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EXTENDED SPECTRUM DOCSIS®: A PRAGMATIC APPROACH

Shift to distributed access, Part 2

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PREFACE

Four cable industry veterans completed a comprehensive paper on May 21, 2012, to move the industry forward in the area of next generation cable access (1). Among other issues, they recognized a threat associated with the limited return path. The paper described OFDM, LDPC, and many technologies that became familiar to industry practitioners at the latest when the DOCSIS 3.1 specification was launched. Now, seven years later, the statement in the abstract of this paper has become highly topical. "We will explain how and why an approach based on the principle of an expanded diplex architecture, and using a 'high-split' of up to 300 MHz, is the best path for operators to manage this growth. This includes considering the simultaneous expansion of the downstream capacity." (1) While the paper recommended "high-split", meaning upstream frequencies up to 300 MHz, it also considered a long-term goal of utilizing a spectrum of up to 1.7 GHz.

CableLabs published the first DOCSIS 3.1 Physical Layer Specification in October 29, 2013. Two years later, Comcast announced that the world's first live DOCSIS 3.1 modem was online in Philadelphia (2). The live test used a standard cable connection, similar to what Comcast had across the country. Also in 2015, CableLabs published several technical reports and specifications that were important milestones for the whole industry: the remote PHY technical reports (CM-TR-MHAv2, CM-TR-DCA) and the upstream external PHY interface (CM-SP-R-UEPI) specification (3). In 2015, DOCSIS 3.1 was a hot topic in Europe as well. While 1.2 GHz networks were not yet a practical challenge in North America, the full 1.2 GHz channel load was a major question in Europe and led to lively discussions in AngaCom in the summer 2015 (4, 5). Pragmatic operators wanted to know that 204MHz/1.2GHz capable network devices were usable also once diplexers were changed and a full 1.2 GHz load was present. At that time, the linearity of RF amplifiers above 1.2 GHz was seen as a major issue but a mix of single carry QAM signals and OFDM blocks seemed to be straightforward. Massive European 1.2 GHz capable network roll-outs were already taking place in 2016. European operators were moving to 1.2 GHz networks followed by DOCSIS 3.1 roll-outs while North American operators had an opposite approach, they started with DOCSIS 3.1 and networks supporting higher frequencies had lower priority. In 2017, Comcast's deployment of gigabit-capable DOCSIS 3.1 technology spanned about 80% of the operator's footprint, and 75% of their residential data customers had speeds of 100 Mbps or more (6).

In the meantime, in the autumn 2017, Cablelabs published the Full Duplex DOCSIS specification (7). While real Full Duplex network roll-outs kept us waiting, Jeff Finkelstein, talking to Alan Breznick in Austin, revealed plans to craft a DOCSIS spec for the next decade, enabling symmetrical speeds as high as 30 Gbps (8). Although agreeing that plenty of operators were not even using 1 GHz yet, he asked: "Why can't we go to 3 GHz?" Finkelstein discussed similar thoughts in his blog May 26, 2018 (9). "From past testing, we know that the hardline cable is capable of frequencies up to about 10 GHz, but realistically we may be limited to 3 GHz to 6 GHz."

Similarly, options for extending DOCSIS capabilities were addressed by Cloonan, who discussed several alternatives for coping with capacity needs in the next two to three years, such as dynamic Full Duplex (FDX) and static FDX, both being capable of working even when network architectures are N+X instead of N+0 (10). He also shortly addressed the total composite power (TCP) level, which is an important parameter when frequencies above 1.2 GHz are used for OFDM signals. Indeed, TCP brings reality to the picture.

Although coaxial cables might have close to unlimited potential, we must discuss what is possible today in laboratories as technologies tested at the moment will be available in 2020 for roll-outs. These practical matters are our focus in this paper. We want to answer a simple, yet important question. What kinds of amplifiers are needed in 1.8 GHz networks and what kind of performance are they expected to have? As DOCSIS 4.0 and 1.8 GHz seem to be married (11), the discussion should take place now. Too often, future expectations become reality later than first thought and industry keeps on waiting for yet another epoch while networks are left to turn sour.

