Remote PHY: Why and How

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Abstract

The success and growth in narrowcast services continues to require MSOs to expand the capacity dedicated to those services. Most MSOs have deployed 4 and 8 DOCSIS^{TM} QAMs and considering expanding beyond that. Deployment of VOD and SDV QAMS continue to expand with HD and network DVR. And, even more QAMs are needed as service groups are segmented further in the network.

As the narrowcast service growth continues, MSOs are putting emphasis in the evolution of the access technologies to make them more efficient. DOCSIS 3.1 was created to enable more efficient use of spectrum, especially by using higher modulation orders and by taking advantage of newer technologies such as better LDPC codes and OFDM modulation.

MSOs and suppliers alike are considering one more aspect of the evolution: moving the RF modulation downstream into the network. By moving the RF modulation from the headend to the node, known as Remote PHY, it is possible to achieve important gains, such as:

<u>*Performance increase:*</u> *by eliminating the analog laser and reducing cascades as segmentation naturally progresses it is possible to support significantly higher order modulations as SNR performance increases both in the DS and US.*

<u>*Cost reduction:*</u> *it seems quite clear that replacing the analog forward link and the analog or digital return link for an Ethernet optical link will be less expensive both from a capital and operational perspective.*

<u>*Operational improvements:*</u> *undoubtedly, the Ethernet optical link will be easier to set-up and maintain than the current HFC links, and should carry a lot more capacity at longer distances.*

To that end, this paper will cover the following areas:

1. Overview of the rational for Remote PHY

2. Elaborate on the options available to implement Remote PHY, and

3. Explain ways in which it could be implemented.

Typical HFC Networks Today

Most MSO's hybrid fiber-coax (HFC) networks have been designed to either 750 or 860 MHz of spectrum capacity. If not fully utilized, it is expected that use of their capacity will be increased to the point of exhaustion as the use of DOCSIS® increases for the higher high-speed data (HSD) service tiers, additional high-definition (HD) programs for both broadcast (BC) and especially narrowcast (NC) services such as video on demand (VOD) and switched digital video (SDV) are deployed, or new services such as internet protocol (IP) video and cloud-based digital video recorder (cDVR) are added.

Proportionally few HFC networks have been deployed to operate up to 1 GHz, although all equipment available today can support the use of spectrum up to 1 GHz and even 3 GHz for some components.

In recent years the growth in, and demand for, HD programming has resulted in the need for allocation of large numbers of EIA channels for HD services, both for BC and NC, which has filled every available portion of the spectrum. This is especially true for BC, where large numbers of programs are offered in HD format, while simultaneously the need for distributing the standard definition (SD) version has persisted. This has resulted in the need for use of 3x to 5x the number of EIA channels than previously required. For example, a typical digital multiplex including 10 to 15 programs would require an additional 3 to 5 EIA channels for the HD equivalent streams, even assuming the newer, more sophisticated multiplexing schemes available in the market. Of course not every program is available, or still sought by subscribers, in HD format. But very large

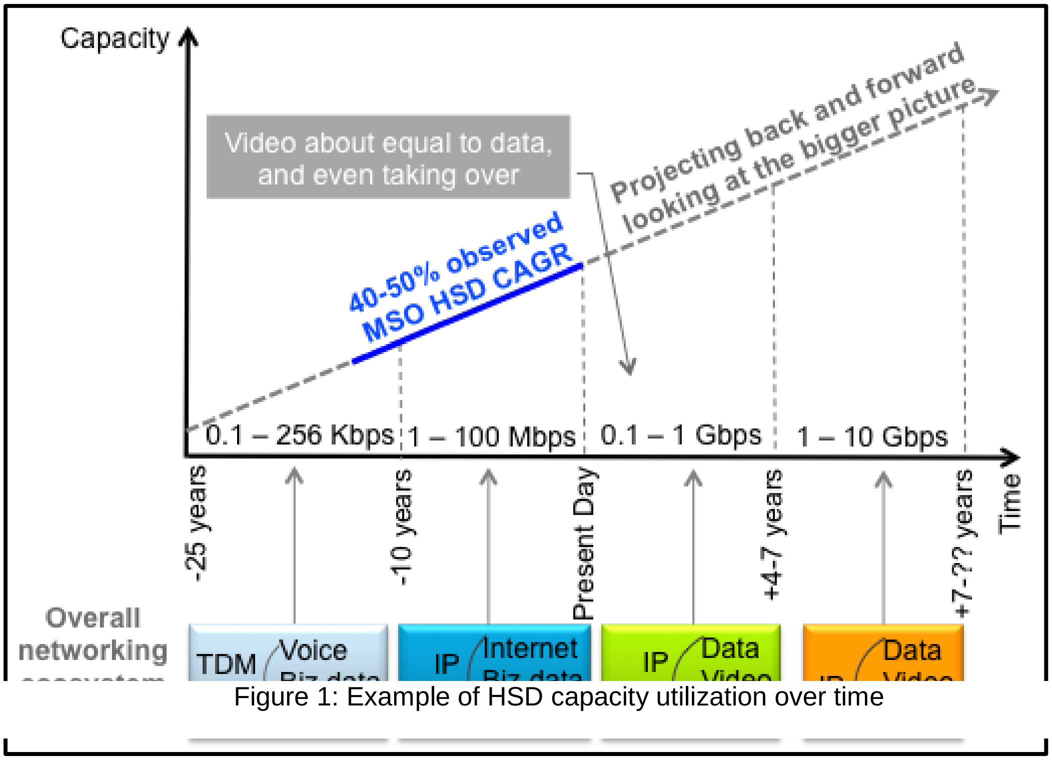

Figure 1: Example of HSD capacity utilization over time

numbers of them are, including 100 to 150 BC programs.

The above is also applicable to a great extent in systems utilizing SDV technology for distribution of its content. The difference is that the HD and SD versions of the program are not distributed unless a subscriber is requesting them, which reduces the marginal increase in capacity. Assuming that all programs are distributed in only one format, which is certainly a valid expectation for programs of low viewership, then the increase in capacity for a conversion from SD to HD would just be the increase in capacity required for the transmission of the HD program without requiring the simultaneous use of bandwidth for both formats.

Additionally, considerable spectrum is needed to deploy high-capacity narrowcast legacy video services, especially cDVR, and a full-array of HD video-on-demand services. For the former, initial observations suggest that network requirements for cDVR may be as high as 4x to 5x that of VOD, and that peak utilization overlaps, at least partially, with that of peak use for other narrowcast services.

Finally, the growth in HSD services continues. Network operators have observed an increased use of HSD service capacity for well over a decade now, as shown in **Error! Reference source not found.**, which amounts to a year-over-year compounded growth of 40% to 60%. The applications have changed throughout this time, but the demand has continued to increase at the same relentless rate.

How does this compare to other operator’s data services and a longer period? As shown in **Error! Reference source not found.**, projecting the MSO’s HSD service growth back in time to when Internet services started as shown in the diagram, 25 years ago services should have been about 100 bps. This coincides with the history of telephone modems from 110 and 300 baud modems from the mid-80s, to 56 Kbps/V.42, into ISDN services.

