Data-Over-Cable Service Interface Specifications
DCA

Distributed CCAP Architectures Overview Technical Report

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1 SCOPE

1.1 Introduction and Purpose

The CMTS has evolved over time, becoming a CCAP supporting both high-speed data and video services. As bandwidth capacity needs grow rapidly, there is increasing pressure on the infrastructure, and new Distributed CCAP architectures are emerging to address the need for smaller scale (where a CCAP is too large), and to offer more flexible deployment options.

Distributed CCAP implementations can bring significant benefits in certain HFC network deployments. It will enable higher PHY layer performance for DOCSIS 3.1, and reduce space and power needs at the headend.

Distributed CCAP Architecture: There are multiple distributed CCAP architectures emerging in the marketplace. The basic idea around Distributed CCAP Architecture (DCA) is to distribute some or all of the functionality of the CMTS/CCAP down to a remote location, like the Fiber Node.

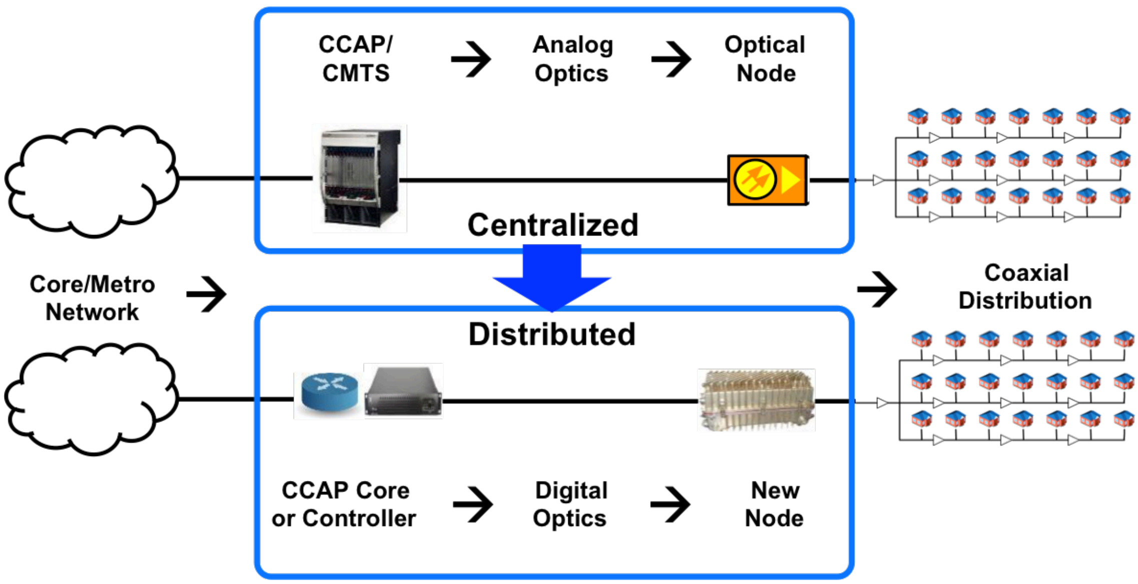

Figure 1 - Centralized vs Distributed CCAP Architecture

This technical report describes various distributed CCAP architectures (DCA) and how they handle data and video.

This technical report is intended to be an umbrella document, to go with the family of DCA specifications and technical reports. The goal is to give the reader a high level overview of the DCA space and to give a quick introduction to the following DCA technologies: Remote PHY, Remote MAC-PHY and variants, and C-DOCSIS II system architecture.

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Phone +1-303-661-9100; Fax +1-303-661-9199; http://www.cablelabs.com
- Internet Engineering Task Force (IETF) Secretariat, 46000 Center Oak Plaza, Sterling, VA 20166, Phone +1-571-434-3500, Fax +1-571-434-3535, http://www.ietf.org
- SCTE - Society of Cable Telecommunications Engineers Inc., 140 Philips Road, Exton, PA 19341; Phone: 610-363-6888 / 800-542-5040; Fax: 610-363-5898; http://www.scte.org/

3 TERMS AND DEFINITIONS

This document uses the following terms:

