The impact of Remote PHY on Cable Service Convergence.

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Abstract

A Converged Cable Access Platform (CCAP), defined only a few years ago, was intended to enable efficiencies such as higher channel densities and deliver operational savings such as a simplified RF splitting-combining network and unified network management. Convergence in delivery of MPEG video and DOCSIS services was the main driving idea behind CCAP.

Today, CCAP convergence has become a mainstream reality as multiple vendors provide fully featured integrated CCAP systems supporting DOCSIS and MPEG video. Next, the industry will be re-focusing its development efforts on a new challenge – the Remote PHY (R-PHY) – an architecture where the PHY components can be separated from service delivery engines.

The R-PHY architecture was conceived with considerable flexibility. It enables numerous deployment scenarios including pairing of Remote PHY Devices (RPDs) with one or multiple, physical or virtualized core service delivery systems. In this environment, the traditional approach to CCAP convergence must be a reexamined.

The paper examines the technical and operational aspects of CCAP convergence starting with the analysis of the rationale for I-CCAP convergence. The authors explain how the original rationale can be optimally fulfilled in R-PHY architecture.

The paper reviews typical I-CCAP deployment scheme, new deployment scenarios enabled by R-PHY, R-PHY operational impact on service scaling, high availability and OSS systems. Finally, the paper provides recommendations for CCAP and post-CCAP planning and discusses which deployment scenarios are best suited to converged or diverged service delivery.

In summary, the paper debates the impact of R-PHY architecture, how the R-PHY technology establishes new trends and redefines the traditional meaning of CCAP convergence, and suggests the tactical approaches that best serve the needs of cable operators and their customers.

Introduction

According to the recent study, Cisco VNI [4] reports that Global IP traffic has increased more than fivefold in the past 5 years, and predicts a nearly threefold increase over the next 5 years. Overall, IP traffic will grow at a compound annual growth rate (CAGR) of 23 percent from 2014 to 2019.

Over the last several years, the architecture of cable access networks has undergone a remarkable transformation in order to keep up with ever increasing bandwidth growth and to better serve the needs of Cable Operators and their customers. The industry capitalized on innovation in silicon integration and signal processing, thus translating Moore's Law into concrete technology milestones: CCAP, DOCSIS 3.1 and most recently Deep Fiber Architecture with Remote PHY.

Before CCAP

Before we dive into the topic of cable service convergence let us briefly review the traditional cable access network before the introduction of CCAP. A representative architecture of access network before CCAP is shown on Figure 1.

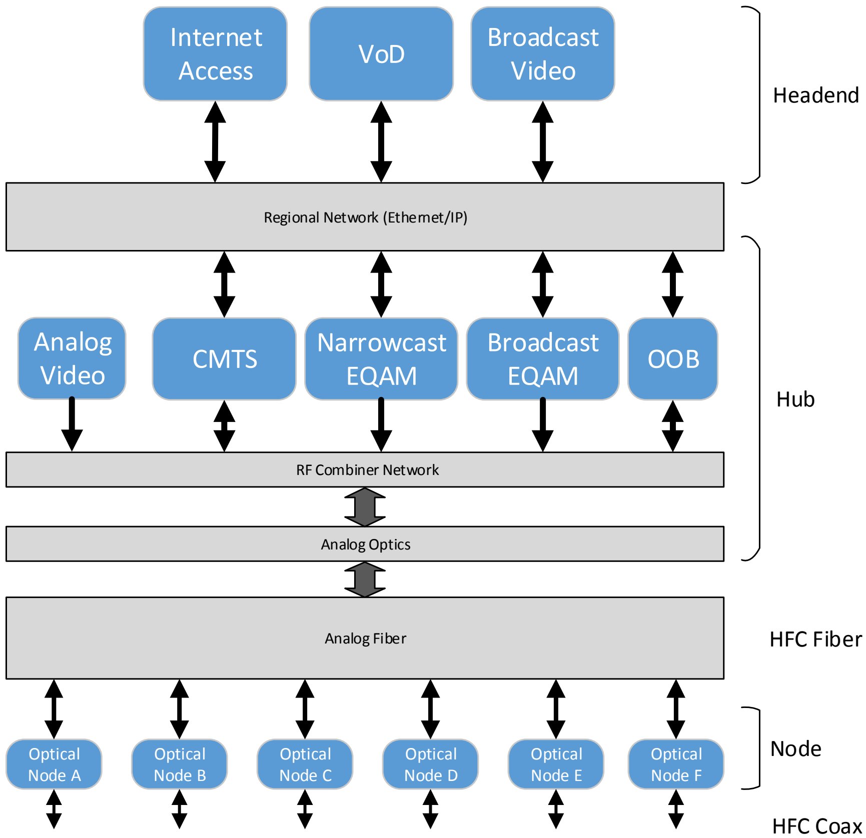

Figure 1 - Traditional Cable Access Network.