This demonstrates that the growth seen in MSO’s HSD services is typical over a much longer period of time, rather than an exception observed by MSOs in recent years.

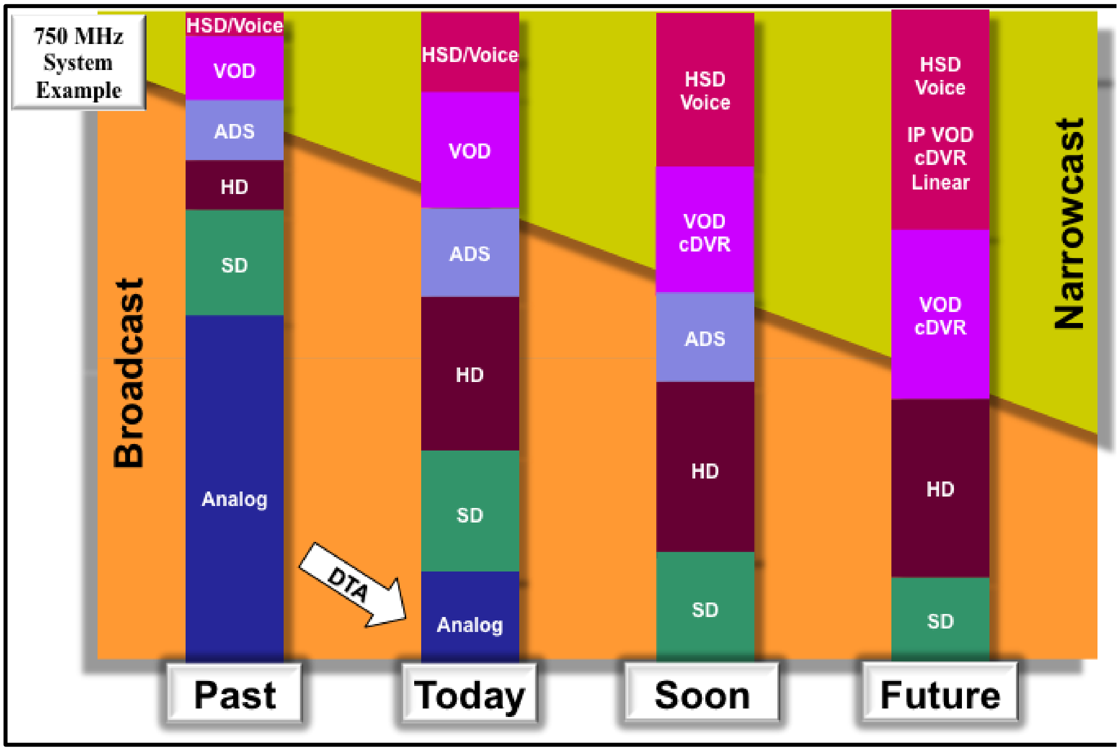

Figure 2: Example of narrowcast service growth over time

Growth Projections

From all of the above, it then follows that, should the usage growth pattern continue at the same rate as in the past, networks will be required to provide HSD services in the range approximating 1 Gbps within the next few years. This growth, coupled with the surge in HD video formats, and more personalized narrowcast services, will result in a significant growth in narrowcast capacity, as shown in **Error! Reference source not found.** below.

To support this growth, MSOs have deployed, or are considering deployment of, bandwidth reclamation tools such as SDV for digital broadcast, digital terminal adapters (DTAs) for analog services, or a combination of both. These tools have been extremely valuable to MSOs, and their operational complexity and cost well justified.

In the case of SDV, early predictions several years back from industry analysts projected that the efficiency of SDV would reach 40% (e.g., programs requiring 10 EIA channels could be carried in 6). This has proven to be understated, since it was based on the use of SDV for reduction in bandwidth required for existing services. As SDV's role in the network grew, the efficiencies have been even greater, especially as SDV has been used to introduce niche services that have low viewership and would have otherwise been difficult to deploy.

The benefit of DTAs has been just as, or perhaps even more, striking. MSOs deploying DTA devices are able to eliminate the need to distribute the analog channels in the network. Even if DTAs are distributed to top analog tier customers, such as only to subscribers of the traditional expanded basic subscribers, such deployment would reduce a channel line up from perhaps 50 EIA channels dedicated to 50 analog programs to perhaps as little as 4 EIA channels dedicated to transport the 50 programs in their equivalent digital transport. Using the same comparison method as the above SDV case, this is a >90% efficiency. If extended to the entire analog tier the efficiency gains are very significant.

Despite the availability of these tools, they are not universally applicable. With respect to SDV, in general it is not likely that all broadcast programs will be switched since experience shows that many broadcast programs are constantly viewed by someone in the service group during peak hours, which will leave a large portion of the spectrum still used for broadcast. Similarly, not all analog channels can be removed in the short term due to operational and/or cost constraints.
Additionally, while many MSOs will use one or both tools, in general these tools won't be used by every MSO for all applications.

Finally, there are also significant potential gains to be achieved from the use of advanced video CODECs (AVCs) and variable bit-rate (VBR). In the case of AVCs, coding efficiencies of approximately 50%, depending on implementation and content type, can be obtain with H.264[1] and/or MPEG-4 Part 10[2]. Furthermore, with the recent release of the H.265[3] standard in April of 2013, it is possible to achieve a 50% improvement over H.264. And the use of VBR promises to result in a capacity efficiency gain of as much as 70% versus CBR[4]. The combined gains from using the above approaches could be very significant.

However, these are difficult tools to take advantage on the network since proportionally relatively few legacy set-tops still support AVCs and VBR, especially the latter. These tools will likely enjoy significant support in newer, IP-video based services equipment moving forward.

But, this approach will require additional capacity on the network. This is especially true when considering that the deployment of these advanced video services will result in an additional simulcast of video programs, at least initially, which is expected since its deployment will not at least initially replace the currently deployed services.

Furthermore, ubiquitous support for such devices would require considerable spectrum if the legacy services are maintained for an extended period, as it is expected since legacy devices are and will continue to be deployed. Moreover, this increase in simultaneous use of advanced, IP video services while maintaining legacy services will be especially impacting over time as its penetration increases.

All of the above, coupled with the success experienced by MSOs in recent with business services, will likely require the deployment of IP capacity beyond what can be supported today, requiring the development of tools for increased efficiency in the use of spectrum and/or unlashing of additional spectrum in the HFC network. The following sections of this paper will enumerate ways in which this can be achieved.

The Advent of DOCSIS 3.1

As it has been pretty well advertised in the media, DOCSIS 3.1 is under development. NOTE: For further details on the DOCSIS 3.1 technology and its implementation, see the DOCSIS 3.1 Symposium planned for the SCTE Expo 2013 show.

