Remote PHY: Enabling Immediate Access to Extra Bandwidth Capacity in Existing Networks

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Abstract

During the last several years, the increasing demand for network capacity created significant uptick in the activity directed towards analysis of the optimal methods of expanding the capacity of wireline telecommunications networks, including broadband HFC networks. Multiple papers described the reason for the increased demand, the ways to expand the network bandwidth and the ways to improve the bandwidth efficiency through deployment of the next generation PHY.

This paper contributes to this discussion by describing the least disruptive method of increasing capacity of the existing networks. Specifically, network design analysis and modeling proves that the existing HFC network can support immediate increase in capacity without resorting to bandwidth expansion and without waiting for the next-generation PHY of DOCSIS® 3.1[1] *and EPoC. Distributed Broadband Access Architecture, a.k.a. remote PHY*[2] *improves the existing network performance from a network capable of supporting 256-QAM Reed-Solomon (R-S) signals, with or without Trellis Coded Modulation (TCM), to a network capable of supporting 500-1000 MHz of 1024-QAM signals of the same J.83 format. The paper presents design guidelines for achieving this capacity increase without having to re-construct either the "F" or the "C" portions of the HFC network.*

The paper takes a snapshot of the status quo of deployed CPE devices to determine the feasibility of taking advantage of this improved network performance with the existing equipment. The paper also presents a partial inventory of silicon chips that can support the transmission of 1024-QAM R-S signals with and without TCM and lists examples of CPE devices capable of the same.

The paper presents test data of 1024-QAM signal delivery to validate the network analysis and modeling and to detail the design guidelines for capacity expansion.

In the summary, the paper presents a set of bandwidth and capacity expansion methods for HFC networks and their ranking based on the outcomes and required effort and investment. This summary encompasses the analysis presented in the previous paper[3]*, including a relatively straightforward expansion of the network capacity by expansion of bandwidth from 750 MHz to 1002 MHz with remote PHY.*

INTRODUCTION

The demand for increased capacity in broadband telecommunications networks comes in waves. Cycles of innovation create new services generated both from within the telecommunication and entertainment delivery industries, and externally by newcomers seeking new markets. Heightened levels of customer expectations force all providers to compete and upgrade. Capacity demand is also fueled by the consumer electronics (CE) industry continuously searching for new sources of revenue in CE technology replacement cycles. We are witnessing insatiable capacity demand in wireless communications networks fueled by the same drivers and, after a period of temporary lull in wireline networks, we see the same build up of capacity demand driven by over-the-top service providers who, despite the wishful thinking of the network operators, do not disappear but are actually growing exponentially in their service delivery offerings; and by the consumer electronics industry that presents to the public 4K HD and 8K HD video sources and video displays of increasing size, often with increased frame repetition rate and pixel depth and in 3D format. The first trend will result in duplication of the same programming, delivered to the same group of households from different providers, which would not and could not be addressed or remedied by multicasting. The second trend, despite the progress in compression algorithms, will increase requirements for the capacity per stream. These trends, combined with increased numbers of display devices per household, often watched simultaneously by the same subscriber and often requiring different resolutions even for the same programming and video streams delivered at the same time, leads to the realization that the increase in capacity to 10 Gbps and beyond for wireline networks will be required within the next 10 years[45].

So, what can network operators do to counterbalance these trends and actually cash in on them in a manageable way that takes into account the cost of the capacity expansion and provides for a reasonable ROI? The place to start is with the outlay part of the ROI equation. The authors will leave the other parts of the equation – revenue and profits – to the wizards of marketing and – operating; and variable costs – to the practitioners of network operations, where cost is partially defined by the outlays, and purchasing magicians of the network operators.

PERFORMANCE MARGINS

Traditional HFC with Analog Forward Links

There are two essential methods of increasing the capacity of broadband networks: increasing their bandwidth and improving the bandwidth efficiency. The method chosen often depends on the all-inclusive[a] cost of achieving the capacity expansion. Sometimes it is less costly to increase the network bandwidth, especially when many network elements are capable of supporting the bandwidth expansion and additional network elements (terminal equipment) facilitate taking advantage of this bandwidth expansion capability. Sometimes it is less costly to increase bandwidth efficiency. In many cases, the tools for achieving both are the same and both could be achieved at the same time thus maximizing network capacity expansion effectiveness[b].

Let us analyze the network performance margins and the weak links that can be improved upon, in search of bandwidth efficiency improvement opportunities.

Headend

The major contributor to the QAM signal impairments in the headend is the signal source itself. Unfortunately, short of replacement of these signal sources, there is little that can be done to improve their performance. Even the little improvement that can be achieved by elimination of the RF combining network in the headend requires replacement of the traditional signal sources with CCAP equipment that performs signal

[a] Cost of the upgrades to distribution network, including in-house wiring, and terminal devices, both in the headend and on customer premises.

[b] Effectiveness of the upgrade for capacity expansion by extending BW and improving BW efficiency at the same time leads often to lower cost per unit capacity gain. The capital outlay management will decide whether to perform both.

combining in the digital baseband domain by signal multiplexing. It is important to note that the major degradation in the RF combining network is not the thermal noise generated by its active components but the signal crosstalk between QAM signals carrying disparate information. This degradation[c] does not practically exist for analog signals which carry the same signals to different outputs of the RF combining network.

The alternative to the replacement of the signal sources is their relocation and creation of a Distributed Broadband Access Architecture with remote PHY. The benefits of this approach will be apparent pending further analysis.

Analog Forward Optical Links

The analog optical links can be incrementally improved but the improvements are bounded by theoretical limits. The typical upper boundaries of analog link performance are listed in Table 1 as "0 km fiber distance" cases. These boundaries assume unrealistic fiber conditions and do not take into account any degradation caused by linear and nonlinear fiber effects (no fiber in the link). For comparison, the typical performances of single-wavelength systems and 20-wavelength systems over 20 to 60 km of fiber are also listed in Table 1. The optical analog links are generating signal impairments at the level comparable to or higher than impairments generated by headend components.

The approaches to improving the optical link performance materially include:

- Split-band dual wavelength approach resulting in increased optical modulation index (OMI) spectral density at the cost of total fiber capacity. This approach requires two fibers per service segment if MWVL system degradation is to be avoided.
- Priority load approach where some part of the bandwidth is allocated higher OMI spectral density. This approach is used in analog optical links supporting NTSC analog signals and QAM signals with higher OMI spectral density allocated to analog signals.
- Significant limits to the number of wavelengths per fiber and careful wavelength allocation to limit nonlinear MWVL fiber impairments (at the extreme, using single wavelength per fiber).
- Deployment of different analog optical link technologies for different distances to optimize technology for the required launch powers and linear and nonlinear fiber impairments.
- Fiber replacement for fibers with better performance for the selected wavelength range and distances.

None of the solutions listed above is low cost and some introduce additional operational burdens (e.g., different alignment processes and design guidelines for different technologies and fibers). Even with unlimited existing fiber count, the opportunity cost eventually adds to the cost of the solutions listed above on top of the analog link component costs.

