4096-OFDM Implementation on the HFC Plant with Fiber Deep and Distributed Access Architecture

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Abstract

The paper will introduce what are the limitations existed in the current HFC architecture, why it is wise to continue the investment on the HFC infrastructure evolution instead of reconstructing to an all - fiber infrastructure, and why the new HFC architecture with the Distributed Access Architecture (DAA) in conjunction with the Fiber Deep (FD) can resolve the limitations and helps make the 4096-OFDM application on HFC plant a reality.

The paper will also introduce the parameters that impact the MER and BER performance such that AWGN, IQ Gain, IQ Phase, Phase noise, CW interfere-nce, Group delay, Micro-reflection, distortion and PAPR; and addresses why the PAPR becomes a major concern in the DAA + FD architecture where the 4096-OFDM application and the higher output RF power of node are both being expected.

In the fiber deep deployment a much higher output RF power is expected for the node that, together with the R-PHY module installed in the node, could cause a significant power increase therefore leading to serious concern at the thermal dissipation. The paper will finally introduce some possible solutions to reduce the PAPR and the power. This is to accomplish the goal to make the HFC a 10Gbps access network while maintaining the good and stable BER performance on top of the 4096-OFDM application.

DOCSIS 3.1 Evolution: A Journey To Continue

The DOCSIS 3.1 developments took place a couple of years ago, and now the 1.2GHz HFC transportation products, CCAP with the DOCSIS 3.1 PHY and MAC implemented, DOCSIS 3.1 cable modem and test equipment become available for demonstrations, applications and deployments.

In the earlier roadmap the DOCSIS 3.1 evolution was planned dividing into two phases. Phase 1 aims for 7Gbps downstream (DS) data throughput and 1Gbps upstream (US) data throughput, and phase 2 shoots for the 10Gbps DS throughput and 2.5Gbps US throughput. To get such the robust increase in throughput, some major changes were planned to introduce into the DOCSIS 3.1 evolution as follows.

- Involve Orthogonal Frequency Division Multiplexing (OFDM).
- Involve the Low Density Parity Check Code (LDPC) for the OFDM FEC.
- Expand the bandwidth to the 1.218GHz in phase 1 and to 1.794GHz in phase 2 for purpose of adding more QAM / OFDM channels.

OFDM has the 1dB improvement in the Signal Noise Ratio (SNR) for its filter edge vs. that of SC-QAM; LDPC with the 88% of coding rate can lower the requirement for SNR by 5dB compared to the Reed Solomon FEC used for SC-QAM. Hereby we can account for the 6dB reduction in the requirement of the SNR by the DOCSIS3.1 PHY.

Phase 1 and phase 2 both aim to keep the HFC plant architecture shown in the Figure 1 unchanged, e.g. with analog fiber for DS; analog or digital fiber for US; and with a long amplifier cascade for cable transportation. In this architecture a node normally connects to about 25 - 30 trunk or line extender amplifiers and may still serve 200 to 500 households (HHP).
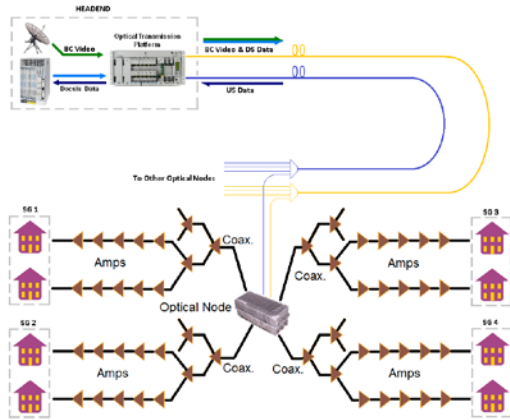

Figure 1: Current HFC Architecture

In such an evolution path, only will those 1GHz or 870MHz or 750MHz active devices such as forward transmitters, nodes and amplifiers be replaced with 1.2GHz devices, but the previously deployed fibers and cables are primarily kept untouched. This is called Active Drop In (ADI) upgrade whose primary benefit is to avoid a "forklift" upgrade to allow MSO's to gradually refresh their network infrastructure depending on the Compound Annual Growth Rate (CAGR). This could be the most economical solution compared to other new access technologies like EPOC and Google fiber. However, the MER performance is unexpected to be improved since analog fiber and long amplifier cascade essentially limit the Signal to Noise Ratio (SNR) perfor-mance that is often considered to be one of the major contributors among the impairments to Modulation Error Ratio (MER). Figure 2 shows an

assessment result for the SNR performance over the millions cable modem in an existing "good" HFC plant.
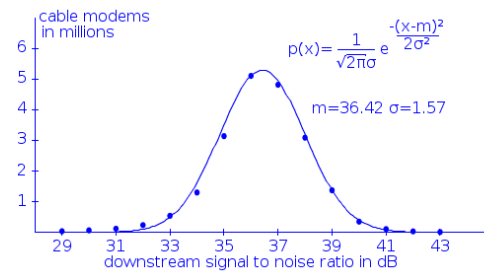

$$p(x) = \frac{1}{\sqrt{2\pi}\sigma} e^{\frac{-(x-m)^2}{2\sigma^2}}$$

$$m = 36.42 \quad \sigma = 1.57$$

Figure 2: SNR Distribution over CM in millions

In the standards of DOCSIS 3.1 MAC and PHY, both CMTS and CM are required to support the 4096-QAM, and optionally support 8192-QAM and 16384-QAM. But typically the current HFC plants could not support beyond 1024-QAM (or even 512-QAM) order due to the limitation in the SNR performance.

DS	Band	Assumed MER	Typ. QAM Mod.	Date Rate / 6MHz	Total Data Rate
	MHz	dB		Mbps	Mbps
D3.0, All QAM,	105 - 1002	33	256	38	5681
D3.1, All OFDM	105 - 1002	33	1024	49	7326
	258 - 1218	33	1024	49	7840
	500 - 1794	33	1024	49	10568

Table 1: Planned DS Throughput Increase

US	Band	Assumed MER	Typ. QAM Mod.	Date Rate / 6MHz	Total Data Rate
	MHz	dB		Mbps	Mbps
D3.0, All QAM,	5 - 85	27	64	28	373
D3.1, All OFDM	5 - 85	27	256	38	507
	5 - 204	27	256	38	1260
	5 - 400	27	256	38	2502

Table 2: Planned US Throughput Increase

The Table 1 shows the planned DS data rate increase by the OFDM w/ LDPC and the spectrum expansion based on assumed MER performance. Though OFDM w/ LDPC can lower

the requirement in SNR, but the 3dB margin is reserved to handle the variation over time and temperature, and interference. The 1024-QAM DS and 256-QAM US account for an improvement in the data rate by approximately 29% compared to the 256-QAM DS and 64-QAM US typically used today. However, the 33dB SNR DS and 27dB SNR US would only be the case for those a few "good" HFC plant. The lower SNR distribution could be expected for other

"not so good" HFC plants where 512-QAM DS and 128-QAM US could be more realistic case.

An upstream spectrum upgrade to 204MHz was planned, but due to an impact to the Out Of Band (OOB) signalling needed for controlling millions of cable modems, this upgrade to 204MHz is still on hold, now the situation is that MSOs take upgrade to 85MHz as an immediate upgrade.

