Upstream Challenges With DOCSIS 3.1

White Paper

A Technical Paper prepared for SCTE/ISBE by

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Introduction

The introduction of DOCSIS® 3.1 means that higher modulation schemes, higher levels and higher bandwidth increase the load on the cable network.

The downstream increases from several QAM channels used in DOCSIS 3.0 in spectrum carrying up to 862 MHz with the addition of a couple of OFDM channels in spectrum expanding up to 1.2 GHz. All these changes greatly increase the load on the equipment used in the network.

However, this is nothing compared to what happens in the upstream. The big change is the bandwidth from the current low split of 42/54 MHz in the USA or 65/85 MHz in Europe to mid-split in the USA 85-105 MHz and high-split in Europe 204/258 MHz. In the USA, the bandwidth has grown by 216% and in Europe by 331%. In addition to the phenomenal bandwidth growth, increased loss in the cables is a reality and as a result, DOCSIS 3.1 increases the maximum level of the upstream carriers by 6dB to 57dBmV per 4 channels.

This growth in level and bandwidth creates four main challenges:

- Passive intermodulation (PIM) in in-home splitters
- 2nd order distortion in in-home amplifiers
- Overloading of the upstream amplifier in access amplifiers
- The downstream reducing the quality of the upstream in the access amplifiers

This White Paper summarizes the four challenges detailed and describes what to do to prevent possible problems.
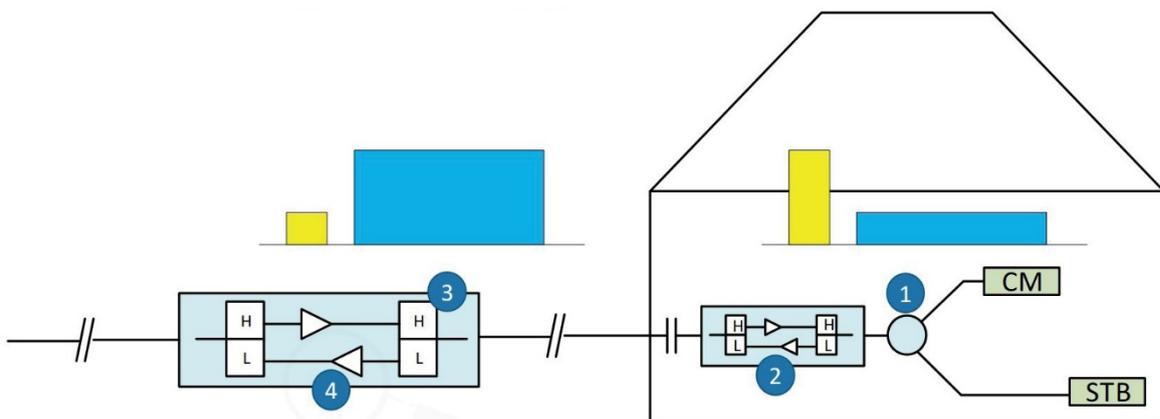
Figure 1 - Cable network

1. Passive intermodulation (PIM) in in-home splitters

Intermodulation is a phenomenon which occurs in almost all components used in broadband networks, both active and passive devices. It is therefore important to ensure this is reduced for improved network performance. Intermodulation is caused by non-linear transfer characteristics of components.

1.1. Theory and background

In the Cable TV, non-linear components include ferrites and diodes in passives and transistors in active devices. In this section, the focus is on in-home splitters. A splitter is made with a ferrite core transmission line transformer.

This ferrite core transmission line transformer transfers energy from one port to the other via a magnetic field inside the ferrite core. See figure below:
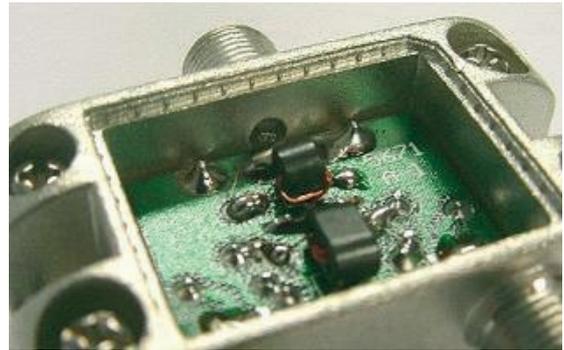
Figure 2 - Splitter
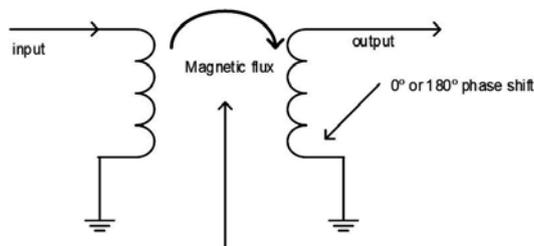
Figure 3 - Non-linear transfer function due to core saturation
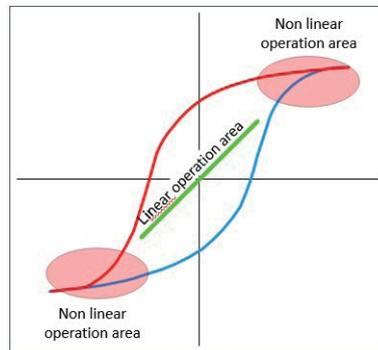
Figure 4 - Transfer characteristic of a ferrite