RF Distribution Network

The RF distribution network with bandwidth up to 1 GHz contributes relatively low signal impairments if designed properly and with short cascades. The major limitation comes when the multiple active cascades need to be expanded in bandwidth beyond 1 GHz. These limitations are diminished in passive coaxial networks (Fiber Deep architecture) in which bandwidth can be expanded significantly up

[c] Multipath degradation of analog signals occurs at much higher crosstalk levels than those introduced by headend downstream RF combining/splitting network, especially after considering multipath differential delays.

to 1.8 and even 2 GHz with simultaneous improvements in bandwidth efficiency. Table 2 presents coaxial network performance in the designed bandwidth based on the designs analyzed in the paper presented at NCTA Spring Technical Forum in 2013[6]. The table does not list the RF cascade CNR performance for the Fiber Deep architecture since the performance of the RF section is defined by the node performance alone and no RF active cascade degradation occurs.

Table 1: Analog Optical Link Performance

Optical Link Description	RF Load	Fiber Distance	Optical Receiver Input	CNR Performance
1310 nm Single Wavelength	74 NTSC analog and 75 QAM channels (6 dB lower)	0 km	0 dBm	53.5 dB analog/46.5 dB QAM
		20 km	0 dBm	52.2 dB analog/45.2 dB QAM
		40 km	0 dBm	51.7 dB analog/44.7 dB QAM
1550 nm Directly Modulated Single Wavelength		0 km	0 dBm	52.2 dB analog/45.2 dB QAM
		20 km	0 dBm	50.2 dB analog/43.2 dB QAM
		40 km	0 dBm	48.2 dB analog/41.2 dB QAM
1550 nm Externally Modulated Single Wavelength		0 km	0 dBm	50.7 dB analog/43.7 dB QAM
		48 km	0 dBm	50.7 dB analog/43.7 dB QAM
1310 nm Single Wavelength	149 QAM channels	0 km	-3 dBm	48.5 dB
		20 km	-3 dBm	48.1 dB
		40 km	-3 dBm	46.4 dB
1550 nm Directly Modulated Single Wavelength		0 km	-3 dBm	47.7 dB
		20 km	-3 dBm	46.4 dB
		40 km	-3 dBm	45.0 dB
1550 nm Externally Modulated Single Wavelength		0 km	-3 dBm	45.0 dB
		60 km	-3 dBm	45.0 dB
20-Wavelength 1550 nm Directly Modulated	149 QAM channels	20 km	-1 dBm	40.0 to 44.1 dB (different frequencies, worst wavelength)
		40 km	-6 dBm	38.9 to 41.9 dB (different frequencies, worst wavelength)

Table 2: RF Active Cascade Performance

Design Scenario	Worst/Best Case CNR for Longest Cascade [dB]
750 MHz N+5 "Moscow" system	49.8/52.2
860 MHz N+5 "Stalingrad" System	56.0/56.2

In-House Wiring and CPE

The signal levels at the outlet of the in-house wiring in combination with the terminal equipment performance define the signal impairments contribution by this network element. The analysis of multiple system designs is presented in Table 3. The results show that the median levels are comfortably higher than the minimum design levels. This data is confirmed by statistical data collected by the industry for millions of terminal equipment modules (cable modems and set top boxes). Nevertheless, some terminal devices will fall below the design levels.

Table 3: Outlet Signal Levels and Performance

Original design Freq & Type	Input Levels @ Highest Freq. [dBmV]	CPE CNR @ Highest Freq. [dB]
750 MHz N+5	-3.02	44.96
860 MHz N+5	-2.22	45.76
860 MHz FD	-6.39	41.59
1002 MHz FD	-2.70	45.28

Table 4: Typical EOL Signal Performance

Original design Freq & Type	Headend performance [dB]	Optical Link performance [dB]	RF Cascade performance [dB]	Median CPE CNR @ Highest Freq. [dB]	Design CPE CNR @ Highest Freq.	EOL CNR @ Highest Freq./Median Level	EOL CNR @ Highest Freq./Design Level [dB]
QAM Signal Performance							
750 MHz N+5	42.2	39.0	49.8	45.0	38.0	36.4	34.5
	42.5	40.0	52.2	45.0	38.0	37.1	34.9
	42.5	45.0	52.2	45.0	38.0	39.0	36.0
860 MHz N+5	42.2	39.0	56.0	45.8	38.0	36.7	34.6
	42.5	40.0	56.2	45.8	38.0	37.3	35.0
	42.5	45.0	56.2	45.8	38.0	39.3	36.0
860 MHz FD	42.2	39.0	NA	41.6	38.0	35.9	34.6
	42.5	40.0	NA	41.6	38.0	36.5	35.0
	42.5	45.0	NA	41.6	38.0	38.0	36.1
1002 MHz FD	42.2	39.0	NA	45.3	38.0	36.7	34.6
	42.5	40.0	NA	45.3	38.0	37.3	35.0
	42.5	45.0	NA	45.3	38.0	39.3	36.1
Analog Signal Performance							
750 MHz N+5	60.0	51.0	57.0	52.2	49.2	47.7	46.4
860 MHz N+5	60.0	51.0	63.2	52.2	49.2	48.1	46.7
860 MHz FD	60.0	48.0	NA	52.2	49.2	46.4	45.4
1002 MHz FD	60.0	48.0	NA	52.2	49.2	46.4	45.4

EOL Signal Performance

Table 4 presents typical EOL QAM signal performance for median and design levels at the terminal devices. For comparison, the table also lists performance of analog NTSC signals at the levels into the terminal devices at 0 and 3 dBmV. One may notice a significant difference that is only partially justified by the difference in terminal device input levels.

The brief analysis of the table clearly points out that the additional major factors contributing to this difference are:

1. headend impairments differences; and
2. optical link impairment differences.

The headend performance for analog video signals is significantly better than the headend performance for QAM signals. There are many reasons for that: the analog signals demand much higher EOL and the limitation of the RF coaxial network and analog optical links demanded almost pristine signal performance at the source of the analog signals at the input to the HFC network. Even more critical was the cost management of the network. Without the high signal quality in the headend, the RF coaxial network cost would increase dramatically. If the headend high signal quality could not have been achieved, then the terminal device input levels would have to be raised during the design process, again drastically increasing the cost of the RF network (and dashing the hopes for bandwidth expansion up to 1000 MHz).

The typical headend performance for analog video signals was historically defined at 60 dB CNR. This is drastically better than 43 dB MER required of QAM signals sources, which are further degraded by 50-52 dB crosstalk levels between narrowcast QAM signals. The crosstalk will be all but eliminated in future replacement of edge QAM modules and headend RF combining networks with CCAP equipment.

Another source of difference comes from the traditionally lower OMI spectral density allocated to QAM signals in analog optical links, again justified by significantly higher analog signal performance requirements.