In traditional cable access networks, the service delivery platforms, namely CMTSs and EQAMs, are installed in the distribution hub at the edge of the HFC plant. These platforms directly interface to the HFC network because, at the physical layer, they convert digital signals into analog RF spectrum. In the downstream direction, the physical layer along with the lower part of the MAC layer (sometimes referred to as the Physical Media Dependent (PMD) convergence sublayer) are largely identical between MPEG video and DOCSIS 3.0 channels. The functional overlap ends there; EQAMs and CMTSs incorporate a multiplicity of higher level functions which are generally dissimilar between these platforms.

<u>CCAP</u>

At the start of the decade, Cable Operators came to realization that the bandwidth demand progresses along the exponential curve with seemingly no end in sight. A new approach was needed to affectively address accelerated bandwidth needs in the foreseeable future. A Converged Cable Access Platform (CCAP) emerged from industry initiatives as the result of combining separate efforts led by Comcast, Time Warner and other Cable Operators. The adjective "Converged" headlined each of these efforts (CMAP - Converged Multiple Access Platform, CESAR - Converged Edge Services Access Router) before they were merged under a single nameplate "CCAP". The notion of cable convergence associated with CCAP was generally understood to signify the integration of DOCSIS and MPEG video services into a single delivery platform with combined RF output at very large scale. As its predecessors, CCAP was designed for operation in the distribution hubs.

In this document, we'll start referring to the original CCAP as the Integrated CCAP or I-CCAP in order to distinguish from the CCAP-Core which is a CCAP derivative concept introduced with Remote PHY architecture and described further.

The I-CCAP requirements extended far beyond simply repackaging CMTS and EQAM technology into a single device. In addition to combining video and data, I-CCAP was envisioned to deliver multiple benefits over traditional cable access equipment. Let us reiterate a number of these benefits which may be relevant to our discussion:

- Efficient implementation of QAM channel generation allowing flexible configuration of MPEG Video and DOCSIS service groups. Each QAM resource in I-CCAP can be configured to operate as a DOCSIS channel or a video channel.
- Reduced power and space requirements.
- Higher port and channel densities comparing to legacy EQAMs and CMTSs.
- Eliminated or simplified RF splitting-combining network due to common RF output for DOCSIS, MPEG video and OOB channels. This benefit was materialized only partially. I-CCAP implementations have not yet completely integrated OOB functionality.
- Standardized modularity and serviceability requirements.
- N+1 redundancy and non-service-impacting failure repair requirements.
- Operational savings via standardized and unified network management interfaces.

Since I-CCAP leveraged existing cable technologies, it provided a very good fit into existing cable access network architecture. Thus, the transition to I-CCAP did not require fundamental changes to the access network around it. This is illustrated on Figure 2.

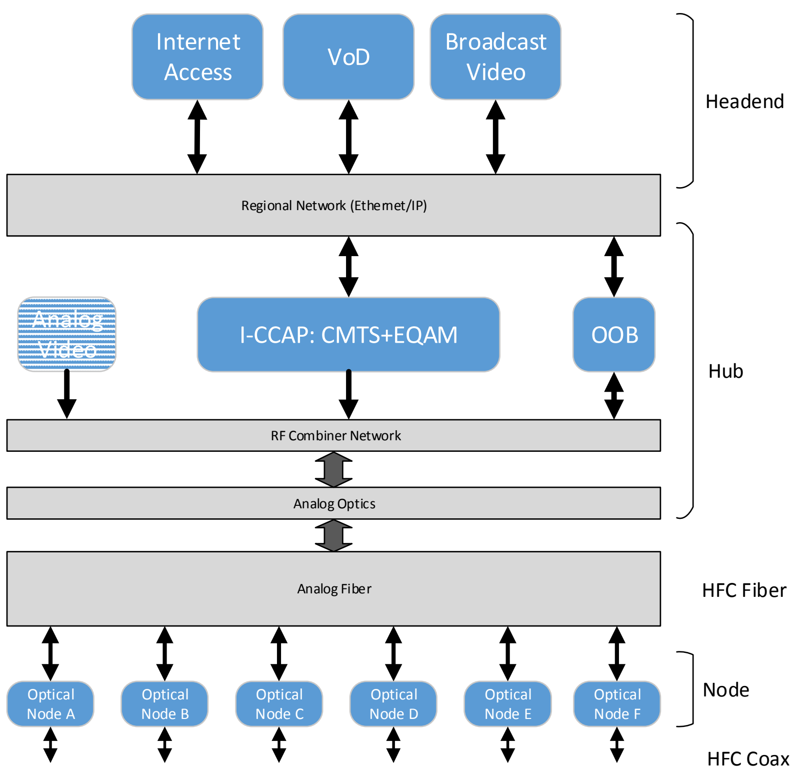

Figure 2 - Typical Access Network with CCAP

As mentioned earlier, I-CCAP was defined as a rack mounted, modular chassis which accommodated a number of line cards, including:

- **SRE Line Card**, which incorporates the management module, the forwarding packet processor and backhaul network interfaces.
- **RF Line Card**, which incorporates upstream or downstream RF ports or a combination of both.
- **EPON Line Card**, which is out of scope of this paper.