If due to surge, the input energy level (current) is too high the ferrite core becomes saturated. In cable TV applications, this energy is usually caused by a pulse, caused by lightning or a power surge, introducing a shift of the magnetic working point. Due to the saturation, the center point of the transfer characteristics of a ferrite moves up or down in the direction of the non-linear part of the graph. The result is that the transfer function is no longer linear and the signal becomes distorted.

In numbers:
The non-linearity changes the input-output characteristic of a splitter; the input output characteristic in the time domain of a linear system is given by:

$$y(t) = ax(t),$$

while this characteristic of a non-linear system can be approximated by a polynomial:

$$y(t) = a_1 x(t) + a_2 x_2(t) + a_3 x_3(t) +$$

If a sinusoid with function $x(t){=}A\cos(\omega t)$ is applied to a nonlinear system, multiples at the frequencies 2ω, 3ω, 4ω, … arise at output $y(t)$ [1]. These multiples are called harmonics.

The products that arise when two or more different frequency signals are applied to a non-linear system are called intermodulation distortion (IMD) products. For example, if signal:

$x(t){=}A\cos(\omega 1 t){+}B\cos(\omega 2 t)$

is applied to a non-linear system, e.g. products arise at frequencies:

$2\omega 1$, $2\omega 2$, $\omega 1{+}\omega 2$, $\omega 1{-}\omega 2$	(= second order IMD)
$3\omega 1$, $3\omega 2$, $2\omega 1{-}\omega 2$, $2\omega 2{-}\omega 1$	(= third order IMD)

These are spurious unwanted products, which are located at frequencies of desired channels.

1.2. **Measurement**

The European Cenelec, "EN 60728-4:2008 Cable Networks for Television Signals, Sound Signals and Interactive Services
- Part 4: Passive Wideband Equipment for Coaxial Networks", describes the IMD measurements for 2nd and 3rd order products in passives. The measurement set up for IMD measurements is shown in Figure 1.

Two signals with different frequencies are applied to the output ports of a passive system, e.g. a splitter or a directional coupler. In the current specifications, two sine waves of 60dBmV at F1=60 MHz and F2=65 MHz are used. These are the two worst case scenario frequency channels of the upstream frequency band of 5 MHz – 65 MHz.

Using a spectrum analyzer, the 2nd order IMD product at 125MHz (F1+F2) is measured, as shown in Figure 2. In these measurements, the amplitude ratio between the fundamental product and second order product is measured.
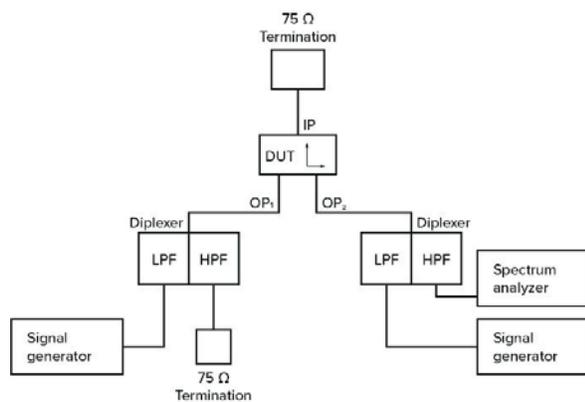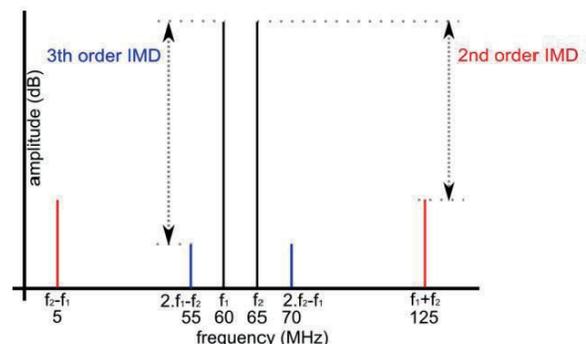

Figure 5 - Upstream IMD measurement setup

Figure 6 - Spectrum with IMD products

With a surge pulse to one of the ports, the ferrite is magnetized. In the test, the IMD is measured before and after the magnetization with a surge pulse:

- A demagnetized splitter can achieve approximately 110 dBc 2nd order intermodulation.
- A magnetized splitter will achieve less than 80 dBc 2nd order intermodulation.

If the frequencies of the carriers are at 34 MHz and 40 MHz, the second order is on 74 MHz, this is in the downstream band.