ABSTRACT

Extended Spectrum DOCSIS (ESD) has been a topical subject due to ever-increasing broadband speeds in the digital landscape. While cable industry veterans have competed over who boasts the highest frequency, very little, if anything, has been published about what moving towards 1.8 GHz or even beyond that means in practice. We have performed real 1.8 GHz full spectrum measurements and, in the process, have revealed what it takes to offer new services using frequencies of up to 1.8 GHz. Our focus is on the amplifiers that are often needed even after distributed access roll-outs. The results of our measurements are enriched by cable operators who have contributed to and grounded our research by providing feedback and real network challenges. Our study covers variables that are expected to limit ESD implementations in North America, such as 1) length of cables, 2) length of amplifier cascades, 3) existing taps, 4) performance of the state-of-the-art amplifiers equipped with the latest hybrids and 5) capabilities of the latest Remote PHY (RPD) products. The results of our study provide pragmatic proposals for how DOCSIS OFDM frequency blocks are placed above currently employed frequencies and what kinds of limitations these proposals have. Our objective is to offer the latest information and unbiased practical proposals that can help cable operators obtain the most out of their networks with minimal changes. Although some changes will be crucial, significant costs can be mitigated through careful planning. Careful planning is not limited to the choice of amplifiers and taps, given that managing the interplay between RPDs and amplifiers must be considered to reach the rising broadband speed expectations of subscribers.

INTRODUCTION

It might be fairly easy to convert some cable networks to support N+0 architectures, while other networks will utilize amplifiers and amplifier cascades even when the next decade arrives. These amplifiers should work up to 1.8 GHz, which is not a walk in the park for engineers. In comparison to 1 GHz networks, the attenuation of coaxial cables at 1.8 GHz is over 40% more. Besides this challenge, also taps and splitters, even when designed for 1.8 GHz networks, cannot have the same attenuation at 1.8 GHz as their predecessors had at 1 GHz. To cope with these challenges, higher amplifier output levels or alternative workarounds are needed. Real tests in real conditions reveal to us what can be expected when the latest amplifier technologies enter the markets in 2020.

Before the tests, we wanted to be sure that the measurements describe a new reality and unlearn old parameters that would falsify our results. Existing amplifier cascades in the field today were built when old-school cable experts used to discuss many parameters, including composite second order (CSO) and composite triple beat (CTB) intermodulation distortion. However, new indicators are needed when services are digital and advanced modulation methods overtake cable networks. These new indicators, Modulation Error Ratio (MER), Bit Error Ratio (BER), Total Composite Power (TCP) and Carrier to Interference Noise Ratio (CINR), are valid scales for analyzing how networks and devices perform when the load is digital. While BER is the only thing that matters for end users, MER is faster for measuring and can be used to indicate BER. MER is also a better indicator than BER as new Forward Error Correction (FEC) methods introduced along DOCSIS 3.1 are extremely effective. The combination of Bose-Chaudhuri-Hocquenghem (BCH) and low-density-parity-check (LDPC) coding is so strong that BER values are either perfect or inferior, but seldom something between, while MER offers a more comprehensive overall snapshot of how tight margins networks have. It should be noted that although DOCSIS standards define MER, they still define carrier to noise ratio (CNR) as well. However, we can use MER and CNR analogously in calculations because network noise can be assumed to have a Gaussian distribution, as we will see in later chapters

TESTS

We started our tests by exploring 1.8 GHz hybrids. After these tests, we proceeded to amplifiers and amplifier cascades. Amplifier cascades were also modelled theoretically to understand if theoretical models and real test results are consistent with each other. In such a case, theoretical models could be used to complement and overcome possible uncertainties raised by real measurement results.

Hybrids

In February 2019, we tested the latest 1.8 GHz hybrids in our R&D, which were still prototypes. We used a various mixed single carry QAM (SC-QAM) and OFDM loads (an example is shown in Figure 1). The used frequency ranges were 602 MHz…1218 MHz and 1218 MHz…1794 MHz, respectively. The source MER was 51 dB over the whole frequency range. This source MER was selected because it is a realistic, perhaps even pessimistic, portrayal of performance that current RPD products are capable of if we ignore their amplifier stages. However, it is enough to fulfil DOCSIS specification for OFDM (CM-SP-PHY) and SC-QAM (CM-SP-DRFI) when 51 dB MER is deteriorated by the amplifier stages that are integrated to the RPD nodes. Figure 2 reveals the performance of the very best hybrid model that we tested in several TCP points. The lines have some angularity as values between the TCP points are approximations. The figure shows interesting spots at 609 MHz (SC-QAM) and 1.7 GHz (OFDM). The worse OFDM MER was clearly caused by the higher frequency, not by OFDM. Indeed, tests with various load mixes revealed that the load caused by SC-QAM and OFDM does not differ if the level and frequency are the same. We increased the full spectrum load until MER at 1.7 GHz in the output of the hybrid reached 40 dB, while Pre-FEC BER was better than 1E-9. At this point, the impact of the source MER was negligible (less than 0.5 dB) and SC-QAM MER at lower frequencies was sound. The best performing hybrid model was able to produce 72 dBmV TCP, while the worst (not in the figure) hybrid reached 70 dBmV. In June 2019, we had improved 1.8 GHz hybrids in our R&D. Now the highest performing hybrid model was able to produce 74 dBmV TCP in the similar setup under the same criteria as in February 2019. Our current estimate is that once hybrids are available in volumes their performance will reach 76 dBmV TCP under the same conditions, and amplifiers equipped with these hybrids are available in 2020.

