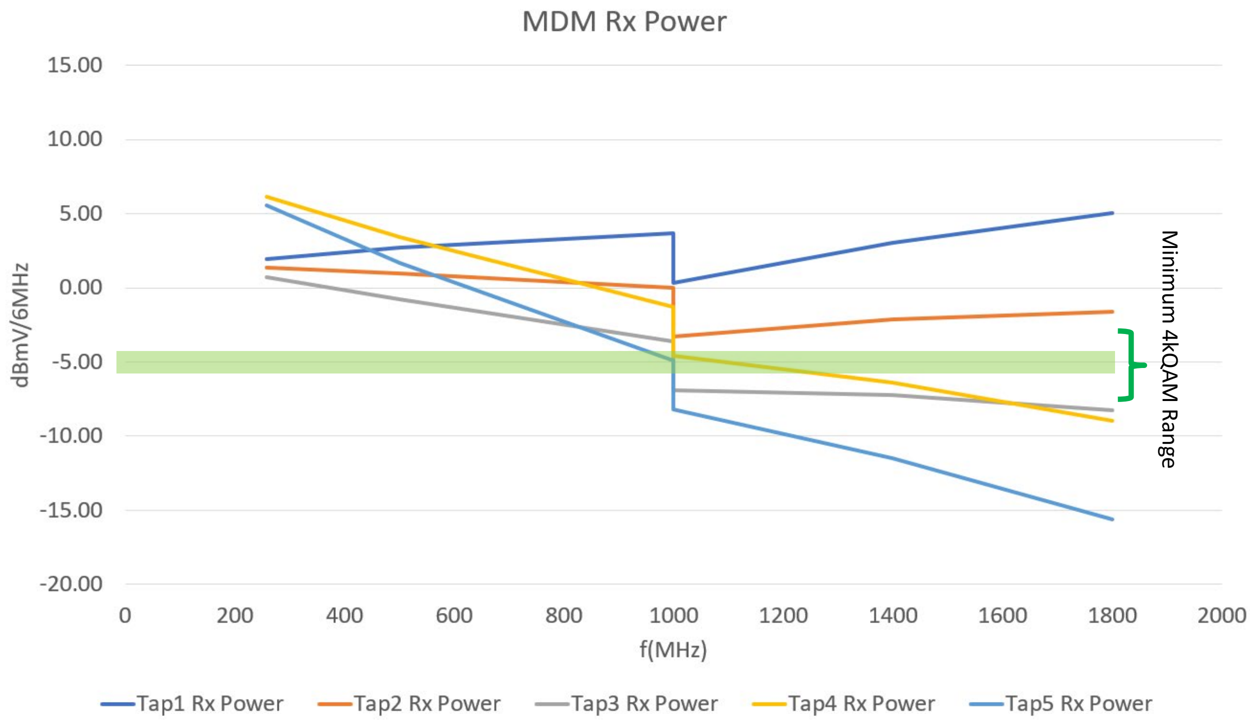

Figure 18 – 204' Span 2 MDM Rx Power/6 MHz

Observation: in the 135' plant, all the modems are capable of receiving 4kQAM with traditional amplifiers only. On the contrary, it can be seen than 190' and 204' plant models struggle with achieving 4kQAM throughout the distribution network. It should also be emphasized that all of the analysis above was done using 150 feet of RG6 as the drops throughout the distribution plant. Reducing this length will improve the Rx levels at each MDM, improving the MER and achievable modulation order.

7. Booster Amplifcation DS Results

Based on the results demonstrated in the previous section, the 190' and 204' plant models struggle with achieving 4kQAM throughout the distribution network. These plant models could be prime candidates for adding booster amplifiers mid-span to not only increase the Rx power at each traditional amplifier input, but also to boost the MDM Rx levels in each span. Given that 135' plant is capable of achieving 4kQAM (Figures 13 and 14), no booster amplification has been considered for this plant model.

As discussed in section 4.1 and given the new additional mid-span gain from the DGA/booster amplifier, the need for a step downs in the output PSD is eliminated. This new output PSD results in a 2.5 dB lower TCP (69.8 dBmV vs. 67.3 dBmV), which can subsequently improve the output C/N of the node. As previously covered in section 3 this has not been considered in overall system C/N calculations.

Note: Based on the early prototype form factors of DGA/booster amplifiers, the final version of the product should approximately be the equal to the size of a mainline splitter. This can have immense benefits when it comes to ease of installation and access. In other words, as long as pedestals (PEDs) are installed for tap locations, an assumption has been made that DGA/booster amplifiers will fit in existing PEDs.

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7.1. 190' and 204' Plant Design with Booster Amplifiers

The following design has been considered for the 190' and 204' plant types, with booster amplification mid-span:

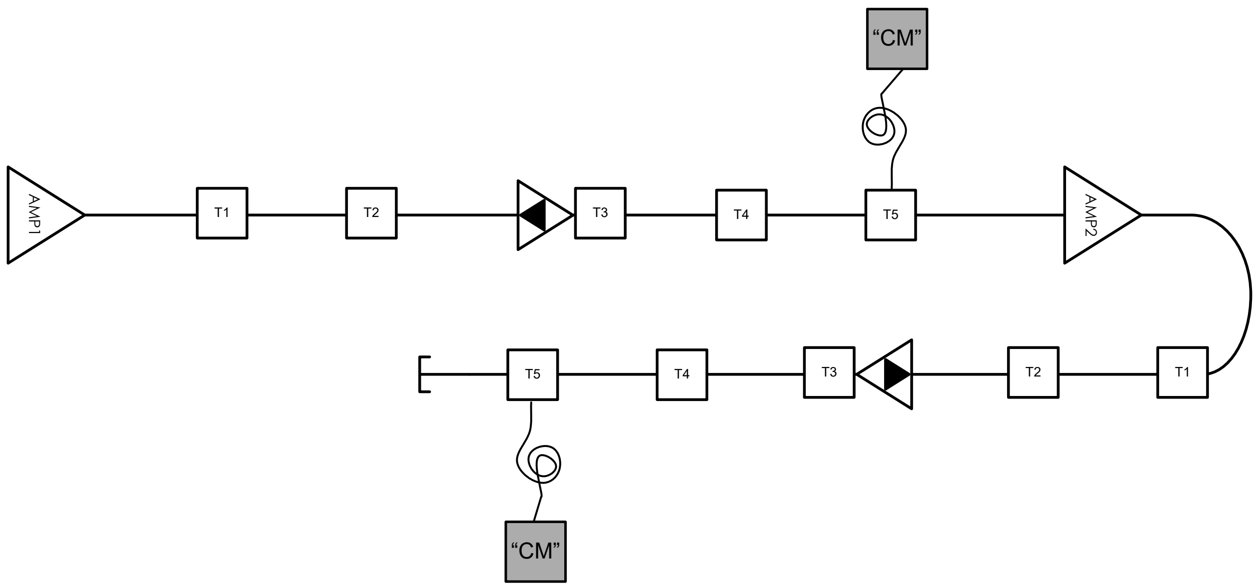

Figure 19 – 190' and 204' Plant with Mid-Span Booster Amplification

In this new design with the added gain mid-span, the tap values after the booster amplifier must be increased to ensure reasonable Rx power at the modem. This will further improve the end-of-line Rx power because higher value taps have lower insertion loss values throughout the spectrum.

Additionally, as discussed in section 4, given the added 20 dB of gain at 1.8 GHz, there is no need for any step down at 1 GHz. DGA gain from Figure 8 has been applied to the node and amplifier outputs.

As a result, the new traditional amplifier Rx levels have been demonstrated below:

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190' Plant Traditional Amplifier Rx Power with Booster Amplification:

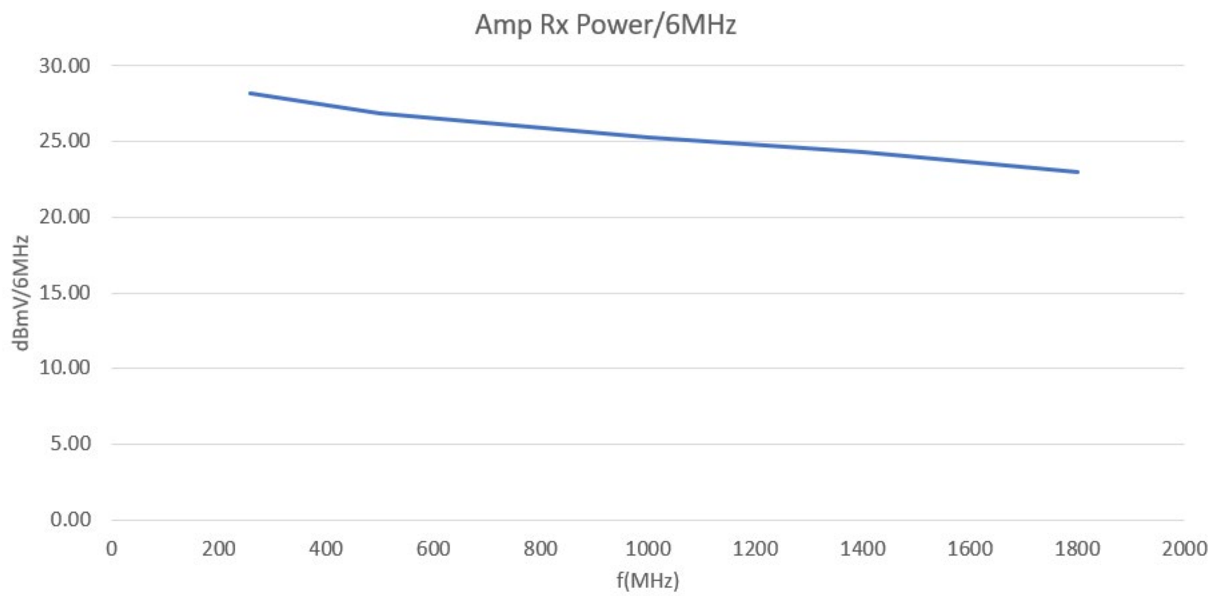

Figure 20 – 190' Amplifier Rx Power @ Port with Booster Amplification

204' Plant Traditional Amplifier Rx Power with Booster Amplification:

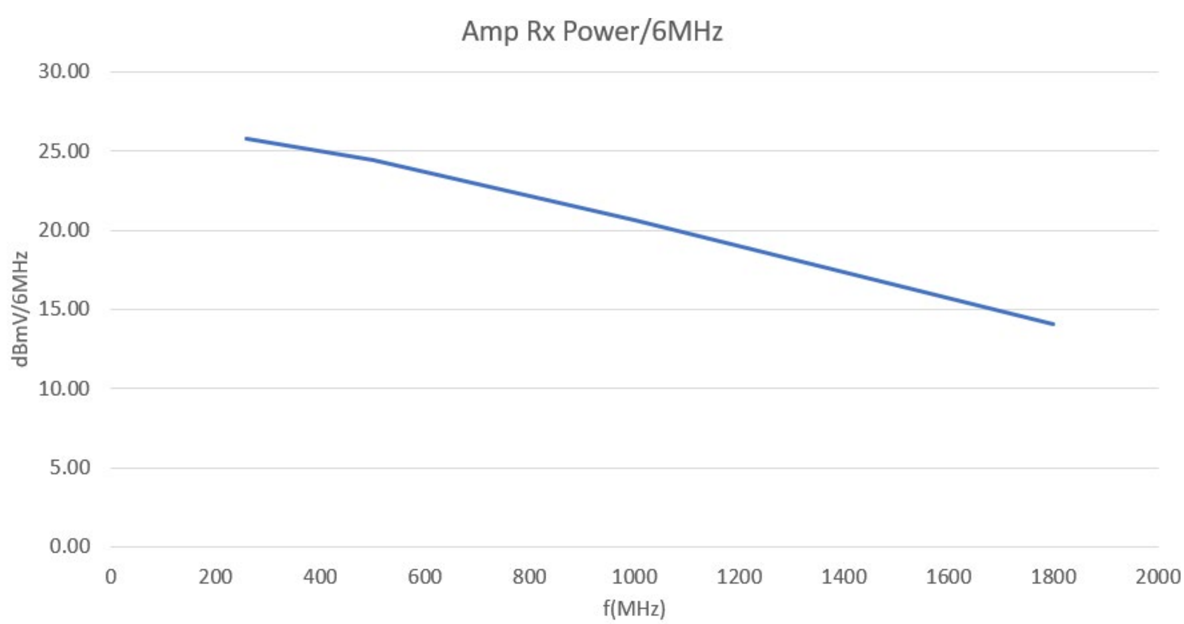

Figure 21 – 204' Amplifier Rx Power @ Port with Booster Amplification

A point of concern would be adding two additional amplifiers, essentially taking the current N+2 design to N+4. The overall contributions of the amplifiers to the system C/N can be calculated for each case, demonstrated in the table below:

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Table 9 – Amplifier Contributions to System C/N

	190' Plant	204' Plant
Amplifier Contributions to C/N @1 GHz	61.8 dB	58.9 dB
Amplifier Contributions to C/N @1.8 GHz	58.7 dB	53 dB

An assumption can be made that the limiting factor in achieving each modulation order is the Rx power at the modem. Keeping that in mind, the figures below demonstrate MDM Rx power at each tap, with the addition of booster amplification mid-span:

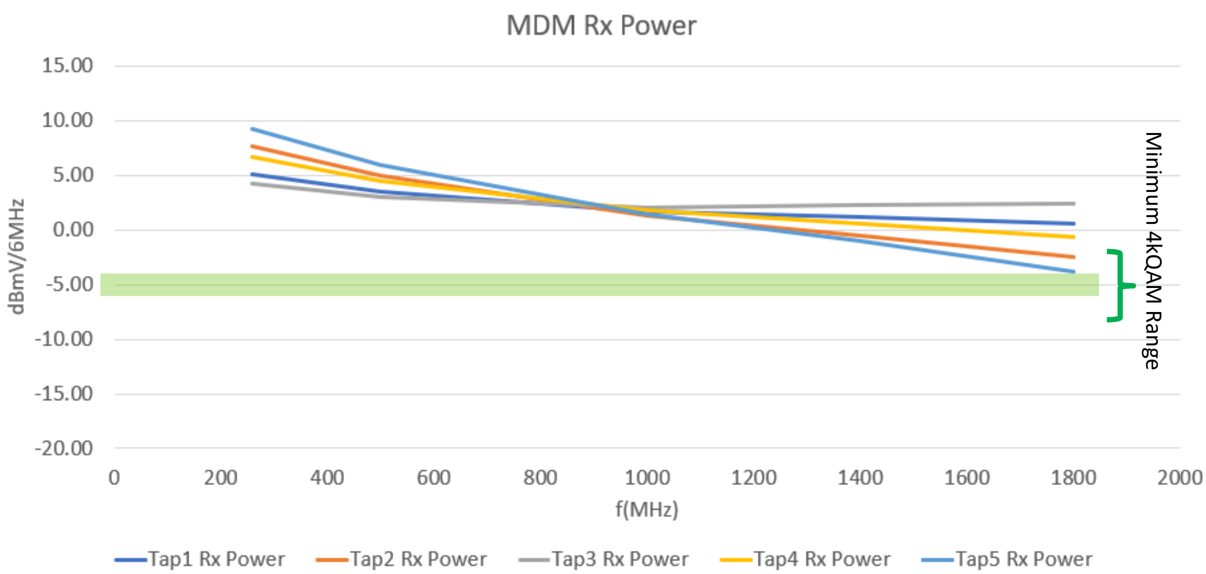

Figure 22 – 190' Span 1&2 MDM Rx Power/6MHz

It can be observed that all the taps along the distribution line are now well above the 4kQAM threshold.

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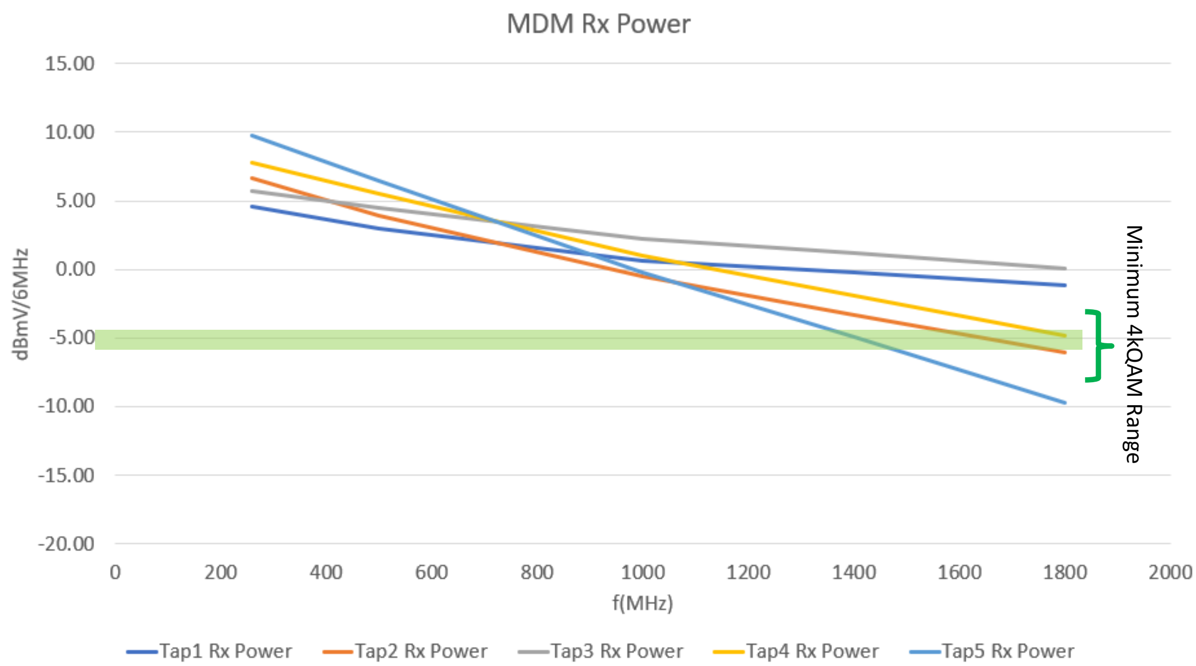

Figure 23 – 204' Span 1&2 MDM Rx Power/6MHz

Aside from ~200 MHz of Tap 5, it can be observed that all the taps along the distribution line are now above the 4kQAM threshold.

7.2. Booster Amplification Observations

Mid-span booster amplification seems to provide a viable option to increase the system C/N and subsequently, the overall system achievable modulation order. This is also assuming that the booster and DGA amplifiers have very low distortion characteristics, where they can be considered negligible.

8. DGA Design and DS Results

DGA design can be described as distributing the gain of traditional amplifiers along the path. This can potentially have the following benefits:

- Enhancing end-of-line performance
- Fully moving away from distortions and intermodulations and, as a result, achieving a noise-limited system
- Eliminating the need for having any step downs in node or amplifier output
- Reducing the output power of the node, resulting in improvement of the output MER
- Reduced power draw (covered in section 10)

Additionally, as discussed in section 7, the form factor of the DGA amplifiers are roughly the size of a mainline splitter. Assuming there are PED locations available for taps, DGA amplifiers should fit before or after the taps, depending on the design.

From an OSP design perspective, DGA can seem strange in comparison to designing a traditional plant. As demonstrated in sections 8.1, 8.2 and 8.3, the 'mid-span' tap values can vary anywhere from 17 to 20 dB taps, depending on where the DGA amplifier has been installed. This can present design challenges

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for operators as new design methodologies have to be crafted in order to optimize plant performance. This will be discussed further in section 12.

DGA designs might also seem counter intuitive to the concept of cascade reduction. As demonstrated in the following sections, the cascade length of the studied N+2 plants can increase up to 8. This cascade length can vary by approximately 2 amplifiers for each case analyzed, depending on the end-of-line performance expectations by the operator. For the purpose of this study, all plant types have been designed to achieve 4kQAM.

An important note to keep in mind is that the designs shown here are moving away from a unity gain design since no pads or equalizers were considered in this analysis. With traditional amplifiers, this can cause concern as distortions can accumulate quite rapidly when a system is not designed with unity gain in mind. Theoretically speaking, given the extremely low distortion characteristics of DGA amplifiers, it has been assumed that distortions will not result in degradation of signal quality at the end-of-line. This needs to be verified in the future as more products are available in this realm.

In the below sections, the performance of each plant type when converted to DGA, has been discussed.

8.1. 135' Plant Design and DS Results

The following design has been considered for 135' plant:

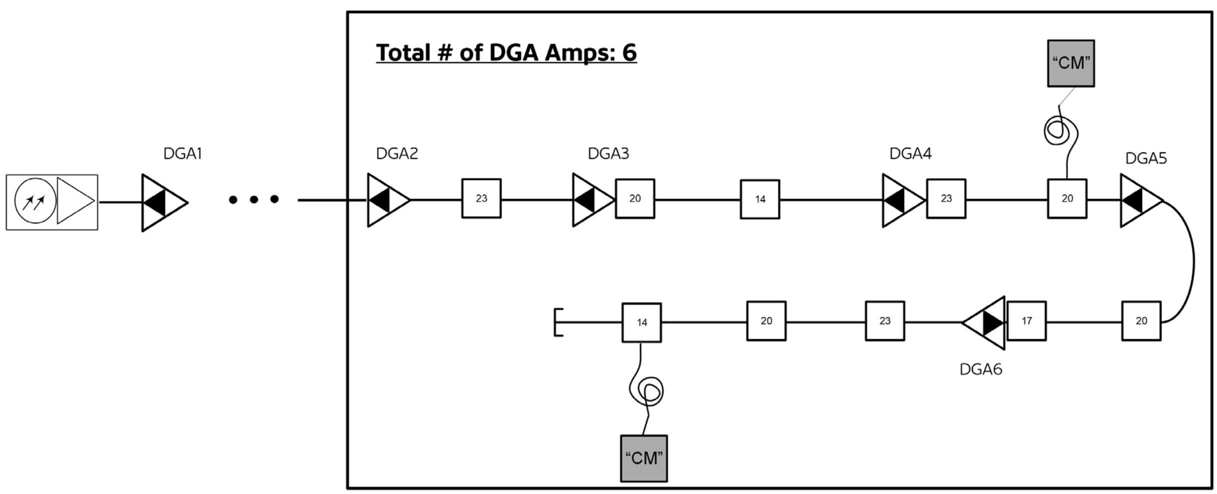

Figure 24 – 135' DGA Conversion

Note: in order to have a baseline, spans 1 and 2 have been kept the same in comparison to the 'traditional' plant spans.