1.3. PIM results with DOCSIS 3.0

The upstream levels of DOCSIS 3.0 are 54dBmV with two carriers:

- The 2nd order product of these signals will be with a demagnetized splitter at -62dBmV
- The 2nd order product of these signals will be with a magnetized splitter at -32dBmV

With a downstream level of 0 dBmV this will create a C/N of 62 dB with a demagnetized splitter and 32 dB with a magnetized splitter. A magnetized splitter will already cause issues, as the CINR of the downstream signal will be critical for 256 QAM signals.

1.4. PIM results with DOCSIS 3.1

The upstream levels of DOCSIS 3.1 are 57 dBmV with four carriers:

- The 2nd order product of these signals will be with a demagnetized splitter at -50dBmV
- The 2nd order product of these signals will be with a magnetized splitter at -20dBmV

Table 1 - PIM by DOCSIS 3.x

	Upstream level 2ch	Intermodulation demagnetized	Intermodulation magnetized
DOCSIS 3.0	54 dBmV	-62 dBmV	-32 dBmV
DOCSIS 3.1	60 dBmV	-50 dBmV	-20 dBmV

With a downstream level of 0 dBmV this will create a C/N of 50 dB with a demagnetized splitter and 20 dB with a magnetized splitter. With a magnetized splitter communication will stop, as the CINR of the downstream signal will be too low.

The previous results have shown the PIM is a problem with DOCSIS 3.1 signals, this issue must be taken seriously. It is not just PIM levels that are an issue, there are many more carriers and therefore a greater PIM total. This combination with DOCSIS 3.1 increases the need for low PIM devices.

The increased frequency band to 1.2 GHz forces the splitter suppliers to go to smaller ferrites and these are even more sensitive to magnetization. To make a splitter that will meet the higher downstream frequency requirements and sustain a good PIM level is very difficult and costly. It is better to protect the ferrite from getting magnetized with a special circuit that will bypass the high RF signals but protect the low RF energy from surges and voltage pulses.

1.5. Conclusion: PIM in in-home splitters

- PIM has always been a critical specification for in-home splitters but the introduction of DOCSIS 3.1 dramatically increases the importance of this specification.
- PIM will reduce the quality of the downstream signals due to intermodulation from the upstream signals.
- There are good standardization methods to measure and qualify the in-home splitters.
- The new increased maximum frequency band of 1.2 GHz will force the splitter vendors to use smaller ferrites and these are more sensitive for PIM.
- It can be resolved with either a special protection circuit that protects the ferrite from being magnetized or using a more expensive high permeability ferrite.

2. Second Order Distortion in In-Home Amplifiers

With the addition of even more digital channels, cable network operators are particularly aware that in-home equipment should not degrade the performance of their network; both upstream and downstream.

2.1. Theory and background

The intermodulation and noise figure is important for the downstream amplifier stage but, it is the intermodulation that is key for upstream amplifiers.

In the upstream a poor intermodulation performance will result in:
- Generated beats in the downstream frequency spectrum but, these are normally filtered by the diplex filters
- Generated intermodulation products in the upstream spectrum
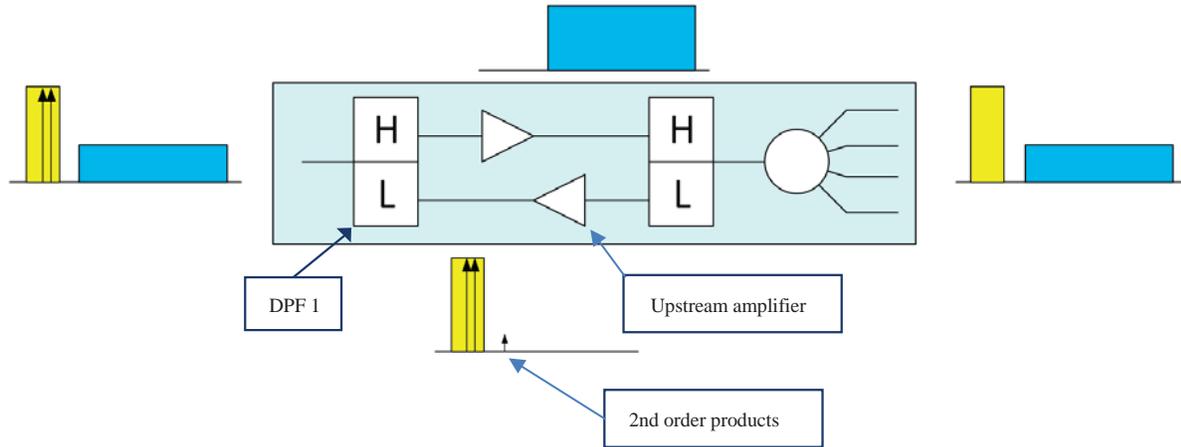
Figure 7 - Blockdiagram low split amplifier

The upstream (yellow) goes from the right side, via the 4-way splitter and the DPF (diplex filter) to the upstream amplifier. The upstream amplifier will also create 2nd order products adjacent to the upstream signal. This unwanted 2nd order product will be stopped in DPF 1 before it reduces the quality of the downstream (blue) signal.