As already mentioned above, the third contributor to disproportionately lower EOL performance of QAM signals comes from the common practice for designing much lower levels into QAM terminal devices. This is again justified by preserving high levels for analog NTSC signals and managing the cost of the network. The success of digital TV and HSD (carried on QAM signals) resulted in proliferation of QAM terminal devices and hence inflation of the number of outlets per household. Providing high input levels to all of them, short of installing house amplifiers that are not preferred for many reasons[d], would inflate the network cost.

All of these sources of significant EOL performance differences may be completely eliminated or materially remedied with DBAA.

RECAP OF DISTRIBUTED BROADBAND ACCESS DIGITAL HFC ARCHITECTURE

Distributed Architecture Synopsis

For detailed descriptions of several approaches to DBAA, the authors refer to the paper[7] presented at NCTA Spring Technical Forum 2013. Here we just remind the readers that in DBAA (see Figure 1 for an example), signal sources are relocated from headend to the nodes thereby eliminating headend RF combining network and analog optical link contributions to signal impairments. This move also simplifies and granulates future upgrades[e] for better signal source performance that may be required for NG PHY. This relocation will also enable some RF coaxial level management to increase the levels into terminal devices after the move to all digital (QAM-only) signal load on HFC networks. The results of the testing to support this claim follow.

The referenced paper presents detailed analysis, showing what can be achieved in HFC with DBAA in terms of significant bandwidth expansion under different outlay costs and of significant improvements in bandwidth efficiency (with or without bandwidth expansion).

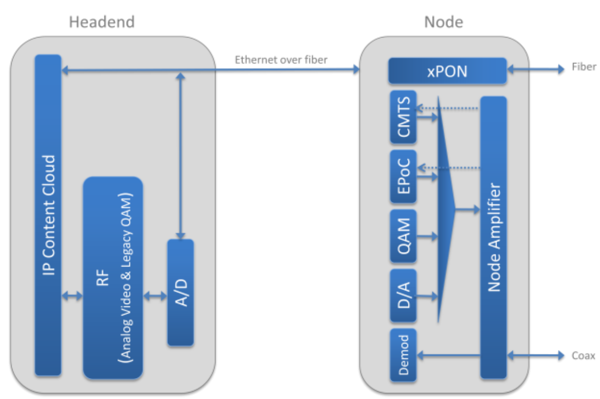


Figure 1: All-Digital Broadband Access Architecture

Immediate Opportunity for HFC Capacity Expansion with DBAA

Implementation of DBAA delivers the immediate opportunity of improving EOL

[d] House amplifiers hinder future BW expansion and upstream level management to mention a couple issues.

[e] The network upgrades can be performed on a node-by-node or segment-by-segment basis depending on demand for increase network capacity, allowing more efficient management of capital outlays.

signal performance and hence bandwidth efficiency for HFC networks. Table 5 summarizes EOL performance improvement for the QAM portion of the network under the assumption that there is no performance degradation from analog NTSC signals and other QAM signals carried on the analog optical links, if they are still used[f]. Table 5 shows that an improvement of more than 2 dB in EOL (from the lowest of 34.5 dB to the lowest of 36.6 dB and higher for other values) can be achieved without additional level increase to terminal devices while more than 4 dB improvement (from the lowest of 34.5 dB to the lowest of 38.7 dB) can be achieved after taking advantage of QAM-only RF active load and increasing levels to terminal devices without reworking in-house wiring (see further test results and Table 6). As the results of the testing show, these EOL performance levels are more than adequate to support 1024-QAM Adv PHY signals with R-S coding, with or without TCM.

The only remaining question is whether we can take immediate advantage of the EOL signal performance improvement to increase HFC network capacity without having to fall back to the more fiscally and operationally costly method of capacity increase through bandwidth expansion.

RECOVERED MARGIN MONETIZATION: CAPACITY

1024-QAM with R-S and TCM: Performance Requirements

To confirm many published numbers and define the performance requirements for 1024-QAM signals, testing of the BER versus SNR was performed in the test setup presented in Figure 2. The testing was performed for 256-QAM J.83 signals Annex C and Annex B with three different data patterns and for 1024-QAM J.83 signals Annex C. Due to the lack of reliable test equipment, the testing for 1024-QAM signals Annex B was not completed. However, the coding gains between Annex C and Annex B 256-QAM signals can be extrapolated to 1024-QAM signals, especially after accounting for the very close correlation of test results and theoretical values. The test results are presented in Figure 3.

The test results confirm 27-28 dB SNR (MER dominated by noise) requirement for post-FEC QAM 256 J.83 Annex B signal and 29-30 dB SNR requirement for post-FEC 256-QAM J.83 Annex C signal. This difference confirms approximately 2 dB TCM gain after R-S coding[g] is applied. The results also confirm the 6 dB required improvement in SNR to support a post-FEC error-free environment for 1024-QAM J.83 Annex C signals (35-36 dB SNR). By extrapolation, 33-34 dB SNR performance is required to support error-free 1024-QAM J.83 Annex B signal transmission.

The comparison of the numbers in Table 4 with the test results and theoretical numbers indicates that the HFC networks are designed and operate at 6 dB and higher operating margins, and at 10 dB operating margins for median EOL performance. It also confirms that this margin would drop to zero for the design performance and many CPE devices would not be able to operate in 1024-QAM J.83 Annex B environment. Table 5 shows that simple implementation of DBAA enables transmission and reception of 1024-QAM J.83 Annex B signals, albeit at lower operational margins of approximately 3.5 dB for the design performance levels and 6-7 dB for median plant performance.

[f] To accomplish this, relatively straightforward bandwidth allocation management guidelines and signal filtering in the node can be implemented.

[g] Different levels of R-S coding for Annexes A and C and Annex B.

Table 5: EOL Signal Performance after DBAA Implementation

QAM Signal Performance							
Original design Freq & Type	Modulator Performance	RF Cascade performance	Median CPE CNR @ Highest	Design CPE CNR @ Highest Freq.	EOL CNR @ Highest Freq./Median Level	EOL CNR @ Highest Freq./Design Level
	[dB]	[dB]	[dB]			[dB]
750 MHz N+5	43.0	49.8	45.0	38.0	40.3	36.6
	43.0	52.2	45.0	38.0	40.6	36.7
860 MHz N+5	43.0	56.0	45.8	38.0	41.0	36.7
	43.0	56.2	45.8	38.0	41.0	36.7
860 MHz FD	43.0	NA	41.6	38.0	39.2	36.8
1002 MHz FD	43.0	NA	45.3	38.0	41.0	36.8