As it can be seen, a previously N+2 plant has been converted to N+6. Although this might seem concerning at first, the Rx power at each DGA amplifier along with the amplifier contributions to the system C/N has been shown below:

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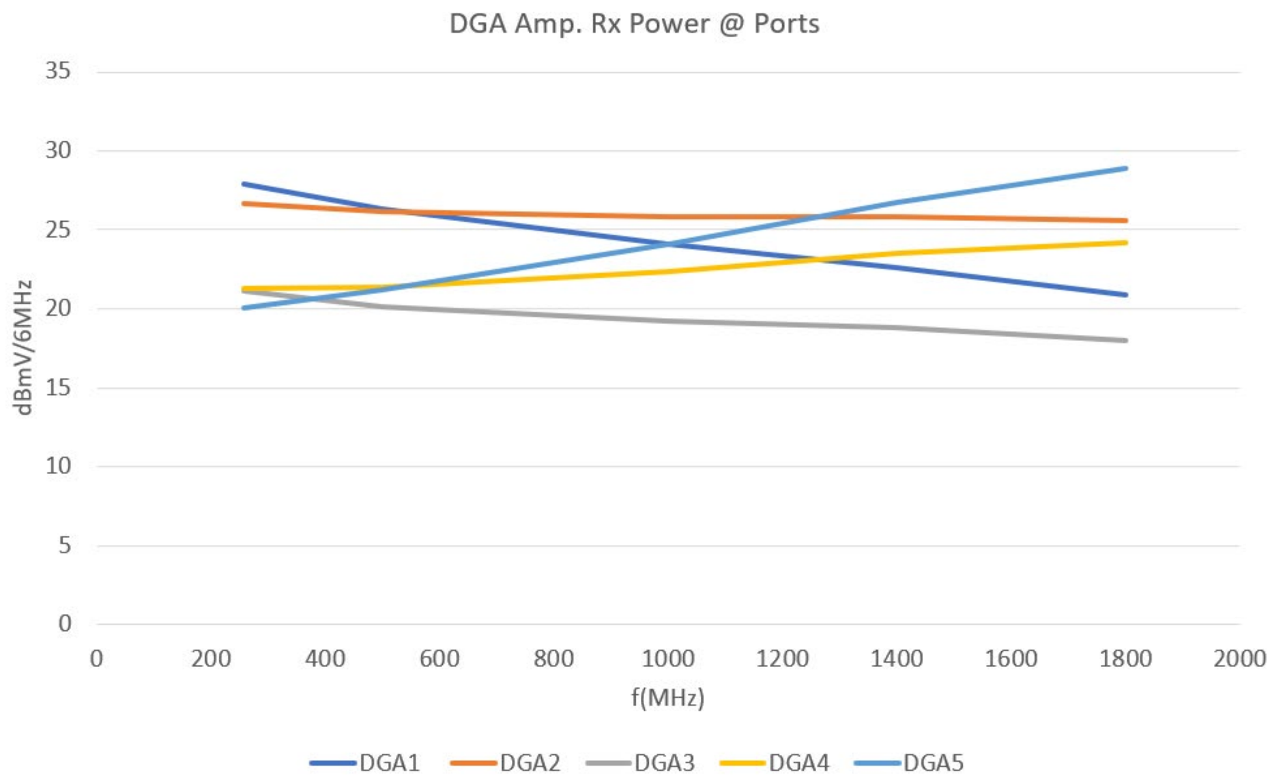

Figure 25 – 135' Plant DGA Amplifiers' Rx Power @ Ports

From the figure above, calculating the overall amplifier contributions to system C/N will result in the following:

Table 10 – 135' DGA Amplifier Contributions to System C/N

	135' Plant
System C/N @1 GHz	61.8 dB
System C/N @1.8 GHz	58.7 dB

Knowing the above, it can be assumed that the limiting factor for plant performance would be the Rx power at the modems. The figures below demonstrate Rx power at each tap's modem location for each span:

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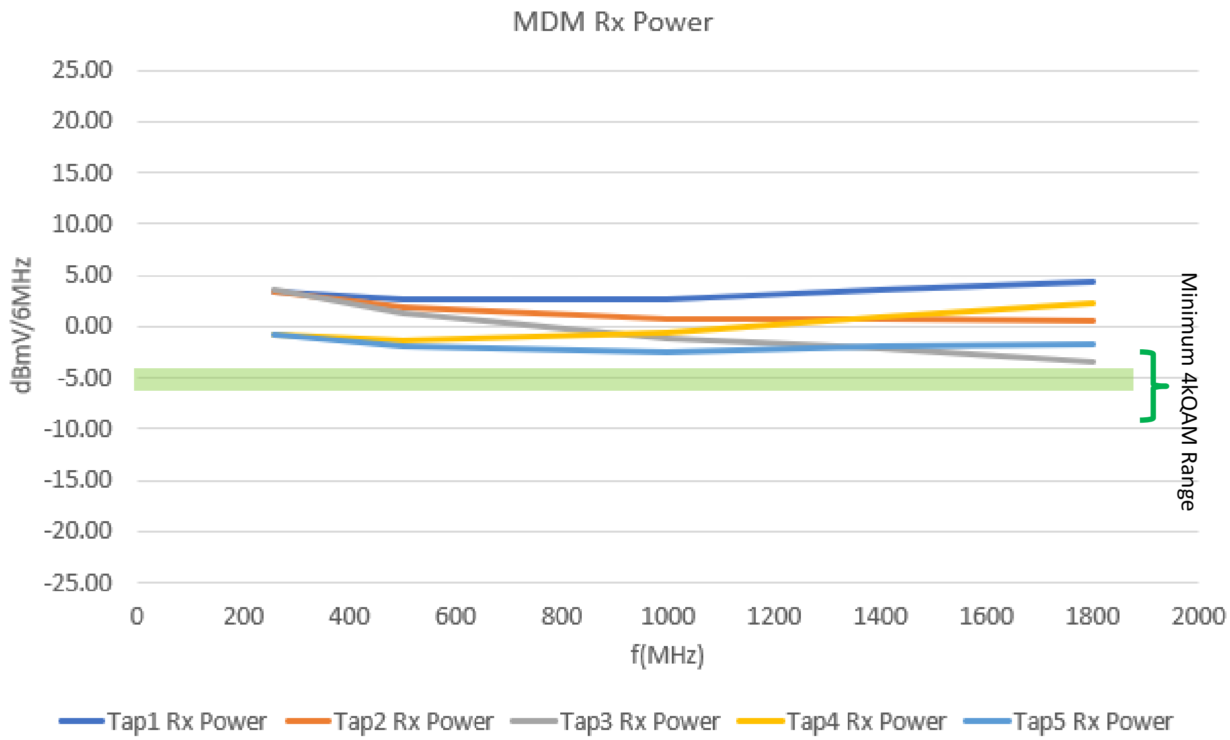

Figure 26 – DGA 135' Span 1 MDM Rx Power/6MHz

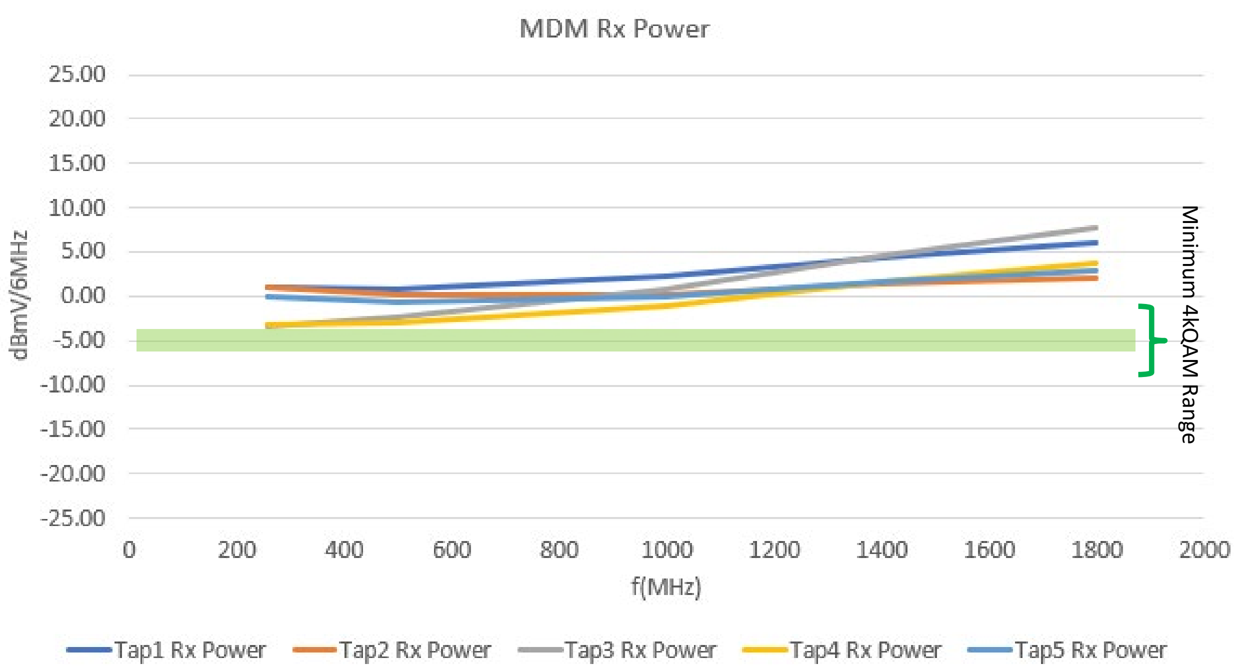

Figure 27 – DGA 135' Span 2 MDM Rx Power/6MHz

Although the 135' plant does not seem to benefit from DGA from an achievable modulation order perspective, it will benefit from the power reductions properties of DGA. This will be further discussed in section 10.

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8.2. 190' Plant Design and DS Results

The following design has been considered for 190' plant:

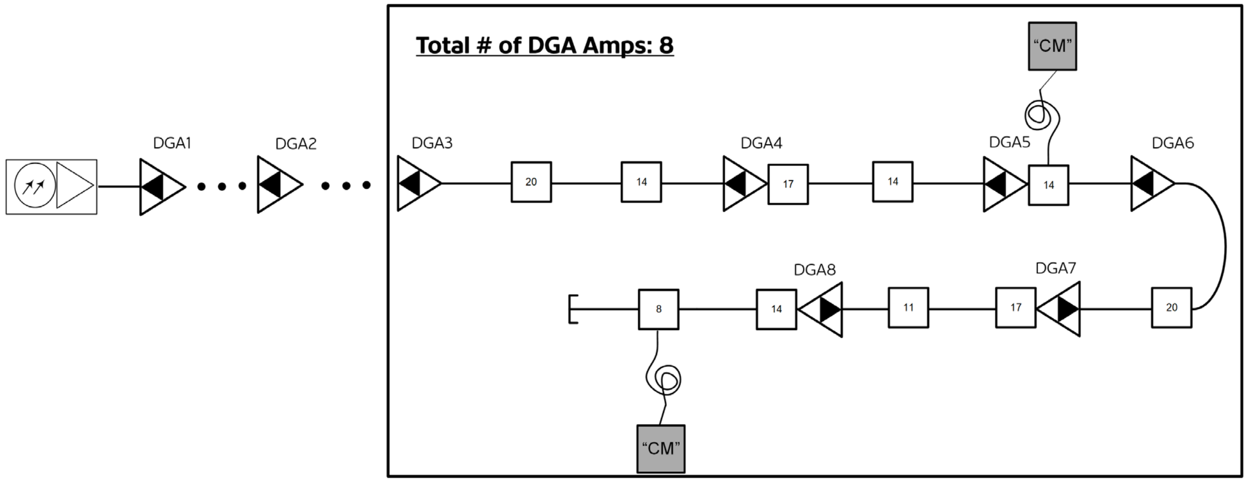

Figure 28 – 190' DGA Conversion

The previous N+2 plant has been converted to N+8. The Rx power at each DGA amplifier has been shown below:

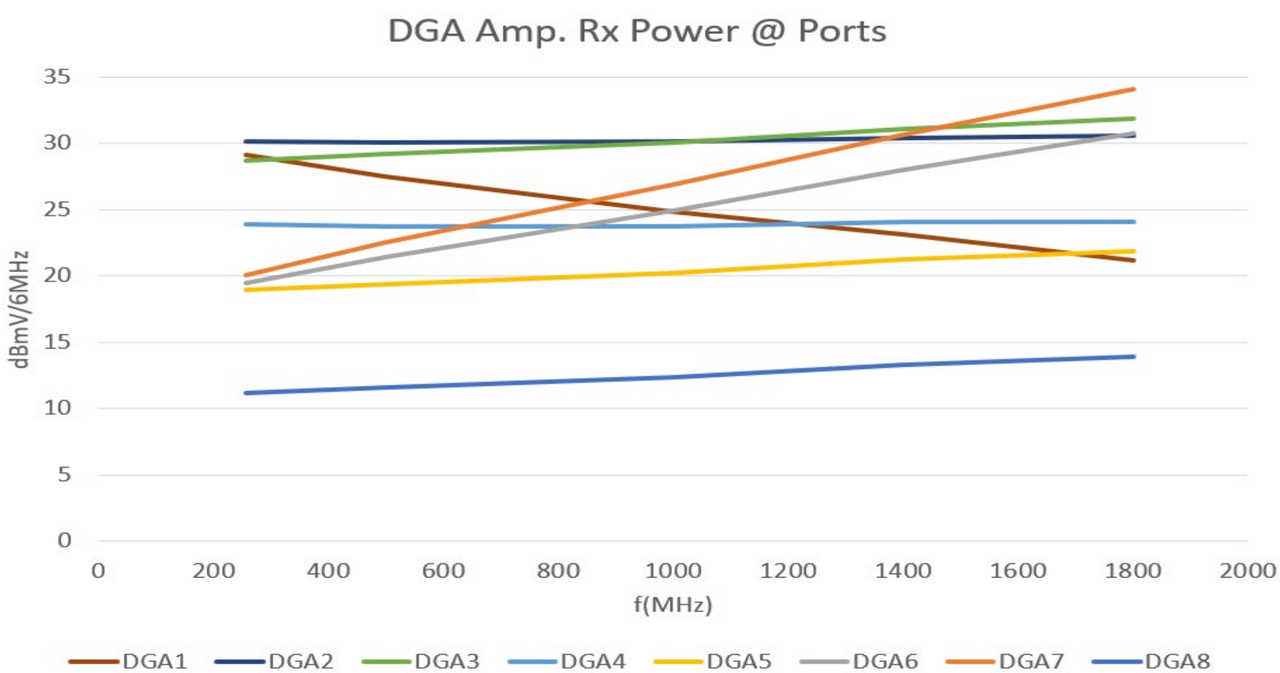

Figure 29 – 190' Plant DGA Amplifiers' Rx Power @ Ports

From the figure above, calculating the overall amplifier contributions to system C/N will result in the following:

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Table 11 – 190' DGA Amplifier Contributions to System C/N

	190' Plant
Amplifier Contributions to CNR @1 GHz	54 dB
Amplifier Contributions to CNR @1.8 GHz	54.5 dB

It can be seen that the overall system C/N can remain high, despite the fact that 8 amplifiers have been designed in cascade.