Data Throughput	Start Frequency	Stop Frequency	MER	Typical QAM Modulation	Data Rate / 6MHz CH	Total Data Throughput	HHP	Data Throughput / Household
	(MHz)	(MHz)	(dB)		(Mbps)	(Mbps)		(Mbps)
DOCSIS 3.1 Downstream, All OFDM	105	1218	30-33	512	43.8	8125	300	27.1
DOCSIS 3.1 Upstream, All OFDMA (long code)	5	85	24-27	128	34.5	460	300	1.53
DOCSIS 3.1 Upstream, All OFDMA (middle code)	5	85	24-27	128	32.9	439	300	1.46
DOCSIS 3.1 Upstream, All OFDMA (short code)	5	85	24-27	128	29.1	388	300	1.29

Table 3: DOCSIS 3.1 Throughput Based on 85/105MHz Split

Table 3 shows a more realistic throughput data based on this situation. We can see that even with the OFDM with LDPC there is still a big gap to accomplish the 10Gbps goal of DOCSIS 3.1 downstream and the 2.5Gbps upstream. From a data rate per household perspective, we see an increase by the OFDM with LDPC compared to DOCSIS 3.0 but not much. The 27.1Mbps DS and 1.46Mbps US (middle code) could potentially limit

those applications such as 4k video, remote education / health care, and video game etc. which require much higher data speed to run.

In the table 4 John Ulm and his co-authors revealed the demands in the data speed across different tiers and the compound annual growth rate (CAGR) projection by the researches to the several large North American MSOs.

Subscriber Distribution	MSO #A	MSO #B	DS Speed (Mbps)	CAGR
Top Tier, Billboard speed	0.20%	0.1 - 1%	300	50%
Performance Tiers	24%	5 - 18%	75	32%
Common, Popular Tiers	64%	50 - 72%	25	26%
Economy Tiers	12%	15 -40%	5	15%

Table 4: Subscriber Mixes across the Service Tier

If we take MSO #A for its distribution percentages, and assume a node serving 300 of Households (HH)

where the four different service tiers coexist, we can calculate the data speed needed for different tiers and the total

throughput needed. Results are shown in the Table 5. Recall that the 8125Mbps calculated for DOCSIS 3.1 DS throughput in the Table 3, it doesn't fully satisfy the demand in the data throughput even for that will come soon, not to mention the needs projected by the CAGR in the Table 4 that will come a few years later.

Subscriber Distribution	MSO #A	DS Speed (Mbps)	CAGR	Number of HH (300 HHP based)	Current Demand (Mbps)	Demand in 5 years later (Mbps)
Top Tier, Billboard speed	0.50%	300	50%	1.5	450	3417
Performance Tiers	24%	75	32%	72	5400	21640
Common, Popular Tiers	64%	25	26%	192	4800	15244
Economy Tiers	13.50%	5	15%	40.5	203	408
Total Throughput Required (MSO #A based)					10853	40710

Table 5: Total Throughput Needed to Satisfy Different Tiers

Spectrum expansion to 1794MHz DS and 400MHz US was ever an option to further increase the data throughput capacity in the DOCSIS 3.1 standards. But this could be too challenge to implement and also could miss the original intent of the ADI upgrade for the following reasons.

- Taps must be replaced. Otherwise the loss at 1.8GHz could be up to 70dB! This suggests that the ADI strategy is not so worthwhile.
- Take CommScope P-III cable and 1705 feet as an example, the loss at 1794MHz is 12.5dB higher than that at 1218MHz. This means that node's output level and amplifier's gain must have another significant increase, therefore leaving treme-ndous challenges for gain-block, filter designs and the reliability associated with increased power / gain.
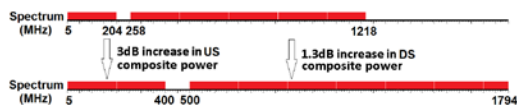
Figure 3: Increases in composite power

- The OMI to analog transmitter would have to reduce by 1.3dB according to the composite power increase shown on Figure 3 and therefore degrade the CNR in the DS.
- The 3dB increase in US composite power would cause 4 to 5dB reduction in the Noise Power Ratio (NPR) range. This appears a big concern against the current HFC architecture where sufficient operational headroom is needed against the variations over temperature from cables and cascaded amplifiers and possibly the analog fiber transportation if digital return is not being used.

Move to All Fiber or Continue HFC

As the current HFC architecture appears to have reached a point lacking the momentum to drive the continuous capacity increase, quite a few MSOs considered transitioning to the all fiber network to be a move for the access network evolution. However, we need to take investment, time, current demand & CAGR and available PON technologies into account.

To date USA has approximately 130 million households where 120 million, the great majority are reached by cable. To a tune of approximately 400 HHP per node, there are a total 300,000 node in the country. While in a typical coax architecture of N+6

there are around 25 actives per node. Comcast has made an estimate that 60 billion U.S. dollar would have to be invested to build up the infrastructure needed for the all fiber access network. Actually, Google spent about 850 U.S. dollar per household to spread its Google Fiber service to several cities in the US.

Verizon FiOS deployment for example took about 8 years to build fiber to roughly 18 million homes. So if the Verizon FiOS build-out rate were projected onto the whole nation, it would take half century to fiberize 120 millions of households in the nation.

Assume the GPON can deliver the 1Gbps per subscriber, then it is far ahead of the needs in the throughput indicated in the table 5. So doing a massive full FTTP migration using GPON would be an unwise move since MSOs may then have to take decades to recoup their tremendous investment.

For a move to full FTTP network, there also are several technical factors to be well considered. First is that PON architectures usually cover 32 or 64 ONUs while a node in a typical HFC network serves eight times of CPE device that implies 8 times of OLT ports be required for CCAP. Those key parameters such as ONU count, LLID per ONU and Grant Cycle time etc. were optimized for 32 ONUs or 64 ONUs on a PON network basis. Thus the impact must be well studied to apply these key parameters in a much larger service group. Especially during the transition to full FTTP network, the legacy HFC network has to be side-by-side operated, thus operators should encounter double challenges in both deploying PON to the serving group whose size is much bigger than it used to cover, and also taking care of maintaining and provisioning two

networks whose protocols can not be coexisted to each other.

Radio Frequency over Glass (RFoG) would be an economical version of the fiber access network. Optical Beat Interference (OBI) has been a serious problem in the RFoG upstream. CMTS scheduler allows multiple CPEs to burst at the same time at different RF frequencies. This upstream multiple access has been a beauty of the traditional HFC system and never causes the collision. But it is not the case when transition to an RFoG system.

In a traditional HFC system depicted in the Figure 1, CPEs in households send their own burst signals via the different RF frequencies, these burst signals are firstly combined in the RF domain and then sent back via transmitter in node to headend. Transmitters with the same wavelength use the separate fibers, or share the same fiber but with the different CWDM or DWDM wavelengths. Thus in principle there should have no chance to cause the collision, and in practice it is.

In an RFoG system, CPEs in households send the burst signal via their own Optical Network Units (ONU) to headend. The ONUs turn on their lasers when the burst is detected. To date most of RFoG system used to use the same optical wavelength, though in reality the wavelength could be slightly different due to manufacturing tolerance.