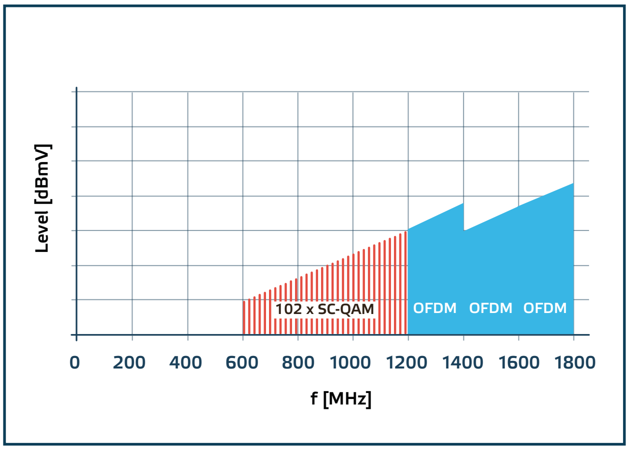

Figure 1: *Downstream load*

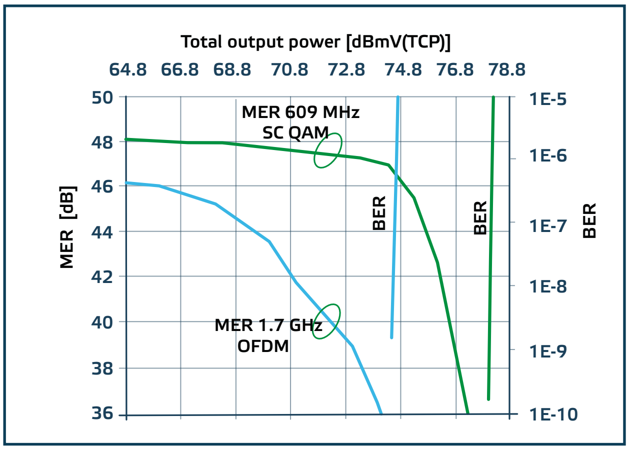

Figure 2: *Performance of the best hybrid.*

Amplifiers

Amplifiers have signal losses after hybrid components as additional components such as feedthrough current chokes, diplexers and connectors are needed in them. In total, these components have up to a 6 dB loss at 1.8 GHz. As higher frequencies carry higher power and cause worse non-linearity, we can estimate that a 1.8 GHz amplifier equipped with the state-of-the-art hybrid (76 dBmV TCP) has at least 70 dBmV TCP in the output port. Figure 3 illustrates what it means in practice if the lowest downstream channels are around 500 MHz and the full load burdens an amplifier up to 1.8 GHz. The output is sloped up to 1.2 GHz, meaning that the virtual level at 1.8 GHz is 56 dBmV, while the practical level is around 48 dBmV for channels above 1.2 GHz. The virtual level can be used to calculate the needed gain. Before calculating the gain we must know the lowest allowed downstream input level that does not lead to poor amplifier CNR impacting MER negatively. Our target is to reach 57 dB CNR, while the noise figure (NF) is 10 dB.

$$CNR = The\ lowest\ input\ level - NF - Thermal\ noise$$
$$The\ lowest\ input\ level = CNR + NF + Thermal\ noise$$
$$The\ lowest\ input\ level = 57\ dB + 10\ dB + (-57\ dBmV) = 10\ dBmV$$

On the other hand, the output level is limited to 56 dBmV as Figure 3 shows. Although the 56 dBmV limitation is virtual, it matters as it defines the needed gain through the needed slope illustrated in Figure 3. Thus, we can calculate that a 46 dB gain is needed as we know that the lowest input level is 10 dBmV.

$$56\ dBmV - 10\ dBmV = 46\ dB$$

The 46 dB gain covers a loss of 1300 ft. cable (P3 500) or, alternatively, it can compensate a feedthrough loss of seven 1.8 GHz taps (3.5dB@1.8GHz) and 90 ft. cable between the taps.

