HFC IMPROVEMENT FOR DOCSIS 3.1 EVOLUTION

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Abstract

The DOCSIS 3.1 PHY and MAC standards have specified the QAM modulation order as high as to 16384QAM, however, we could not go beyond 512QAM (or 1024QAM) order on the current HFC plant as the CNR performance is primarily limited by analog optics and long amplifiers cascade. Hence, to achieve the 10G cable access goal we will have to expand the cable spectrum to a very high frequency like 1794MHz. But the 1794MHz expansion in cable spectrum appears too challenging and leaves tremendous concerns…

The paper aims to explain the ideas of evolving the HFC plant to have the better CNR performance and hereby be able to support the high QAM modulation like 4096 QAM, so that we may just need to expand the cable spectrum to a relatively lower frequency like 1.44GHz to make HFC a 10G access network.

1.0 HFC Challenges in DOCSIS 3.1 Evolution

In order to provide the 10Gbps high speed data through the existing Hybrid Fiber Coaxial (HFC) network to be able to compete with other access technologies like 10G PON and EPOC, many of cable operators and CableLabs worked together for the standardization of the DOCSIS 3.1 (D3.1) which defines the specifications for the 4th generation of high-speed data-over-cable system primarily including PHY, MAC, MULPI, CCAP and CMSI etc.

The DOCSIS 3.1 evolution is to get the robust data throughput increase through two phases. The phase 1 aims for 7Gbps downstream (DS) data throughput and 1Gbps upstream (US) data throughput, and the phase 2 shoots for the 10Gbps DS throughput and 2.5Gbps US throughput. To get such robust increase in throughput, there are some major changes being introduced into the DOCSIS 3.1 evolution as follows.

- Involve the Orthogonal Frequency Division Multiplexing (OFDM) to improve the date rate per cable spectrum (bit / Hz) efficiency
- Involve the Low Density Parity Check Code (LDPC) for the OFDM FEC to further improve the bit / Hz efficiency
- Expand the bandwidth to the 1.218GHz in phase 1 and to 1.794GHz (could change later) in phase 2 to ultimately explore the cable spectrum for use of adding more QAM / OFDM channels
- Add the OFDM channels primarily above 1GHz, gradually shut down traditional analog channels and SC-QAM channels and replace with the OFDM channels

The DOCSIS 3.1 PHY and MAC standards have specified the QAM modulation order as high as to 16384QAM, however, we could not go beyond 512QAM (or 1024QAM) order on the current HFC plant as the Carrier to Noise Ratio (CNR) performance is primarily limited by analog optics and long amplifiers cascade (N+5, N+7 etc). Hence, one way to achieve the 10G cable access goal is to expand the cable spectrum to a very high frequency like 1794MHz.

Downstream Data Throughput (long amplifier cascade, increased OMI)	Band	MER	QAM Modulation	Date Rate (6MHz CH)	Total Data Throughput
	(MHz)	(dB)		(Mbps)	(Mbps)
Current Capacity	105 - 1002	33	256	38	5681
Capacity increase by OFDM w/ LDPC	105 - 1002	36	1024	49	7326
Capacity increase by OFDM w/ LDPC & Spectrum Expansion	258 - 1218	36	1024	49	7840
Capacity increase by OFDM w/ LDPC & Spectrum Expansion	500 - 1794	36	1024	49	10568

Table 1

The Table 1 shows the phased data throughput increase by the OFDM w/ LDPC and the spectrum expansion on top of the available Modulation Error Ratio (MER) performance primarily associated with CNR & distortion performance on the HFC network. Note that the actaul data throughput shall be getting less when taking the guard band of OFDM channel into account.With the introduction of the OFDM w/ LDPC we can go to the 1024 QAM from today's 256 QAM to increase the data rate by approximately 29% with the same CNR as today.

But to achieve the 10Gbps cable access the cable specturm still needs to expand to an extremely high frequency like 1794MHz that appears too challenging as the loss at 1794MHz is huge (could go as high as 70dB), and therefore leaving tremendous challenges and concerns in chip and product development particularly at the reliability associated with significant power increase.

The band from 500MHz to 1794MHz contains 217 QAMs (in 6MHz bandwidth), it accounts for 0.7dB increase in the composite power at input of transmitter (Tx) compared to 185QAMs in a band from 108MHz to 1218MHz. Unless we use better laser which could be costly, the OMI to Tx will have to reduce 0.7dB accordingly, otherwise the increased power will hurt distortion performance.

We also need to increase the reverse spectrum to approximately 400MHz to achieve 2.5Gbps target upstream data throughput as shown in the Table 2.