The key technology enabling convergence of data and video was the invention of cost effective full-spectrum downstream modulators. A number of technical constraints dictate that the PHY components (DS PHY modulators and upstream demodulators) are implemented on the I-CCAP RF Line cards along with MAC processing resources. This is illustrated by an example of data plane components of the I-CCAP RF line card, shown on Figure 3. For clarity, the diagram includes only one DS and one US port. I-CCAP RF line cards typically incorporate 8-32 RF ports.

The diagram presents logically separated MAC subsystems for DOCSIS and MPEG video because their functional requirements are different. The actual implementation of MAC subsystems can be based of common hardware components such as FPGAs or ASICs. While there are many design options, the author believes that the presented example reflects a typical I-CCAP RF Line card implementation with US and DS functions.

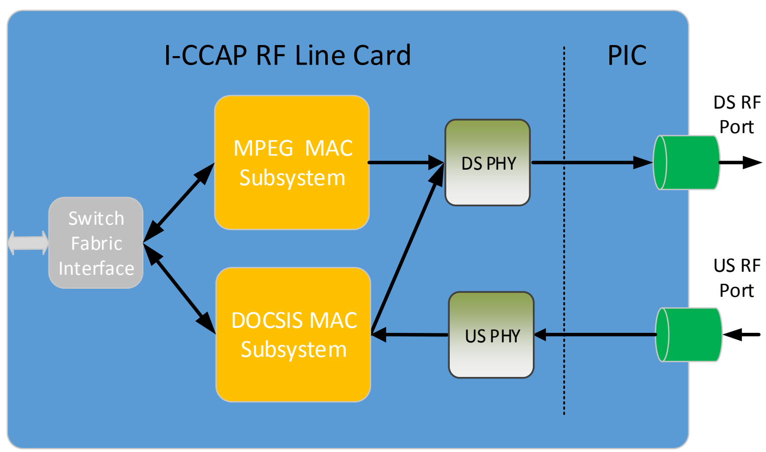

Figure 3 - Example of I-CCAP RF Line Card Components

The collocation of MAC and PHY processing resources on common H/W components results in two of issues.

- Availability. CCAP improves the overall service reliability as non-DOCSIS services get an upgraded N+1 HA architecture, and that there is an overall decrease in chassis, cables, and power supplies. The implementation of multiple services on shared hardware modules increases the system complexity and may result in a decrease of the overall reliability of the CCAP system. Operators have been wary of a situation where a failure such as a hardware or software fault within a subsystem dedicated to one service can interfere with a subsystem dedicated to another service. Unless the cable operator deploys I-CCAP with N+1 redundancy, software or firmware failures or upgrades may affect both DOCSIS and Video services simultaneously.

- Fixed scaling for MAC and PHY. I-CCAP RF line card is the main element of modularity for I-CCAP. The service capacity of I-CCAP can be increased or decreased by the addition or by the removal of RF line cards. Collocation of PHY and MAC results imposes the need to scale them in the same increments. This is undesired, especially considering that broadcast video lineup occupies a significant portion of the over bandwidth. I-CCAP implementations partially mitigate this issue by supporting an additional level of modularity - the removable PHY modules.

Remote PHY

With DOCSIS 3.1 development well under progress, the industry has shifted its focus to a new challenge, Remote PHY (R-PHY). R-PHY is the next step in the evolution of DOCSIS and video service delivery. It is a progression of the current CCAP architecture in which the PHY components are moved from the CCAP platform into a separate Remote PHY Device (RPD). The RPD is connected to the CCAP-Core (CCAP minus the RF PHY functions) by an IP network.

The combination of the CCAP-Core and the RPD provides the functional equivalent of the integrated CCAP. Essentially, R-PHY takes the digital interface to the PHY component from the circuit board in the CCAP and extends it over the IP network to the RPD using pseudowire technology as shown on Figure 4. From a protocol perspective, the MAC layer and the layers above MAC are implemented within the CCAP-Core while the physical layer and the PMD Convergence Layer are implemented in the RPD. The upstream and downstream channel resources in the MAC (MAC-level channel resources) are associated with channel resources in the PHY (PHY-level channel resources).