The key motivation for the new version of the DOCSIS specification is, in a nutshell, to scale DOCSIS more efficiently, both from the cost and operations perspectives.
While for the first 10 years or more it was possible to offer Internet services and support its growth with just 1 DOCSIS channel, services today require many more channels. This is because 1 DOCSIS channel provides almost 40 Mbps, which was well above the data rate of the services offered in the past. However, the year-over-year growth drove service speeds well above the initial levels, to 20, 50 and even higher Mbps tiers today, which can't be supported by the single channel. MSOs then went to multiple DOCSIS channels, now reaching 4 and even 8 channels, and soon requiring well beyond that.

To that end, the 3 key goals and features of DOCSIS 3.1 are:

1. Much more efficient use of spectrum, with up to 50% improvement in bandwidth efficiency (or bps/Hz, resulting from:

[1] ITU-T Recommendation H.264: 2005, Advanced Video Coding for generic audio-visual services

[2] ISO/IEC 14496-10: 2005, Information technology – Coding of audio-visual objects – Part 10: Advanced Video Coding

[3] ITU-T Recommendation H.265: 2013, High efficiency video coding

[4] Capacity, Admission Control, and Variability of VBR Flows, CableLabs Winter Conference, February, 2009

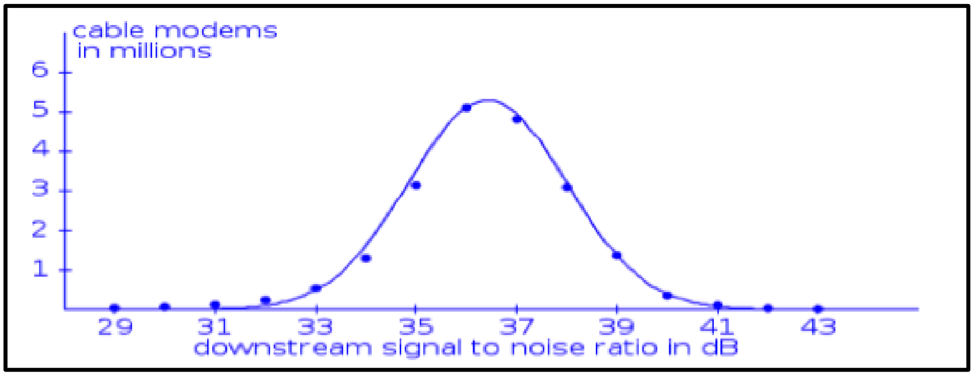

Figure 3: Example of downstream SNR for a large population of cable modems

a. The use of more efficient forward error correction (i.e., replacing the older and less efficient Reed-Solomon approach for the more modern and far more efficient Low Density Parity Check, and

b. Addition of the higher-order modulations 1024 and 4096 QAM downstream and 256 and 1024 QAM upstream.

These new modulation schemes provide 2 and 4 bits/Hertz/second improvement in both upstream and downstream, while the use of the new forward error correction approach provides approximately 5 dB better RF performance. The end result is that MSOs will be able to transport 1 Gbps of DOCSIS capacity in about 120 MHz of spectrum while doing the same with the current DOCSIS approach using single-carrier QAM requires about 180 MHz of spectrum.

2. Cost reduction, mainly by leveraging technologies commonly used in other transmission media, such as the inclusion of Orthogonal Frequency Division Multiplexing, which is used extensively in wireless and wireline transmission media. Specifically, the addition of OFDM for the downstream and OFDMA for the upstream should enable MSOs to reduce costs while "packing" more bits in the HFC network more efficiently since these technologies likely result in a larger supplier ecosystem, increasing innovation and fueling competition.

3. Enable a simple and orderly transition strategy, both with respect to compatibility with previous generation CMTS and CM equipment while supporting an expanded spectrum capacity in the HFC network. Specifically, DOCSIS 3.1 cable modems will operate with DOCSIS 2.0 and 3.0 CMTS/CCAP equipment, enabling deployment of DOCSIS 3.1 CPE as soon as available. Similarly, DOCSIS 3.1 CCAPs will support DOCSIS 2.0 and 3.0 CPE allowing MSOs to upgrade headend equipment without having to change any of the existing CPE. And, both DOCSIS 3.1 CM and CMTS equipment will support the currently required upstream and downstream spectrum, plus an expansion of the upstream to 85 MHz and beyond, and of the downstream up to 1.2 GHz.

Error! Reference source not found. depicts the downstream signal-to-noise ratio (SNR) as reported by a very large population of cable modems [5]. This data verifies that many cable modems will be able to support the high-order modulation profiles included in DOCSIS 3.1. However, others will not without an increase in SNR.

Assuming an 8/9 coding ratio, **Error! Reference source not found.** shows the required SNR for the modulation rates included in DOCSIS 3.1:

Modulation	Signal-to-Noise Ratio
512 QAM	27 dB
1024 QAM	30 dB
2048 QAM	33 dB
4096 QAM	36 dB
8196 QAM[6]	39 dB
16384 QAM	42 dB

Table 1: SNR required for DOCSIS 3.1

Applying the SNR requirements from **Error! Reference source not found.** to the population

[5] Data collected by Comcast and reported to the DOCSIS 3.1 working group

[6] 8196 QAM and 16384 QAM are included for future consideration in the DOCSIS 3.1 specifications

of modems shown in **Error! Reference source not found.**, we can easily see that a large population of cable modems would not achieve sufficient SNR to operate at 4096 QAM. Furthermore, if sufficient headroom is allowed to account for environmental fluctuations, the population of cable modems that would not receive signals with sufficient SNR to operate at 4096 QAM would be significant.

The Analog Modulated Forward Link in HFC Networks

As their name indicates, hybrid fiber-coax networks use a fiber transport between the headend and the coaxial cascade. This fiber link, intended to reduce the size of cascades, mainly driven to improve performance, was originally developed with analog modulated lasers and receivers in both directions, upstream and downstream.

Over time, the performance of the upstream link was improved by replacing the analog modulation with a digital transport. This change improved performance significantly, and allowed for longer distances between the headend and the node. Different vendors implemented their own methods and technical capabilities to implement a digital transport, which resulted in incompatible systems and required the use of the same vendors' components for both the node and the headend.

However, the downstream link remained almost unchanged over time, with the only enhancements focused on improving distance and RF spectrum capacity. Performance has not really been an issue like it was in the upstream.

But more importantly, while the digital capacity of the upstream was limited to a few megabits per second, well under a gigabit of digital capacity which could easily be digitized and carried with Ethernet optics, the downstream digital capacity necessary to transport the downstream spectrum has been considerably higher, reaching and even exceeding 10 gigabits per second.

Because of the above, analog forward links continue to be used to date. And, while headend equipment is currently capable of launching signals with >47 dB MER performance, which would be sufficient to generate and transport 16,384 QAM signals, analog lasers are limited to about 35-38 dB of MER performance, which would limit end-of-line performance to barely enough for 2,048 QAM or 4,096 QAM in short cascades the best of the cases.