Upstream Data Throughput (long amplifier cascade)	Band (MHz)	MER (dB)	QAM Modulation	Date Rate (6MHz CH) (Mbps)	Total Data Throughput (Mbps)
Current Capacity	5 - 85	27	64	28	373
Capacity increase by OFDM w/ LDPC	5 - 85	30	256	38	507
Capacity increase by OFDM w/ LDPC & Spectrum Expansion	5 - 204	30	256	38	1260
Capacity increase by OFDM w/ LDPC & Spectrum Expansion	5 - 400	30	256	38	2502

Table 2

As a result, the upstream RF power from subscribers CPE's will have to increase according to the cable and Tap losses at 400MHz. Also, the reduction of the Noise Power Ratio (NPR) range because of the increased power loading on the upstream is the big concern against the current HFC architecture where sufficient operational headroom is needed to maintain against the variations from the analog fiber transporation and long cascade of amplifiers.

The following secions will explain the ideas of evolving the HFC plant to have the better CNR performance and hereby be able to support the high QAM modulation like 4096 QAM or even higher modulation, so that we may just need to expand the cable spectrum to a relatively lower frequency like 1.44GHz to make challenge down to a manageable degree but still accomplishing a 10G cable access network.

2.0 HFC Performance Impact By Different DOCSIS 3.1 Loadings

The Figure 1 depicts the phased data throughput increase through DOCSIS 3.1 evolution on a spectrum loading view. It also depicts complexity of the spectrum loading at the phase 1 as there could be a few interim upgrades going on. As DOCSIS 3.1 standards allow cable operators to gradually (rather than "folklift" reconstruction) shun down traditional analog channels and Single Carrier Quadrature Amplitude Modulation (SC-QAM) channels, and switch to OFDM channels, there will be the mixed loadings of analog, SC-QAM and OFDM channels coexisted in the same cable spectrum.

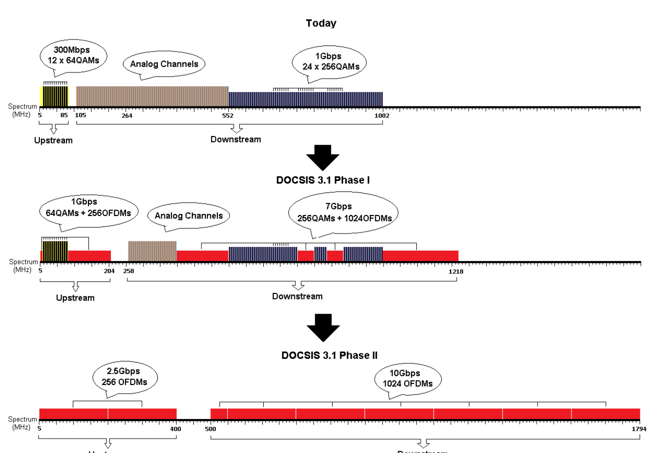

Figure 1

Following let's take some case studys to see if we have opportunities for the HFC performance improvement through the interim spectrums.

2.1 Case Study I _ "Heavy Analog" to "Light Analog"

For instance there is a HFC network where 74 analog channels are loaded from 54MHz to 550MHz and above 550MHz to 1002MHz 75 SC-QAM channels are loaded. Now for the sake of an interim throughput increase, a cable operator plans shutting down 48 analog channels to free up 288MHz band and filling in a 192MHz OFDM channel and a 96MHz OFDM channel. This upgrade scenario is from so called a traditional "heavy analog" to a "light analog".

The Figure 2 depicts two options in freeing up the band where analog channels are presently loaded and adding one 192MHz OFDM channel and one 96MHz OFDM channel at the freed band in addition to the OFDM channel added above 1GHz to 1.2GHz. i.e. option I is to shut down analog at the band from 264MHz to 552MHz, and option II is to shut down analog at the band from 105MHz to 393MHz.

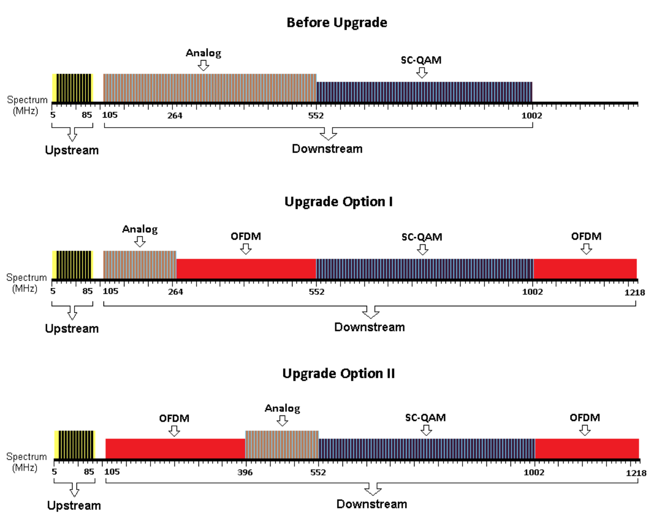

Figure 2

So, which is the better option from the HFC performance perspective? Followings will try to answer this question. Assume that the level of the newly added OFDM channels are 6dB down to those analog channels at the transmitter input, then we can expect the less composite power for this "light analog" compared to "heavy analog" at the input of forward optical transimtter and the output of nodes and amplifiers. Following table shows the calculated results of the Composite Power (CP) vs. channel loadings at transmitter input and node/amp output.