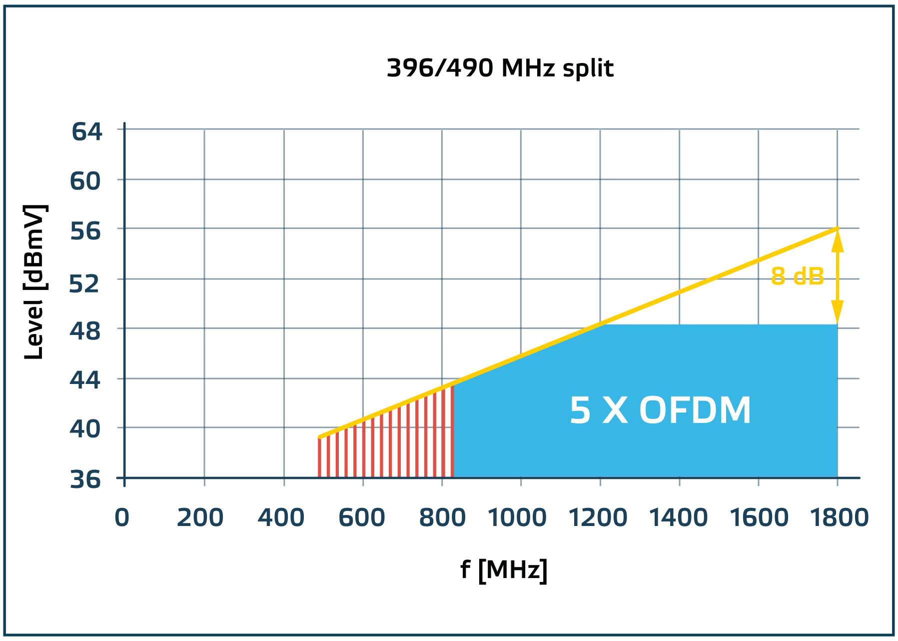

Figure 3: *An example load leading to 70 dBmV TCP*

Amplifier cascades

A theoretical analysis of amplifier cascades can be done using the following equation:

$$MER_{out} = -10\log_{10}\left(10^{\frac{MER_{in}}{-10}} + 10^{\frac{CNR_{amp_1}}{-10}} + 10^{\frac{CNR_{amp_2}}{-10}} + 10^{\frac{CNR_{amp_n}}{-10}}\right)$$

The equation points how the CNR performance of amplifiers reduces MER in the output. The equation can be simplified when all amplifiers have the same CNR performance.

$$MER_{out} = -10\log_{10}\left(10^{\frac{MER_{in}}{-10}} + n \times 10^{\frac{CNR_{amp}}{-10}}\right)$$

The theoretical analysis of three cascaded amplifiers is shown in Figure 4, illustrating how theoretical MER decreases in function of the output level as amplifiers have a lower CNR when the output level increases. Besides the theoretical calculation, we measured real cascades. Less surprisingly, real cascades behave almost according to the theory. However, even when distortions start to dominate, the theoretical analysis holds, although it should apply only when noise can be assumed to have the Gaussian distribution.