Description of Options for Digital Forward Link

As time has gone by, technology evolution and certain developments as described below have enabled options for implementing a digital forward link. These include:

1. Evolution of QAM edge modulators which have gone from single and/or a few modulators to supporting 32, 64 or even more modulators,

2. Development of the CCAP, combining the functions of the video QAM modulator and DOCSIS into a single platform, and

3. Migration to digital video, either partially for now or already completely.

With this technology evolution, it is conceivable to remove the RF combiner network, and instead implement it digitally in the edge device, such as the CCAP.

Figure 4 conceptually depicts the output of a CCAP device.

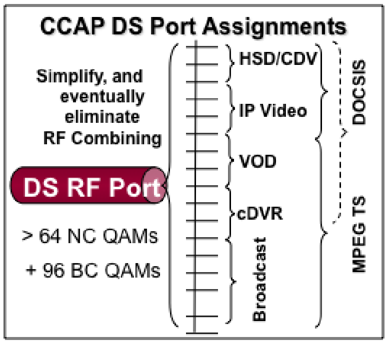

Figure 4: CCAP Downstream Port Functions

This evolution of the edge headend devices makes it possible to envision several options for digitizing the forward link.

Fundamentally, the migration to a digital forward includes the components included in Figure 5, as follows:

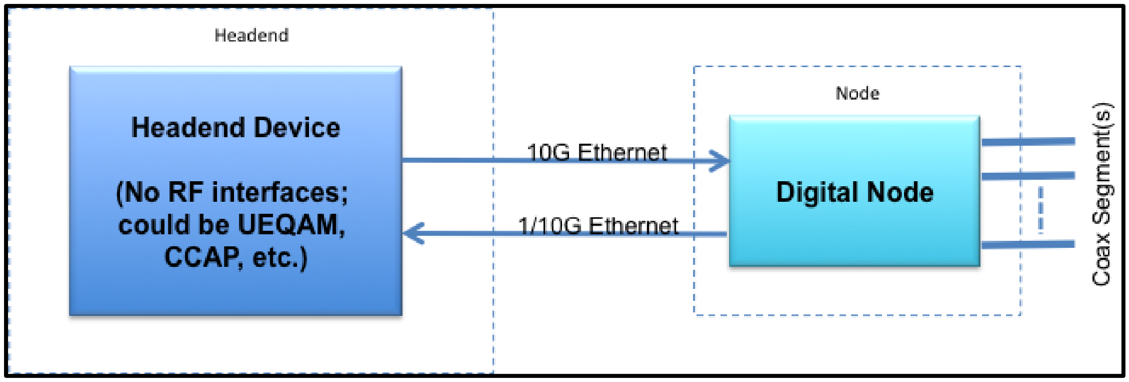

Figure 5: Digital Forward – High Level Architecture

- The headend device, such as a CCAP, which would be a high-density edge QAM comprising QAM modulation for the entire spectrum,
- The node would contain components normally implemented in the edge QAM or CCAP which generate the RF signals,
- The link between the headend device and the node would be comprised of a digital interface, such as an Ethernet link.

replace the currently used analog link. These various approaches for distributing the various components can be categorized into 4 groups, plus 1 option that would still leave an RF generation at the headend device, as outlined in Table 2:

Option	Description and Approach
1. Maintain RF output in the headend	1.a Headend equipment remains unchanged 1.b Headend RF output is digitized, transported digitally, and RF is regenerated in the node
2. Remote the DAC from the PHY	2.a The DAC is removed from the headend 2.b Digital samples are transported digitally to the node where the DAC generates the RF signals
3. Partition the PHY and remote the lower portion of the PHY	3.a The PHY is split between the headend and the node 3.b The digital bit stream between upper and lower PHY is transported from headend to node
4. Remote the entire PHY	4.a The entire PHY modulation is moved to the node 4.b The MAC remains in the headend, and MAC frames are transmitted from the headend to modulator that resides in the node
5. Remote the entire PHY and MAC	5.a The entire PHY and MAC is removed from the headend device and placed in the node 5.b IP frames are transported from the headend to the node.

Table 2: Categories of options for implementing a digital forward link.

There are then various approaches for how a digital forward link can be implemented to

Comparison of Options for Digital Forward Link

There are pros and cons for each of the options. The following sections outline these trade-offs.

Option 1: RF remains in the headend

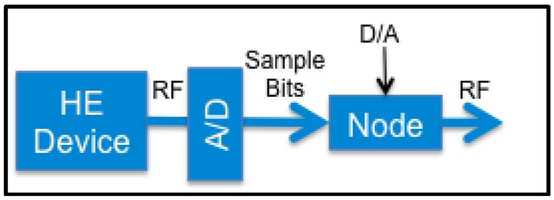

Figure 6: Block diagram for Option 1

- Equivalent to digital return, the RF output from the headend device is digitized, transported digitally, and converted back to RF in the node.
- Maintains HFC transparency
- This option results in the highest bitrate over fiber; the capacity for multiple nodes would not fit into the available capacity of one 10G fiber
- There is a loss of MER in the double conversion, so this option provides the least performance improvement
- Results in the least intelligence placed in the node, but an additional conversion stage is added in the headend

Option 2: Digital-to-analog conversion is moved to the node

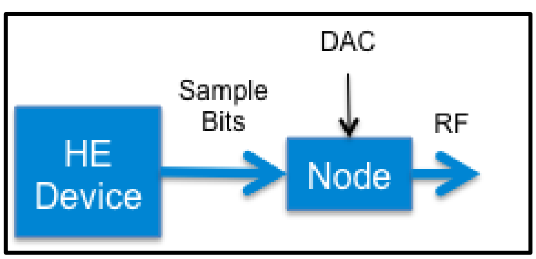

Figure 7: Block diagram for Option 2

- Requires separation of the digital-to-analog conversion from the modulator
- Together with Option 1, results in the least intelligence in node
- Similar high bitrate over fiber as Option 1; capacity for multiple nodes would not fit into the available capacity of one 10G fiber

Option 3: Lower PHY is moved to the node

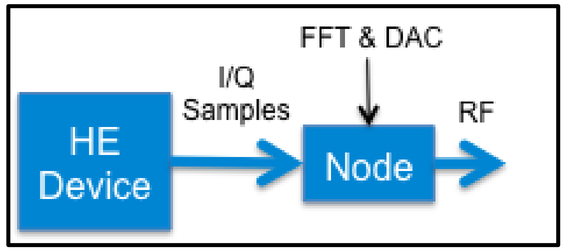

Figure 8: Block diagram for Option 3

- The PHY layer needs to be split into two components: upper and lower PHY
- More intelligence than in either of the previous options is placed in the node
- Although lower than the previous options, this option also results in a very high bitrate over fiber
- This option would require and industry proprietary point-to-point link between the headend port and the node to transport the I and Q samples
- Implementation of this option would require the definition of interfaces which have never been defined in previous versions of the DOCSIS specifications, which in turn would result in modification of the silicon used and/or planned to date, and therefore results in the highest implementation complexity