Scenarios	Level / Tilt at Fwd Tx, Node/ Amp	Loading Description	CP (dBmV)
Before Upgrade	15dBmV(QAM 6dB down), flat at Tx Input	108 – 552MHz Analog; 552 – 1002MHz QAM	34.68
	58dBmV(QAM 6dB down), 14.5dB tilt at Node/Amp Output		70.35
Upgrade option I	15dBmV(QAM 6dB down), flat at Tx Input	108 - 264MHz Analog; 264 - 552MHz OFDM; 552 - 1002MHz QAM; 1002 - 1218MHz OFDM	33.19
	58dBmV(QAM 6dB down), 18dB tilt at Node/Amp Output		68.85
Upgrade Option II	15dBmV(QAM 6dB down), flat at Tx Input	108 - 396MHz OFDM; 396 - 552MHz Analog; 552 - 1002MHz QAM; 1002 - 1218MHz OFDM	33.19
	58dBmV(QAM 6dB down), 18dB tilt at Node/Amp Output		69.15

Tabel 3

We can see that at the transmitter input both the options have the composite power (total OMI) 1.47dB less than that before upgrade which is because the newly added OFDM channels have the 6dB backoff relatively to the analog channels. In principle we can increase the OMI per channel by 1.47dB to improve the SNR by 1.47dB while unlikely degrading distortion performance at the transmitter side since the CP is ketp unchanged.

The added QAMs will introduce more noise - like intermodulation products and may therefore degrade the Carrier to Intermodulation Noise (CIN) performance a little bit in case new distortion products have higher level than existing ones. The CIN degradation may or may not affect MER performance depending where is applied. For purpose of simplicy this paper will not include MER degradation possibly introduced by the added QAMs into analysises.

At nodes and amplifiers side we can see the different reductions in the composite power between two options that the option I is reduced to 68.85dBmV and option II to 69.15dBmV. The difference comes from the tilt used for node /amp. The Figure 3 pictures how the tilted output of the nodes and amp makes difference in the composite power for the option I and option II.

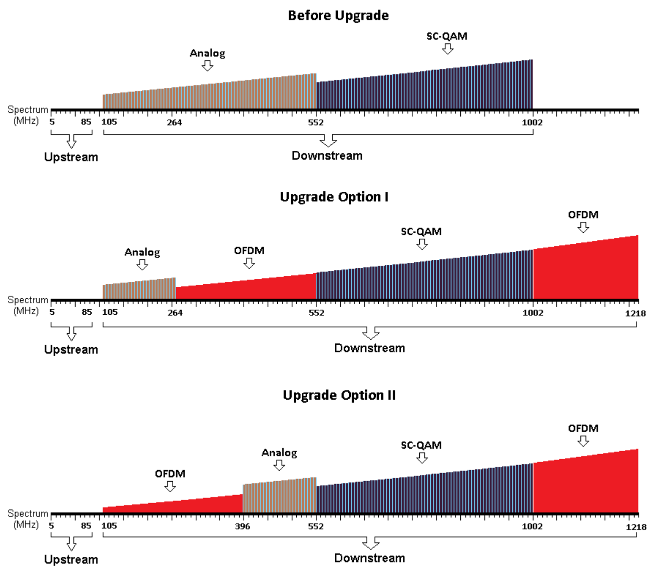

Figure 3

For composite power wise we could increase the node / amp output level by 1.5dB for option I and by 1.2dB for option II for the CNR improvement while maintaining the equivalent distortion performance at the node / amp output.

The option I sounds to be the better choice because if cable operators increase the OMI per channel at transmitter by 1.47dB for the SNR improvement, then the output levels of nodes and amps are automatically increased by 1.47dB, hence if we choose the Option I we can keep the CP on those nodes and amps' output to avoid hurting the distortion performance.

Is there something beyond composite power that matters? Having the QAMs (SC-QAM and OFDM) locate in the continuous bands should yeild the better CIN performance than that be spread out in discrete bands. And when the numbers of the analog channels is reduced from 75 to 30, the numbers of CTB and CSO shall have the significant reduction from approximately 200k down to 15k. The positive impact from a reduced number of analog channels may cancel the negative impact from an increasing number of QAM channels from distortion perspective, but let's get it verified before making conclusion.

2.2 Case Study II _ "Light Analog" to "All QAM"

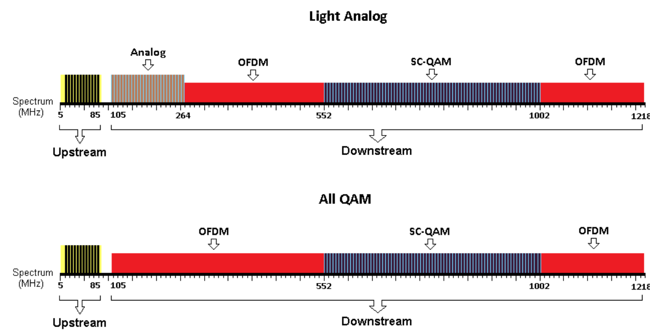

Figure 4

The Figure 4 illustrates an upgrade from a light analog to the All QAM. The All QAM refers to that the entire forword spectrum is loaded by either SC-QAM or OFDM channels but no analog channels. We can do same analysis for this upgrade scenario. The table 2 shows the difference in composite power between the "light analog" and "All QAM.