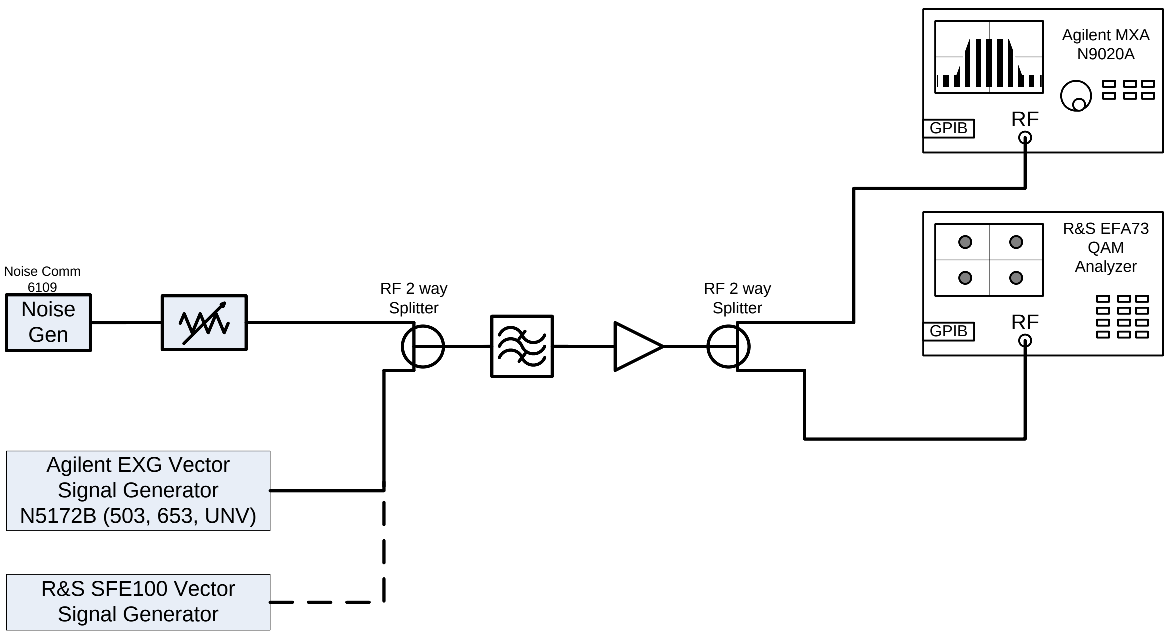


Figure 2: Test Setup – QAM Signals Sensitivity to Gaussian Noise

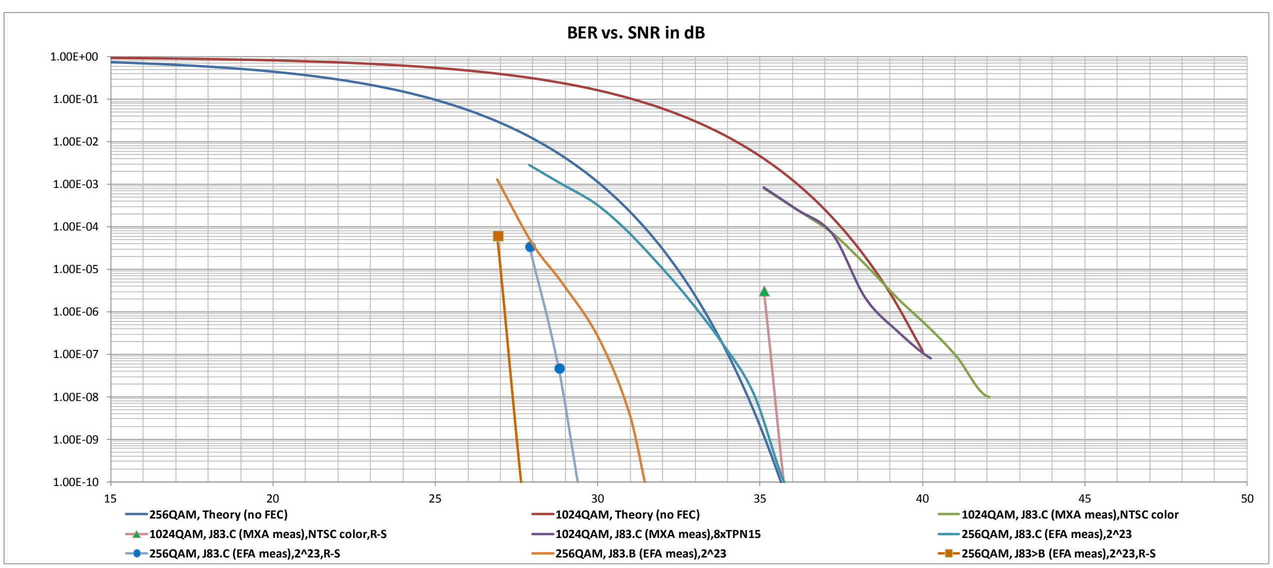


Figure 3: Test Results: QAM Signal Sensitivity to Gaussian Noise

Higher operating margins are critical for:

- achieving and maintaining low operating cost at high level of service satisfaction;
- supporting the operational outliers among terminal devices[h].

The test results also show that TCM gain is approximately 4 dB before R-S coding is applied. Total gains are lower after R-S coding due to the additional FEC gains realized with R-S coding in Annexes A and C.

Analog Forward Optical Links

The performance of the optical links is already pushed to the clipping limits with minimal margin left. The linearization technologies evolved over the years and took advantage of any theoretical margins. Lowering these margins further or eliminating them altogether would bring limited performance improvement in the order of 1 dB but would push the operation of optical links to the brink of disaster even if anti-clipping and AGC circuitries are implemented. To achieve any sizeable improvement approaching that secured by DBAA deployment is practically unachievable even with all the remedies listed previously (even if cost is not a concern).

For example, deploying two single-wavelength split-band systems would require 2 wavelengths per node segment and would yield approximately 48 dB SNR in 1 GHz QAM-only links. This performance, in combination with 42.2 dB headend performance, would yield approximately 41 dB SNR, a far cry from the guaranteed DBAA performance, and would still be a major contributor to the EOL performance (a dominant contributor for the median performance terminal devices).

RF Distribution Network and CPEs

As is apparent from Table 5, even with DBAA, 1024-QAM signal deployment would lower the operating margins by 2-3 dB. To address this degradation in operating margins, the output levels of RF actives must be increased accordingly to avoid major upgrades to in-house wiring. To verify whether there is sufficient margin in the RF network actives to achieve this, a series of test were conducted at the upper range of the RF actives operating output levels. The test setup was similar to the test setup used to determine whether analog optical links have any OMI margin available before clipping occurs. This is presented in Figure 4.

The test results (presented in Figure 5) show that the BER for channels at 999 MHz approaches 10E (-4) for 1024-QAM J.83 Annex C signals at the RF active levels higher by 1.5 dB at 1 GHz than the levels of QAM signals at 1 GHz in nodes loaded with 75 CW carriers and 75 QAM signal channels (set 6 dB lower). Results also show that for these BER numbers, there are no errors after R-S. The plots in Figure 5 also show results for 256-QAM J.83 Annex B and C signals. These test results show more than 1 dB gain in output level for the same pre-FEC BER between Annex C and Annex B. Similar gain is expected for 1024-QAM J.83 Annex B signal.

[h] The statistical data collected by the industry shows that approximately 5% of terminal devices operate at performance lower than the design goals and some are barely above the required performance levels.