As the levels of the downstream signals are low, it is important to use good diplex filters with enough isolation, otherwise these signals will reduce the quality of the downstream signal.

Signals below 15 MHz are not normally used due to the galactic noise creating too low a CINR noise. Therefore, signals are normally 15 MHz and higher.

Example 1, with a low split of 42/54 MHz,:

- $F1 = 20$ MHz

- $F2 = 26$ MHz

- 2nd order $= F1 + F2 = 46$ MHz. This is outside the upstream band and is stopped by the diplex filter.

So, with a low split, the diplex filters are helping to prevent reduction in the quality of the signals.

If the split become mid-split 85/105 MHz or high-split 204/258 MHz, this becomes a different story.
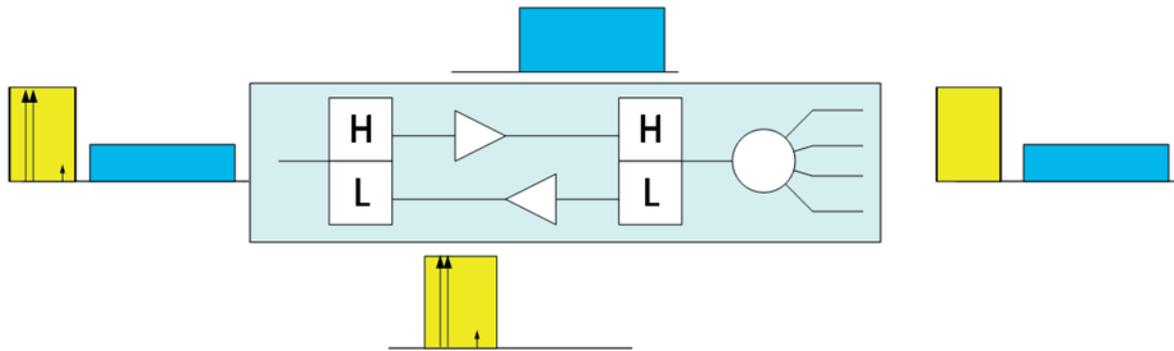
Figure 8 - Blockdiagram mid split amplifier

With this split, the 2nd order products are in the same upstream band. For example 2, with a mid-split of 85/105MHz:

- F1 = 20 MHz
- F2 = 26 MHz
- 2nd order = F1 + F2 = 46 MHz. This is in the middle of the upstream band.

This is also the case with the higher frequencies:

- F1 = 76 MHz
- F2 = 30 MHz
- 2nd order = F1 - F2 = 46 MHz. Again, this is in the middle of the upstream band.

With a high split of 204/254 MHz, this only becomes worse. The 2nd order becomes much more important with a mid or high split than with a low split as IMD products are no longer out-of-band.

Note: this is a little different with a split of 65/85 MHz but also most of the 2nd order products are outside the band and will be filtered out by the diplex filter.

The best way forward is to design an upstream amplifier with reduced 2nd order products. There are several ways of building these amplifiers:

- Negative feedback amplifier
- Push-pull amplifier
- Balanced amplifier

All three have their own challenges, a summary of each follows.

2.2. Negative feedback

This is the most widely used circuit in cable TV amplifiers. It not only reduces intermodulation but also reduces gain and improves frequency response resulting in a wideband, flat frequency response amplifier. In fact, the improvement of the frequency response is usually the main reason for its use in cable TV applications.

Negative feedback also reduces noise and intermodulation. See figure 9 for the modelled amplifier.
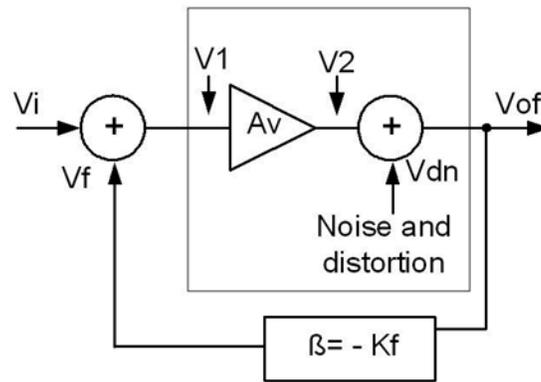
Figure 9 - Negative feedback

The output voltage can be expressed as:

Vof= V2+Vdn Vof =Av·V1 + Vdn

Vof = Av (Vi+Vf) + Vdn

Vof = Av (Vi – Kf·Vof) + Vdn

Vof = Av ·Vi – Av·Kf·Vof + Vdn

Vof (1+ Av·Kf) = Av·Vi + Vdn

$$Vof= \left[\frac{Av}{1+Av\cdot Kf}\right] Vi + \left[\frac{1}{1+Av\cdot Kf}\right] Vdn$$

The conclusion is twofold:

- first part of the equation shows that the gain is reduced
- second part of the equation shows that the noise and distortion is reduced The equation shows that more feedback results in lower gain and lower distortion.