Scenarios	Level / Tilt at Fwd Tx, Node/ Amp	Loading Description	CP (dBmV)
Light Analog	15dBmV(QAM 6dB down), flat at Tx Input	108 - 262MHz Analog; 264 - 552MHz OFDM; 552 - 1002MHz QAM; 1002 - 1218MHz OFDM	33.19
	58dBmV(QAM 6dB down), 18dB tilt at Node/Amp Output		68.85
All QAM Option I	15dBmV(QAM 6dB down), flat at Tx Input	108 - 552MHz OFDM; 552 - 1002MHz QAM; 1002 - 1218MHz OFDM	31.67
	58dBmV(QAM 6dB down), 18dB tilt at Node/Amp Output		68.67
All QAM Option II	15dBmV(QAM 6dB down), flat at Tx Input	108 - 552MHz OFDM; 552 - 1002MHz QAM; 1002 - 1218MHz OFDM	31.67
	58dBmV(QAM 6dB down), 25dB tilt at Node/Amp Output		67.32

Tabel 4

As the remaining analog channels are replaced with OFDM channels, the CP at the Tx input is reduced by 1.52dB. Obviously, one should consider increasing the channel level to Tx by 1.52dB to improve the CNR. However, there is only 0.18dB reduction at the node output if the 18dB tilt is still being used. We need to find a way to get same amount of CP reduction at node and amp side to eliminate the concern at distortion performance degradation.

Fortunately, we can resolve the concern by increasing the tilt of node. The Table 2 also includes the All QAM option II which is to use the 25dB tilt instead by which one can have the 1.53dB CP reduction at node and amp outputs. By changing the tilt one can improve the CNR and unlikely causing the distortion degradation at nodes and amps.

Somebody may worry about the NF degradation for low band concerning the 25dB tilt being used. Yes it does affect the NF at equalizer's starting frequency of 52MHz, however, for the case discussed here at 105MHz the NF reduction is only about 0.3dB, and for above frequencies the degradations are getting even smaller. Since the optical link is usually the more domindant factor than amplifiers cascade for the link CNR performance, this 0.3dB degradation in node and amp's NF would merely make 0.1dB degradation for the overall link CNR performance.

2.3 Performance Impact By PAPR of OFDM

The Peak to Average Power Ratio is considered the primary disadvantage of the OFDM due to the fact that OFDM symbol has Gaussian amplitude distribution (due to its multicarrier nature). It is true, but mainly in a comparison to a single channel or a small number of channels. The PAPR impact from an OFDM channel with 192MHz bandwidth is at comparable level if compared it to the composite effect of the SC-QAM channels occupying the 192MHz bandwidth as well.

Furthermore, unlike single-carrier, OFDM offers ways of reducing peak-to-average power. One such method illustrated using this graph is called tone reservation. In this method a few (< 1%) of the tones are reserved to reduce the high amplitudes in an OFDM FFT. The results shown have been obtained by simulating the specific method given in the DVB-T2 specification. It is seen that the peak power of OFDM can be made to be less than four single-carrier channels at clipping probabilities of interest to cable applications. Another way is to implement the CCDR.

Nevertheless, the MER degradation had been noticed when node or amp with QAMs loaded is about to saturate. The PAPR effect drives the gainblocks in node or amp into non-linear region and therefore causing the unnegligible MER degradation. Particularily for All QAM loading, the overall PAPR impact shall increase in light of the OFDM's that are in replacement with analogs and added at newly expanded spectrum. Thus, some compression margin must be considered for node and amp's application to avoid MER degradation.

2.4 Reverse Analysis

The Composite Power (CP) of the reverse spectrum is continuingly increasing as more and more SC-QAM and / or OFDM channels are added into rerverse spectrum as driven by CAGR. On the following table the 26dB of link gain is assumed, we can see how the CP is increased over the reverse spectrum loadings.

Loading	Level at Rev Tx / Rx	CP (dBmV)
4 ch (5-42MHz)	17dBmV at Tx Input	23.02
	43dBmV at Rx output	49.02
8 ch (5-85MHz)	17dBmV at Tx Input	26.03
	43dBmV at Rx output	52.03
31 ch (5-204MHz)	17dBmV at Tx Input	31.91
	43dBmV at Rx output	57.91

Tabel 5

The CP increase analysis above is for a fixed Tx input level, however we actually care more about the Noise Power Ratio (NPR) range for the reverse band concerning cable temperature variation, reverse noise funneling effect, ingress noise and component variations etc. NPR stands for a dynamic level range in which the CNR or the MER or the Bite Error Ration (BER) can meet or exceed a given threshold. It is interesting to study how much NPR is reduced becaused of the CP increase and if there are ways to improve it.