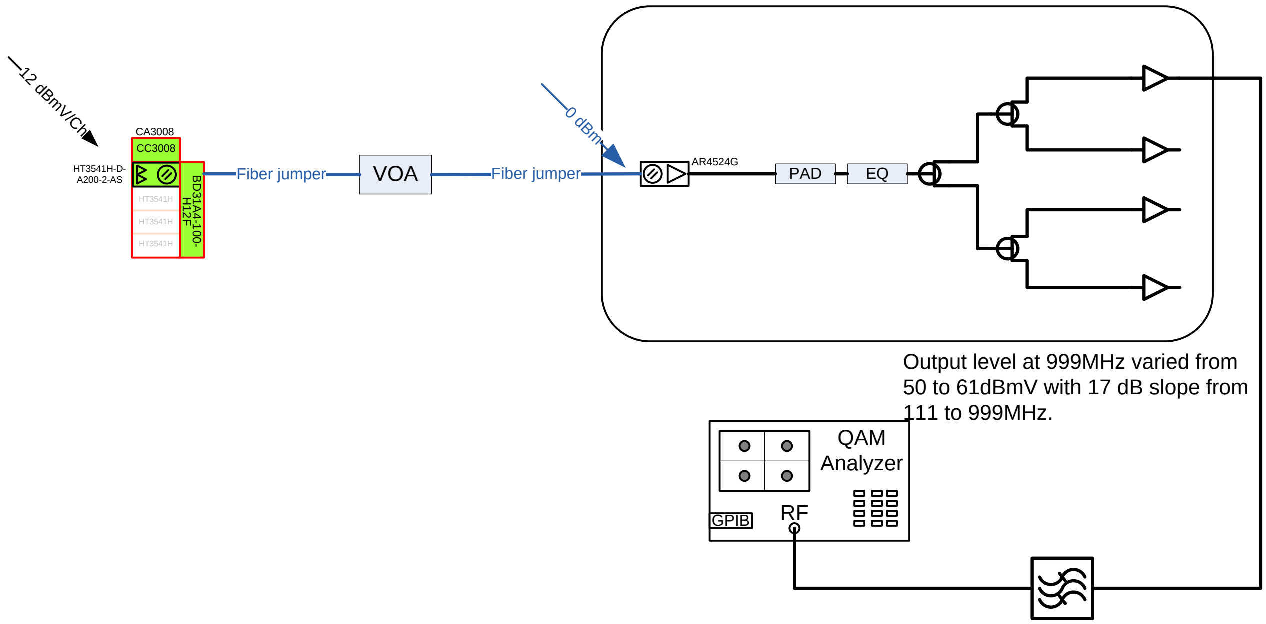
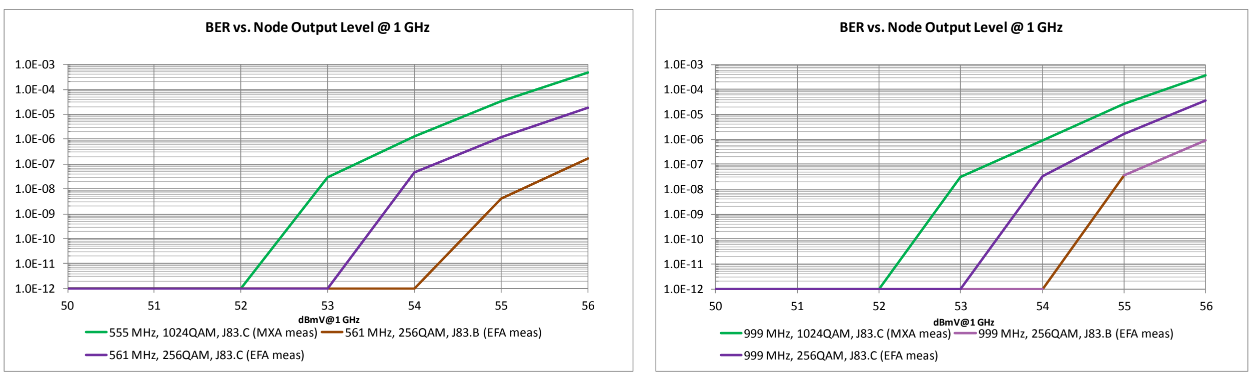


Figure 4: Test Setup: Performance versus RF Active Output Levels



a) Channel at 555 or 561 MHz **b) Channel at 999 MHz**

Figure 5: BER Performance versus RF Active (Fiber Deep Node) Output Levels

The tests were conducted for the highest levels in nodes used in a Fiber Deep architecture with no additional RF actives. In a traditional HFC architecture with RF actives, the RF active output levels are de-rated accordingly and are much lower than the clipping levels. Hence increasing their levels by up to 3 dB will result in a minimal degradation of BER, if at all, and in CIN noise cascaded at much lower levels[i].

These test results lead to an assertion that the levels in all RF actives loaded exclusively with QAM channels, especially with Annex B QAM channels, can be increased by 2 to 3 dB.

If the 2-3 dB increase in the RF active output level is difficult to maintain and provides too low an operating margin, then the split band settings with priority load that does provide sufficient operating margin can be implemented instead

Figure 6 presents the BER results as a function of the node output level with 74 channels of 6 dB higher priority load and 75

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[i] Cascading of CIN is on a 10*log basis while the CIN levels drop at a higher rate than 1-to-1 with the drop in RF active levels, although the rate of change varies depending on the frequency and on the order of nonlinearity causing the CIN.

channels of lower priority load. For comparison, it also shows BER results for 1024-QAM J.83 Annex C signal for even level load. The results indicate that quite a significant bandwidth of priority load can be supported with 3 dB higher levels (even up to the full 894 MHz load) to 9 dB higher levels (for 444 MHz of priority load) than the levels of QAM signals with 75/75 analog/QAM load. For Annex C, level increase for acceptable performance will be 2 dB lower but more than 500 MHz of priority load at levels 3-7 dB higher can be supported.

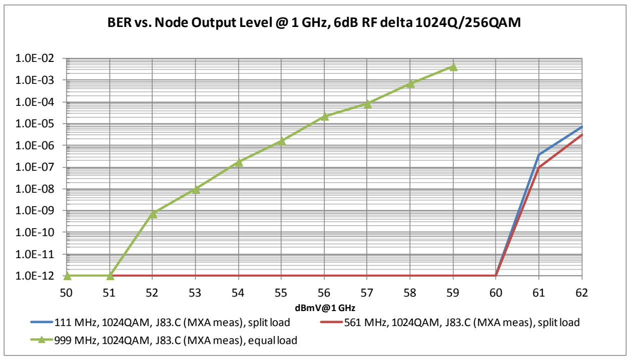

Figure 6: BER Performance versus RF Active (Fiber Deep Node) Output Levels for Split Band Load (with Priority Signals)

Table 6 presents the EOL performance for the network with DBAA and with levels increased by 3 dB (whether for the entire bandwidth or for the priority load bandwidth). Note that the results presented in the table are for the highest design frequency. Terminal devices will see higher levels at lower frequencies unless significant forward slope reaches the in-house wiring.