The most common form of negative feedback is the single transistor with resistive feedback circuit as shown in fig 10.

Analysis of the schematics show that feedback occurs through resistor (Rt) being in series with the input impedance. The output voltage (Uc) has a 180° phase shift with respect to the input voltage (Ub), hence the negative feedback of the circuit.
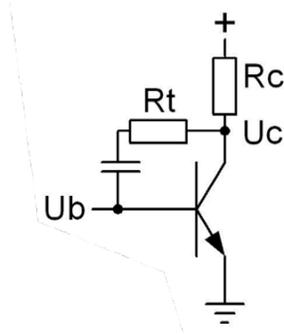
Figure 10 - Resistor as negative feedback

It is advisable for the collector current be made adjustable for best performance, since most transistors have a distinct point for lowest 2nd order distortion as a function of collector current. See figure 3 as an example of the BFG 135 specifications. The distinct minimum 2nd order point does not coincide with the lowest 3rd order intermodulation hence the need for an adjustable current.

V_CE = 10 V; V_o = 50 dBmV; T_amb = 25 °C;
f_(p+q) = 810 MHz.

Second order intermodulation distortion as a
function of collector current

V_CE = 10 V; V_o = 850 mV; T_amb = 25 °C;
f_(p+q-r) = 793.25 MHz.

Fig.9   Intermodulation distortion as a function of
collector current.
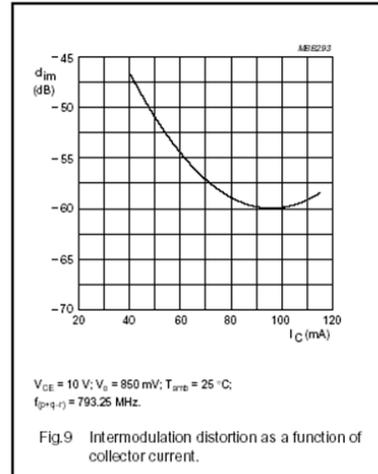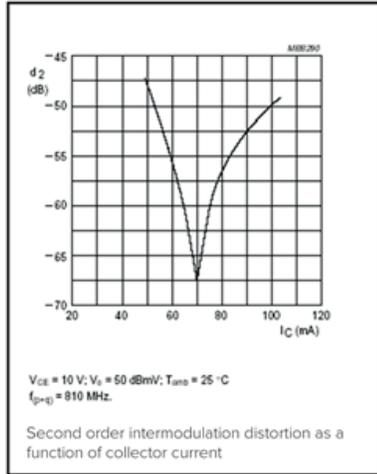
**Figure 11 - Intermodulation as a function of collector current
(BFG-135)**

2.3. Push-pull

This type of amplifier is widely used in all sorts of applications, including: cable TV power hybrids, GSM, linear RF power amplifiers, etc.

In cable TV applications this type is mainly used in hybrids; it is rare to find this type inside in-home amplifiers. There are exceptions where a push-pull architecture is used for the upstream amplifier or downstream amplifier.

Figure 12 shows a simplified circuit for analysis.
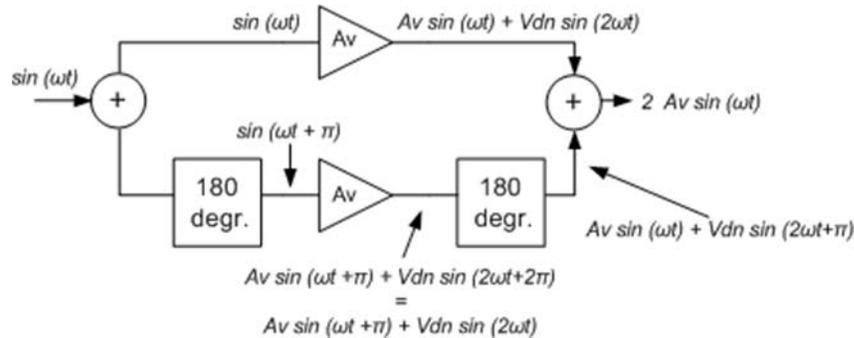
Figure 12 - simplified push-pull circuit

It is assumed the divider/combiner is lossless therefore the gain of the circuit equals 2 Av. In the real world, the divider loss is 3dB and therefore the gain of the circuit equals Av.

From the figure above it can be seen that even (2nd, 4th, …) order intermodulation products are cancelled. Odd (3rd, 5th,...) order intermodulation performance improvement is only marginal with two amplifiers in parallel.

In the practical world, cable TV type push-pull circuits use a balun as a combiner/divider. This is a relatively simple solution but, it has some drawbacks:

- Impedance of the amplifiers must be 75/2= 37.5 Ω.

- Balance of the circuit (and therefore 2nd order cancellation) relies totally on the symmetry between the amplifiers used. A slight difference in amplifier impedance will result in imbalance because of the lack of isolation in the divider/combiner.