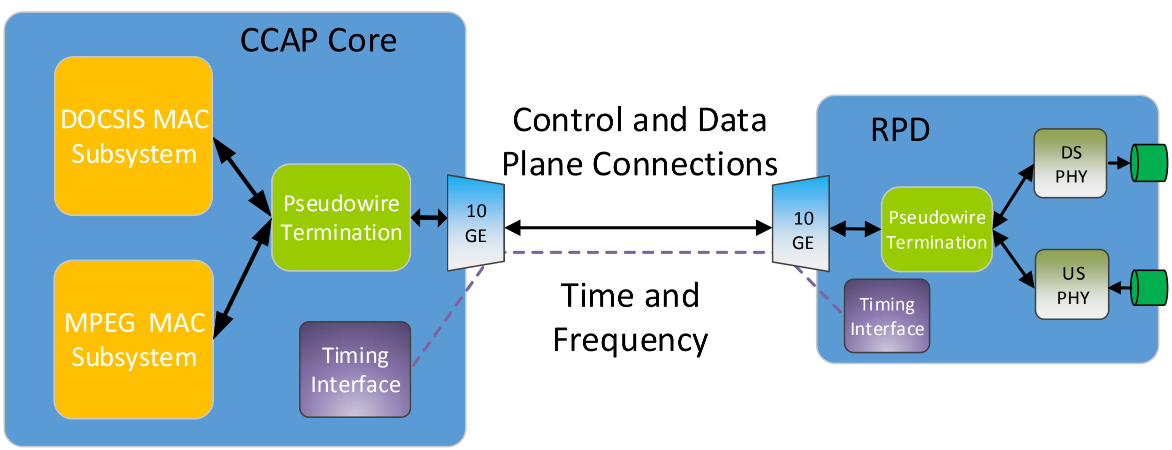

Figure 4 - Remote PHY System.

The connections between the CCAP-Core and the RPD can be established over any L2/L3 network. Both CCAP-Core and the RPD typically facilitate network connections over Ethernet, 10 Gbps or higher. An example of an access network architecture is presented on Figure 5.

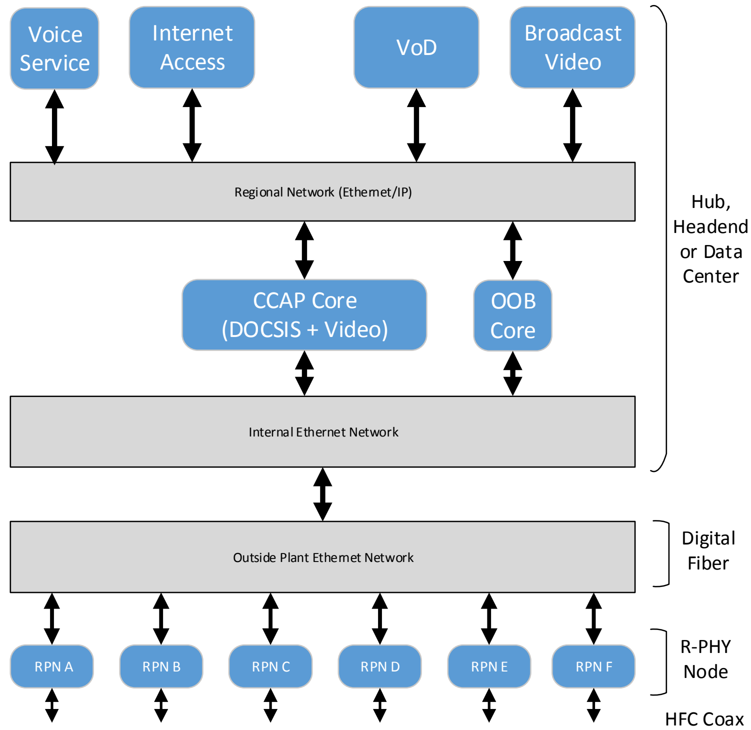

Figure 5 - Access Network Architecture with R-PHY

The CCAP-Core and the RPD communicate over a set of IP connections which includes a Generic Control Plane (GCP) connection for exchange of control information and a set of L2TPv3 pseudowires for transfer of service data between the systems. Additionally the CCAP-Core operates an L2TPv3 control connection to manage the L2TPv3 pseudowires and their network attributes.

The L2TPv3 pseudowires carry data for single DOCSIS or video or OOB channel between the MAC and the PHY. DEPI (Downstream External PHY Interface) specification defined downstream and overall L2TPv3 control plane operation. UEPI (Upstream External PHY Interface) specifies upstream data plane operation. To reduce the number of required pseudowires, DOCSIS or video channels can be grouped and their data carried in a single pseudowire. The R-PHY specifications define certain implementation simplifying rules on what types and how many channels can be grouped in a single pseudowire.