Optical Beat interference (OBI) is the hyterodyning effect resulted form two or more wavelengths that are close enough (less than 0.0125nm) present on the same detector of receiver. OBI appears as the wideband noise and often severely degrading the SNR and

BER performance. When OBI effect occurs it affects no only the ones that send bursts simultaneously but also all the others within the same service group!

The elimination to OBI can not be solved in an opportunistic manner relying on the manufacturing tolerance of laser wavelength since nowadays laser manufacturers normally specify the wavelength tolerance less than 2.5nm. Thus the probability of two or more lasers in a 32 ONUs or 64 ONUs RFoG system falling into the OBI region of the 0.025 nm is high.

In reality the probability gets much higher because of the start up drift of the laser. The lasers in ONUs are turned off until there is a burst detected. So every time in the transition of laser tuning on, the laser starts absorbing bias current and output the optical power and drifts the wavelength through the initial start until reaching the steady state because of changes in the bias current and the temperature. The wavelength drift is about 0.5nm from initial start to a steady state. The drift usually lasts about 100 to 200 us that is being too fast to be possible for any correction.

Eliminating OBI therefore requires the ONU wavelengths to be separated by at least 0.5nm, preferably around 1nm to be thoroughly getting rid of the OBI even in a start-up event. Using DWDM is the only way to make it a reality. Such a solution is apparently expensive, and also operationally impractical in allocating the different wavelengths to households.

Using the Single Tx CMTS scheduler to allow only one cable modems to transmit at a time is simple and common in the DOCSIS 2.0 system. However, it ultimately limits the capacity if using the Single Tx CMTS Scheduler in the DOCSIS 3.0 and 3.1 systems. The capacity of a Single Tx CMTS scheduler would be merely half of that a 3.0 scheduler does, and gets even much less than that of a 3.1 scheduler. Thus attempting solving the OBI problem in a simplistic manner using Single Tx CMTS Schedule is totally against the purpose of moving to the all fiber network.

Fiber Deep and Distributed Access Architecture

Distributed digital architecture (DDA) can bring the significant benefits to the HFC network evolution such as enabling the higher PHY performance of DOCSIS 3.1, reducing the needs of space and power at the headends, hence the trend has become quite clear to evolve towards a distributed architecture rather than continuing investing the centralized architecture.
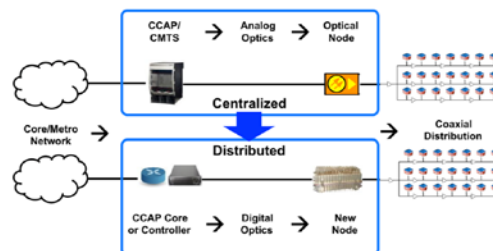
Figure 4: Centralized Vs. Distributed Architecture

Above figure illustrates a transition from the Centralized architecture to the Distributed architecture. There are two significant changes in this transition i.e. one is to move the PHY to a remote entity e.g. in HFC node, second is to use the digital fiber.

There are quite a few distribution technologies as to Baseband Digital Forward (BDF) / Baseband Digital Reverse (BDR), Remote PHY (R-

PHY), Remote PHY & MAC and Remote CMTS. Among these technologies, now Remote PHY has stood out as being accepted by almost all the major cable operators, system vendors, chip vendors, test equipment vendors. In the context of this paper the R-PHY will refer to DDA.

Using digital fiber can bring many benefits. We can leverage the existing WAN / LAN fiber infrastructures. The on/off keyed digital demodulation would only require about 20dB SNR to recover distorted digital signal to ideal 1 and 0, thus the degradation in SNR caused by fiber cross-talk effects, fiber non-linear effect do not play a role in limiting the application of multiplexing and de-multiplexing and long haul transportation. This is quite beneficial to support the fiber deep (FD) architecture where a significant increase in the number of optical node is expected.

In contrast, the link CNR performance of an analog optical transportation system is limited by a number of factors in terms of Relative Intensive Noise (RIN) of laser, shot noise, Optical Modulation Index (OMI) thermal noise, optical input power to Rx, photodiode's efficiency, noise current of receiver (EIN), and Amplified Spontaneous Emission (ASE) if EDFA is being used.

Let's take the following assumption to see how the link CNR performance looks like and varies vs. the change in the input power to receiver.

Assumptions:
- Wavelength: 1550nm
- Photodiode Efficiency: 0.9
- OMI / QAM channel: 1.5%
- EIN of Receiver: 6.5 pA / Hz
- Noise Figure of EDFA: 5.5

| Optical Input Power to Receiver (dBm)	-4	-2	0
CNR (dB)	39.3	41.3	43.3

Table 6: CNR Variation over Optical Input

We can see that for the "best case" with 0dBm optical input, the link CNR performance is 43.3dB which could merely support the 4096-OFDM, and it varies 1dB as a result of 1dB change in the optical input power to Rx. In this regard the analog link CNR performance is quite optical link loss dependant. Other factors such as Optical Modulation Index (OMI), EIN of receiver, noise figure of EDFA that are varied from equipment to equipment, and operation to operation alter the analog link CNR performance, and in some cases make dramatic variation.

As CNR, SNR and MER are being referred in different places of this paper for the specific intents, so let's see the difference and the relationship between them for the benefit of addressing the following sections. Both CNR and SNR refer to the Adaptive White Gaussian Noise (AWGN), but as their terms imply: CNR is for the ratio expressed in decibels between the RF carrier and the noise; SNR is for the ratio expressed in decibels between the baseband signal and the noise.
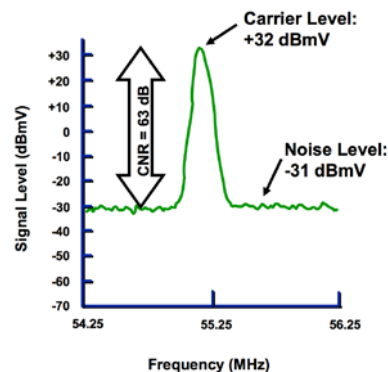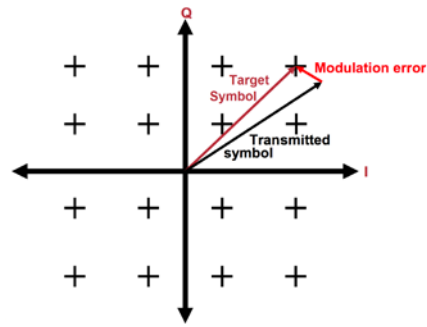

Figure 5: CNR definition
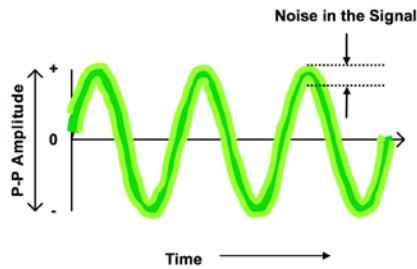
Figure 6: SNR definition

Figure 7: MER definition

CNR is more often measured with the unmodulated carrier to yield the better measurement accuracy. SNR is the baseband measurement that has to be measured at either pre-modulation or post-detection and the noise. In other words CNR measurement is at the RF domain and ideal for characterizing the impact from those impairments specifically generated from network transportation including transmitter, optical amplifier, RF amplifier, transport path, and receiver; SNR measurement is at the baseband domain and ideal for characterizing the end–to–end signal quality which is impacted by signal source and demodulator in addition to those impairments that matter the CNR.