- Intermodulation performance is therefore influenced firstly input and output impedance and secondly the intermodulation performance of the individual amplifiers.
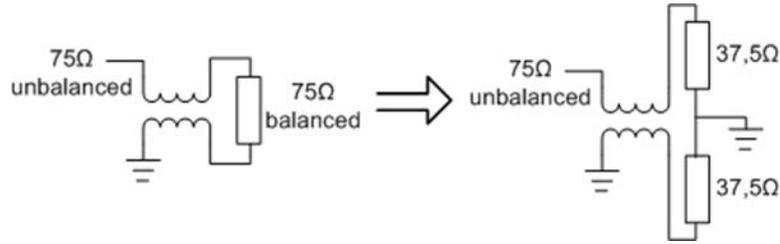
Figure 13 - BALUN as divider/combiner

2.4. Balanced amplifier

This type of amplifier is referenced only for completeness since the practical realization of the circuit has too narrow a bandwidth for cable TV applications.

The 90 degree delay lines used are frequency dependent, limiting the useable bandwidth of the amplifier. This type of amplifier is commonly used in microwave applications or in narrowband RF applications.
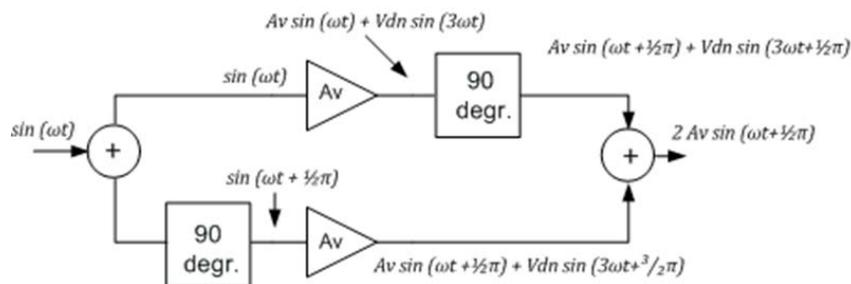
Figure 14 - Simplified Circuit of a Balanced Amplifier

As can be seen in figure 9, this type of amplifier has improved odd order intermodulation performance, while even order intermodulation is improved with 3dB w.r.t. a single amplifier. Some high-power RF amplifiers use this kind of circuit to combine two push-pull amplifiers achieving the best of both worlds (no even or odd order distortion products) but at the cost of 4 single amplifiers.

As previously stated, the cable TV band is wide and as it's not possible to create 90 degrees commercial delay lines, therefore this amplifier is unsuitable for cable TV implementations.

2.5. Conclusion 2nd order distortion in in-home amplifiers:

- Mid and high split drive the complexity of upstream gain stages in the in-home amplifiers.
- There are different styles and gain stages and all have their pros and cons.
- As the 2nd order by mid and high split becomes more important, the push-pull seems a good solution.
- The DPF in the in-home amplifier will prevent a lot of the intermodulation products but, this also increases the importance of a good DPF.

3. Overloading of the upstream amplifier in access amplifiers

3.1. Theory and background

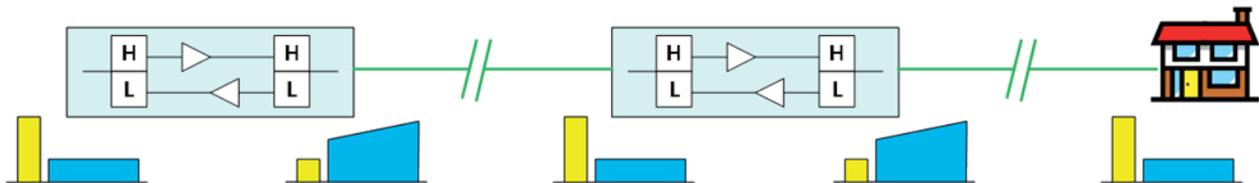An upstream amplifier in an access amplifier purpose is to overcome the loss in the subsequent cable.

Figure 15 - Signal Path Up and Downstream

Upstream signals (yellow) from the home arrive at the amplifier. The upstream signal at the second amplifier has the same input level as the signal on the first amplifier.

The signal on the output for the upstream of amplifier has a higher level to compensate the cable loss between the amplifiers.

3.2. DOCSIS 3.0 way of specifying the upstream performance

Historically, the performance of an upstream amplifier was provided via the so-called Noise Power Ratio method (NPR).