Option 4: Entire PHY is moved to the node

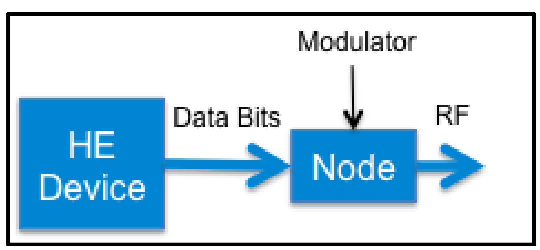

Figure 9: Block diagram for Option 4

- More intelligence is placed in the node than with all previous options
- This option results in the lowest bitrate over fiber; multiple nodes fit into the capacity of a 10G fiber

- Enables a packet-based link between the headend and node, which results in significant benefits outlined later in this paper

- Could use existing/planned silicon devices, and thus may be the easiest and quickest to implement

- Offers the best MER performance improvement over analog

Option 5: Move PHY and MAC to the node

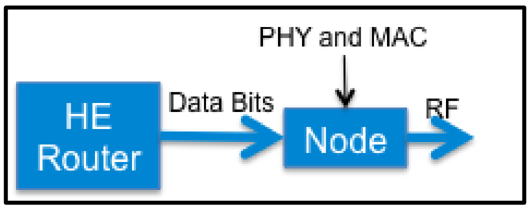

Figure 10: Block diagram of Option 5

- This option puts the most intelligence in the node

- The data rate between the headend and the node is equivalent to the actual data transmitted, except for the addition of ancillary network data

- Same packet-based network benefits as Option 4

- Same highest MER performance as Option 4

Proposed Tenets for Digital Forward Link

In considering the various approaches for implementing the digital forward link, and the 5 options in which these approaches could be categorized, it might make sense to consider tenets for its implementation.

The following list outlines proposed basic, underlining tenets for digital forward link:

1. Headend and node devices for digital forward link should be interoperable

2. Limit the specifications to the areas that are absolutely needed for interoperability

3. Minimize the electronics that is housed in the node to the extent possible

4. Minimize the software that is placed to run in the node

5. Minimize the amount of capacity needed in the optical link

6. Keep as much of the higher layers as possible in the headend

7. Make the timing requirements for the node as simple as possible

8. Keep the independence between the DS and US as much as possible

9. Maintain the digital forward link independent from the DOCSIS version

Additional objectives could be established that would further limit the options to be considered for the digital forward link. What follows are additional proposed objectives:

A. Develop an architecture that enables scalability as capacity is needed over time

B. Minimize the need for replacing the node components as additional capacity is needed

C. Leave system components that scale with capacity in the headend

D. Use technologies used in other communications protocols when possible

E. Minimize space and power requirements in the headend

F. Minimize power requirements in the node, targeting the power consumption of a line extender as the maximum power requirement

G. Enable the use of the digital forward link for other networking functions

		BDF/BDR	Remote DAC	Remote Lower PHY	Remote PHY	Remote CCAP
Basic Tenets	1	✓	Should be	Should be	✓	Should be
	2	✓	✓	✓	✓	Should be
	3	✓	✓	✓	✓	✗
	4	✓	✓	✓	✓	✗
	5	✗	✗	Not likely	✓	✓
	6	✓	✓	✓	✓	✗
	7	✓	Should be	Should be	Should be	Should be
	8	✓	✓	✓	✓	Not likely
	9	✓	Should be	Should be	Should be	Not likely
nal Objectives	A	✓	✓	✓	✓	✗
	B	✓	✓	✓	✓	Not likely
	C	✓	✓	✓	✓	✗
	D	✗	✗	✗	✓	✓
	E	✗	Not likely	✓	✓	✓

Table 3: Comparison of tenets and additional objectives for digital forward link options

Comparison of Digital Forward Link Options

is an analysis of the pros and cons for each of the 5 options considering the tenets and additional objectives outlined above:

Given the comparison of the applicability of each of the proposed tenets and proposed additional objectives outlined above, it appears clear that Option 4, Remote PHY, is the best target for the proposed tenets and objectives.

High-Level Overview of Remote PHY

At the highest level, the Remote PHY separates the PHY from the CCAP device, and places it in the node. As shown in Figure 4, the CCAP device continues to provide all MAC and higher-layer functions, while the PHY modulation and demodulation is moved to the Remote PHY node (RPN).

The interface between the CCAP and the RPN could be any digital link. However, Ethernet links are very appropriate for this application given their preponderance in the market, ability to scale as capacity growth demands it, and low cost resulting from very wide market use.

The downstream link capacity would have to support at least 5 Gbps, which is required for an all-digital. Therefore, a 10 Gbps Ethernet interface is appropriate for such link.

However, the upstream capacity could be significantly lower. Given today's requirements, and considering an expected growth of the upstream capacity, it seems that an upstream link

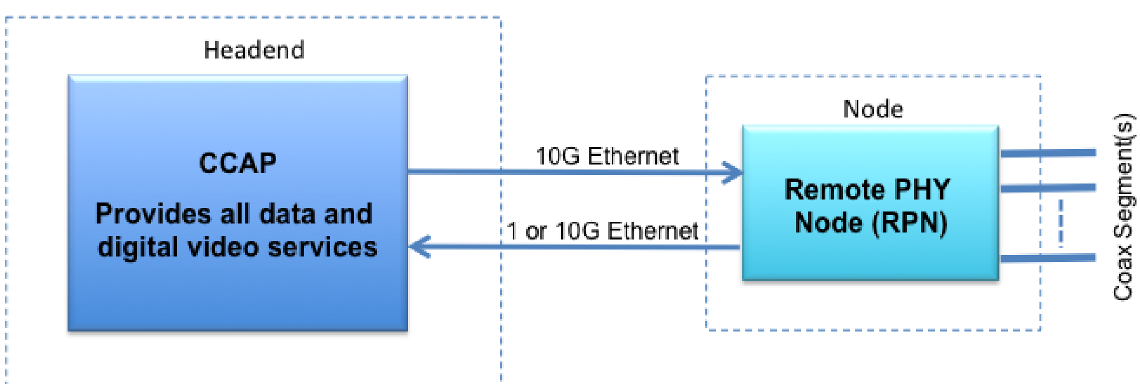

Figure 11: High-level overview of Remote PHY

with a capacity of 1 Gbps might be sufficient. This may reduce cost and simplify implementation of the Remote PHY node. However, for simplicity it may just be easier to use a 10 Gbps symmetrical link.

Benefits of Remote PHY

As described above, one key benefit of Remote PHY is the improved performance resulting from the migration from an analog to a digital link. This gain varies depending on the characteristics of the analog link being replaced, but can be generalized as at 5 dB of improved signal-to-noise ratio at the end of the line. This gain will result in higher capacity/Hz as it will be possible to run higher order modulations for more of the cable modems in the network.

In addition, Remote PHY will offer the benefit of enabling longer distances between the headend and the node. This is because digital interfaces, such as an Ethernet link, are designed to operate over much longer distances while carrying the designated capacity. Extending the distance between the CCAP and the RPN would enable MSOs to move their CCAP devices back in the network to more centralized facilities, leaving the hub or OTN free of CCAP equipment. The benefit of such change could be very big for some MSOs, especially as segmentation of the network continues towards smaller service groups, for which additional CCAP equipment needs to be deployed.