MER is the ratio between average signal power and average impairment power across all the constellation points in a QAM or an OFDM format used, and is a composite index covering all kinds of impairments such as phase noise, AWGN, I/Q gain error, I/Q phase error, distortion, clipping, ingress / impulse noise, compression, micro-reflection, and group delay etc. MER is considered to be a merit of the composite index representing the QAM / OFDM signal quality. Bit Error Ratio (BER) is defined as the ratio between the error data and the total data sent. MER typically has the certain relationship with BER for a certain QAM modulation order.

In the most of communication systems including DOCSIS, the AWGN usually makes the dominant contribution to MER degradation, so CNR, SNR and MER are all used in the context to address the analysis needs depending on whether it is of interest in the RF domain, or in the baseband domain, or for the QAM / OFDM signal quality.

Since we are focusing to implement the 4096-OFDM, so let's see what the MER, SNR and CNR performance be needed to support this high order modulation of OFDM. A sub-carrier of an OFDM or a QAM has a number of the constellation points depending on the order of QAM modulation.
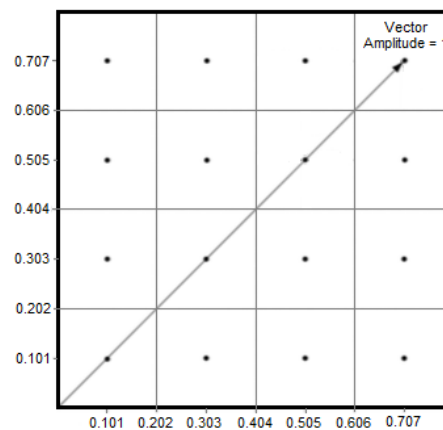
Figure 8: Quarter of Constellation diagram of 64QAM

Above is a quarter of the constell-ation diagram of a 64QAM. The right-top corner symbols has the maximum

vector amplitude. Assign a normalized amplitude of "1" to this symbol, then its I and Q components have 0.7071 of amplitude $1^2=0.7071^2+0.7071^2$. From 0.7071 to x (or y) axis, there are three constellation points. We can calculate out the boundary spacing for 64-QAM: $0.7071 / (n^{0.5}-1) = 0.1010$ (n=64) Accordingly, the boundary spacing for 256-QAM, 1024-QAM and 4096-QAM are 0.0471, 0.0228 and 0.0112 respectively.

For a pure AWGN channel, the BER can be calculated with the following formula.

$$f_x(x) = e^{-x^2 / 2* \sigma ^2} / (\sigma * (2\pi) ^0.5)$$

Where σ is the ratio between the boundary distance and the half average noise power (rms). Half average noise power (rms) is the half of noise power (corresponding to 3dB bandwidth relative to the symbol rate e.g. 5.0569MHz or 5.03605MHz in Annex B) derived from the SNR and average power across the constellation points. 64-QAM, 256-QAM, 1024-QAM and 4096-QAM have the respective average powers -3.68dB, -4.23dB, -4.50dB, and -4.64dB.

| QAM Order	64	256	1024	4096
Bits	6	8	10	12
Boundary Distance	0.1010	0.0471	0.0228	0.0112
SNR (dB)	24	30	36	42
Half Noise Power (dB)	30.68	37.23	43.50	49.64
Half Average Noise Power (rms)	0.0292	0.0138	0.0067	0.0033
Distance in σ	3.45	3.43	3.41	3.40

Table 7: Distance in σ calculations for different QAMs

3.4 of distance in σ yields 6e-4 BER, this pre-FEC BER should work well since the error rate is low and usually be corrected to 10^{-8} by Reed-Solomon FEC. To get the 3.4 of distance in σ, the higher order QAMs / OFDMs that have the denser constellation points and the smaller boundary distance have to have the better SNR, usually 6dB penalty per 2 bits increase.

The 42dB of SNR requirement appears too severe. OFDM uses the LDPC FEC by which we can lower the SNR requirement to 36dB to support the 4096-OFDM applications when 87.85% of code rate is applied. The 87.85% of code rate means a spectral efficiency of 10.5 bps / Hz which is half bit higher than 1024-QAM. 4096-OFDM with the 36dB SNR works only in a pure AWGN system, but in reality there are many more impairments involved, the over temperature stability also needs to be considered. So if to leave the 3dB to 5dB margin for the degradations introduced by other impairments and the 2dB for the variation over temperature, we would need about 41dB to 43dB of the SNR in an end-to-end system.

Per the results shown in the table 6, the CNR performance on the analog optical link for those scenarios where the optical input power to receiver is below -2dBm apparently doesn't meet the requirement in supporting 4096-QAM. In contrast, the link performance of a digital transportation system is distance independent that the same MER can be maintained from 0 km to 100 km. The optical input power to Rx is no longer the key factor in determining the system CNR.
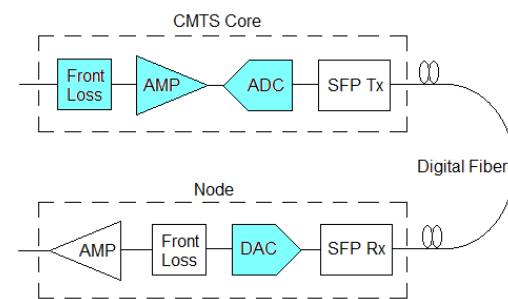
**Figure 9: Noise Contributors in BDF System**

Figure 8 shows the major noise contributors (blocks in cyan color) involved in the baseband digital forward (BDF) where the front loss and the noise performance of driving amplifier before ADC, the SNR performance of ADC, and the SNR performance of the digital to analog converter (DAC) do matter the link SNR performance.

The BDF solution has been considered for years but not been implemented because: it doesn't eliminate the noise contributions from front loss, driving amplifier and ADC; An ADC with ultra-high sampling frequency is too costly; BDF continuously produces 100% of throughput depending on bandwidth, sampling frequency, and overhead etc. but regardless the actual traffic; it doesn't allow CMTS to traverse a generic IP network to remote entities.
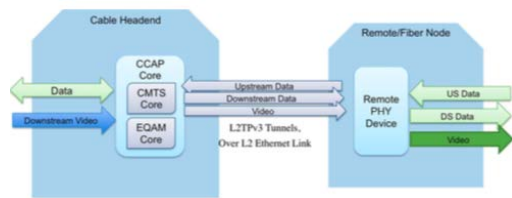
Figure 10: Remote PHY Architecture

The Remote PHY architecture shown in the Figure 9 uses a protocol with a concept of a pseudowire (PW). A pseudowire protocol used in the Remote PHY provides an IP tunnel and to move MPEG-TS packets and DOCSIS frames between CMTS core and Remote PHY. In this architecture the noise contribution only come from the DAC and the Noise Figure (NF) of node driving amplifier. Above the 50dB of SNR performance can be achieved by the DAC (or in an integrated chip) offered by major vendors.
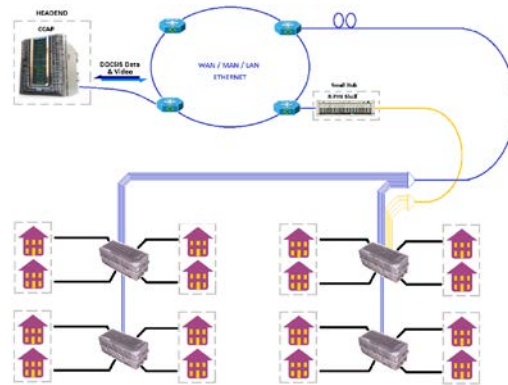
Figure 11: Fiber Deep Architecture

Figure 10 depicts a FD network where no RF amplifier is between nodes and households. We can get approximately 63dB of CNR for the driving amplifier in the node by the following assumptions.