With that in mind, the modem Rx power still seems to be the limiting factor in the achievable modulation order. The figures below demonstrate Rx power at modems in each tap location:

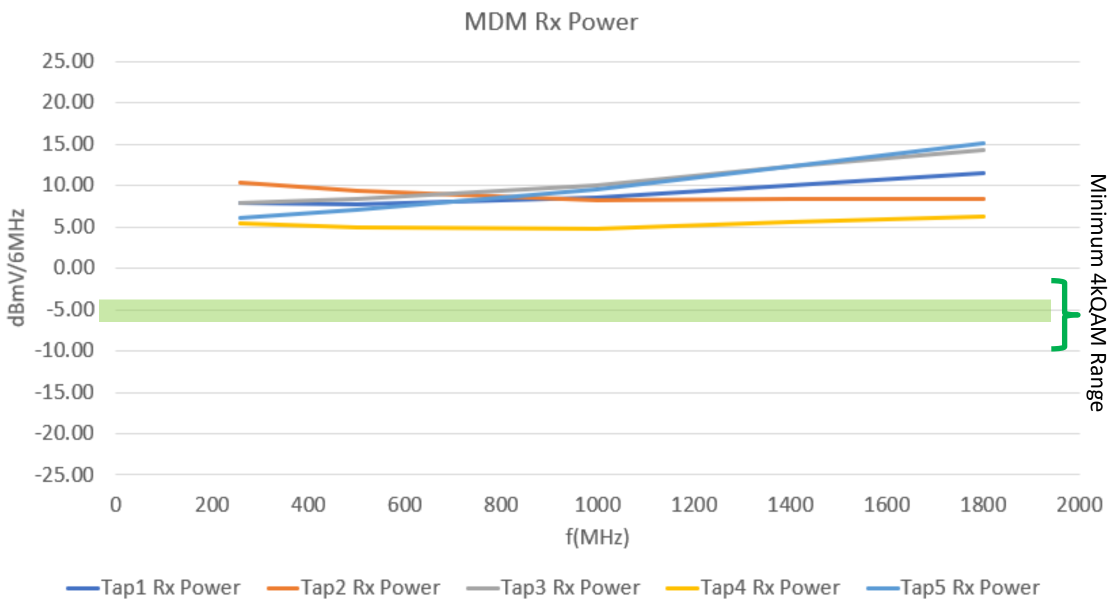

Figure 30 – DGA 190' Span 1 MDM Rx Power/6 MHz

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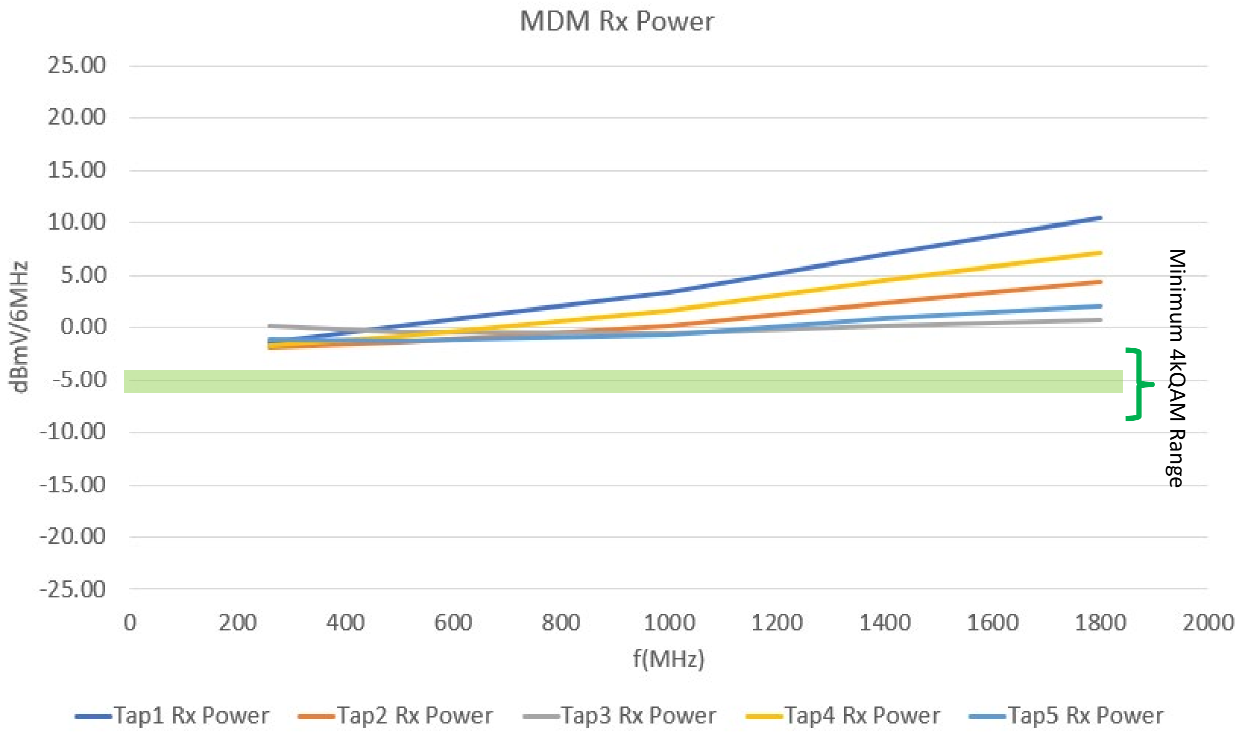

Figure 31 – DGA 190' Span 2 MDM Rx Power/6 MHz

It can be observed that all the Rx powers throughout the distribution plant are well above the minimum 4kQAM threshold.

8.3. 204' Plant Design and DS Results

The following design has been considered for 204' plant:

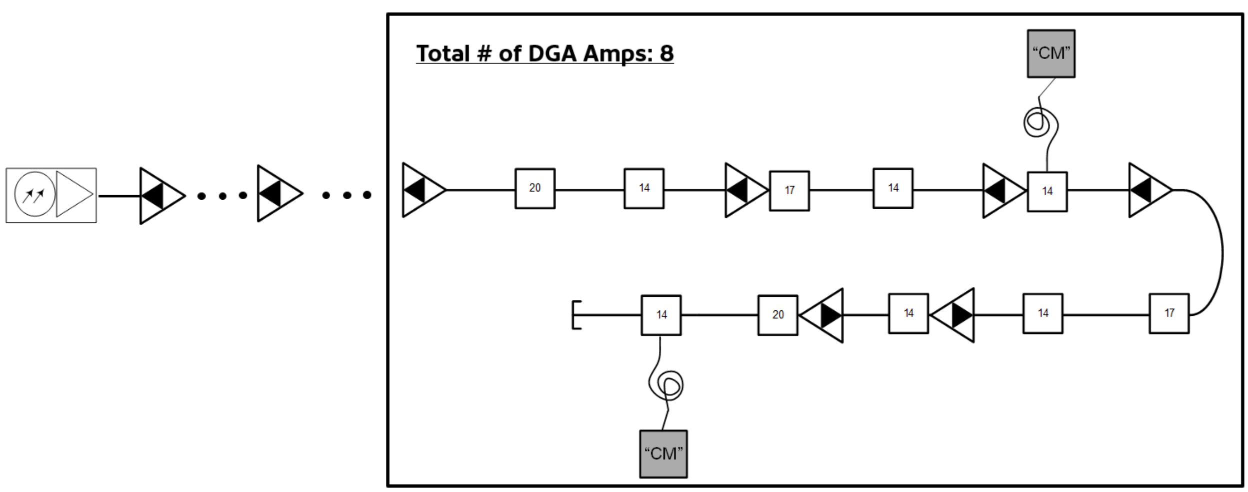

Figure 32 – 204' DGA Conversion

The previous N+2 plant has been converted to N+8. The Rx power at each DGA amplifier has been shown below:

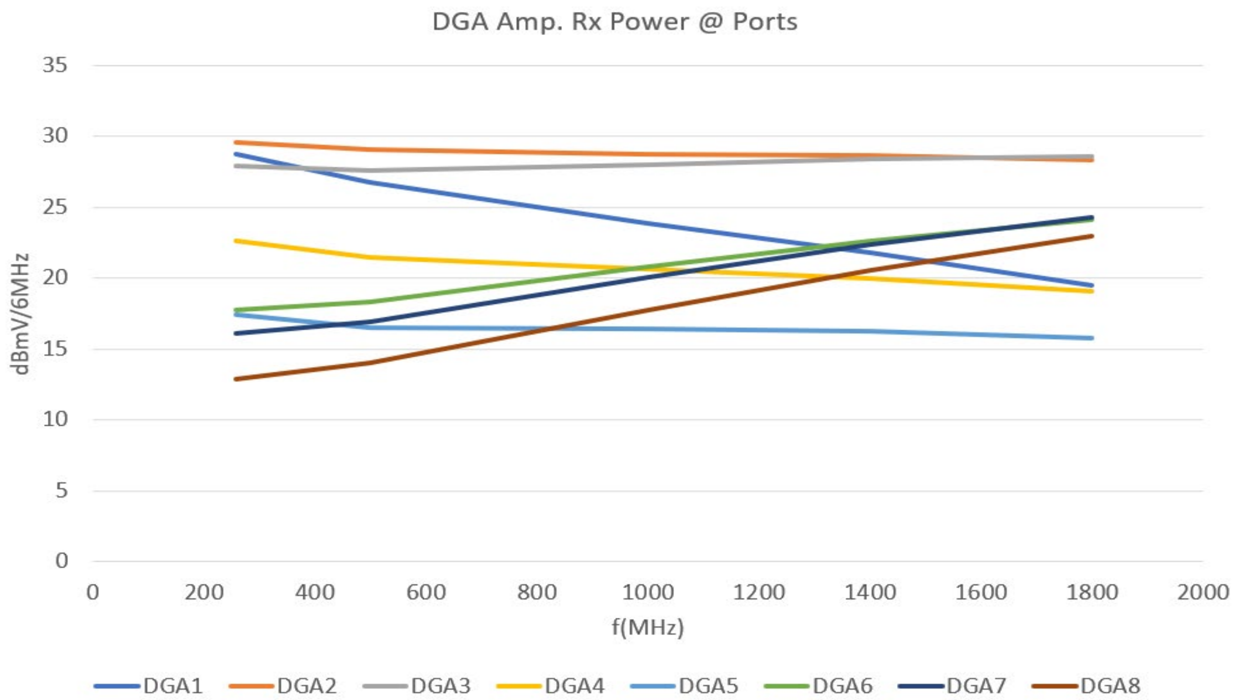

Figure 33 – 204' Plant DGA Amplifiers' Rx Power @ Ports

From the figure above, calculating the overall amplifier contributions to system C/N will result in the following:

Table 12 – 204' DGA Amplifier Contributions to System C/N

	204' Plant
System CNR @1 GHz	54.2 dB
System CNR @1.8 GHz	53.5 dB

It can be seen that the overall system C/N remains high, despite the fact that 8 amplifiers have been designed in cascade.