A third benefit from Remote PHY is improved reliability of the optical link. It is well known that analog links require period maintenance and are subject to the effects of environmental changes. By contrast, Ethernet optical links are far more stable across a wider range of environmental conditions, and require little to no maintenance. The impact of this benefit could be very significant to MSOs.

Increased Headend Equipment Density

The implementation of Remote PHY makes it possible to improve the density of CCAP devices in several ways.

First, while CCAP devices are normally implemented via separate upstream and downstream line cards, a Remote PHY line card would be implement both upstream and downstream. This, in effect, doubles the capacity of a CCAP chassis.

In addition, a typical CCAP downstream line card will house 8 or perhaps 12 RF ports because of the printed circuit board space required by the components required for RF modulation plus the sheer connector spacing required. However, Ethernet connectors can be placed considerably closer to one another, allowing a similar line card to easily house 16 to 24 ports. This additional density gain once again doubles the capacity of a CCAP=]p0-o9w2q chassis.

Finally, it is possible to consider “daisy chaining” RPNs off of a single CCAP Ethernet port. This is because, on the one hand the capacity of an 10 Gbps Ethernet link would support the capacity needed for a single RPN, plus in addition it is possible to generate an RPN “channel line-up” by transmitting the broadcast content once to multiple RPNs. As depicted in Figure 12, the data stream transmitted from the CCAP could contain a single “copy” of the broadcast line-up content, plus individual versions of the narrowcast content for each of the RPNs. The RPNs would then reuse the broadcast line-up content to recreate the individual RPN channel line-up. In this way each service group served by the CCAP port would contain the same broadcast line-up but its individually different narrowcast line-up.

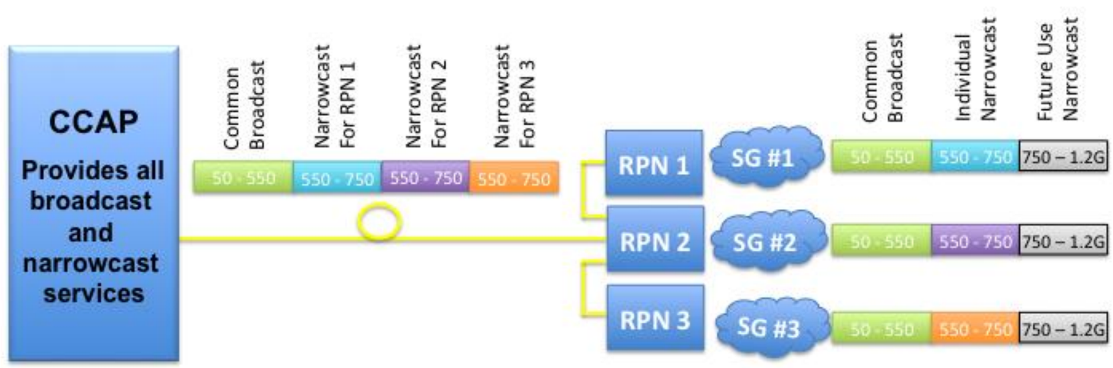

Figure 12: Reuse of broadcast capacity across multiple RPNs

Then, as the narrowcast line-up capacity grows over time, CCAP ports would be segmented to support less RPNs, akin to the way service groups are split today to support more narrowcast capacity as it is required.

As summarized in Table **4** below, the combined effect of the 3 factors described above is very significant, ranging from 8x to 18x of headend capacity gain. From a space and power perspective, this is hugely impacting savings.

Density Factor	Density Gain
Combined US/DS line card	2x
Greater number of ports per line card	2x to 3x
Multiple RPNs per CCAP port	2x to 3x
Combined capacity gain	8x to 18x

Table 4: Remote PHY headend density gain

But, just how meaningful is this headend density gain?

Considering that a migration from an HFC architecture with an average of N+5 (i.e., a node plus 5 amplifiers in average) to N+0 would require about 10x the number of nodes, the headend density benefits resulting from Remote PHY would neutralize the potential increase in CCAP equipment.

It is then quite clear that from a space and power savings, Remote PHY takes the benefit of CCAP to a whole new level.

Integration of HFC and Fiber Services

One of the largest areas of growth for MSOs is business services. MSOs have deployed business services via both cable modems and fiber-based infrastructure. The fiber-based services are either point-to-point, using Ethernet and wave-division multiplexing (WDM), or point-to-multipoint, using PON technologies (either EPON or GPON).

This duality results in the existence of two parallel networks. One of them, the HFC infrastructure, uses fiber from the headend to the node via an analog modulated link for the forward direction and either analog or proprietary digital return, followed by coax infrastructure from the node to the home. The other consists of digital fiber from the headend to the subscriber, which is used for commercial services.

Given the use of a digital fiber in both the forward and the return for Remote PHY, and especially because this digital fiber is based on Ethernet technology, it is possible to collapse both of these networks into a single infrastructure.

Therefore, the implementation of Remote PHY with an Ethernet interface between the CCAP and the RPN would make it be possible to implement a PON interface at the RPN.

The benefits from this integration include:

- Reduce the optical link for PON to the distance between the node to the customer premise
    - Since the typical distance from a node to a customer premise in an N+0 architecture would be 1-2 kilometers. This would virtually eliminate any distance limitations for PON, making it possible to implement the largest possible densities as network capacity enable.
    - In addition, this shortened distance would enable the use of lower power optics, which can translate into significant savings, especially for 10 Gbps optics, and especially for the upstream which results in significant savings in the ONU.
- Leverage a single network for multiple services, which will reduce maintenance and increase operational efficiencies.

Migration Strategy

Clearly, one of the more concerning issues to MSOs is the migration strategy.

Any migration that requires synchronized cut-overs, or which requires changes in multiple locations to execute, is problematic, and usually results in a barrier to adoption. Therefore, it is very important that the migration to Remote PHY allow for unsynchronized changes.

Furthermore, ideally the migration to Remote PHY allows for opportunistic changes in the network. For example, one such change would be to migrate a single node, such as would be the case in an MDU to increase capacity.

As it turns our, Remote PHY enables such gradual, unsynchronized and opportunistic changes in the network. What follows is an overview of the steps and components involved in the migration to Remote PHY.

Starting with the components of the network on both sides of the Remote PHY, neither the back-office nor the various components in the customer premise need to be modified in any way. All back-office components are unaffected by the migration to Remote PHY, and any additional MIBs for management and/or commands for configuration as needed can be added well before the first Remote PHY CCAP line card or node are deployed. With respect to customer premise devices, these would not be affected in any way in order to deploy Remote PHY, and any enhancements that are made possible through the introduction of Remote PHY would be implemented in CPE equipment that can be introduced before or after the migration to Remote PHY.

The critical portion of the network were changes need to be made are in the headend and the plant.