The results presented in Table 6 show that we achieved similar operating margins for 1024-QAM J.83 Annex B signals as in the original network design (see Table 4) with analog optical links. These limited network upgrades thus allow delivery of 1024-QAM J.83 Annex B signals to terminal devices within the entire design bandwidth or at least in a sizeable portion. Hence, we can increase network capacity by up to 25%. This translates to the following capacity gains:

- 1 Gbps in 256-QAM only load 750 MHz network (from 4 Gbps to 5 Gbps);
- 1.2 Gbps in 870 MHz network (from 4.8 Gbps to 6 Gbps);
- 1.4 Gbps in 1002 MHz network (from 5.6 Gbps to 7 Gbps).

Table 6: EOL Signal Performance after DBAA Implementation and 3 dB RF Active Level Increase

QAM Signal Performance						
Original design Freq & Type	Modulator Performance	RF Cascade performance	Median CPE CNR @ Highest	Design CPE CNR @ Highest Freq.	EOL CNR @ Highest Freq./Median Level	EOL CNR @ Highest Freq./Design Level
	[dB]	[dB]	[dB]			[dB]
750 MHz N+5	43.0	52.8	48.0	41.0	41.5	38.7
	43.0	55.2	48.0	41.0	41.6	38.8
860 MHz N+5	43.0	59.0	48.8	41.0	41.9	38.8
	43.0	59.2	48.8	41.0	41.9	38.8
860 MHz FD	43.0	NA	44.6	41.0	40.7	38.9
1002 MHz FD	43.0	NA	48.3	41.0	41.9	38.9

TERMINAL DEVICES

The previous sections showed that with the deployment of DBAA and after realignment of RF actives in the HFC network, we can improve the network performance to enable transport of 1024-QAM J.83 signals for up to 25% capacity expansion without bandwidth upgrades while maintaining similar operational margins. The question is whether network operators can take immediate advantage of this development. The authors analyzed the availability of terminal devices capable of transmitting and receiving 1024-

QAM J.83 signals. Implementation of this level of modulation would allow extra margin of time for the deployment of DOCSIS 3.1 PHY with all its increased complexity and cost related to the technology replacement cycle for only 3 dB performance gain at the cost of higher overhead[j] and hence lower capacity gain. A slightly longer equalization tap chain[8] would allow up to 32 channel pooling for up to 1.5 Gbps communication trunk size with 1024-QAM J.83 Annex B signals. Some silicon vendors did implement higher modulation levels in their silicon despite the fact that they were not specified by the standard. This silicon has been used in many CPEs deployed by network operators and is commercially available. As for the signal sources, some CMTS are capable of generating 1024-QAM signals. But most importantly, DBAA modules that are FPGA based are designed to support 1024-QAM transmission and hence can deliver video and high-speed data at 25% higher speeds to the CPE devices.

CPE Devices for 1024-QAM Signal Reception: Are They Capable and How To Make Them Ready

When assessing a cable modem or set top box for its ability to support 1024-QAM demodulation, three things need to be taken into consideration: the performance of the tuner; the capabilities of the demodulator; and the ability of the software to accommodate the higher data rates and the additional modulation rate.

1024-QAM demodulator support in cable modem and set top box silicon has been present in certain chipsets for over a decade. See Appendix A for a partial list. However, the ability to reliably manufacture affordable tuners with sufficient SNR lagged by several years, due to the difficulty in mitigating traditional impairments such as frequency error, microphonics, linearity, thermal noise, and phase noise. With only a few exceptions, the tuners of adequate performance to support 1024-QAM reception and demodulation have all been silicon-based implementations.

Silicon support for 1024-QAM is not sufficient for end-to-end 1024-QAM transport support in cable modems and set top boxes. CPE firmware must also be enabled to direct the device to lock onto and demodulate 1024-QAM signals, as well as accommodate the higher data processing rates required. Until the recent introduction of miniCMTS products, there were no commercial deployments of 1024-QAM, so CPE vendors disabled or removed firmware support for 1024-QAM, in order to improve channel ranging and acquisition speeds and reduce memory requirements.

The process of re-enabling 1024-QAM support in silicon-capable devices differs among different device models and implementations, depending on the current version of firmware. In some, it can be as simple as using a CLI parameter to enable the functionality. In others, a compile-time option includes or excludes 1024-QAM support. On the other end of the difficulty spectrum, multiple libraries and routines might have to be modified. Note that "silicon-capable" refers not just to the tuners and demodulators with support for 1024-QAM, but also to the amount of RAM required to support the larger firmware images.

CPE Device Snapshot: 1024-QAM J.83 Capability

Some current-generation cable modems and set top boxes can support 1024-QAM modulation (see Appendix B for just a few examples). Some older, deployed devices

[j] NG PHY at 3 dB higher performance than that required for 256-QAM J.83 Annex B signal allows 1024-QAM modulation at <17% capacity gain while 512-QAM J.83 if available would deliver 12.5% capacity gain at 3 dB better performance

may also be able to support 1024-QAM, either with existing firmware or with new firmware. Because the logistics of supplying 1024-QAM-capable equipment is much simpler for a node-wide population (rather than plant-wide), increasing spectral efficiency is a viable method of adding plant bandwidth (both data *AND* video) without having to expand the bandwidth or replace terminal devices for ones capable of DOCSIS 3.1 PHY or having to split the nodes and incur the extra space/power/cooling burden of the replicated headend equipment.

One benefit of the approach analyzed in this paper, which cannot be provided by DOCSIS 3.1 PHY, is that downstream data delivery over DOCSIS 3.0 and its older versions and MPEG-2 video delivery can both benefit from 1024-QAM signals in J.83 format while DOCSIS 3.1 improves only IP traffic options. Basically, DOCSIS 3.1 can improve only IP traffic bandwidth efficiency (data, IP video and other IP services) while 1024-QAM J.83 signals can improve bandwidth efficiency by 25% without bandwidth expansion and CPE equipment replacement (pending the system-by-system and operator-by-operator assessments of the CPE equipment capability) with deployment of DBAA modules and CPE upgrades (often with remote upgrade implementation). Considering the deployed volume of CPE equipment with J.83 capability, this additional benefit of increasing the digital video bandwidth efficiency is not something to disregard lightheartedly.

CAPACITY EXPANSION OPTIONS

The DBAA implementation provides several options for upgrading capacity. The opportunities for the capacity expansion differ in possible timing and cost of implementation. Table 7 lists several opportunities ranked starting from the ones that are available sooner and at a lower burden to network operators to ones that could be implemented at higher cost and at a later time based on terminal equipment technology availability. The following subsections describe these options in detail and list some approaches and guidelines for their implementations.

Performance Upgrade within Existing Bandwidth

Deployment of DBAA modules with 1024-QAM J.83 capability makes this option the most appealing from cost and time-to-market points of view.