With this in mind, the modem Rx power still seems to be the limiting factor in the achievable modulation order. The figures below demonstrate Rx power at modems in each tap location:

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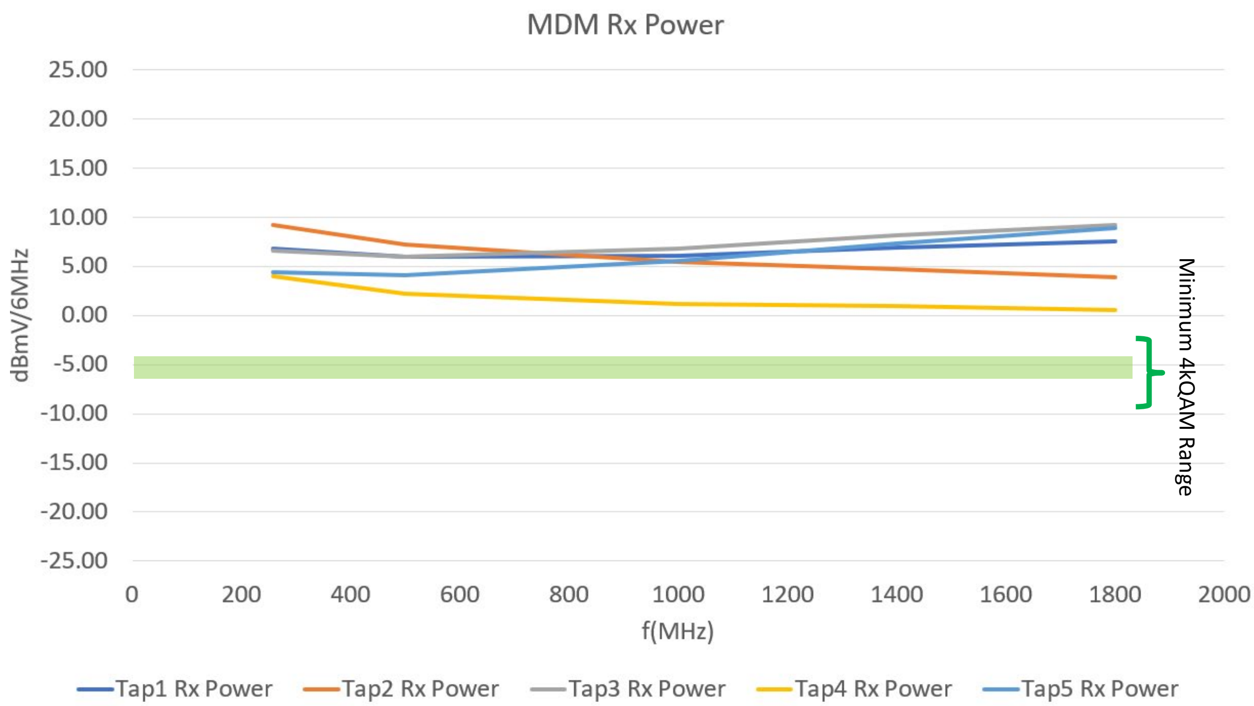

Figure 34 – DGA 204' Span 1 MDM Rx Power/6 MHz

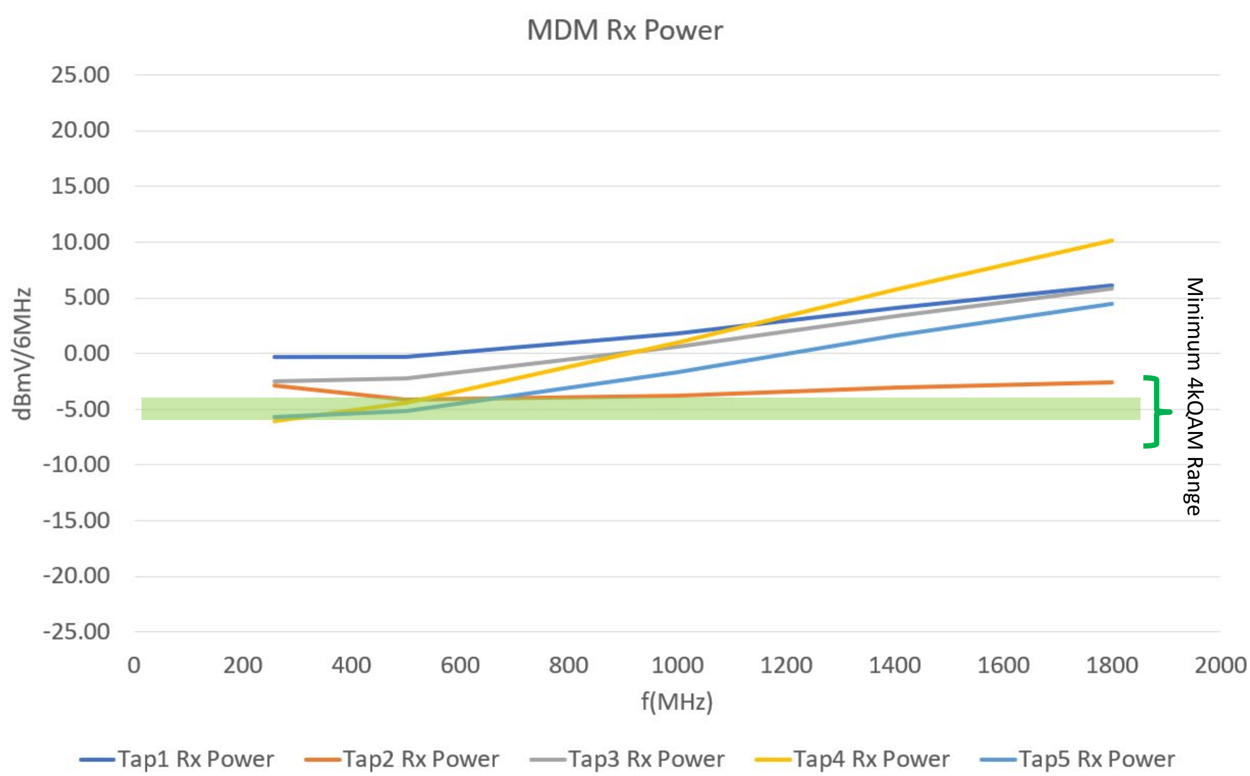

Figure 35 – DGA 204' Span 2 MDM Rx Power/6 MHz

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It can be observed that all the Rx powers throughout the distribution plant are above the minimum 4kQAM threshold.

8.4. DGA DS Design Observations

DGA appears to provide a high system C/N and end-of-line performance in each of the plant models analyzed. This is most visible in the 190' and 204' plant models analyzed. It can be observed that although the cascade length in the analyzed plant models were increased from +2 to +8, the achievable modulation orders were increased by roughly 2-3 orders of magnitude.

9. Upstream Analysis and Considerations

Given the complexity of US analysis in a system and due to noise funneling from amplifiers and modems, this paper has focused on the potential points of concern in a DGA plant, especially regarding 204' plant, given that it is the longest plant type analyzed.

It should be noted that no closed loop gain control has been considered in this analysis. It is assumed that all the modems in the distribution will be transmitting at maximum power in accordance to Figure 7, to determine any shortcomings in the upstream network.

Assuming that the modems sitting at each location will be transmitting with their maximum capability in the return path in accordance to Figure 32, the following Rx powers/6.4 MHz can be expected at the port of each DGA amplifier:

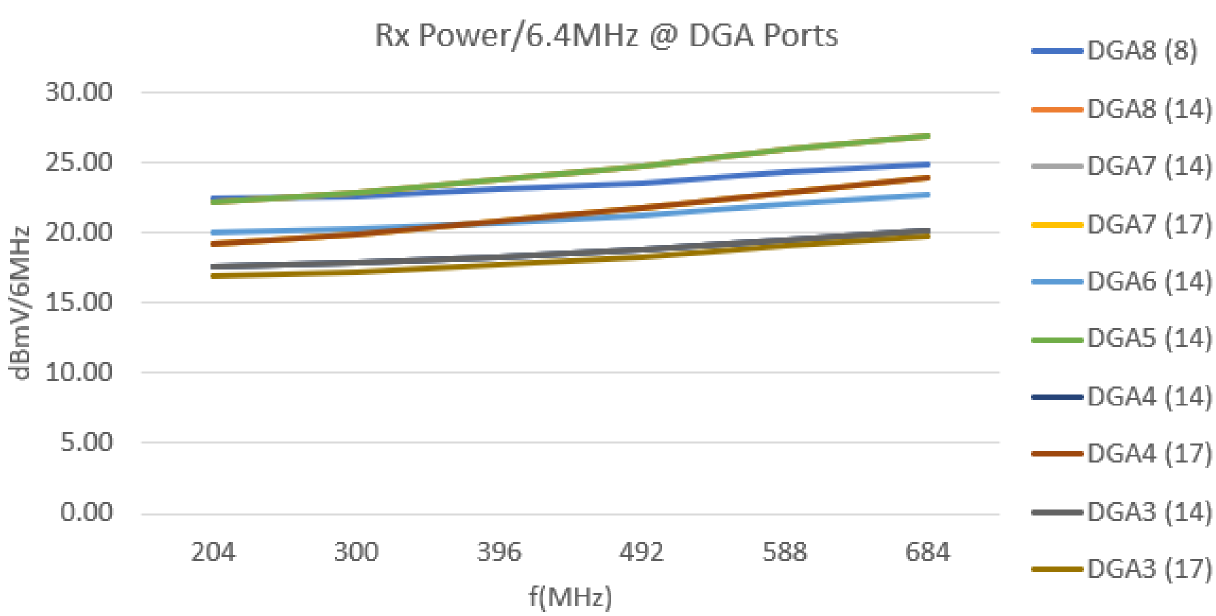

Figure 36 – 204' Plant Return Path DGA Amplifiers' Rx Power @ Ports

<u>**Note**</u>: In order to simplify the figure above, only data from tap values in parenthesis have been shown. These are modems that are subject to the highest amount of loss in the distribution plant. Furthermore, since the focus area of the analysis for this paper is in the distribution plant (DGA3-DGA8), no data from DGA1 and 2 have been shown in the figure above.