To begin with, the changes required in the headend are principally in the CCAP platform. The CCAP architecture was specifically designed to support multiple technologies simultaneously, which makes it possible to install regular RF upstream and downstream line cards and Remote PHY line cards in the same chassis. While some MSOs may chose to deploy a separate CCAP platform for Remote PHY, it is certainly possible to support both types of line cards in the same chassis. Of course, these Remote PHY line cards can be installed at any time prior to beginning the migration in the plant, and any removal of RF upstream or downstream line cards can follow the deployment of any number of Remote PHY line cards or nodes.

Turning our attention to the plant, it is similarly possible to migrate regular nodes to Remote PHY nodes in any sequence. As an example, what follows is a sequence of steps where a single node is gradually converted from standard HFC to Remote PHY.

Figure **13** depicts a single HFC node connected to a CCAP device.

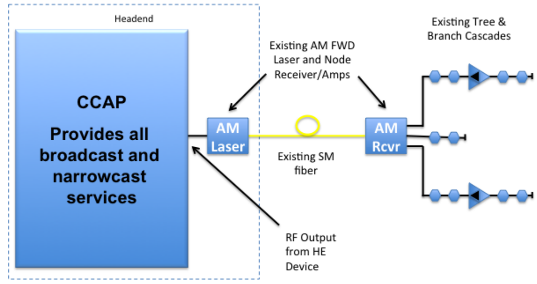

Figure 13: Single traditional HFC node

Figure **14** shows how the HFC node would be converted to Remote PHY while the rest of the HFC network remains unchanged. The Remote PHY line card in the CCAP would have been deployed in the headend a priori, and even the Remote PHY node could have been deployed before the day of the cut-over. Then, the day of the change the fiber cable could be swung in the headend from one AM laser to the CCAP Remote PHY line card, and in the field from the HFC node to the Remote PHY node. Of course it is not necessary to perform the migration in such a fashion, but it would be possible if desired.

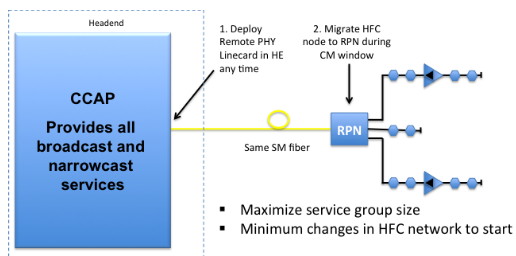

Figure 14: Remote PHY deployment step 1

Figure **15** depicts a possible step 2 in the process, whereby additional Remote PHY nodes are installed to segment the original service group further. These additional Remote PHY nodes could be daisy chained from the original Remote PHY node by taking advantage of the broadcast reuse feature, minimizing complexity in the deployment process.

NOTE: The example depicted is one in which fiber is run to every amplifier station. However, a more efficient segmentation scheme would include optimal placement of Remote PHY nodes in an N+0 HFC architecture with some turn-around of passive components.

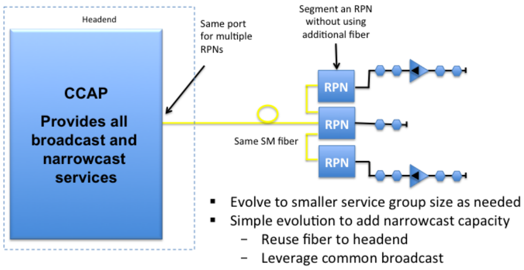

Figure 15: Remote PHY deployment step 2

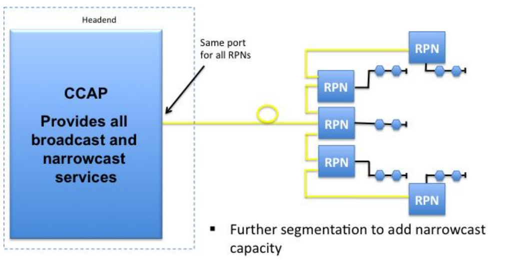

Figure **16** shows how further segmentation could take place by replacing the remaining amplifiers in the network with Remote PHY nodes.

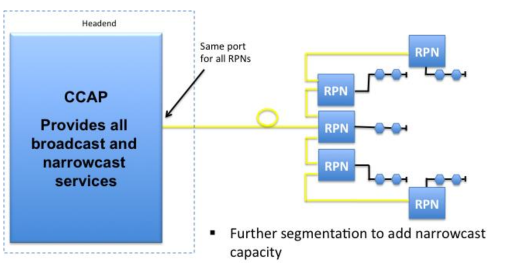

Figure 16: Remote PHY deployment step 3

Figure 17 shows the Remote PHY service group depicted above is segmented as additional narrowcast capacity is required. In this example, 2 of the RPNs from the Remote PHY service group shown in Figure 16 are split into separate service groups using separate CCAP ports.

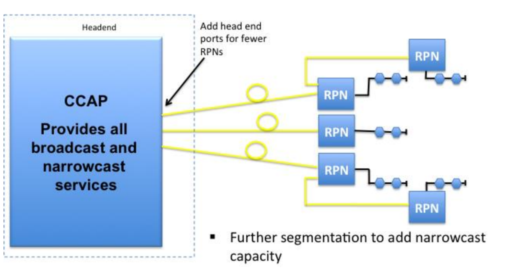

Figure 17: Remote PHY deployment step 4

Eventually each of the RPNs could be connected to an individual CCAP Remote PHY port. This would provide up to 10 Gbps of capacity to each RPN. This could, for example, be desirable to provide both RF and PON services from the RPN.

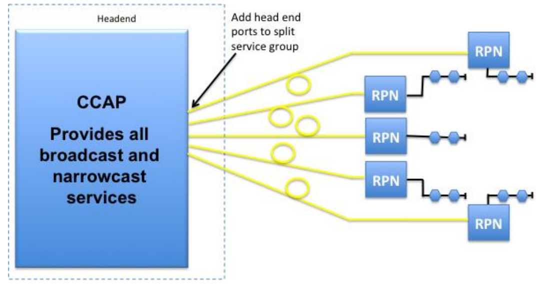

Figure 18: Remote PHY deployment step 5

Similarly, the Remote PHY line card in the CCAP could be upgraded to support even more capacity as such capacity is needed and becomes cost effective. For example, the Ethernet link from the CCAP to the RPN could eventually be upgraded to 40 or 100 Gbps, both of which are already commercially available.

Implementation and Interfaces

Having determined that a digital forward link is beneficial, and that Remote PHY is the best approach for doing so, the next step is to determine how best to move forward.

One key consideration for implementing Remote PHY is to enable interoperability between CCAP and RPN implementations. This would enable supplier with expertise in CCAP to focus their efforts on implementing the denser line cards that would interface with the RPN, and suppliers that have developed an expertise on nodes to implement the RPN device.

While one of the tenets outlined above is to minimize specifications to what is absolutely needed (see tenet #2 above), clearly describing an open interface for this purpose will be valuable to the market. Examples abound for how standards such as the one referenced here have improved choice and reduced costs for MSOs, and made the supplier ecosystem stronger. With such interface it would not only be possible to maintain and even increase the system supplier base, but also to develop a strong silicon supplier base.