For the data shown on the Figure 4 it comprises of low, mid, and high frequency splits (edge frequenies of 42MHz, 85MHz and 204MHz) using 64 QAM and 256 QAM channel loading, for an analog DWDM return transmitter, operating at +8dBm output power over a 16dB optical link (40km of fiber plus 8dB of passive loss).

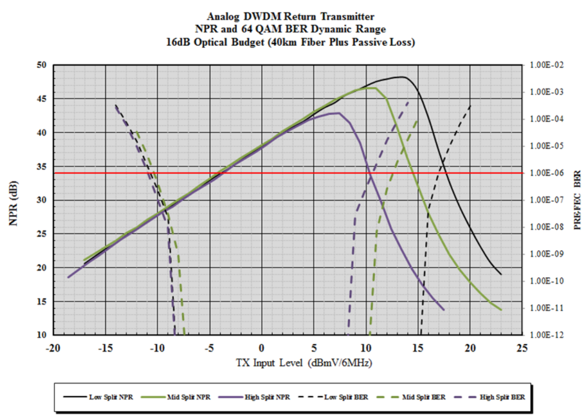

Figure 5

The plot shows the measured BER as a function of incremental RF input level. The left hand side of the curve is generally regarded as the "CNR" side as there is very little to no distortion occurring as RF levels are too low to cause it. The BER increases as RF level increases because the signal is increasing relative to the system noise floor. The right hand side of the curve is generally referred to as the "clipping" or "distortion" side of the curve as bit errors are being caused primarily by signal distortion due to overdriving the reverse gainblock in the analog return or A/D converter input in the digital return.

Looking at the NPR results of the three splits we can see the right side curve is shifted, in other words the dynamic range is reduced, because the increased CP makes mid split and high split enter the non-linear zone earlier than low split. We can see the reduced range is about 2dB bigger than the increased CP because of the nature of the non-linear clippng.

In optical networking, the amount of dynamic range for a given modulation format needs to be considered to ensure proper operation of the transmitter under fielded conditions. Typically, 12dB of operational headroom has been recommended for robust operation. Unless we can significantly imporve the noise or distortion performance for whole reverse system, but that is too challenging, the NPR reduction can not be avoided and appears to be a big concern against the DOCSIS 3.1 evolution. We should consider smaller node sizes and shorter cascades to reduce the amount of ingress noise and the impact of temperature and component variations, and using the analog DWDM lasers with tightly controlled over temperature.

3.0 HFC Performance Improvement By Fiber Deeper

In regard to the concerns mentioned in previous section we should look at reducing the number of the cascaded amplifiers which we call it the fiber deeper. Let's take a N+7 (a node plus 7 amplifiers) as the benchmark to see how much CNR can be improved by going for different scenarios of N+5, N+3, N+1 and N+0.

3.1 Forward Analysis

Majar Assumptions for CNR Analysis to the analog channels and the QAM channels:

- NF of Single Amplifier: 8dB
- Input Level To Each Amplifer: 8dBmV
- Wavelength: 1310nm
- OMI / analog channel: 3%

- OMI / QAM channels: 1.5%
- Nyquist noise bandwidth: 4MHz
- Symbol rate of QAM channels: 5.0569Msym/sec
- EIN of Receiver (Rx): 5.5 pA / Hz
- Optical Input Power to Rx: -2dBm
- Channel Loading: 79 analog plus QAMs to 1218MHz

Following let's see the End of Line (EOL) CNR comparison for Analog and QAM channels,

Scenarios	N+7	N+5	N+3	N+1	N+0
EOL Analog CNR	48.1	48.8	49.7	50.8	51.5
Δ (N+7)	0.0	0.7	1.6	2.7	3.4
EOL QAM CNR	43.4	43.7	44.1	44.4	44.6
Δ (N+7)	0.0	0.3	0.6	1.0	1.2

Table 6

If we change the optical input power to Rx to -6dBm while keeping other assumptions unchanged, we will get the following results.

Scenarios	N+7	N+5	N+3	N+1	N+0
EOL Analog CNR	45.6	46.0	46.4	46.9	47.2
Δ (N+7)	0.0	0.4	0.8	1.3	1.6
EOL QAM CNR	39.7	39.9	40.0	40.1	40.2
Δ (N+7)	0.0	0.1	0.3	0.4	0.5

Table 7

We can see that the overall CNR improvement for the -6dBm input to Rx is less compelling than that for the -2dBm input. That is because the optical link (consists of transmitter, fiber and node receiver) becomes a more dominant factor than the RF amplifiers cascade at the lower optical input. It means the analog optics is distance depedant (Rx getting lower optical power). But in the HFC fiber deep networks, Rx are expected to get lower optical input power because of the use of DWDM / CWDM supporting an increasing number of fiber deep nodes.

Per the previous study for respective scenarios of "Heavy Analog" upgrade to "Light Analog" and "All QAM" in the section 2.1, the OMI can increase 1.47dB and 1.52dB respectively and unlikely hurting distortion performance. In light of HFC networks are already on the way (or planned) converting to All QAM loading, we could assume the 3dB (≈ 1.47dB + 1.52dB) increase in OMI from "Heavy Analog" to "All QAM" upgrade, to see the combination effect of going for All QAM loading plus Fiber Deeper.