In traditional HFC networks, supporting 1024-QAM modulation plant-wide is a tricky proposition due to the variability of end-of-line network performance. However, in a distributed architecture model, the use of 1024-QAM is more easily phased in by virtue of the fact that QAM devices are addressable (uniquely identifiable), and 1024-QAM-capable plant conditions are created node-by-node (or service group-by-service group). The limited population makes it easier to upgrade or exchange CPE devices, and enables service upgrades to be done as local needs dictate. For example, if an area serviced by a single node was in need of increased data bandwidth, then by upgrading that node to Hybrid DBAA and using node-based modulators only for the DOCSIS traffic, the frequency allocated to that service could support a 25% increase without switching to new technologies. The only changes, beyond installing the node-based modulators, would be to upgrade the M-CMTS and cable modems for that node to support 1024-QAM. Narrowcast video would require an upgrade to the VoD/SDV resource manager, to accommodate the higher throughput.

After deployment of DBAA, the RF coaxial part of the network becomes the only contributor to the signal impairments but by itself is not materially contributing to the impairments of even 1024-QAM signals as long as it is reasonably maintained. It also can be re-aligned for higher levels in the entire or in a significant part of the bandwidth to increase CPE device input level and support 1024-QAM with operational margins, similar to the margins for 256-QAM signals, to which the network is designed today. It is actually expected that the elimination of the analog optical links with all the intricacies of fiber design will improve operational margins and lower the maintenance costs.

The most important benefit of this option is the potential for immediate implementation as a selective approach or as a wholesale upgrade of an area or system with CPE device upgrades (firmware) and re-allocation/replacement if some CPE devices are not capable of supporting 1024-QAM J.83 signals. It is also of the lowest cost and poses the least, if any, service disruption.

Table 7: HFC Network Capacity Expansion Options

Option Description	Optical Link Activity	Coaxial Plant Activity	Terminal Equipment Activity	Upper Boundary of Capacity Expansion	Earliest Implementation Timing
Performance upgrade within the existing bandwidth	Replacement (or addition to) analog optical link with DBAA node modules	Realignment of RF actives for higher output levels	Activation of 1024-QAM J.83 mode in CPEs and CMTSs if possible.	1 to 1.4 Gbps depending on upper network frequency (to 5 or 7 Gbps)	Immediate
Bandwidth and performance upgrade to 1 GHz (in the existing 1 GHz networks, refer to the option above)	Replacement (or addition to) analog optical link with DBAA node modules	Upgrading RF actives to the new 1 GHz (or 860 MHz) BW if needed with higher output levels	Activation of 1024-QAM J.83 mode in CPEs and CMTSs if possible. If needed, upgrading CPEs to 1 GHz.	From the existing capacity to 7 Gbps in 1 GHz upgraded network (from 4, 4.8 and 5.6 Gbps)	Immediate at cost of RF active upgrades if needed. No re-spacing required.
Bandwidth and performance upgrade to 1.2 GHz	Replacement (or addition to) analog optical link with DBAA node modules	Upgrading RF actives to the new 1.2 GHz BW with higher output levels. Possibly selective upgrades of passives.	Activation of 1024-QAM J.83 mode in CPEs and CMTSs if possible. If needed, upgrading CPEs to 1 GHz. Implementing NG PHY technology above 1 GHz or in the entire BW	From the existing capacity to 8.5 Gbps with NG PHY 2048-QAM to 10 Gbps with NG PHY 4K/8K QAM in the entire upgraded BW	Immediate to 1 GHz with keeping 256-QAM operation and/or activating 1024-QAM J.83 and adding NG PHY technology when available
Bandwidth and performance upgrade to 1.5 and 1.8 GHz	Replacement (or addition to) analog optical link with DBAA node modules	Upgrading coaxial plant to FD or N+0 passive coaxial network	Any combination of the above technology up to complete replacement of all with NG PHY technology	From the existing capacity to 12 Gbps with NG PHY 2048-QAM up to 1.5 GHz to 15 Gbps with NG PHY 4K/8K QAM in 1.8 GHz BW	Immediate to 1 GHz with keeping 256-QAM operation and/or activating 1024-QAM J.83 and adding NG PHY technology when available

Bandwidth and Performance Upgrade in Sub-1 GHz Networks

This approach shares many characteristics of the options described previously. A detailed analysis of the approach and the following options is presented in *Distributed Digital HFC Architecture Expands Bi-directional Capacity* from NCTA Spring Technical Forum 2013. The RF actives do not require re-spacing, the technology to expand the network to 1 GHz exists today, the passives deployed during the last 15 years are 1 GHz capable and the 1024-QAM J.83 terminal equipment availability is the same as in the option described above. The only additional requirement is to upgrade RF actives (nodes only in FD, N+0 architecture) to 1 GHz if they are not already 1 GHz capable. Their re-alignment requirements for level and BW mirror those stated above.

The upgrade can be performed selectively per node/segment or per area/system and can be implemented immediately and the capacity can be also expanded immediately. An additional benefit of this option is that expanded capacity can be realized even without upgrading terminal equipment to 1024-QAM J.83 capability while adding close to 1.5 Gbps capacity with 42 256-QAM channels between 750 MHz and 1002 MHz. The time-to-market may be even shorter than in the previous option with this approach and the upgrade of terminal devices to 1024-QAM J.83 capability can be implemented in the next step.

Bandwidth and Performance Upgrade to 1.2 GHz

This option is a reasonable step to implementation of NG PHY as an addition to and replacement of the existing digital service delivery technologies. The upper limit of this upgrade is dictated by passive performance and network upgrade limits with DBAA[9]. Most 860 MHz networks can be readily expanded to 1.2 GHz in bandwidth without RF active re-spacing. Indeed, the upper limit can be expanded to 1.3 GHz (without re-spacing) based on the performance of passive equipment. Fiber Deep (N+0) networks can be upgraded to higher bandwidth (1.5 GHz to 1.8 GHz) as dictated by the limitation of the passives and operator readiness to upgrade the passives. The RF plant upgrade in HFC networks is predicated on availability of higher bandwidth RF actives and is easier to accomplish in FD networks where only the RF section of the node needs to be upgraded. In FD networks, the RF section upgrade can actually be avoided by deploying DBAA (remote PHY) modules with BW capability above 1 GHz and combining the existing RF module outputs with couplers or filters (guard bands required) as output level capabilities for both (RF node module and DBAA module) allow.

However, the timing to take advantage of the BW upgrades is defined by availability of NG PHY terminal devices (remote PHY modules and CPE devices).

Bandwidth and Performance Upgrade to 1.5 and 1.8 GHz

This option requires implementation of FD or N+0 (passive coax) architecture in DBAA format (with remote PHY). However, in the existing FD networks, it is no different than the previous option where DBAA modules may deliver signal above 1 GHz without upgrading node RF modules unless operational and power consumption benefits promote an RF module upgrade with new silicon amplification technologies for higher reliability and lower power consumption.

In traditional HFC networks with cascades of RF actives, expanding bandwidth beyond 1.3 GHz will require drastic cascade shortening and the benefits of a passive coaxial network would usually promote FD (N+0) solutions if such an upgrade is to be undertaken by the operator to significantly increase the capacity.

The passive coaxial network can support in that case >10 Gbps downstream capacity with >2 Gbps upstream capacity (total network capacity >16 Gbps) as well as TDD technologies with all its cost and traffic management advantages.