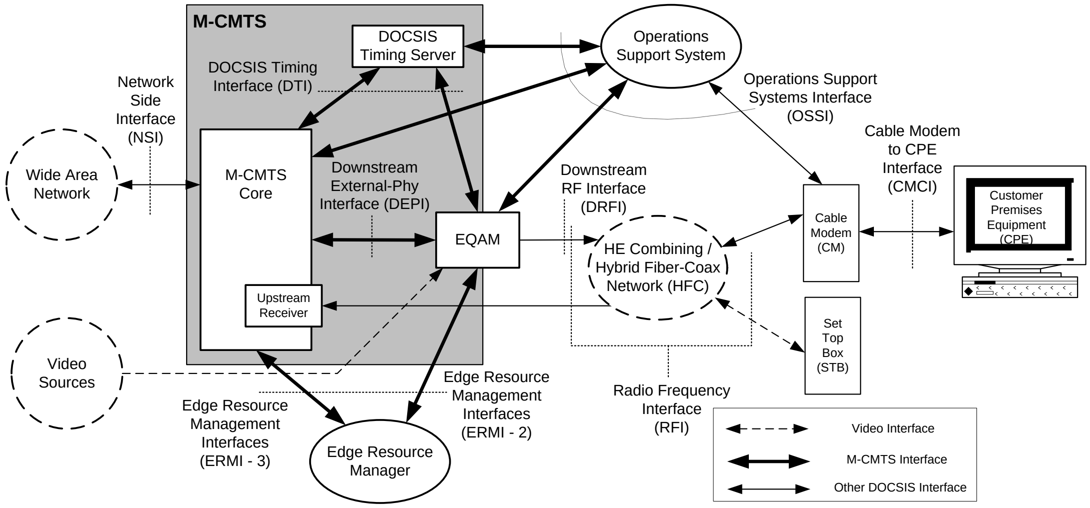

Figure 19: CableLabs Modular Headend Reference Architecture

To that end, the logical path is to expand on specifications that already exist in the market. A set of specifications developed by CableLabs a few years ago, collectively known as Modular Headend Architecture[7] (MHA) already describe the separation of the physical layer in the forward direction.

As shown in Figure 19, MHA defines several interfaces, including the Downstream External PHY Interface (DEPI) and the DOCSIS Timing Interface (DTI), amongst others. These interfaces make it possible to separate the RF downstream modulation from the DOCSIS CMTS into an external Edge QAM.

At the time a separation of the upstream RF demodulation was considered, but not described in the form of a specification. However, such interface, known as Upstream External PHY Interface (UEPI), was actually developed privately and implemented between the commercially available upstream burst receivers and the upstream media access control (MAC) layer.

It then makes sense to extend these existing specifications to support Remote PHY. The following would be required in order to do so:

A. Expand the DEPI pseudo-wire specification to support video, since the current version of DEPI only supports DOCSIS. In addition, it makes sense to update DEPI to support the latest version of the DOCSIS specifications, DOCSIS 3.1.

B. Similarly, expand the UEPI pseudo-wire specification to support DOCSIS 3.1, and publish the specification.

C. Develop a new specification to support the physical separation of the resulting CCAP Core from the RPN. Unlike in the MHA architecture, where the Edge QAM is located within a very short distance from the CMTS Core (i.e., within the same building, a few racks apart), in the Remote PHY architecture the distance from the CCAP Core to the RPN will span 10s and perhaps even 100s of kilometers. This will be a new specification, called R-DTI, which will leverage advances in timing sourcing and recovery developed by the Institute of Electrical and Electronics Engineers (IEEE), known as IEEE-1588 and included in DOCSIS 3.1.

The above 3 specifications, DEPI, UEPI and R-DTI, are being developed and should be published shortly.

However, by themselves the above interface specifications do not define the operational requirements for the RPN, or how the Remote PHY CCAP line card should be implemented to support operator's requirements such as to handle video out-of-band (OOB). Such requirements will be included in a set of product requirements.

[7] DOCSIS Modular Headend Architecture, CM-TR-MHA-V02-081209

Remote PHY Product Requirements

Following the completion of the DEPI, UEPI and R-DTI specifications, Cable MSOs will develop a set of specifications to define the operational requirements for Remote PHY. Similarly to other efforts where suppliers require guidance from operators to develop equipment, the Remote PHY Product Requirements will define the following:

I. RPN Hardware and Functions. These requirements will include information on topics such as: environmental requirements for the RPN enclosure, number and capacity of interfaces, RF requirements, scaling factors, handling of OOB, etc.

II. Remote PHY CCAP Line Card. These objectives and requirements will include requirements such as interfaces, scaling, redundancy, etc., and will be included in the CCAP Hardware and Functions Specification.

III. Remote PHY Configuration and Management. The requirements contained in this specification will allow an RPN device developed by any supplier to be configured by any Remote PHY-capable CCAP developed by any other supplier. In addition, the requirements contained within this specification will enable an MSO to directly monitor and manage a RPN, much in the same way as it is done with DOCSIS Cable Modems today.

Conclusions

Capacity for narrowcast services in HFC networks continues to increase. MSOs continue using well-known techniques for increasing capacity through service group segmentation.

With the advent of DOCSIS 3.1 MSOs will have the opportunity to use much higher modulation orders, which will result in more efficient use of RF spectrum. Higher end-of-line SNR than currently implemented will be required to enable such higher modulation orders for the majority of cable modems.

One area where improvements can be made is in the optical link from the headend to the node. The performance of the currently used analog-modulated link can be improved by converting it to digital.

While there may be several approaches to convert the link to digital, the one that seems most appropriate is that of moving the RF modulation and demodulation to the node. In this approach the physical layer is moved to the node, called Remote PHY node, or RPN, while all other functions remain in the CCAP. The link between the CCAP and the RPN is then implemented using Ethernet interfaces.

Remote PHY offers many benefits, including: improved performance, enable longer distances, and improved reliability.

Remote PHY makes it possible to increase headend equipment density. This results from several factors, such as: combined upstream/downstream line cards, increased port density, and “daisy chaining” RPNs. The combined effect of these density factors results in a density gain of 8x to 18x.

In addition, the use of an Ethernet link between the CCAP and the RPN makes it possible to integrate fiber-based services into a single consolidated network. For example, it is possible to implement a PON OLT interface from the RPN, which being within 1-2 kilometers from the customer premise would enable higher splits and/or the use of lower cost optics.

The migration to Remote PHY would be a very smooth one, requiring no synchronization between network and customer premise changes. Migration could begin with the deployment of CCAP Remote PHY line cards, followed by migration to Remote PHY nodes on a case-by-case basis.

Finally, implementation of Remote PHY will be described in both interface and product specifications. The interface specifications will be derived from the existing CableLabs Modular Headend Architecture, and will include: an updated version of DEPI, an updated and published version of UEPI, and a new R-DTI timing interface. The product specifications will include: RPN Hardware and Functions Specification, Remote PHY CCAP Line Card (to be included in the CCAP Hardware and Functions Specification), and the Remote PHY Configuration and Management Specification.