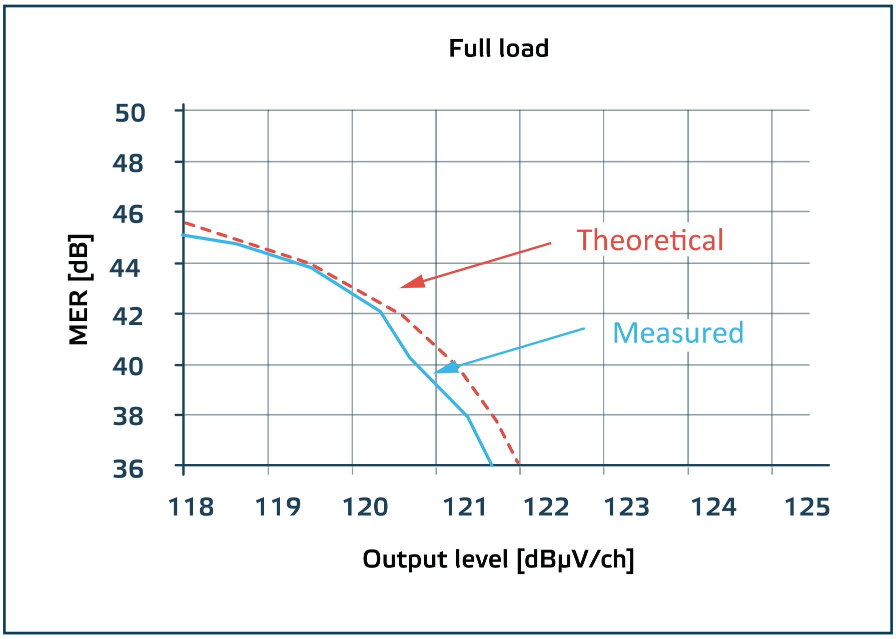

Figure 4: *Three cascaded amplifiers, theoretical MER versus measured MER*

METHODS & IMPLICATIONS

Two alternative methods cope with high TCP

The linearity of amplifiers declines at higher frequencies. Therefore, the maximum TCP that 1.2 GHz amplifiers are able to produce is not available with 1.8 GHz amplifiers. As RF load on higher frequencies limits TCP more than the same load on lower frequencies, the solution could reduce the RF load above 1.2 GHz. We propose two alternative methods that can also be done in practice.

Method 1

In Method 1, the reduction of RF power is performed by a remote PHY device (RPD) node using back-off for OFDM signals as Figure 5 demonstrates. The RPD node is equipped with amplifier stages in combination with high pass filters. First, the RPD staggers OFDM blocks and after the amplifier stages and filters the output of the RPD node is sloped up to 1.2 GHz. While every OFDM block has the same slope their signal level is reduced. Due to the tilt of coaxial cables, the Cable Modem (CM) sees a flat level until 1.2 GHz and the staggered OFDM blocks up to 1.8 GHz.

- Back-off for OFDM signals
- The RPD staggers OFDM blocks
- Output of the RPD node is sloped
- CM sees a flat level until 1.2 GHz and the staggered OFDM blocks up to 1.8 GHz.

Method 2

Figure 6 describes Method 2 that uses a flat top above 1.2 GHz. This is achieved by filters before the last amplifier stage. Channels below 1.2 GHz are sloped in the output of the RPD node in the same way as in Method 1. Due to the tilt of coaxial cables, the cable modem sees a flat top until 1.2 GHz and every received OFDM channel has around -3 dB negative slope. The flat top approach can use, for instance, a 1 GHz verge frequency instead of 1.2 GHz if it is seen as more appropriate for the existing network.

- Flat top above 1.2 GHz
- Filters before the last amplifier stage
- Channels below 1.2 GHz are sloped
- CM sees a flat level until 1.2 GHz and every received OFDM channel has around -3 dB negative slope