The basic connectivity between a MAC channel and the PHY channel is defined at pseudowire level and expressed as a combination of a pair of IP addresses and a negotiated L2TPv3 session ID and under the control of CCAP-Core software and its configuration logic. Per channel granularity in connectivity permits the Remote PHY architecture to support considerable flexibility in how the PHY-level channels in the RPDs can be connected to MAC-level channels in the CCAP-Core(s). This flexibility can be illustrated as a combination of three methods built in the R-PHY protocol.

<u>Independent Grouping of MAC Resources.</u>

As explained earlier, in Remote PHY protocols the data plane exchange is accomplished via L2TPv3 pseudowires. The protocol provides the means for creating the data plane connections between an RPD and one or more CCAP-Cores. In other words, MAC-level channels corresponding to the

PHY-level channels in a single PRD can be located in one or in multiple CCAP-Cores.

Two examples of MAC resource grouping are illustrated on Figure 6 and Figure 7.

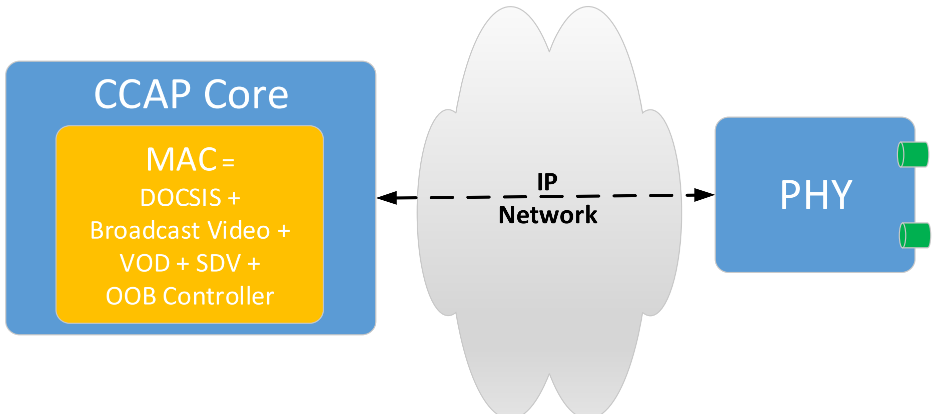

Figure 6 - All MAC resources located in a single CCAP-Core

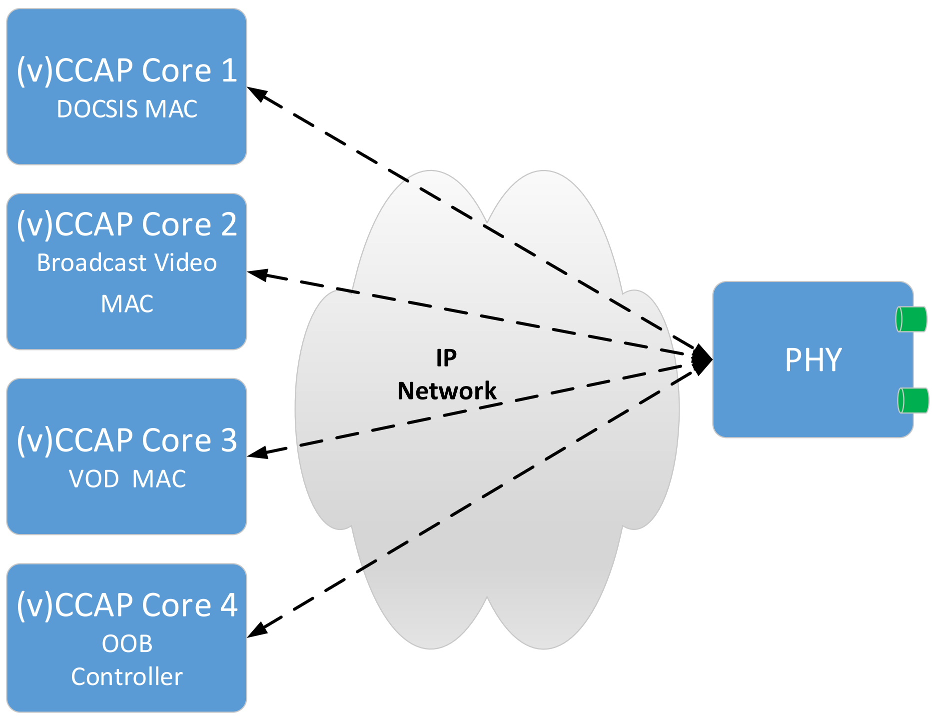

Figure 7 - Logical separation of MAC Resources to multiple CCAP-Cores

Figure 6 depicts a scenario with a single CCAP-Core which provides all MAC resources for all types of channels terminated by the RPD. This diagram exemplifies a scenario most closely resembling the pairing of MAC and PHY resources as implemented on I-CCAP. Such scheme represents the most straightforward step in evolution of the I-CCAP architecture. The virtual RF ports on the CCAP-Core are one-to-one matched to the physical RF ports in the interconnected RPDs. Each RPD is attached to exactly one CCAP-Core. This approach, perhaps combined with certain optimizations may be best suited for those vendors who are planning to evolve their existing I-CCAP systems which already implement DOCSIS and MPEG video services into CCAP-Cores.