Assumptions for CNR Analysis for All QAM loading:

- NF of Driving Amplifier: 15dB
- DAC's Output: 20dBmV
- Noise band: 5.0569MHz

In the FD architecture, there may still have a few active components along cable to households. Active components should add very little degradation to overall noise performance. The home gateway network would contribute some and may need to be improved if it limits supporting 4096-QAM applications. But generally, the new architecture with remote PHY in conjunction with fiber deep network eliminates the limitation in the CNR performance required for 4096-OFDM.

However, to support the 4096-QAM, we must consider a number of impairments generated from signal source, transportation network such as AWGN, CW interference, phase noise, I/Q gain error, I/Q phase error, distortion, compression, group delay micro-reflection etc.

Additive White Gaussian Noise (AWGN) is the most common and unavoidable impairment that could be the dominant factor for the overall SNR performance in an analog optical system as addressed in the previous sections. AWGN is White (flat power density function in frequency) and Gaussian (mathematically "normal" amplitude density function). It spreads the received symbols in a cluster around the ideal location.

Phase noise (PN) can be generated from any signal source with frequency synthesizer and oscillator. It is normally caused by thermal "agitation". PN is cumulated from the signal source through the network to the receiving instrument.

CW interference can be sourced from various place, some from the modulator / up-converter (residual Local Oscillator or beat), some from the transportation network such as ingress and distortion beats etc., and some from receiving equipment like very denser tuners. CW interference introduces vector error power that circles around the ideal symbol appearing like "doughnut", the radius of error power depends on the difference in frequency between carrier and interferer.

Distortions such as CTB and CSO are the narrow band interference but cannot be considered as CW interferer. Unlike CW interferers, CTB and CSO can have huge number of products that vary dramatically in amplitude, 15dB difference between peak and average can be observed. CTB / CSO looks similar to CW interference on the spectrum analyser display, but appear differently from a constellation view, rather than "doughnut" it looks like noise especially in the presence of so many CTB and CSO beats.

I/Q gain error is caused by imperfection of signal source and is a difference in gain between the In-phase and Quadrature components of the constellation shapes it into a rectangle instead of a square.

I/Q phase error is caused by imperfection of signal source and is an error in quadrature between the In-phase and Quadrature axes of the constellation shapes into a lozenge or diamond instead of square.
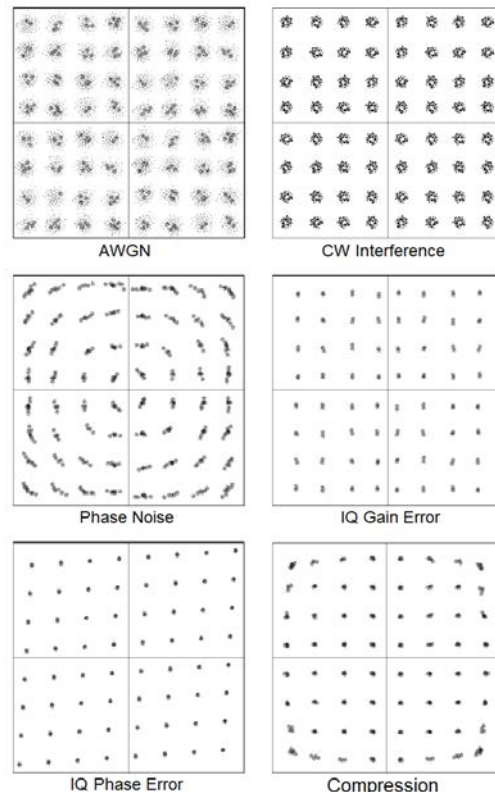
Figure 12: Distorted Constellation Diagram due to Impairments

Echo results from an imperfect impedance matching between express cables, nodes and amplifiers in the HFC plant. Nodes and amplifiers usually have a minimum 16dB return loss, assume a 1925-foot express cable, a 4.5µs echo could be expected. Echo would cause the Inter-symbol Interference that was ever of concern for OFDM. Now a simple method adding a single guard interval can

eliminate the inter-symbol interference without needing to know the channel response, so long as the guard interval is greater than the longest echo. The guard interval is configurable in the DOCSIS 3.1 PHY.

If the subcarrier frequency spacing is too small, then the phase noise generated from oscillators and frequency synthesizers could play a big role in degrading the performance. The OFDM sampling frequency must be larger than the channel width. DOCSIS 3.1 standards choose 204.8MHz as the sampling frequency, 192MHz as the biggest channel width, and the FFT size as 8192 or 4096. This keeps the complexity relatively low while providing a long enough useful time and wide enough subcarrier frequency spacing against the phase noise.

Subcarriers in an OFDM channel have a long time period, so that an impulse noise that is short in time can be averaged over a long symbol time to minimize its impact. OFDM has an ability to load bit differently, which means a single OFDM channel can contain different modulations such as 4096-QAM, 2048-QAM, 1024-QAM and so on of sub-carriers, to balance date rate vs. SNR over frequency. This ability can be utilized to handle the ingress noise. Ingress noise usually lasts long in time but short in frequency, having a few subcarrier adjusted to a lower bit modulation could be a good trade-off in handling the ingress noise.

The input level to the cable modem (CM) or set-top box (STB) primarily determines the SNR performance at the home gateway. Thermal noise is always present in any electronic device and it is flat over frequency. At room temperature, the thermal noise is -174dBm / Hz which can be converted

to -125.25dBmV / Hz by adding 30 + 10 * log10 (75) for a 75ohm system. The noise floor is then added by the 192MHz bandwidth of an OFDM channel and the 10dB of noise figure of CM. If 42dB of SNR is required, we will at least need 43dB of CNR and therefore requiring 10.6dBmV level for a 192MHz of OFDM at CM (or STB) input. To compare to SC-QAM used today, the 10.6dBmV at 192MHz band can be extrapolated -4.5dBmV in the 6MHz band.

CM Input requirement		
Thermal noise	dBm/Hz	-174
Thermal noise	dBmV/Hz	-125.25
OFDM bandwidth	MHz	192
NF of Rx in CM	dB	10
CNR requirement	dB	43
CM Input requirement (192MHz)	dBmV	10.6
CM Input requirement (6MHz)	dBmV	-4.5

Table 8: CM Input Requirement

A statistics indicates that in the current HFC plants only 85% CM have an input level great than -6dBmV while the rest don't. As cable amplifier which usually includes the automatic gain control (AGC) to compensate for the change in cable loss due to the variation over temperature be eliminated in the FD network, the FD network should be designed with higher input level than current HFC plant, maybe -1.5dBmV to all the cable modems at room temperature to ensure 3dB margin to guarantee above the -4.5dBmV over temperature, for the 4096-OFDM implementation. A penalty is that FD node needs to output a higher level that could lead to an increase in power dissipation and therefore a thermal concern.