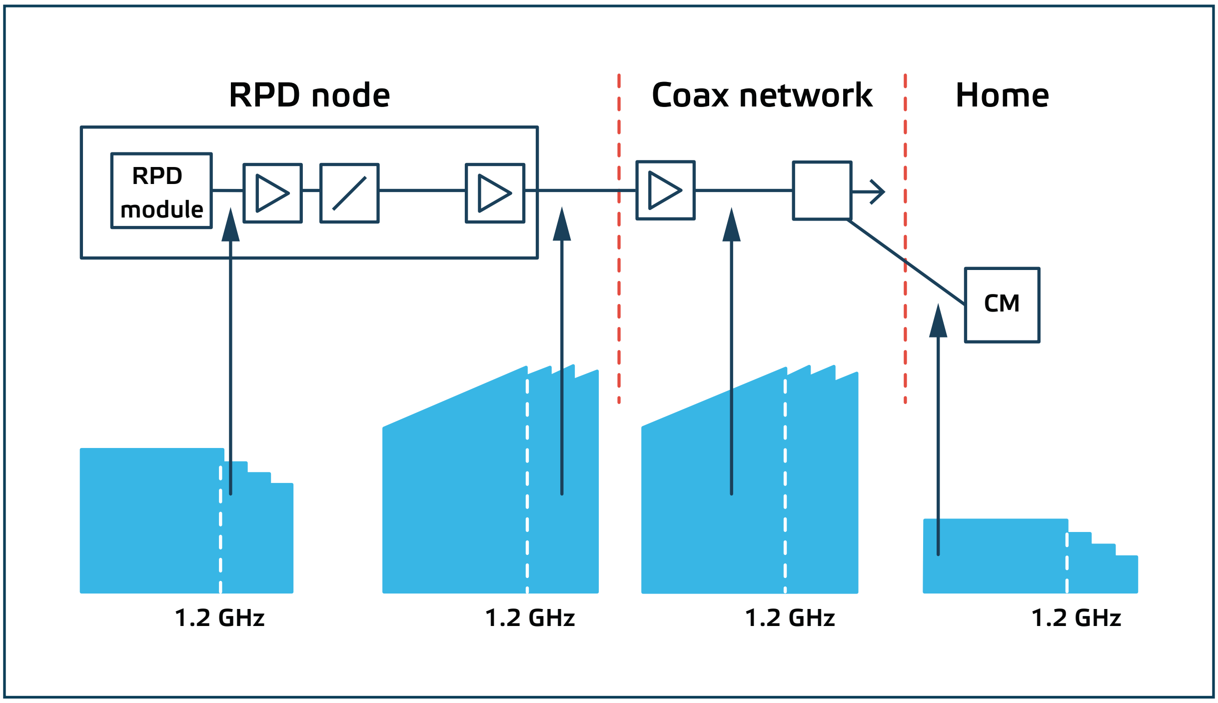

Figure 5: *Method 1*

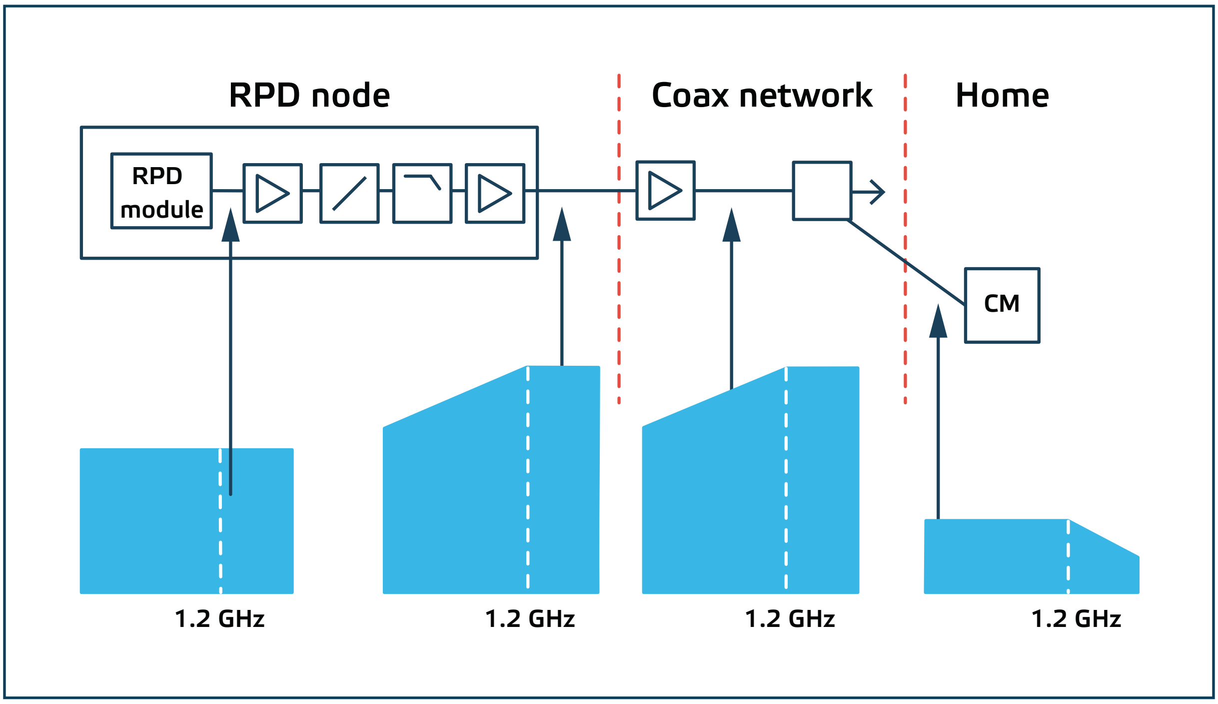

Figure 6: *Method 2*

Throughput

Based on measurements demonstrating performance of 1.8 GHz amplifiers, we built two example cases demonstrating throughput of the 1.8 GHz network by using method 1. Both cases use 492/602 MHz split and similar upstream load but different downstream modulations and cascade lengths. The throughput and used modulation methods in the cases are presented in Figures 7 and 8. Networks in both cases employ frequencies of up to 108 MHz for legacy services and frequencies between 108 MHz and 492 MHz for four OFDM blocks (each 96 MHz).