An upstream amplifier must meet a certain Carrier to Interference Noise Ratio (CINR) on a specified input level, over a specified input window, with a specified gain and over a specified frequency range. Such as:

- Input power $P=6$ dBuV/$\sqrt{Hz}$

- Input window +/- 12 dB
- Gain = 25 dB
- Frequency 5 – 65 MHz
- Min CINR, 50 dB

This results in performance of the upstream amplifier where, if the input level is between -6 dBuV/√Hz and 18 dBuV/√Hz, the output performance is always more than 50 dBc.
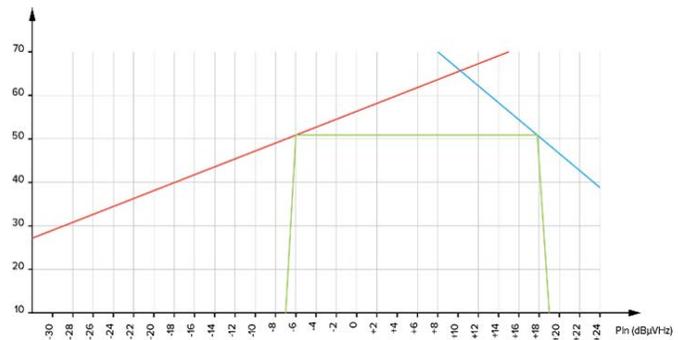
Figure 16 - CINR versus input power graph

3.3. DOCSIS 3.1 way of specifying the upstream performance

With the new DOCSIS 3.1 standard, the same performance is often requested but, only with an upstream band until 204 MHz and limited gain in dB's. This is because of the additional loss at higher frequencies, resulting in:

Input power P=6 dBuV/√Hz

Input window +/- 12 dB

Gain = 28 dB

Frequency 5 – 204 MHz

Min CINR, 50 dB

The difference between a channel of 6.4 MHz and √Hz = 10log6,400,000 = 68 dB This results a maximal power per channel of 6.4 MHz of:

P out= 6 dBuV/√Hz + 12 dB (input window) + 28 dB (gain) + 68 dB (6.4 MHz) = 114 dBuV = 54 dBmV 204 MHz has 30 channels, this results in a total composite power of:

54 dBmV + 10log30 = 69 dBmV

This is too much power to be created in a mimic and a hybrid is required with an additional power consumption of 8 Watts.

In reality, this is never the case:

1) Generated beats in the downstream frequency spectrum but, these are normally filtered by the diplex filters

2) Generated intermodulation products in the upstream spectrum and a NF of 8 dB and NP of 2 dBuV the C/N towards the node of the 10 amplifiers together:

C/N upstream   = Input level - (8 db (NF) + 2 dBuV (NP)) – 10log10 (Nb of amplifiers)

= Input level – 20 dBuV

With an input level of 10 dBmV, the C/N from the access network is still 50 dB. This means it is nil versus the noise from the home and this will lower the input but more importantly the output level of the upstream amplifier.

With the 2 points above, the output composite power on the output will drop a lot and this will make it feasible to use a normal mimic instead of a hybrid and this will improve the quality and reduce the power consumption.

3.4. Conclusion: overloading of the upstream amplifier in access amplifiers

- The current method of setting levels and specifying upstream amplifiers in access amplifiers will drive power consumption too high.
- The level currently used for upstream can be reduced because less amplifiers are combined behind an optical node, due to segmentation in the network.
- The new DOCSIS 3.1 channel drives a new way of alignment of the cable TV network for the upstream.

4. Downstream: reducing upstream quality in access amplifiers
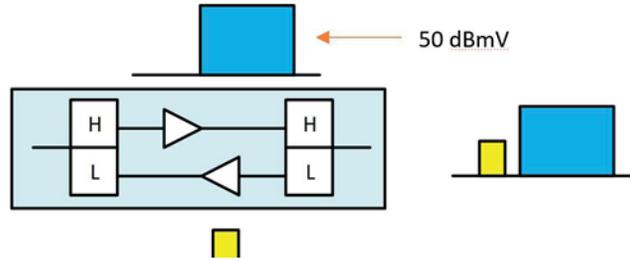
4.1. Theory and background

A block diagram of an access amplifier is given below:
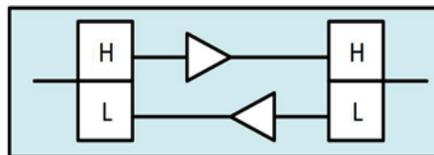
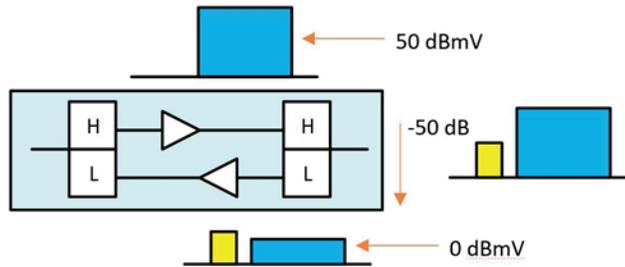**Figure 17 - Block Diagram Access Amplifier**

As described in section 4, the input level of the upstream amplifier is approximately 10 dBmV.

The downstream signal of an access amplifier can be up to 50 dBmV in the real world.

Figure 18 - Block Diagram Access Amplifier with Levels

The isolation of a normal diplex filter is approximately 50 dB, this means that the downstream signal reaching the upstream amplifier is approximately 0 dBmV.