In the FD architecture, we need to count in the MER degradation from R-PHY node that includes the R-PHY module and the RF power amplifier

module. DOCSIS 3.1 specifies the 47dB MER at 1002MHz for complete OFDM, so it is reasonable to assume the R-PHY module can achieve the 47dB of MER performance as well. The RF power amplifier offered by major vendors could have above 41dB of MER performance before running into compression.

Based on the currently achievable MER performance for R-PHY module and RF power amplifier, and the target MER performance at CPE (CM or STB), we can see the EOL MER performance in the following table.

Device	MER (dB)	
	Room Temp.	Over Temp.
R-PHY	47	46
Power Amplifier	41	39
CPE	42	41
EOL	37.9	36.4

Table 9: EOL MER Estimation

As addressed in the previous sections we can lower the SNR requirement to 36dB to support the 4096-OFDM applications by applying the LDPC FEC with the 87.85% of code rate. The MER variation over temperature for a node should be within 2dB, thus the 37.9dB of EOL MER performance at room temperature should support the 4096-OFDM application in a wide temperature basis.

In summary,

- By the R-PHY that can guarantee 50dB above SNR performance at DAC's output, and by the FD architecture that eliminates the degradation in the noise performance from amplifier chain, the limitation in the SNR performance required for 4096-OFDM applications is primarily eliminated.
- Those impairments generated by the signal source such I/Q gain error, I/Q phase error, and phase noise can be controlled by the MER spec of R-PHY module.
- OFDM has the guard interval mechanism against the inter-symbol interference due to micro-reflection.
- The effect of an impulse noise short in time can be averaged by a long symbol time of OFDM.
- Adjusting a few sub-carriers to a lower modulation order can mitigate the impact by an ingress noise narrow in frequency.
- FD architecture eliminates the degradation in the distortion performance such as CTB, CSO, XMOD and HUM etc. So a FD node with the legacy distortion spec or even a relaxed spec shall ensure the distortion not be a limiting factor.
- A -4.5dBmV input to CM or STB can ensure the MER performance at household's home.

The above summary doesn't include the compression that is one of impairments caused by the Peak to Average Power Ratio (PAPR) related to QAM / OFDM modulation format and the non-linear characteristic of RF power amplifier (PA).

PAPR is often considered as the main disadvantage of the OFDM technique. An OFDM channel with 192MHz bandwidth and 8192 FFT has 7540 sub-carriers. These sub-carriers are located at the different frequencies but transmit simultaneously in the time domain. The envelop of an OFDM signal approximates to the Gaussian distribution and can have the large fluctuation. The RF power amplifiers have a limited linear region. In case the peak envelop exceeds the linear region of PA, as a result, in-band and out-band distortions are being created. In-band distortion would appear as the

noise degrading the OFDM channel's own MER performance, and out-band distortions degrade the adjacent channel leakage ratio (ACLR) performance and therefore interfering the adjacent channels.
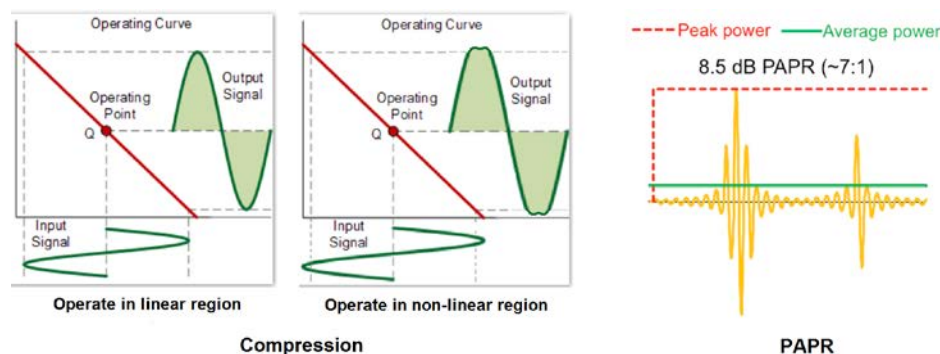
Figure 13: Compression and PAPR

The Complementary Cumulative Distribution Function (CCDF) is used to measure the probability of the time ratio spending on a given power. Table 10 shows results of the CCDF measured with PRBS for the respective loadings for all SC-QAMs and all 4096-OFDMs on 105 to 1218MHz band. The Power amplifiers used for the HFC system are usually sensitive with the crest power at the probabilities from 1% to 0.1%. According to the results in the following table, All 4096-OFDM loading has 0.39dB at 1% and 0.44dB at 0.1% higher crest power than all SC-QAM loading.

Probability	All SC-QAM	All OFDM
	Crest Power (dB)	
1.00%	6.33	6.72
0.10%	7.83	8.27
0.01%	8.83	9.55
0.001%	9.56	10.35
0.0001%	10.2	10.48
Peak	10.39	10.58

Table 10: CCDF SC-QAM vs OFDM

A 192MHz 4096-OFDM should have 1.87Gbps of the data rate that is 48 times bigger than the 38.7Mbps data rate delivered by a 256-QAM, so the impact must be well considered to avoid a significant data loss due to PAPR.

Output Power Back Off (OPBO) is a common but undesirable approach to handle the PAPR in both wired and wireless systems. The OPBO approaches setting the output signal power by $(OPBO_{(dB)})$ away from PA's saturated point. It is actually a trade-off between PA output capability and BER performance. DOCSIS 3.0 HFC plants use the 6dB OPBO to handle the PAPR of 256-QAMs. Increasing the $OPBO_{(dB)}$ for the DOCSIS 3.1 deployment in a DAA + FD architecture is unwise approach. The output power of a FD node is expected getting much higher but appearing very challenging for the following reasons.

The input level to CM or STB in household's home needs to be above the -1.5dBmV that is 4.5dB to 6dB higher than the current plant.

8 times or 10 times of FD node need to be deployed to cover an area which used to be served by a node plus about 25 to 30 pcs of trunk or line extender amplifiers. From operator's economic perspective, the higher output power that FD node can output, the less

number of new nodes are to be deployed.

HFC node used to use the class A power amplifier that has the best linearity but the least RF-to-DC power efficiency among all type of PAs. The best-case efficiency for class A PA would be around 13%, and for the worst case it is even lower than 4%. A 4-port FD node aiming to output 64dBmV of RF power per port would have an increase of about 25 watt of DC power and 29.4 watt (assume 85% of power supply efficiency) of AC power that is quite significant. A R-PHY module in replacement with 4 receivers and 4 transmitters previously used for node segmentation application would cause another increase of 20 watt of DC power and 23.5 watt of AC power. These bring an unprecedented thermal challenge for the node design. So adding more $OPBO_{(dB)}$ could make mission very difficult or impossible.

Device	MER (dB)	
	Room Temp.	Over Temp.
R-PHY	47	46
Power Amplifier (compression)	39	37
CPE	42	41
EOL	36.8	35.2

Table 11: EOL MER Degradation due to Compression

Assume power amplifier compressed due to the PAPR has 2dB degradeation in the MER. Indicated by Table 11 the EOL MER degrades to the 36.8dB at room temperature to have become marginal supporting the 4096-OFDM, and the 35.2dB of MER over temperature even can't support the 4096-OFDM.