Constellation	CNR (dB) Up to 1 GHz	CNR (dB) 1 GHz...1.2 GHz	Min $P6_{AVG}$ dBmV
4096	41.0	41.5	-6
2048	37.0	37.5	-9
1024	34.0	34.0	-12
512	30.5	30.5	-12
256	27.0	27.0	-15

Table 1: *CM Minimum CNR performance (CM-SP-PHYv3.1-I11-170510)*

It should be noted that in both cases even the RPD node includes amplifiers as we expose in Figures 5 and 6. Both cases employ cabling and taps but they do not impact MER as they are passive. However, as passives elements attenuate, we made sure that cable modems received enough high signal levels specified in the DOCSIS standard extract presented in Table 1. In both cases, the TCP was in line with limits discussed in the section Amplifiers (page 4).

In the first case (Figure 7), we use frequencies between 602 MHz and 814 MHz for 37 SC-QAM channels, frequencies between 814 MHz and 1402 MHz for 1024 OFDM and frequencies between 1402 MHz and 1794 MHz for 512 OFDM. The setup consists of one RPD node and three cascaded 1.8 GHz amplifiers. Table 2 shows MER over four different frequencies, in the RPD node output and after 3 amplifiers. With the given values, the example can be used to reach 9.7 Gbps downstream capacity.

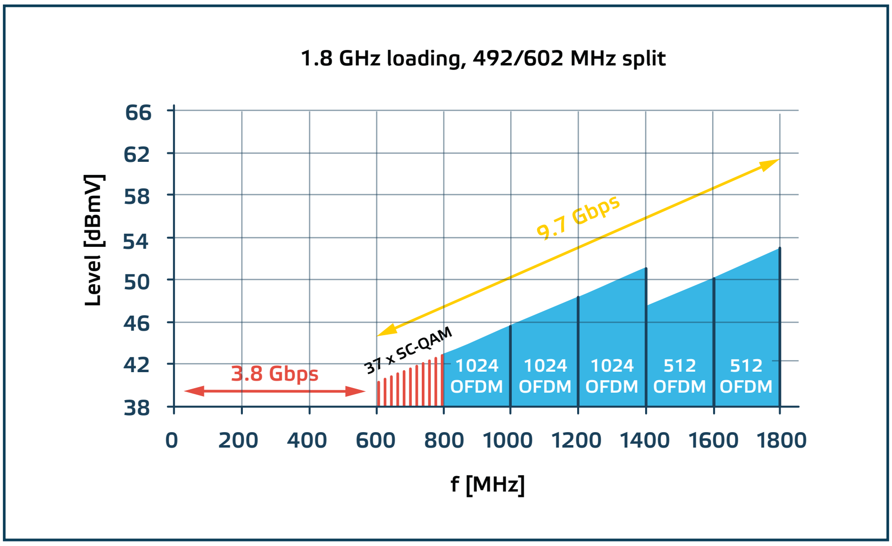

Figure 7: *Throughput, RPD Node and three cascaded amplifiers*

Frequency	MER (N+3 network)	
	RPD node	N+3
830 MHz	48.0 dB	43.0 dB
1.1 GHz	47.5 dB	42.5 dB
1.3 GHz	45.5 dB	39.0 dB
1.7 GHZ	41.5 dB	34.5 dB

Table 2: *MER, N+3 network*

In the second case (Figure 8), we stress the network even further through higher order modulation methods and a longer amplifier cascade. Now we use frequencies between 814 MHz and 1218 MHz for 4096 OFDM, frequencies between 1218 MHz and 1410 MHz for 2048 OFDM, frequencies between 1410 MHz and 1602 MHz are used for 1024 OFDM, while frequencies above 1602 MHz are used for 512 OFDM. In this case, we have an RDP node followed by four cascaded amplifiers, the MER is reported in Table 3 over different frequencies in the RPD node output and after four amplifiers. With the given values the example leads to 10.6 Gbps downstream capacity being around 1 Gbps higher than in the first case, although the cascade of the amplifiers is longer. The difference is explained by more effective use of frequencies and lower MER margins than in the first case.