Majar Assumptions for CNR Analysis for All QAM loading:

- NF of Single Amplifier: 8dB
- Input Level To Each Amplifer: 8dBmV
- Wavelength: 1310nm
- OMI / QAM&OFDM channels: 2.12%
- Symbol rate of QAM channels: 5.0569Msym/sec
- Optical Input Power to Receiver: -6dBm
- EIN of Receiver: 5.5 pA / Hz
- Channel Loading: All QAMs from 105MHz to 1218MHz

Scenarios	N+7 (1.5%OMI)	N+7 (2.12%OMI)	N+5 (2.12%OMI)	N+3 (2.12%OMI)	N+1 (2.12%OMI)	N+0 (2.12%OMI)
EOL QAM CNR	39.7	42.3	42.5	42.8	43.0	43.2
Δ (N+7)	0.0	2.6	2.8	3.1	3.3	3.5

Table 8

Now the CNR improvement by combinaion effect of the OMI increase and the Fiber Deeper looks significant.

Distortion improvement is another major benefit from going for Fiber Deeper.

Majar Assumptions for Distortion Analysis:

- Channel Loading: 79 analog plus QAMs
- CTB of Single Node / Amp: 73dB
- CSO of Single Node / Amp: 65dB
- CCN of Single Node / Amp: 52dB

Scenarios	N+7	N+5	N+3	N+1	N+0
CTB	54.9	57.4	61	67	73
CSO	56	57.2	59	62	65
CCN	43	44.2	46	49	52

Table 9

The distortion improvement as a result of reducing the number of cascaded amplifiers looks significant. The distortion improvement is indeed helpful to go for the higher modulation of QAM. The Fiber Deep HFC network will be also helpful for other HFC performance improvement in terms of HUM, group delay e.t.c.

3.2 Reverse Analysis

We can do same analysis for the upsteam path to see how CNR be improved by reduing the number of cascaded amplifers. However, the upstream CNR of a cable network is calculated somewhat differently than the downstream CNR. In the forward path, the network branches out from a common point—say, a node. The worst-case downstream CNR is almost always through the longest individual cascade of amplifiers. In the reverse path, the network combines at a common point—the node, hub site, or headend. This results in a reverse funneling effect for system noise and impairments. Instead of calculating the CNR for a given cascade of amplifiers, the upstream CNR accounts for all the reverse amplifiers that are connected to a common point.

Assume the current HFC network is N+7 where has 30 amps in total connecting to node. Let's take the following assumption for the reverse CNR analysis

Majar Assumptions:

- NF of Amplifier: 13.5dB
- Input Level To Amplifer: 10dBmV
- Wavelength: 1310nm
- OMI / channel: 3%
- Optical Input Power to Receiver: -13dBm
- EIN of Receiver: 2.5 pA / Hz
- Symbol rate of QAM: 5.12 Msym/sec

Scenarios	N+7	N+5	N+3	N+1	N+0
Amp Number	31	21	9	2	1
Headend CNR	30.47	30.64	30.85	30.98	31
Δ (N+7, Original)	0	0.17	0.38	0.51	0.53

Table 10

The CNR improvement by the Fiber Deeper looks relatively small. Unlike downstream links the upstream links usually don't use optical amplifiers, therefore reverse Rx in headend get low optical input power unless optical link is short. Hence the optical link primarily determines the overall upstream CNR performance.

However, it is absolutely wrong to conclude that Fiber Deeper be not helpful for the upstream improvement. By the the Remote PHY or Baseband Digital Return (BDR) technology, we can make the link CNR performance indepedant with optic distance. It will yield significant improvement for the overall link CNR performance together with the CNR improvement on the amplifiers cascade shown in Table 11.

Amp Number	31	21	9	2	1
Amp Cascade CNR	39.67	41.37	45.04	51.58	54.59
Δ (31 Amps, Original)	0	1.7	5.37	11.91	14.92

Table 11

The Figure 5 is the plot showing the reverse MER data vs. incremental input levels to Tx tested in an optical link with different optical input power (+2dBm, -8dBm and -18dBm) to Rx. We can see that the MER keeps about 1:1 relationship with the Tx input level 1dB before entering the non-linear zone of Tx. As in principle the 1dB increase in OMI makes CNR 1dB better. Thus for some operating range, we can count on the better MER on the improved CNR.