Such a degradation in the MER can make the constellation diagram of 4096-OFDM indistinguishable and even could cause the OFDM

constellations unlocked and therefore a significant data loss, this appears to be a big concern or say a severe problem.

Crest Factor Reduction (CFR) is the technique for the PAPR reduction. A number of the CFR techniques have been created and evolved, namely, Clipping and Filtering technique, Coding (C-OFDM) technique, Partial Transmit Sequence (PTS) technique, Active Constellation Extension (ACE) technique, Selective Mapping (SM) technique, and Pilot Reservation (PR) / Pilot Injection (PI) technique etc. Each technique has its own unique advantages and disadvantages. Among these techniques the Adaptive Baseband and Pilot reservation would be suitable for use in the DOCSIS 3.1. But their trade-offs in performance and computational complexity need to be taken into considerations.

Adaptive Baseband is one of Clipping and Filtering technique that is to implement the CFR at the baseband or say in the digital domain. Adaptive baseband is good for the ACLR improvement and can be implemented in the R-PHY module with a reasonable computational cost. Although the effect in the PAPR reduction by Adaptive baseband is not so deep, however, since the probability of exceeding 8dB PAPR for a wideband which may contain 6 x 192MHz OFDM channel is very low, so setting the 8dB as the threshold by the Adaptive Baseband would be good enough to prevent 4096-OFDM from running into a deep compression at which the OFDM is unlocked by receiver and all data lost.

Tone reservation is a sophisticated CFR technique that has the reserved tones allocated in the profile. These tones do not bear any information and are orthogonal to each other. The

amplitude of the peak reduction carriers is greater than those data carriers so that it can cancel out the peaks generated by the composite signal, removing them from the useful tones. Although tone reservation promises to accomplish CFR without

degrading signal quality, it has several disadvantages that need to be considered, including a loss of spectral efficiency (due to pilot carriers added), loss of useful power, and increased computational overhead.
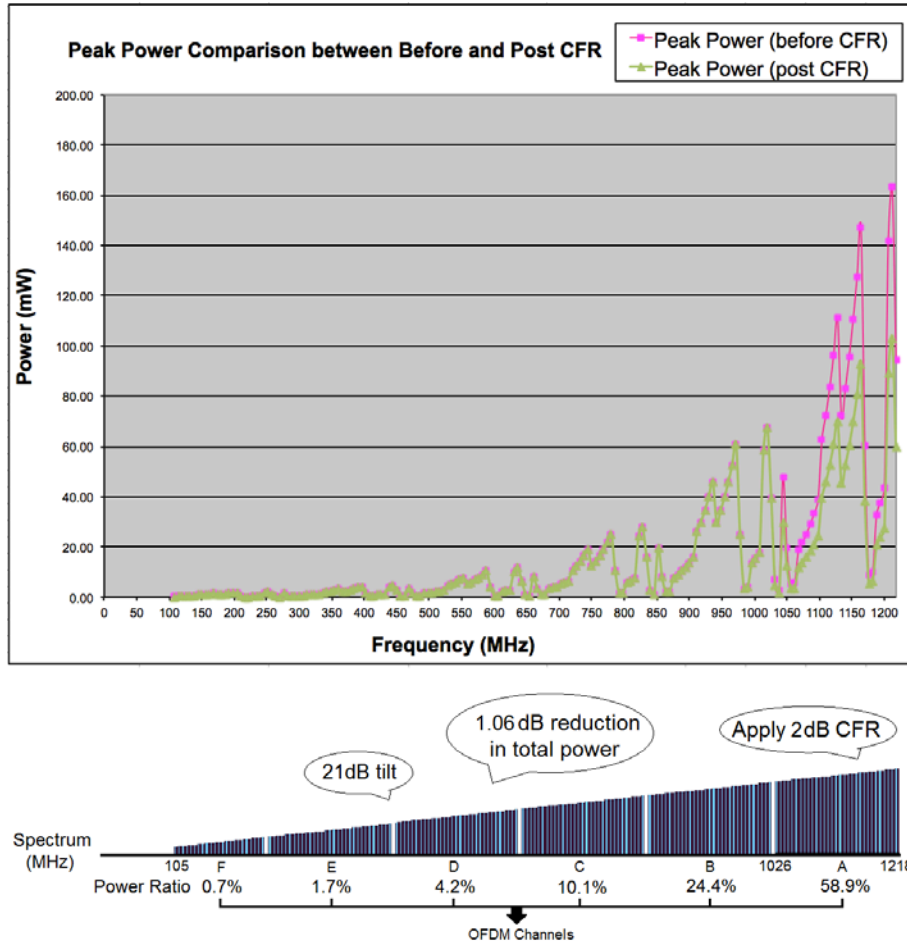

Figure 14: CFR implementation on the partial band

The cable spectrum has a unique character as having a tilted spectrum loading. As a consequence, OFDM or QAM channel at the higher frequencies have the much greater power than that of channels at the lower frequency. For instance, in the Figure 14, the channel A accounts for the 58.9% of power that is even greater than that all the rest channels combines. We can take advantage of this unique character to apply the CFR on the partial band to solve the concern at the increase in

PAPR while keeping performance degradation and computational complexity relatively low. Given by an example illustrated in Figure 14, apply 2dB CFR on the OFDM channel A can reduce the total power in spectrum by 1.06dB.

As proven by simulation and test, the OFDM or QAM channels that are near to the upper edge of cable spectrum suffer more degradation in MER and BER than channels at lower

frequencies. To mitigate the risk in losing the data for an entire OFDM channel that may transmit up to 1.87Gbps of data, we may consider the another trade-off that is to lower the modulation order for the upper frequencies of OFDM sub-carriers, like from 1126 to 1218MHz. This is also in line with the partial CFR approach that would degrade the performance for the OFDM channel with CFR applied. We can still accomplish the more than the 10Gbps throughput as indicated by Table 12. Thus, this would be a more worthwhile trade-off than having the more $OPBO_{(dB)}$ for PA.

DS Data Throughput of DAA + FD Architecture	Start Freq.	Stop Freq.	MER	QAM Modulation	Date Rate / 6MHz CH	Total Data Throughput
	(MHz)	(MHz)	(dB)		(Mbps)	(Mbps)
4096-OFDM	105	1126	42	4096	58.5	9955
1024-OFDM	1126	1218	36	1024	48.7	747
Total						10701

Table 12

As addressed, moving the PHY to the HFC node and enabling the super high output significantly increase the power dissipation, and therefore bringing an unprecedented thermal challenge for HFC node.

In the wireless system, Digital pre-distortion (DPD) and envelope tracking (ET) are popular techniques for improving the RF to DC power efficiency for the PA.
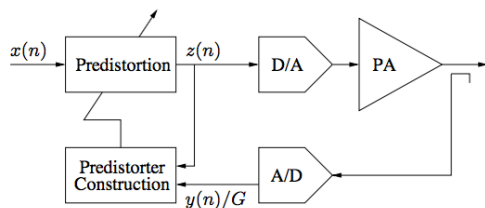

Figure 15: DPD System Diagram

Digital pre-distortion (DPD) adds a digital pre-distorter in the baseband to create an expanding nonlinearity that counteracts the compressing characteristic of the power amplifier. Ideally, the cascade of the pre-distorter and the power amplifier produces a constant gain for the original signal. With the pre-distorter, the power amplifier can be utilized more close to its saturation point while still maintaining a good linearity, thereby significantly increasing its efficiency. In reality, the power amplifier characteristics may change over time because of temperature drift, component aging, etc. Therefore, the pre-distorter should also have the ability to adapt to these changes.