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Although all the Rx power levels at the ports of each DGA amplifier seems sufficiently high, the primary point of concern is the return signal being subject high attenuations from long coaxial spans and higher insertion losses from low value taps. Assuming DGA amplifiers' return gain in Figure 9, the following Rx powers/6.4 MHz can be expected at the port of the node, in the 204' plant model:

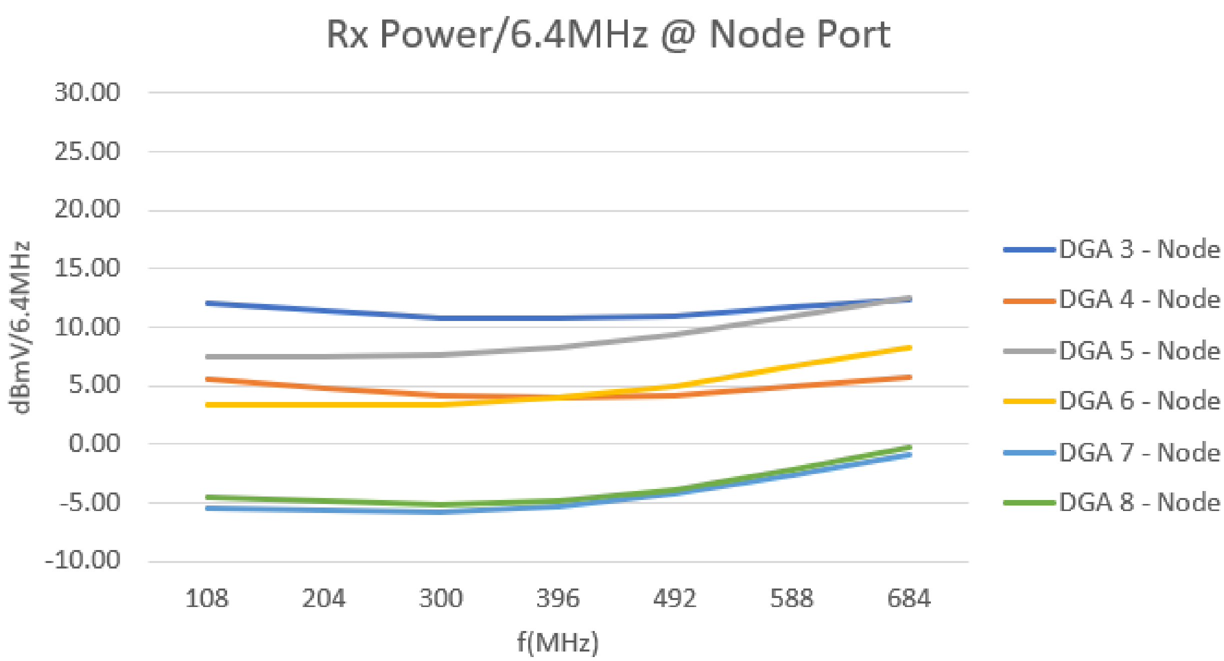

Figure 37 – 204' Plant Return Path Node Rx Power @ Port

Given that the focus area of analysis for this paper is in the distribution portion of the plant (from DGA3 to DGA8), DGA1 and 2 have not been included in the figure above.

The figure above can raise concerns with regards to system performance in the US. This is especially the case because modems in DGA7 and 8 spans are the lowest common denominator, setting the limit for overall system performance in the return path.

The return path gain of DGA amplifiers is not the only point of concern. Given the DS DGA design in 204' plant, many 14 and 17 taps were used to ensure high DS Rx power levels at the MDM. Although this can improve the DS Rx power levels at MDM locations and subsequently increase the system's achievable modulation order in the DS, it will make the US performance suffer. For comparison, based on the tap data available today, typically 23 taps have 1.2-1.4 dB of loss in the legacy band. The same band will have 2 dB higher insertion loss in lower value taps such as 14 and 17 dB taps.

To show the significance of high insertion loss values from low value taps on the return path network, it can be assumed that higher value taps were used throughout the distribution network.

Note: In practice, this can be considered unrealistic in OSP designs, since increasing the tap values results in lower DS Rx power at the MDMs. This assumption is made simply to quantify the impact that low value taps can have in the overall system performance.

Assuming a lower insertion loss of 1.5 dB for the distribution taps, DGA8's new Rx Power at the node has been shown in comparison to Figure 37:

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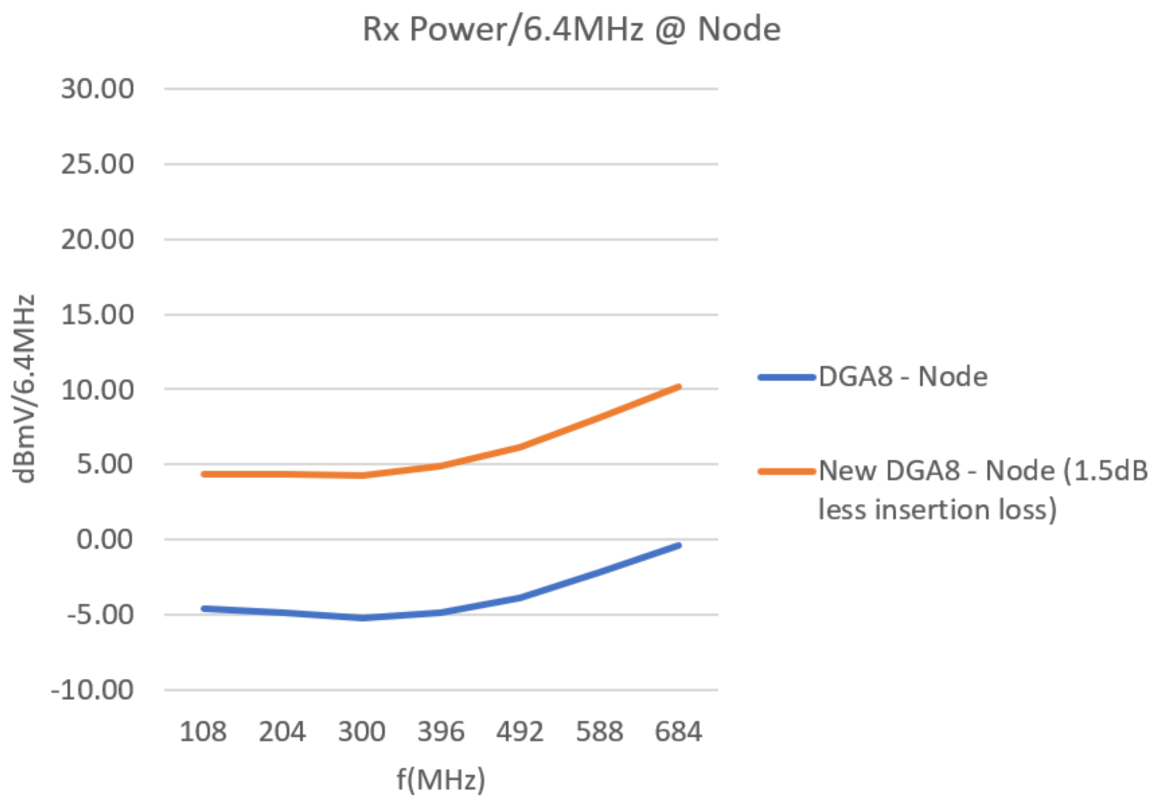

Figure 38 – Last Span DGA-to-Node Level Comparison – 2dB Insertion Loss Taps vs. Regular Taps

Although 1.5 dB of insertion loss may seem insignificant in traditional plant design, it makes a drastic difference in DGA. This is because in traditional HFC design, one or two low value taps may be installed in each distribution span. As shown in section 8.2 and 8.3, the number of low value taps can vary from 5-8 when converting a traditional N+2 environment.

In order to overcome the challenges in the US, two proposals are made in the following sections.

9.1. Higher MDM Transmit Levels in Lower US Splits

Knowing that the DOCSIS 4.0 MDM transmit channel set (TCS) will have 64.5 dBmV of TCP available and assuming that operators may not go to 684 MHz in the US, given the DS upper limit of 1.8 MHz, the 'unused' TCP from the upper frequencies in the return band can be re-allocated to the lower bands. This can result in an 'up-lift' of the transmit PSD of the MDM, which is demonstrated in the figure below:

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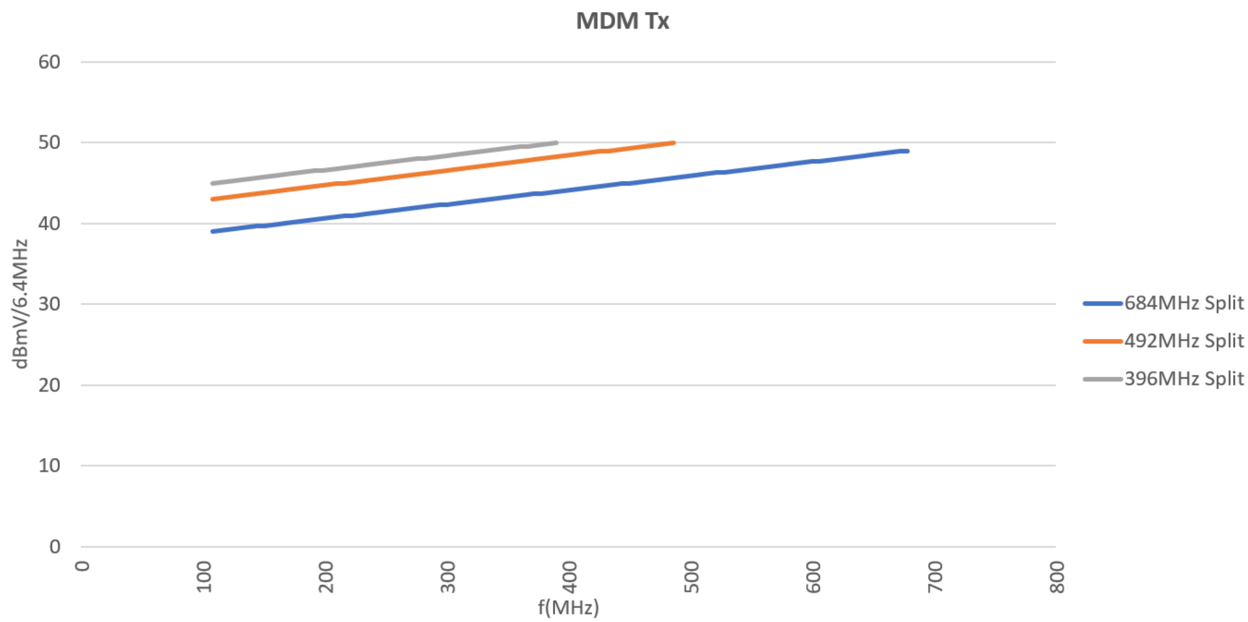

Figure 39 – Raised MDM Output Power PSD in Various Splits

Increasing the transmit PSD may raise concerns regarding spurious emissions and fidelity requirements in accordance to the DOCSIS 4.0 specifications. This needs to be studied more extensively to ensure adherence to said specifications.

With that in mind, let us assume a 396 MHz split. Applying the 6 dB additional available power to DGA8 in Figure 37 will result in the following US Rx power at the port of the node:

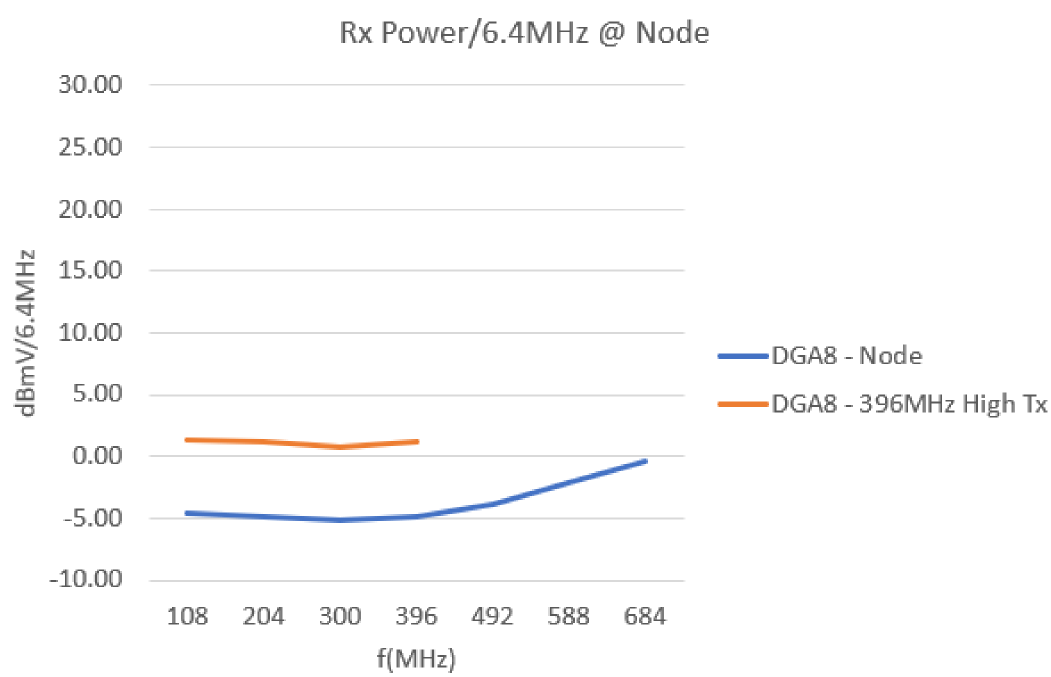

Figure 40 – Last Span DGA-to-Node Level Comparison – Raised MDM PSD

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It is visible that re-allocating the power from the unused 396 MHz - 684 MHz to the active 5 MHz to 396 MHz can approximately result in a 6 dB increase in US Rx power at the node without increasing the modem's TCP.