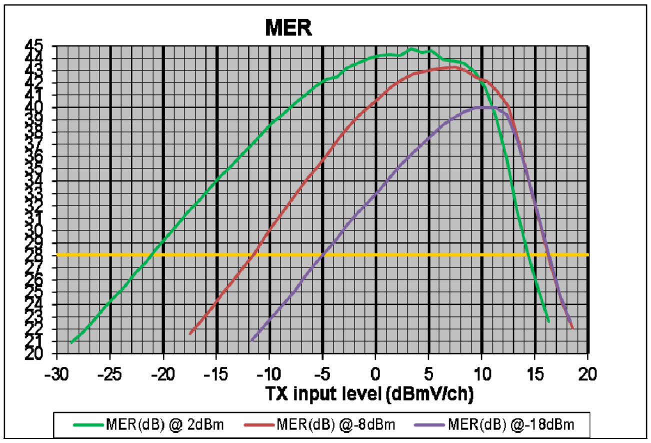

Figure 6

The above analysis is only from normal operation view, but in case there are some ingress noise the reverse CNR at the headend gets dramatically worse, for some cases it severerly impacts the BER and therefore reducing the data throughput. The prominent benefit from going fiber deeper is significantly reducing the probability and the degree of the ingress noise, hereby maintaining relatively stable BER performance through the high speed data rate.

More meaningfully, as the cable temperature variation and the probability of ingress noise are getting much smaller as a result of going fiber deeper, we can be safe to increase the reverse loading as the operational headroom is no longer remained that critical as before.

3.3 Bit / Hz efficiency Improvement By Fiber Deep And OMI Increase

By approaches of the OMI increase and the Fiber Deep we can see the 3.5dB CNR improvement in the Table 8 and 9dB CCN improvement in the Table 9 on the downstream, but considering the possibly bigger PAPR impact and worse CIN because more QAMs are added. Now let's assume 3dB MER improvement and see what we can benefit from a bit / Hz efficiency improvement view.

Table 12 shows that we can go 2048 QAM modulation on top of 39dB MER and therefore have approx 29% of the bit / Hz efficiency improvement. As a consequence, it requires the less cable bandwidth to achieve the 10Gbps DS rate.

Downstream Data Throughput	Band	MER	QAM Modulation	Date Rate (6MHz CH)	Total Data Throughput
	(MHz)	(dB)		(Mbps)	(Mbps)
Capacity increase by OFDM w/ LDPC & Spectrum Expansion	500 - 1794	36	1024	49	10568
Capacity increase OFDM w/ LDPC & Fiber Deep	500 - 1680	39	2048	54	10620

Table 12

The cable loss at 1680MHz still appears high. We could consider Fiber Deeper architecture of N+1 or N+2 and shortening the cable lengths between node to amp (or amp to amp), so that the cable loss is reduced accordingly, hereby we can maintain relatively low design challenge for HFC product development.

The bit / Hz efficiency for the upstream is unexpected to improve if we keep using the analog optics as discussed in the section 3.2. Thus it sounds necessary to introduce the digital return technology like Remote PHY if we want to improve the bit / Hz efficiency for the upstream.

4.0 HFC Performance Improvement By Remote PHY

Heading to the Remote PHY architecture is definitely helpful for the HFC performance improvement. It is said that we can get the 3dB CNR improvement by moving to the remote PHY. More meaningfully, the optical link CNR of the Remote PHY system is no longer dependant on optical link distance.

In the analog optical transpotation system the noise contributions are from a number of factors in terms of Relative Intensive Noise (RIN) of laser; shot noise and thermal noise relevant to OMI, optical input power to Rx, photodiode's responsivity, noise current of amplifier etc; and also Amplified Spontaneous Emission (ASE) of EDFA when is being used.

However, in the Remote PHY digital transportation system, the link performance is distance independent – same MER for 0 km as for 100 km. The optical input power to Rx is no longer the key factor in determining the system CNR. The number of wavelengths used is not a factor since on/off keyed digital modulation only requires ~20dB of SNR; thus fiber cross-talk effects do not play a role in limiting performance in access-length links (<160 km).

The output of the receiver is no longer dependent on optical input power, which allows the operator to make modifications to the optical multiplexing and de-multiplexing without fear of altering node output levels. It is quite meaningful to support the fiber deep architecture.

4.1 Further Bit / Hz efficiency Improvement By Remote PHY

Let's see what happens on the bit / Hz efficiency improvement by the combination efforts of OFDM w/LDPC, All QAM loading, Fiber Deep and Remote PHY.

By moving to the Remote PHY and the Fiber Deep architecture the CNR performance is no longer limited by optical distance and cascaded amplifiers, but primarily determined by the reverse gainblock performance. In light of the reverse gainblock available today can meet the 39dB MER for more than 25dB of the input dynamic range, so let's assume the 39dB MER for the following analysis.

Upstream Data Throughput	Band	MER	QAM Modulation	Date Rate	Total
	(MHz)	(dB)		(Mbps)	(Mbps)
OFDMA w/ LDPC & Fiber Deep & Remote PHY	5 - 284	39	2048	54	2511

Table 13

Now it only requires expanding the reverse band to approximately 284MHz to be able to achieve the 2.5Gbps US rate goal. Compared to previously planned 400MHz, the output level from subscribers CPE's will have the significant reduction. A reverse band from 5MHz to 284MHz makes the less NPR reduction compared a band from 5MHz to 400MHz.