Figure 7 illustrates the opposite approach to the example shown on Figure 6. Each CCAP-Core accommodates the MAC resources for only one service type. The diagram shows a separate DOCSIS CCAP-Core, Broadcast Video CCAP-Core, VOD Core and OOB Controller CCAP-Core. Each of the CCAP-Cores is dedicated to only one service category.

There are several benefits of separation of the CCAP service functions. Such an approach not only allows the operators to independently scale MPEG video, DOCSIS and OOB services but also removes many interdependencies in the systems providing these services resulting in improved availability and manageability. Unlike in integrated CCAP, the system maintenance functions, such as software upgrades or module replacement can be performed independently for each service. With proper accommodation in R-PHY protocols, failures within the DOCSIS domain will not affect the MPEG video domain and vice versa.

This approach may be best suited for those vendors who are planning new development of CCAP-Core systems, for example systems leveraging NFV technology.

When CCAP functions are separated to specialized systems providing a single service function, the RPD becomes the central point where the cable services actually convergence. Consequently, the acronym CCAP becomes obsolete. Is this a paradox or a paradigm shift? Does R-PHY architecture reinterprets "Cable Convergence" by ultimately forcing convergence deeper into the access network? For the first time that all services have to be converged. Before it was an option.

Efficient Use of Multicast Replication

R-PHY protocols define downstream data plane operation with IP multicast. The operators can provision the CCAP-Core to create a multicast DEPI pseudowires, each representing a single MAC channel or a set of MAC channels. A multicast group (S, G) sourced by the CCAP-Core can include one or more multicast pseudowires. The CCAP-Core advertises the multicast groups it originates via a multicast routing protocol, such as PIM.

During the RPD configuration process, the CCAP-Core instructs a number of RPDs to join the multicast group via IGMP/MLD in order to receive the data at the end of distribution tree. The RPDs subscribed to a multicast group can pick which pseudowires to receive by filtering based on L2TPv3 Session ID. DEPI multicast can be configured with granularity of a single DS channel.

An example DEPI multicast operation is shown on Figure 8.

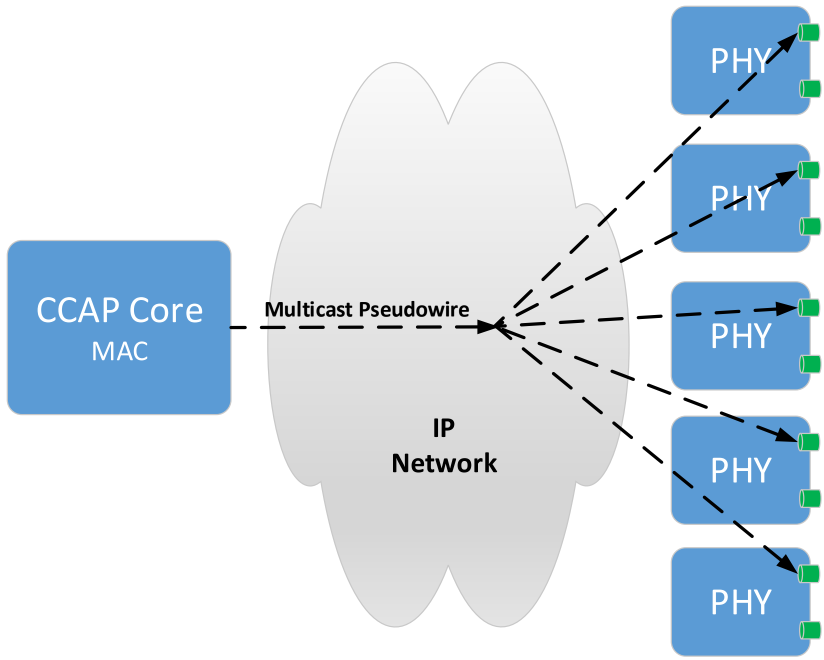

Figure 8 - DEPI multicast

Multicast operation can provide tangible savings to the operator. Multicast reduces the number of required MAC channel resources in the CCAP-Core and the bandwidth of the network connecting the CCAP-Core to the RPDs. One MAC resource in the CCAP-Core may serve tens of even hundreds of RPDs.

The primary use case for DEPI multicast is to distribute of video broadcast service where the same content, typically consisting of tens of MPEG video channels is intended to reach a larger serving group including possibly hundreds of RPDs.