9.2. Higher Return Gain in DGA Amplifiers:

Let us assume the gain of the DGA return amplifier is increased by 2 dB at 108 MHz and by 1 dB at 684 MHz, resulting in the following figure:

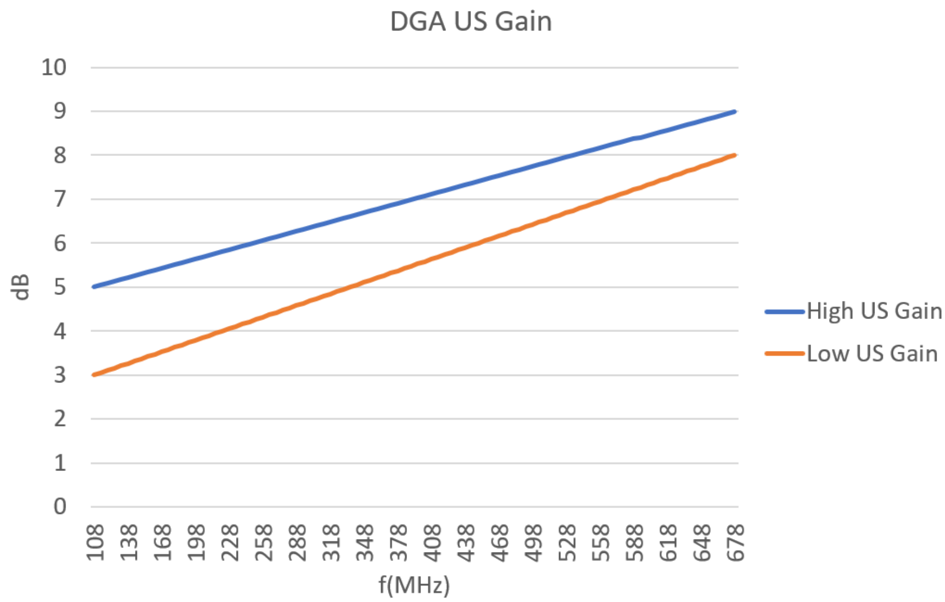

Figure 41 – High vs. Low Gain DGA Return Amplifier

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DGA8's new US Rx power at the node with the newly assumed gain has been demonstrated in the figure below:

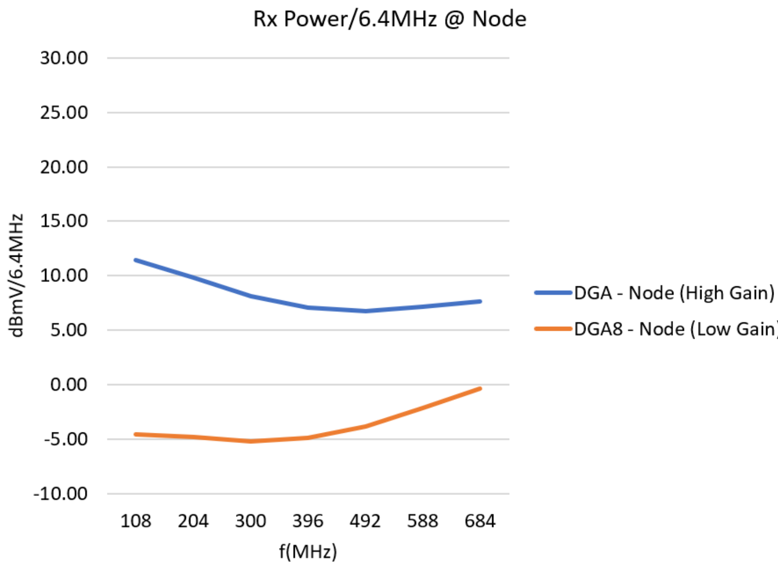

Figure 42 – Last Span DGA-to-Node Level Comparison – High Gain vs. Low Gain Return DGA Amplifier

10. Power Draw

One of the most attractive concepts of DGA is reduced power draw in the OSP. Traditional plant design can be quite power hungry with 150 watt nodes, and amplifiers that draw anywhere from 30 to 60 watts.

Power supplies themselves can be quite challenging to deploy, given the reduced amount of available real estate for installing them. Due to this, the current power supplies installed in the OSP are expected to support the future technologies deployed by operators, which may seem very challenging

DGA can reduce the power consumption in the OSP drastically in comparison to traditional designs. In order to quantify this in the plant models analyzed in this paper, the following has been assumed:

- N+2 plant
- 4 outputs from each node
- 150 watt node
- 40 watt line extenders
- 7 watt DGA amplifier

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The following table demonstrates the potential power saving in an N+2 plant.:

Table 13 – Power Draw Comparisons

Traditional	Booster	DGA 135'	DGA 204&190'
460 Watts	515 Watts	320Watts	375Watts
	⬆ 10%	⬇ 30%	⬇ 20%

Although the power draw in the booster amplification case has increased by 10%, it was demonstrated in section 7 that the performance at the end-of-line can increase by 2-3 orders of modulation. This is also assuming that future amplifiers will not be able to adjust power consumption based on their output power and utilized TCP.

It can be seen that DGA saves 20-30%, depending on the plant model. This is dependent on the number of DGA amplifiers used in each span to overcome the existing span losses.

This reduction in power draw from existing power supplies presents countless opportunities for operators to deploy other technologies in the access network, such as DAA, small cell and 5G.

11. Plant Reliability

Here we compare the availability of a traditional cable plant with the new distributed gain amplifier (DGA) system.

We assume that the failure modes of traditional amplifiers and DGAs are comparable, and one does not impact any more customers or impact any customers differently than the other. For example, customers on a branch are not impacted by the failure of an amplifier on another branch, and generally only the customers downstream of a failed amplifier are impacted by the failure of an amplifier.

Therefore, we can model these systems as simple series systems of replaceable components.

Further, we will define the components of each system as amplifiers and non-amplifiers.

The variables n_tamp and n_dga are respectively the number of traditional amplifiers and DGAs in the comparable systems

Given the systems are equivalent except for the number and type of amplifiers, we can define the availability of each of these systems as follows, for an arbitrary customer of the systems.

Traditional system availability: $A\_tsys = A\_line * A\_tamp^{n\_tamp}$

DGA system availability: $A\_dgasys = A\_line * A\_dga^{n\_dga}$

A_line is the availability of the line system, everything but the amplifiers, which is the same in both architectures. A_tsys is the traditional system amplifier availability component, a series of amplifiers each with availability A_tamp. A_dgasys is the availability of the series of DGAs in the system, each with availability A_dga.

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Now we compare the two systems. We want the new system to be at least as good as the old, so we have the constraint

$$A\_dgasys \geq A\_tsys$$

Or

$$A\_line * A\_dga^{n\_dga} \geq A\_line * A\_tamp^{n\_tamp}$$

So

$$A\_dga^{n\_dga} \geq A\_tamp^{n\_tamp}$$

Given that the number of amps in either system is an integer, and n_dga = n_tamp + n for some integer n greater than 0, we can rewrite the previous equation as

$$A\_dga^{n\_tamp+n} \geq A\_tamp^{n\_tamp}$$

And then taking the n_tamp + n root of both sides, with acknowledgement that the variables are bounded positive, and the availabilities are between 0 and 1, we get

$$A\_dga \geq A\_tamp^{n\_tamp / (n\_tamp + n)}$$

We refer later to this above equation as the amplifier relation. Considering the architectures analyzed:

If n_tamp = 2, n = 6, n_tamp/(n_tamp+n) = 0.25

If n_tamp= 2, n = 5, n_tamp/(n_tamp+n) = 0.29

If n_tamp = 2, n = 4, n_tamp/(n_tamp+n) = 0.33

The tighter constraint is 0.25, and so a goal to reach is

$$A\_dga \geq A\_tamp^{0.25}$$

But most plant designs will only use 6 DGAs so the more common constraint will be

$$A\_dga \geq A\_tamp^{0.33}$$

If the probability that the above two equations are each true is greater than 50%, then odds are the new architecture will perform better on average in a large sample.

Now let's look at some comparisons based on amp availability values.

We can assume reasonably that A_tamp ranges from 0.999 to 0.99999 given service performance; with some data collection we can narrow it down further, and even find estimates based on use conditions, environment, etc. But based on this broad range of estimates, setting the inequality in the amplifier relation equation to an equality to see the worst case for the DGAs, we find that A_dga relates to A_tamp as in the figures below. We show results as dots for two deployments: 6 DGAs and 8 DGAs. The line of equality is added as a solid line for reference. The first graph shows availability in linear scale, while the second shows unavailability (1-availability) in log scale (U_dga and U_tamp respectively).

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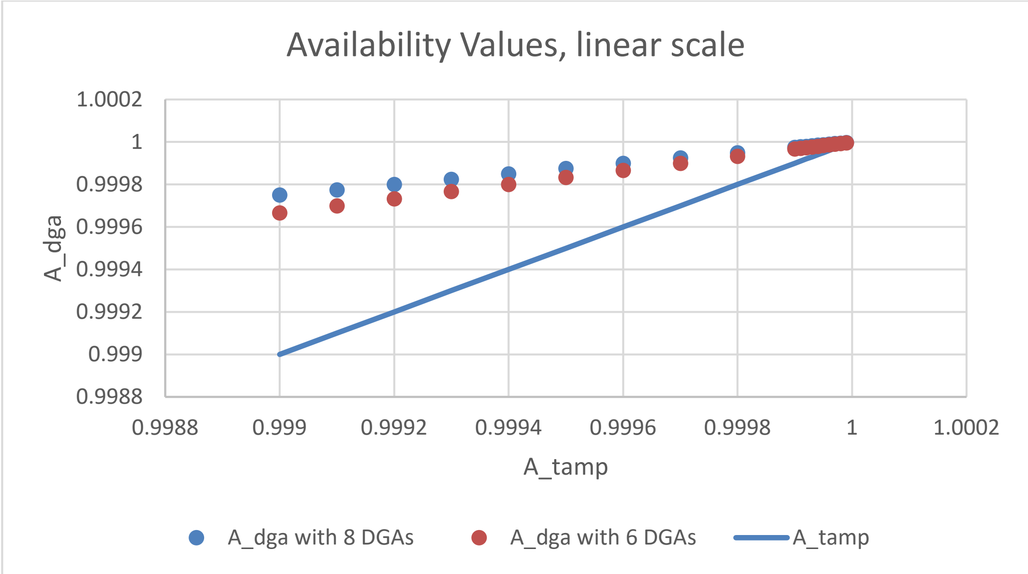

Figure 43 – DGA Availability

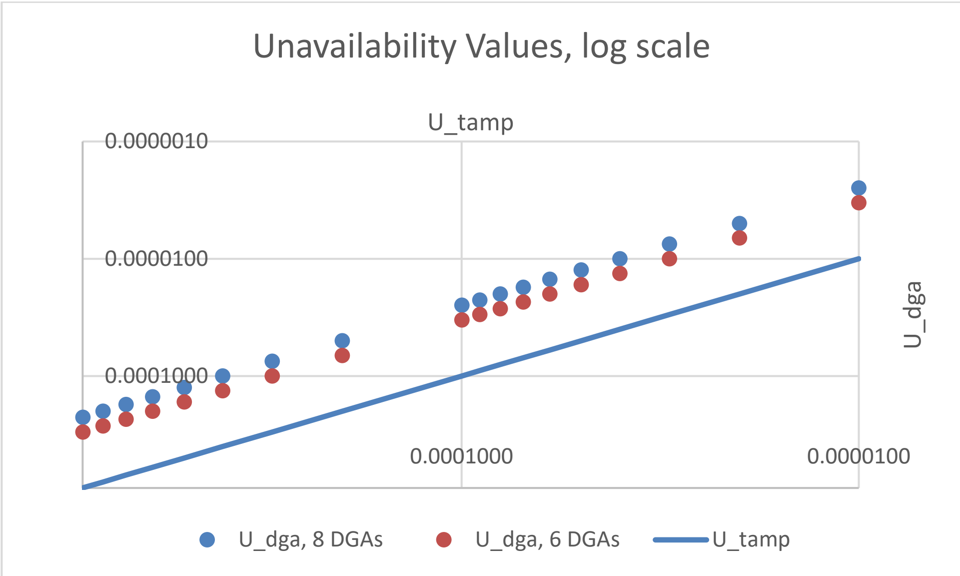

Figure 44 – DGA Un-availability

Table 4 – Unavailability Comparison for DGAs for Two Example Architectures versus Traditional Amplifiers