Now let's take 284MHz as the US edge, and with necessary crossover band needed for diplexer, we could determine 360MHz as the starting frequency of DS band. Similar to upstream now the MER performance is primarily determined by forward gainblock. In light of the forward gainblock available today can mostly meet the 40dB MER before entering non-linear region and the OFDM w/ LPDC can make another 3dB improvement, so let's assume the 42dB MER to do the following analysis.

Downstream Data Throughput	Band	MER	QAM Modulation	Date Rate (6MHz CH)	Total Data Throughput
	(MHz)	(dB)		(Mbps)	(Mbps)
OFDM w/ LDPC & Fiber Deep & Remote PHY	360 -1440	42	4096	59	10620

Table 14

It does make difference in the coaxial cable bandwidth required for achieving the target 10Gbps DS data throughput. The QAM numbers in a forward band of 360MHz to 1440MHz is even less than that of a band from 108MHz to 1218MHz, thus we could at least maintain the current OMI to forward Tx.

5.0 Summary and Conclusion

In addition to the introduction of OFDM with LDPC, we really can do something from the HFC side to help head to the target data throughput. We could take via several leaps as to expanding coaxial cable bandwidth, heading to Light Analog or All QAM loading, going to Fiber Deeper, and deploying Remote PHY.

The first leap introduced by the OFDM w/ LDPC makes approximately 29% increase based on the current infastructure, but there still remains the tremendous challenges to explore the cable bandwidth to 1794MHz and the concerns against the CPE's output level increase and the reduced operational headroom on the upstream. We will have to tremendously increase the gain, RF output power, bandwidth and power dissipation for device and product to compensate the cable loss rolling out to 1794MHz DS and 400MHz US that makes the mission almost impossible. And if the long amplifier cascade story continues, the operational headroom reduction on the upstream will turn out to be a big concern against cable temperature variation, component variation, ingress noise and reverse funneling noise effect. We must consider other approach to lighten the concerns that have addressed.

Upgrading to "light Analog" or "All QAM" is something MSO's are going to, or plan to, do as driven by CAGR. We could take the opportunies to improve DS CNR by increasing the OMI to Tx as the second leap.

The third leap of going to the Fiber Deep architecture is the necessary evolution for HFC. With the Fiber Deep approach we can improve the bit / Hz efficiency with the improved CNR and distortion to require less cable bandwidth for achieving 10Gbps DS throughput; Have less concern against the reduced operational headroom on the upstream. However, the significant bit / Hz efficiency is unexpected on the upstream since the CNR performance is still primarily limited by use of the analog optics.

We could depoly the Remote PHY architecture as the fourth leap. Remote PHY is the significant value adder in helping imporve the system CNR and hereby requiring the even less cable bandwidth to achieve the target throughput. More meaningfully, as the Remote PHY is the optical distance indepedant, we can add multiplexing and de-multiplexing to support the Fiber Deep architecture without fear of degrading MER performance. And then together with Fiber Deep architecture the US MER performance is no longer dependant on optic distance and amplifiers cascade.

The Table 15 and 16 indicate the bit / Hz efficiency improvements by these movements to achieve 10Gbps DS and 2.5Gbps US throughputs but with the much lighter cable spectrum expansion.

Upstream Data Throughput	Band	MER	QAM Modulation	Date Rate	Total
	(MHz)	(dB)		(Mbps)	(Mbps)
Current Capacity	5 - 85	24	64	27	360
OFDMA w/ LDPC & Spectrum Expansion	5 - 204	30	256	38	1260
	5 - 400	30	256	38	2502
OFDMA w/ LDPC & Fiber Deep & Remote PHY	5 - 284	39	2048	54	2511

Table 15

Downstream Data Throughput	Band	MER	QAM Modulation	Date Rate (6MHz CH)	Total Data Throughput
	(MHz)	(dB)		(Mbps)	(Mbps)
Current Capacity	105 - 1002	33	256	38	5681
OFDM w/ LDPC & Spectrum Expansion	258 - 1218	36	1024	49	7840
	500 - 1794	36	1024	49	10568
OFDM w/ LDPC & Fiber Deep	500 - 1680	39	2048	54	10620
OFDM w/ LDPC & Fiber Deep & Remote PHY	360 -1440	42	4096	59	10620

Table 16

The reduced cable specturm expansion would help make the challenges for chip and product development down to a manageable degree. The DS bandwidth of 360 to 1440MHz is close to what we have today that helps maintain the composite power at Tx input and node / amp output; Compared to US bandwidth 5 to 400MHz, the 5 to 284MHz bandwidth makes the less reduction for the NPR range..

The DOCSIS 3.1, when getting the target data throughput achieved, has the good position to compete with the fiber to home technologies in light of its QoS, scailability, and much less CAPEX to rolling out the 10G cable access network.

6.0 Reference

(1) John T. Chapman, Mike Emmendorfer, Robert Howald, and Shaul Shulman "An Evolutionary Approach to Gigabit-Class DOCSIS, DOCSIS NG WP," May.21, 2012

(2) Steve Contra, "HFC Architecture Evolution"