In another use case, the operator may create downstream service groups consisting of several RPDs' downstream ports by configuring the CCAP-Core to replicate the complete lineup of downstream channels, or a set of downstream channels belonging to a particular service to RPDs in the selected group. This technique is referred to as virtual splitting because is the protocol equivalent of electrically or optically splitting the RF signal to multiple fiber nodes.

In such scenario each RPD DS RF Port individually converts identical digital signals to RF signals and all downstream CPEs, i.e. settop devices and DOCSIS Cable Modems receive identical content. The virtual splitting scheme may be useful to construct individually sized service groups for each service type or to support independent scaling of MAC and PHY resources.

For example, let us consider a transitional scenario where an operator builds up a complete deep fiber plant, splitting the nodes and installing as many RPDs as necessary to fulfill long term bandwidth needs. With virtual splitting, such a plant can operate with reduced number of downstream MAC resources in the CCAP-Core until the actual bandwidth demand rises to the level exceeding CCAP-Core capacity. Only then the downstream MAC resources in the CCAP-Core need to be scaled up.

Certain downstream PNM (Proactive Network Maintenance) functions require customization due to virtual splitting because these functions are implemented in the downstream modulator. To illustrate the problem let us consider a virtually split OFDM channel. The downstream symbol capture function requires that the DS OFDM modulator in the RPD captures the set of digital samples representing a complete OFDM symbol. In the case of virtually split OFDM channel, there are multiple RPDs and multiple modulators involved. Therefore the symbol capture function needs to take place in multiple DS OFDM modulators. Current PNM specification do not cover such possibility. An adequate solution is currently under study.

Virtual Combining of Upstream Channels.

Remote PHY offers another technique, virtual combining of upstream channels which serves a similar purpose in the upstream direction as virtual splitting serves in the downstream. As the name suggests, virtual combining provides functionality equivalent to combining input signals from two fiber nodes. Conceptually a single MAC-level upstream channel resource in the CCAP-Core can be associated with more than one upstream PHY-level channel resources in the RPDs. All PHY-level US channels in a combined group have the same PHY-level parameters and share combined spectrum.

Unfortunately, since in this topology the data flows from many sources to one destination, virtual combining cannot rely on multicast transport. The number of upstream pseudowires scales accordingly with the number of involved upstream PHY-level channel resources in the RPDs. For example, if the US PHY-level channels are combined from four RPDs to feed into a single MAC-level US channel, the CCAP-Core needs to create four separate data pseudowires.

Virtual combining can be best described a method of multiplexing of data at PHY layer. There is impact of to CCAP-Core operation at the MAC layer and to higher layers. The upstream bandwidth scheduler in the CCAP-Core generates a single MAP stream, which is distributed to all burst receivers in a combined group. The CCAP-Core software manages a single set of resources and protocol identifiers such as SIDs.

The CCAP-Core needs to account for minor side effects of virtual combing. Certain statistical counters, for example the “burst collision” counts and “not energy burst” counts will be reported by burst receivers independently and need to be corrected as if they were a result of operation with a single burst receiver. Also, those upstream PNM functions which are implemented in the US burst receiver (Spectrum Analysis, Upstream Histogram) require re-work because the current specifications assume one to one mapping between the MAC layer and the PHY layer.

Virtual combining is completely transparent to the RPDs. RPDs are not at all aware that they participate in virtually combined group; no changes are needed to Remote PHY protocols. All knowledge of virtual combining, necessary configuration and packet mapping functions are implemented solely on the CCAP-Core.

In theory, virtual combining can be deployed with the granularity of a single DOCSIS US physical channel. In practice, more likely virtual combining will be applied on a service group level; each DOCSIS channel in the upstream lineup will be combined together with corresponding channels in a combined group of RPDs.

By deploying a combination of the techniques described above the operators can construct R-PHY access networks which exhibit a number of advantages over I-CCAP based design:

1. The size of the service delivery platforms can be scaled independently and tuned to the desired service footprint.

2. Broadcast services can be cost effectively scaled through network based multicast replication.
3. Virtual splitting and combining enables operators to independently craft per service serving group sizes and to flexibly match the ratio between the MAC-level resources to the PHY-level resources.

An example of a completed HFC access network is shown on Figure 9.