SUMMARY: DBAA ENABLER OF IMMEDIATE AND FUTURE CAPACITY EXPANSION

It is agreed that the need for increased network capacity will continue. While there are a multitude of options available to network operators, the challenge for them today is to find the optimum solution to meet that increased capacity need.

Building upon analysis presented in earlier papers, this paper shows that the Distributed Broadband Access Architecture, a.k.a. remote PHY improves the existing network performance from a network capable of supporting 256-QAM Reed-Solomon (R-S) signals, with or without Trellis Coded Modulation (TCM), to a network capable of supporting 500-1000 MHz of 1024-QAM J.83 signals. This results in a 25% increase in network capacity within the frequency range allocated to these signals. With the presented availability of CPE devices to support this higher level modulation, this is a very efficient first step to increasing capacity.

Moreover, combining the DBAA (remote PHY architecture) with higher bandwidth options – up to 1.8 GHz, and eliminating the RF actives in the network, the potential for network capacity is significantly increased, to more than 15 Gbps, a net increase of more than 10 Gbps.

With installed coax drops into the home and the recent advances in architectures and technologies, cable operators are well-positioned to continue to lead the charge for the subscriber!

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ABBREVIATIONS AND ACRONYMS

AGC	Automatic Gain Control
BER	Bit Error Rate
BW	Bandwidth
CCAP	Converged Cable Access Platform
CE	Consumer Electronics
CIN	Composite Intermodulation Noise
CLI	Command-line Interface
CMTS	Cable Modem Termination System
CNR	Carrier-to-Noise Ratio
CPE	Customer Premises Equipment
CW	Carrier wave
dB	decibel
DBAA	Distributed Broadband Access Architecture
DOCSIS®	Data over Cable Service Interface Specification
EOL	End-of-Line
EPoC	EPON Protocol over Coax
FD	Fiber Deep
FEC	Forward Error Correction
FPGA	Field-Programmable Gate Array
Gbps	Gigabits per second
HD	High-definition
HFC	Hybrid Fiber Coaxial
HSD	High-speed Data
IP	Internet Protocol
Mbps	Megabits per second
MER	Modulation Error Ratio
MWVL	Multiwavelength
NTSC	National Television System Committee
OMI	Optical Modulation Index
QAM	Quadrature Amplitude Modulation
R-S	Reed-Solomon
RF	Radio Frequency
ROI	Return on Investment
SDV	Switched Digital Video
SNR	Signal-to-Noise Ratio
TCM	Trellis Coded Modulation
TDD	Time Division Duplex
VoD	Video on Demand

APPENDIX A

CPE Components with 1024QAM support

Tuners and Demodulators

Chipset	**Features**	**Year**
BCM3252	Dual Front-end DOCSIS 2.0+ STB with channel bonding	2007
BCM3255	Triple Front-end STB with DOCSIS 2.0	2007
BCM3348	DOCSIS 2.0 cable modem	2003
BCM3349	DOCSIS 2.0 cable modem	2005
BCM3360	DOCSIS 1.1 gateway cable modem	2002
BCM3361	DOCSIS 2.0 gateway cable modem	2004
BCM3367	DOCSIS 2.0 MTA	2006
BCM3368	DOCSIS 2.0 cable modem with dual VOIP	2006
BCM3371	DOCSIS 2.0 cable modem gateway	2011
BCM3378	DOCSIS 2.0 cable modem with VOIP and integrated tuner	2008
BCM3379	DOCSIS 2.0 cable modem with VOIP	2009
BCM3380	DOCSIS 3.0 (8x4) cable modem gateway	2009
BCM3381	DOCSIS 2.0+ (3-channel) cable modem	2006
BCM3382	DOCSIS 3.0 (8x4) cable modem gateway	2013
BCM3383	DOCSIS 3.0 (16x4)cable gateway	2012
BCM3384	DOCSIS 3.0 (24x8) cable modem	2013
BCM33843	DOCSIS 3.0 (16x4) cable modem	2013
BCM3385	DOCSIS 3.0 (32x8) cable gateway	2013
BCM3409	STB Low Power Direct conversion cable tuner	2007
BCM3419	DOCSIS 2.0 Direct conversion cable tuner	2006
BCM3420	DOCSIS 2.0 Low power Direct-conversion cable tuner	2006
BCM3421	DOCSIS 2.0 Direct conversion cable tuner	2006
BCM3422	DOCSIS 3.0 Direct-conversion cable tuner to 1 GHz	2007
BCM3520	ATSC/NTSC/QAM Cable ready TV receiver	2006
BCM3545	QAM digital receiver	2008
BCM3560	Analog and DTV STB	2006
BCM7002	DTA	2011
BCM7003	SD Cable Interactive Receiver with USB DVR	2009
BCM7004	Basic STB SD Receiver	2009
BCM7013	Basic STB SD Interactive Receiver with Ethernet and USB DVR	2009
BCM7014	Basic STB SD	2009
BCM7110	STB with PVR and DOCSIS 2.0 cable modem	2003
BCM7115	STB with PVR	2003
BCM7118	HD STB with DOCSIS 2.0 modem	2007
BCM7583	Fullband Capture CATV Tuner + DVB-C HD STB	2014
BCM7584	Fullband Capture CATV Tuner + DVB-C HD DVR STB	2014
Temic 4937 - 3x7702	Dual conversion cable modem tuner	2002?

APPENDIX B

Examples of 1024QAM-Capable CPE Devices

Castlenet	CBC33843D	DOCSIS 3.0 (16x4)cable modem
Castlenet	CBC3383D	DOCSIS 3.0 (8x4) cable modem gateway
Kathrein	DCV8400	DOCSIS 3.0 (8x4) cable modem gateway

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[1] J. Chapman, M. Emmendorfer, R. Howald, S. Shulman. *Mission is Possible: An Evolutionary Approach to Gigabit-Class DOCSIS.* NCTA Spring Technical Forum 2012

[2] O. Sniezko, D. Combs, R. Brockett. *Distributed Digital HFC Architecture Expands Bi-directional Capacity.* NCTA Spring Technical Forum 2013

[3] O. Sniezko, D. Combs, R. Brockett. *Distributed Digital HFC Architecture Expands Bi-directional Capacity.* NCTA Spring Technical Forum 2013

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[6] O. Sniezko, D. Combs, R. Brockett. *Distributed Digital HFC Architecture Expands Bi-directional Capacity.* NCTA Spring Technical Forum 2013

[7] O. Sniezko, D. Combs, R. Brockett. *Distributed Digital HFC Architecture Expands Bi-directional Capacity.* NCTA Spring Technical Forum 2013

[8] J. Chapman, M. Emmendorfer, R. Howald, S Shulman. *Mission is Possible: An Evolutionary Approach to Gigabit-Class DOCSIS.* NCTA Spring Technical Forum 2012

[9] O. Sniezko, D. Combs, R. Brockett. *Distributed Digital HFC Architecture Expands Bi-directional Capacity.* NCTA Spring Technical Forum 2013