There are several challenges in implementing the DPD into DOCSIS 3.1 as follows.

DPD requires 5 times of over-sampling to be able to detect the distortion effects. For the current 1218MHz cable spectrum, an Analog to Digital Converter (ADC) with the approximate 6GHz sampling frequency is way too expensive and could not be economically justifiable by the DPD itself regarding its gain at the power reduction.

Power amplifier exhibits the memory effects when working for the wideband application and being deeply compressed. DOCSIS is the wideband application, and power amplifiers need to be deeply compressed in order to yield a compelling power reduction. So very likely, the DPD algorithm has to be based on the memory effect that is to deal with the instantaneous and past

signal, which certainly adds more challenge.
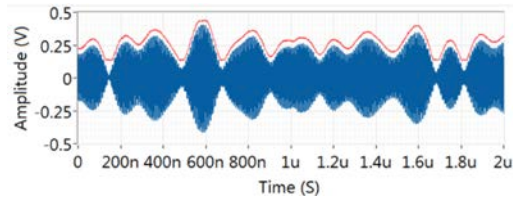
Figure 16: Envelope Tracking

Envelope tracking (ET) technique was created based on a fact that the actual envelope of OFDM or QAM signal fluctuate greatly, but because PA is supplied with a constant voltage, thus a big amount of energy becomes heat instead of RF output power particularly for those valley envelopes.

There are several challenges and concerns in implementing the ET into DOCSIS 3.1 as follows.

One of the main implementation challenges for an envelope-tracking IC concerns the bandwidth of the power supply that must accurately track the signal amplitude of the RF signal without clipping or introducing distortion. This requires a power supply with a control bandwidth of 1.5 to 3.0 times the RF channel bandwidth, i.e. 2GHz to 4GHz for a 1218MHz of DOCSIS 3.1 band.

The power supply needed in the ET system is also required to have the constant high efficiency simultaneously adapting the change in the supply voltage, very low noise, and high peak output currents. These don't make it technically infeasible but certainly ending up with a costly power supply.

With up to 40k sub-carriers simultaneously transmitting in the system, the probability of getting envelope peaks becomes relatively low, so does the envelope valleys! This suggests that the effect of power

reduction by the ET becomes less significant.

As being discussed, the implementations of DPD and ET on the DOCSIS 3.1 system would face some challenges that may not be overcome in the short term. They could still have long way to go to be practical and cost-effective for the implementation in DOCSIS 3.1. Hence we must find a solution that can be immediately implemented to address the thermal challenge brought by R-PHY and super high output PAs in the HFC node.

The power amplifier devices are usually designed with the current adjustment feature to allow designers setting the PA current to an optimal performance associated with the output level. But in the past, it was always set to the maximum bias current to enable the maximum output capability of PA. But as illustrated in the Figure 16, in fact there is always slight or moderate difference in the cable loss between each of ports.

A power saving solution called Bias Adjustment in Field (BAiF) is to have an ability in the node to adjust the bias current for the PA in field according to the actual cable loss on the port of interest. Given by an example illustrated by the left part in Figure 17, assume node can compensate 54dB cable loss as a maximum, the bias current of PAs can be reduced according to the reduction in the cable loss. Three ports that are with 1dB, 2dB and 3dB reduction can save 19% - 27% of power on the power amplifier. The BAiF can be utilized when some channels are shutdown in the low traffic event. Given by an example illustrated by the right part in Figure 17, the shutdown to an OFDM channel near to upper edge with 192MHz bandwidth can lead to 30% to 40%
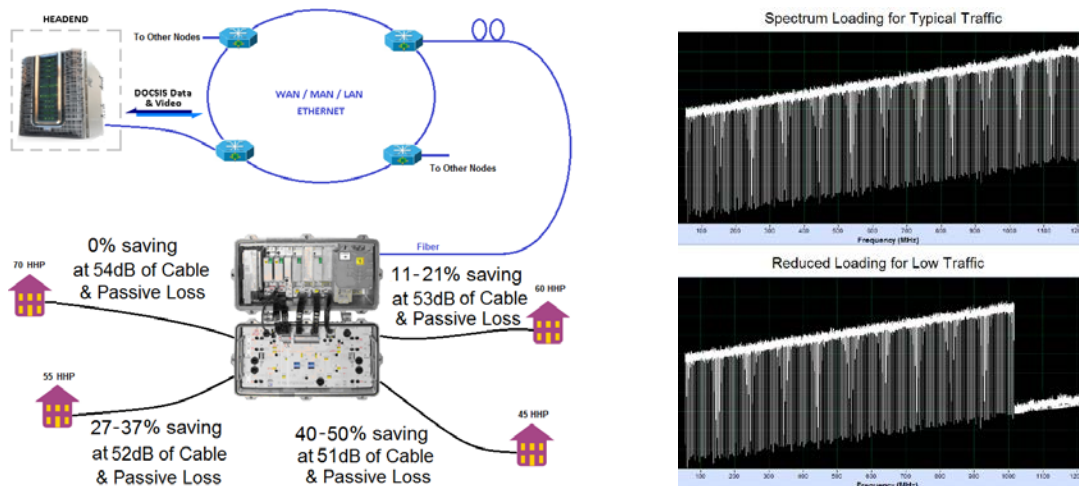
power saving by the BAiF on the power amplifier.

Figure 17: Cable Loss Based and Spectrum Loading Based Power Saving

Summary and Conclusion

Current HFC architecture becomes a limiting factor for the 4096-OFDM applications in regard to analog fiber and long amplifier cascade that are used. As a result, DOCSIS 3.1 can not meet the 10Gbps goal, and hereby may not keep pace with the CAGR in the data speed demand.

A move to an all-fiber access network using GPON is too costly and far ahead of CAGR that a tremendous investment spent would take decades to recoup. The OBI issue concerning the RFoG architecture, an economical version of fiber access network, and the operation challenge in managing two different networks side by side during transition could be the showstopper against this move.

The architecture with the Remote PHY plus the fiber deep primarily resolve the limitation in the link SNR performance and hereby making the 4096-OFDM implementation feasible. This new architecture is also good for

the further spectrum expansion. However, the concerns at the increases in the PAPR from OFDM and in the power dissipation need to be taken care.

The increase in the PAPR could degrade the MER performance to an insufficient level to support the 4096-OFDM. CFR techniques such as the Adaptive Baseband and the Tone Reservation are the effective ways for the PAPR reduction but also resulting in some trade-offs. To minimize the negative effects we could apply the CFR for the partial band at the higher frequency where has the dominant power distribution over the entire spectrum.

The power increase brought by introducing the R-PHY module and enabling the super high output in the HFC node brings an unprecedented thermal challenge. A power reduction solution called the Bias Adjustment in Field that is readily to implement can significantly save the power based on the actual cable loss and the spectrum loading.

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