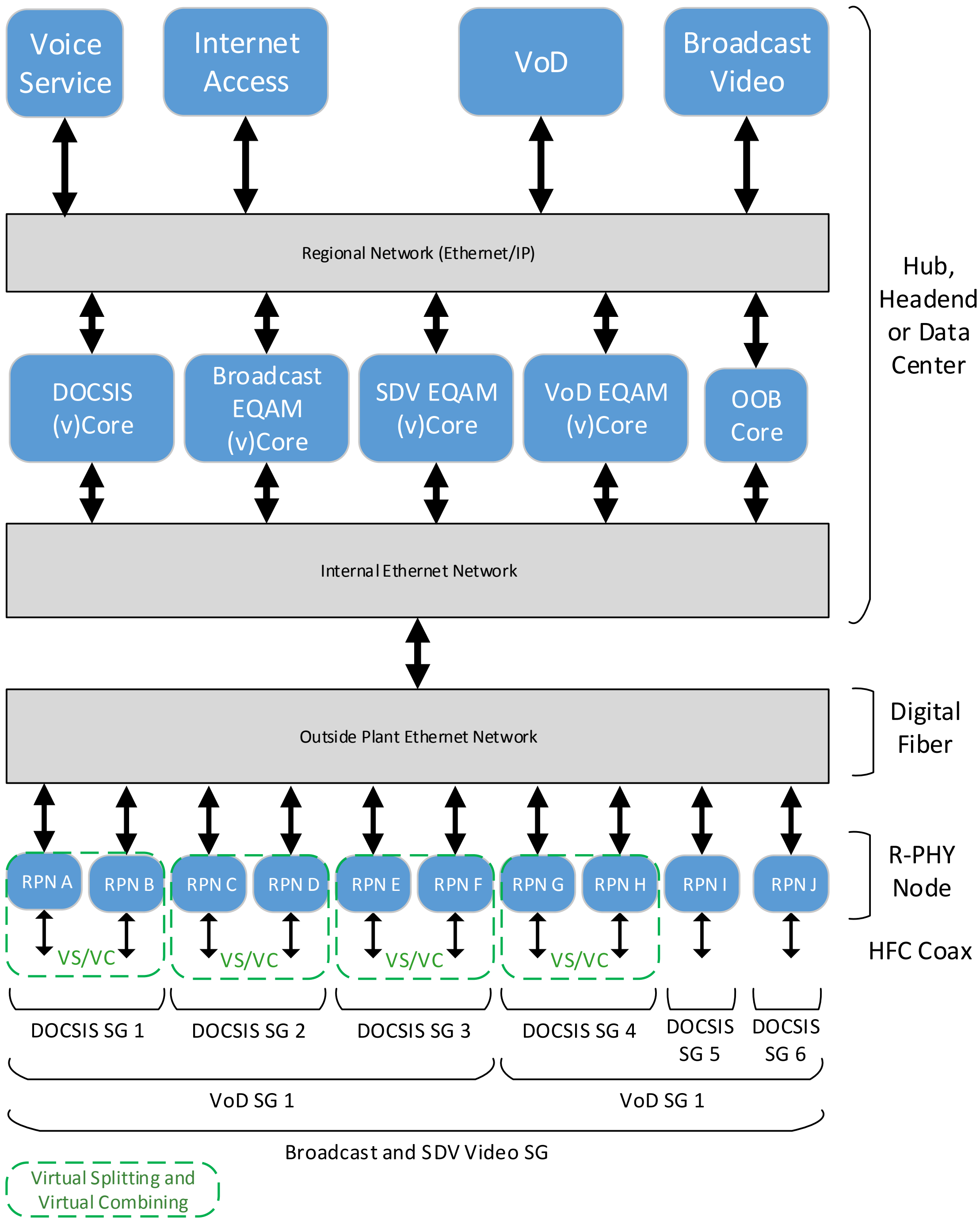

Figure 9 - Service Group in HFC access network

Conclusion

The paper demonstrates that Cable Operators can leverage Remote PHY technology to construct cable access networks that fulfill or even exceed the convergence goals for CCAP. Remote PHY replaces analog HFC connections with Ethernet and IP network, as result the operators are given new options to effectively configure service groups and match MAC and PHY resources with unparalled flexibility.

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Abbreviations & Acronyms

CCAP	Converged Cable Access Platform
CMTS	Cable Modem Termination System
CPE	Customer Premise Equipment
CPU	Central Processing Unit
DEPI	Downstream External PHY Interface
DOCSIS	Data Over Cable System Interface Specification
EQAM	Edge Quadrature Amplitude Modulator
HFC	Hybrid Fiber Coax
I-CCAP	Integrated CCAP
IP	Internet Protocol
MHAv2	Modular Headend Architecture version 2
MPEG	Moving Picture Experts Group

MSO	Multiple System Operator
NFV	Network Function Virtualization
OAM&P	Operations Administration Maintenance and Provisioning
OOB	Out of Band
OSS	Operational Support System
PIM	Protocol Independent Multicast
PMD	Physical Media Dependent
RF	Radio Frequency
RPD	Remote PHY Device
RPN	Remote PHY Node
SDN	Software Defined Networking
SG	Service Group
UEPI	Upstream External PHY Interface