Figure 19 - Block Diagram Access Amplifier with Levels

The downstream signal will load the upstream amplifier and this will create harmonics in the upstream band.
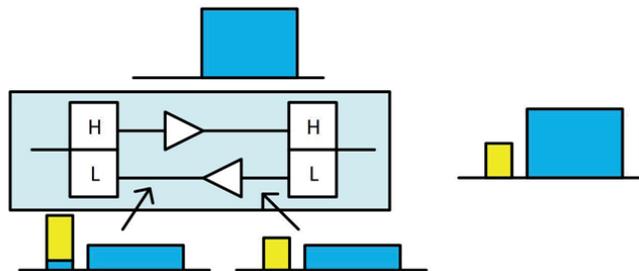
Figure 20 - Block Diagram Access Amplifier with Levels

This will reduce the CINR in the upstream and, as a result, reduce the capacity.

4.2. Measurements

Extensive testing has been done to support the above issue:
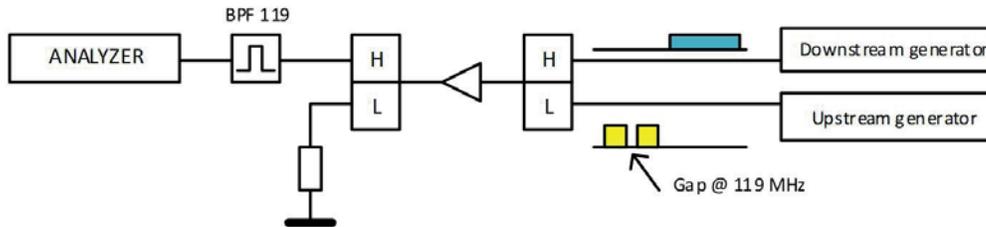
Figure 21 - Test Setup

The upstream connected to the DUT via the DPF 204/258 has a gap at 119 MHz. In this channel, we measure the CINR. To be certain we don't overload the analyzer, we first measure the level of the upstream without filter and then the noise and interference in the gap is measured.

Results

Table 2 - Upstream CINR versus Downstream level

downstream signal (dBmV/6MHz)	CINR
-10	42.01
-8	42.01
-6	42.01
-4	42.01
-2	42.01
0	42.01
2	42.01
4	42.01
6	42.01
8	41.61
10	40.41
12	38.91
14	35.91
16	30.51
18	23.21
20	17.41
22	9.81

The results above show the upstream amplifier starts to produce intermodulation products caused by the downstream signals above 10dBmV in the upstream band. These intermodulation products are caused by the downstream and if multiple amplifiers are added on one node, the interference will add with 10 log the number of amplifiers.

New style amplifiers often have a better push-pull and more isolation than 40 dB in the diplex filters. This will result in a lower downstream signal coupled to the upstream amplifier and the push-pull can better handle the loading. Both improvements will reduce the impact of the downstream signal on the upstream quality.

4.3. Conclusion: downstream reducing the quality of the upstream in the access amplifiers

- Poor isolation in diplex filters will reduce the quality of the upstream due to loading of the upstream amplifier with downstream signals.
- The downstream intermodulation products in the upstream will look like CPD.
- This is solved by good DPF and amplifier stages.

Conclusion

Upstream needs with DOCSIS 3.1

There are several challenges to driving upstream through the existing cable TV network but, all of these challenges are resolvable with the latest technology.

PIM in splitters

- PIM are intermodulation products from the upstream signals that reduce the quality of the downstream signals.
- Standards drive the measurability.
- PIM can be reduced by better ferrites or special protection circuits.

2nd order in-home amplifiers

- Intermodulation products in in-home amplifiers are products created by upstream signals reducing the quality of upstream signals.
- The 2nd order problem in upstream amplifiers becomes critical with mid and high split.
- There are several types of in-home amplifiers and they all have their pro's and con's.

Overloading of the upstream amplifier in access amplifiers

- Overloading of the upstream amplifier in the access network can be solved by a new method of specifying and alignment of the upstream signals.
- The segmentations mean that levels on the input of the upstream amplifiers can be reduced.

Downstream: reducing the quality of the upstream in the access amplifiers

- The upstream amplifier can be overloaded by the downstream signals which will reduce the quality of the upstream signals.
- This problem can be solved by good DPF and the latest state-of-the-art amplifier technologies.

Abbreviations

CINR	Carrier to Interference Noise Ratio
CNR	Carrier to Noise Ratio
CPD	Common Path Distortion
DOCSIS	Data Over Cable Service Interface Specification
DPF	Diplex Filter
GHz	Giga Hertz = 1.000.000.000 Hz
IMD	Intermodulation
MHz	Mega Hertz = 1.000.000 Hz
NF	Noise Figure
NP	Noise Power = kTB (k= Boltzmann's constant, T = temperature in Kelvin, B = Bandwidth)
NPR	Noise Power Ratio
OFDM	Orthogonal Frequency Division Multiplexing
PIM	Passive intermodulation
QAM	Quadrature Amplitude Modulation
RAF	Radio Frequency