U_dga, 8 DGAs	U_dga, 6 DGAs	U_tamp	%diff, 8 DGAs	%diff, 6 DGAs
0.0002501	0.0003334	0.0010000	74.991%	66.656%
0.0002251	0.0003001	0.0009000	74.992%	66.657%
0.0002001	0.0002667	0.0008000	74.992%	66.658%
0.0001750	0.0002334	0.0007000	74.993%	66.659%
0.0001500	0.0002000	0.0006000	74.994%	66.660%

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U_dga, 8 DGAs	U_dga, 6 DGAs	U_tamp	%diff, 8 DGAs	%diff, 6 DGAs
0.0001250	0.0001667	0.0005000	74.995%	66.661%
0.0001000	0.0001333	0.0004000	74.996%	66.663%
0.0000750	0.0001000	0.0003000	74.997%	66.664%
0.0000500	0.0000667	0.0002000	74.998%	66.665%
0.0000250	0.0000333	0.0001000	74.999%	66.666%
0.0000225	0.0000300	0.0000900	74.999%	66.666%
0.0000200	0.0000267	0.0000800	74.999%	66.666%
0.0000175	0.0000233	0.0000700	74.999%	66.666%
0.0000150	0.0000200	0.0000600	74.999%	66.666%
0.0000125	0.0000167	0.0000500	75.000%	66.666%
0.0000100	0.0000133	0.0000400	75.000%	66.667%
0.0000075	0.0000100	0.0000300	75.000%	66.667%
0.0000050	0.0000067	0.0000200	75.000%	66.667%
0.0000025	0.0000033	0.0000100	75.000%	66.667%

From Figure 43, it appears that the DGAs need to have a much higher availability than the traditional amplifiers. But looking at Figure 44, from an unavailability (downtime) perspective, the difference is not unlikely to be achieved. Table 4 shows the values used to plot Figure 44. The percent difference in unavailability (%diff) is calculated as (U_tamp – U_dga)/U_tamp.

For comparative perspective, the DGA needs to have about 75% less unavailability than the traditional amplifier over its useful life if 8 are used. But if just 6 are used, then just 67% less unavailability is needed. Think of this percentage of unavailability as a reduction in downtime overall. While a ¾ reduction in downtime might seem aggressive, these DGAs are much simpler, with newer components, so have a chance to beat that mark if designed for reliability. Recall that in most cases only 6 DGAs are needed, so most cases need just a 2/3 reduction.

An additional consideration too is that, if DGAs have significantly higher availability, it is not likely because they are significantly more repairable, but rather because their rate of occurrence of failures over the same lifetime of the original amplifiers is much lower. This means DGAs are likely to have much longer useful lifetimes, and therefore may further reduce lifetime costs for providing service. However, highly accelerated life testing should be conducted to verify this assertion, and to provide evidence of the seemingly aggressive availability and reliability targets.

Note that the same equations describe the relationships for reliability as well as availability, as these are series systems. But as this is a repairable system, availability is the measure that makes more sense for the system. Fortunately, the system availability is an important contributing factor to the service availability which is important for customer experience. Reliability of the service from a user experience may be important as well.

12. Future Considerations

This section summarizes and discusses the points of concern that were brought up in the previous sections of this paper.

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12.1. Unity Gain, Distortions and Cascade Limits

One of the primary assumptions of this paper was that DGA amplifiers' distortions accumulate less quickly than the current amplifiers deployed by operators. This is primarily due to the simplicity and the low gain characteristics of these amplifiers, being single stage, with a fixed gain and tilt.

As mentioned in section 3.3, unity gain has been one of the primary design focuses for OSP in the past. Operators have adjusted their networks by adjusting node and amplifier outputs to balance both noise and distortions. Moving away from unity gain can raise concerns, especially regarding distortions. Knowing that almost all carriers deployed in the spectrum in the future will be digital, the distortion products can be summed into CIN, which can be translated to increase in noise level that should be considered in the system C/N. Due to lack of availability of data in this realm, this was not considered in this paper but it is something that needs to be studied extensively.

This subject needs to be studied further in the future when more products are available in this realm, to ensure that CIN products will not decrease the overall signal quality.

It should be noted that unity gain design can theoretically be achieved with DGA, assuming adjustments can be made in DGA amplifiers. This can also increase the number of DGA amplifiers needed in comparison to a non-unity gain design. It is worth noting that unity gain designs with DGA should be easier to achieve in green-field, in comparison to drop-in upgrades in brown-field applications. This can be achieved by simply balancing span losses and gain of DGA amplifiers, as currently done in traditional plant design.

The increased number of DGA amplifiers itself can raise concerns as well. Afterall, operators have been reducing cascades by pushing fibre deeper into the distribution plant. As demonstrated in section 8, when converting an N+2 plant, the number of DGA amplifiers can vary anywhere from 6-8, when designing for optimal performance (4kQAM).

When discussing the potential maximum number of DGA amplifiers in cascade, it requires a fine balance between the available spectrum, system C/N and distortions (CIN). The figure below, extracted from Broadband Cable Access Networks by David Lafarge and James Farmer, demonstrates this perfectly:

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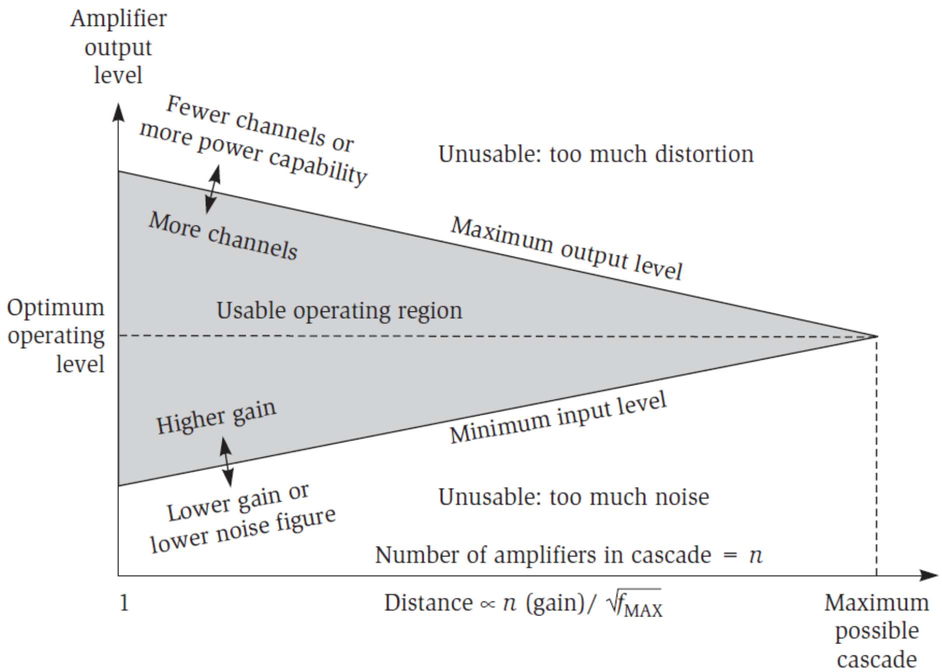

Figure 45 – Relationship between Cascade, Noise and Distortion

12.2. US Gain and Performance

As discussed in section 9, the US system performance can be a major point of concern, especially in longer span (higher span-loss) plant types. This is due to the increase amount of loss that the signal is subjected to. The higher loss is due to the longer coaxial distances along with higher insertion losses in low value taps.

The following proposals were made in sections 9.1 and 9.2:

- Raised output PSD's at the MDM
- Increased return gain in DGA amplifiers

The two proposals have to be studied individually and in combination to determine the feasibility of them being implemented by the vendor community.

12.3. Design Standards

DGA presents a major shift in how access networks are designed. Given that OSP designs have remained more or less the same in the previous decades, such a drastic shift in design could be a multi-year endeavor.

A slower and incremental implementation of DGA is something to be considered. As MSO's reduce cascade lengths in the OSP while pushing fibre deeper, booster amplifiers can be implemented in sections of the plant that struggle with the current spacing, especially when upgrading the available spectrum to 1.8 GHz. This can also help with not having to potentially deploy DGA in N+3 or N+4 architectures. This may result in 15+ amplifier cascades which can present difficulties regarding plant maintenance and performance in the future.

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12.4. 3 GHz

DGA presents exciting insights into what access architecture and designs could look like when contemplating 3 GHz spectrum expansions. In 2019, a paper was published under the title “Blueprint for 3 GHz, 25 Gbps DOCSIS” by John T Chapman, Hang Jin, Thushara Hewavithana and Rainer Hillermeier, which covers this topic in great detail. As MSO’s reduce cascades and reach passive networks (N+0) in the future, DGA can be the answer to achieving 3GHz of available spectrum and 25 Gbps.

13. Conclusion

This paper discussed how booster amplification and DGA implementations can improve performance in the analyzed plant models. A comparison for overall system performance and C/N contributions from amplifiers were discussed between a traditional N+2 plant models, N+2 models with the introduction of booster amplifiers mid-span, and DGA converted versions of them.

From a downstream performance perspective, it was observed that the analyzed plant models in a DGA system can achieve much higher orders of modulation in comparison to the traditional plant model. This is despite increasing the cascade length from +2 to +6 or +8, depending on the spacing. This was especially visible in longer plant models that have been ‘stretched’ to their current spacing limits.

It was also demonstrated that DGA can substantially reduce the power draw in the OSP, leaving headroom for future technologies to be deployed in the access network. This is one of the most attractive points of a DGA system, given the current limitations and challenges that operators face regarding plant powering.

Furthermore, the form-factor of the DGA amplifiers alleviate a number of concerns regarding available real estate for installing traditional amplifiers and PEDs. High gain amplifiers require large PEDs to accommodate their large form-factors, along with cooling requirements. DGA amplifiers’ form-factors are more comparable to main-line splitters, making them extremely convenient for installation in the OSP. They can be installed in almost any existing PED in the access network.

It was also demonstrated that a DGA plant can be as reliable as a traditional one, despite the increase in the number of amplifiers in a distribution run.

As attractive as the items mentioned above may be, DGA can be seen as a major shift in how access networks are designed. Various challenges were also discussed throughout this paper that require more in-depth research. Upstream gain and performance of a DGA system, maximum cascade length and unity gain designs are some of the points of concern.

Although this concept is in its infancy, it does seem to offer extremely attractive solutions to some of the major challenges that operators may face when upgrading their networks to 1.8 GHz and beyond. It would be worth the effort to analyze the challenges identified, to ensure they can be alleviated.

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Abbreviations

C/N	carrier to noise ratio
CIN	carrier to intermodulation noise
CINR	carrier to interface noise ratio
CSO	composite second order distortion
CTB	composite triple beat distortion
dB	decibels
dBmV	decibels relative to one millivolt
DAA	distributed access architecture
DGA	distributed gain architecture
DOCSIS	data over cable service interface specification
DS	downstream
ESD	extended spectrum DOCSIS
GHz	gigahertz
HFC	hybrid fibre-coax
ISBE	International Society of Broadband Experts
MDM	modem
MER	modulation error ratio
MHz	megahertz
NF	noise figure
NPR	noise power ratio
OFDM	orthogonal frequency division multiplexing
OSP	outside plant
PED	pedestal
PoE	point of entry
PSD	power spectral density
QAM	quadrature amplitude modulation
RF	radio frequency
Rx	receive
SCTE	Society of Cable Telecommunications Engineers
TCS	transmit channel set
TCP	total composite power
Tx	transmit
US	upstream

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