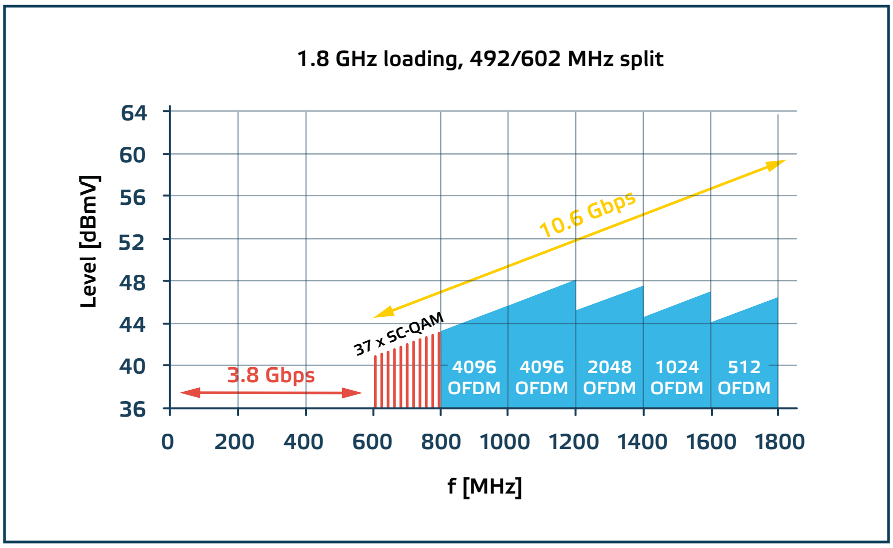

Figure 8: *Throughput, RPD Node and four cascaded amplifiers*

Frequency	MER (N+4 network)	
	RPD node	N+4
830 MHz	48.0 dB	42.0 dB
1.1 GHz	47.5 dB	41.5 dB
1.3 GHz	45.5 dB	38.0 dB
1.7 GHZ	41.5 dB	33.5 dB

Table 3: *MER, N+4 network*

Practical guidelines

Certain practical details must be considered when 1.8 GHz amplifier cascades are built.

1. Amplifiers must have a cable equivalent frequency response apart from the used input equalizer values. This eliminates cumulating errors that a linear frequency response would cause. As these amplifiers will compensate preceding cables, amplifier outputs would have the same linear frequency response that exists in the RPD node output.

2. The accuracy of up and downstream alignments becomes paramount when MER margins turn narrow. Our proposal would be to use automatic adjustments performed by the amplifiers as manual "roughly right" will not be enough when the last decibels matter.

3. Automatic Level and Slope Control (ALSC) must support flexible pilot frequencies if networks will first employ 1.0 GHz or 1.2 GHz frequencies and later on are upgraded to employ frequencies of up to 1.8 GHz. Otherwise, operators are forced to change pilot detection units during the upgrade.

4. 1.8 GHz amplifiers will need more power even if the state-of-the-art technology is used. Not only because of higher downstream frequencies but also because of the higher upstream frequencies. Even if future hybrids become more effective, alternative ways to mitigate increased power consumption should be investigated. Currently available adaptive power methods and active power factor correction are examples, but research producing even more effective methods should continue.

CONCLUSIONS

As we have discussed, amplifier cascades will be a reality in the coming years even though N+0 networks are on the horizon. However, as we substantiate by theoretical and practical methods, even four amplifiers in a cascade can carry the magical 10 Gbps capacity. Our paper presents two methods that cope with high TCP and provides examples of how the methods could be exploited. More importantly, these methods are based on technologies that are commercially available in 2020. Nonetheless, to harvest the full potential of HFC networks, 1.8 GHz amplifiers should perform automatic adjustments or alternatively cable technicians should define rigorous methods to test that amplifier cascades are tuned to perfection even when outdoor conditions such as temperature change.

LIMITATIONS

Our study used a 492/606 MHz split, although it is only one of the options. Moreover, tighter guard bands are possible if more complex diplexer technologies are used, but we wanted to stay pragmatic and use a method that has been widely tested, namely robust but changeable diplexer plug-ins. While FDX amplifiers offer significantly tighter guard band, our study did not cover their use. As industry has discussed their benefits, we encourage future studies to address their limitations, such as increased complexity, higher power consumption and lower CNR performance.

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The authors thank Teleste Corporation and the research team for their support.

Jouni Karlsson (illustrations & layout)

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ABBREVIATIONS

ALSC	automatic level and slope control
BCH	Bose-Chaudhuri-Hocquenghem
BER	bit error ratio
CINR	carrier to interference noise ratio
CM	cable modem
CNR	carrier to noise ratio
CSO	composite second order
CTB	composite triple beat
dB	decibel
dBmV	decibel millivolt
DOCSIS	Data-Over-Cable Service Interface Specifications
ESD	extended spectrum DOCSIS
FDX	full duplex
FEC	forward error correction
Gbps	gigabits per second
GHz	gigahertz
HFC	hybrid fiber coax
LDPC	low-density-parity-check
Mbps	megabits per second
MER	modulation error ratio
MHz	megahertz
NF	noise figure
OFDM	orthogonal frequency division multiplex
QAM	quadrature amplitude modulation
RPD	remote PHY device
SC-QAM	single carry QAM
SNR	signal to noise ratio
TCP	total composite power

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