Blast and Split or Broadcast-Narrowcast Overlay	A downstream HFC optical architecture where common broadcast video RF channels are transmitted using a high-power laser on one fiber, and narrowcast channel groups for nodes are each provided with a laser on a separate wavelength for combining onto another fiber or fibers. At the far end of the fiber run, the broadcast light signal is split, and the narrowcast light signals are separated by wavelength and combined with the split broadcast light for service to separate HFC nodes.
C Band	In infrared optical communications, C-band refers to the wavelength range 1530–1565 nm, which corresponds to the amplification range of erbium doped fiber amplifiers.
Cable Modem (CM)	A modulator-demodulator at subscriber locations intended for use in conveying data communications on a cable television system.
CCAP-Core	A CCAP device that uses [RPHY] protocols to interconnect to an RPD.
Edge QAM modulator (EQAM)	A headend or hub device that receives packets of digital video or data. It re-packetizes the video or data into an MPEG transport stream and digitally modulates the digital transport stream onto a downstream RF carrier using quadrature amplitude modulation (QAM).
Media Access Control (MAC)	Used to refer to the Layer 2 element of the system which would include DOCSIS framing and signaling.
NETCONF	The Network Configuration Protocol (NETCONF) is a network management protocol developed and standardized by the IETF.
Out-of-Band	Signaling channel that is used to control set-top boxes.
Pseudowire	IP tunnel between two points in an IP network.
RESTCONF	A REST-like protocol that provides a programmatic interface over HTTP for accessing data defined in YANG, using the datastores defined in NETCONF.
Remote MACPHY Device	The Remote MACPHY Device (RMD) is a device in the network that implements DOCSIS MAC and PHY functions in a remote node.
Remote PHY Device	The Remote PHY Device (RPD) is a device in the network that implements the Remote-PHY/MHAv2 [RPHY] specifications to provide conversion from digital Ethernet transport to analog RF transport.
Remote PHY pseudowire	A set of pseudowires that carries data between the CCAP-Core and the RPD in both directions.
Remote PHY System	An approach to DOCSIS framing and signaling that takes the PHY chip out of a CMTS box and puts it at the edge of an IP network.
Split EQAM	A variation in video functionality partition in Remote MAC-PHY Architecture where video MAC functionalities and above is located in CCAP-Core and Video PHY is located in remote MAC-PHY device.
YANG	A modeling language developed by the IETF.

4 ABBREVIATIONS AND ACRONYMS

This document uses the following abbreviations:

CAPEX	Capital expenditures
CCAP	Converged Cable Access Platform
CDT	C-DOCSIS Data Tag
CIN	Converged Interconnect Network
CM	Cable Modem
CMTS	Cable Modem Termination System
DCA	Distributed CCAP Architecture
DEPI	Downstream External PHY Interface
DFB	Distributed Feedback
DRFI	Downstream Radio Frequency Interface
DS	Downstream
DSCP	Differentiated Services Code Points
DTI	DOCSIS Timing Interface
DTP	DOCSIS Timing Protocol
EDFA	Erbium Doped Fiber Amplifier
EPON	Ethernet Passive Optical Network
EQAM	Edge-QAM (modulator)
GCP	Generic Control Plane
GPON	Gigabit Passive Optical Network
HFC	Hybrid Fiber/Coax
IETF	Internet Engineering Task Force
IoT	Internet of Things
IP	Internet Protocol
IPv4	Internet Protocol version 4
IPv6	Internet Protocol version 6
L2TPv3	Layer Two Tunneling Protocol version 3
LDPC	Low-Density Parity Check
MAC	Media Access Control
MAP	Upstream Bandwidth Allocation Map (referred to only as MAP)
MBH	Mobile Backhaul
MDU	Multi Dwelling Unit
MHA	Modular Headend Architecture
MPLS	Multiple Protocol Label Switching
MPT	MPEG Transport
MPTS	MPEG Transport Stream
NDF	Narrowband Digital Forward
NDR	Narrowband Digital Return
NETCONF	Network Configuration Protocol
NFV	Network Function Virtualization
NG-PON2	Next-Generation Passive Optical Network

OFDM	Orthogonal Frequency Division Multiplexing
OPEX	Operational expenditures
PCMM	PacketCable Multimedia Specification
PCR	Program clock reference
PHY	Physical Layer
PID	Packet Identifier used in MPEG-TS
PSP	Packet Streaming Protocol
PTP	Precision Time Protocol
QAM	Quadrature Amplitude Modulation
R-CCAP	Remote CCAP
R-DTI	Remote DOCSIS Timing Interface
R-OOB	Remote Out-of-Band
RMD	Remote MAC-PHY Device
RPD	Remote PHY Device
R-MACPHY	Remote MAC-PHY
R-PHY	Remote PHY
SDN	Software-Defined Networking
SNMP	Simple Network Management Protocol
SNR	Signal-to-Noise Ratio
SPTS	Single Program Transport Stream
STB	Set-top Boxes
SyncE	Synchronous Ethernet
TCP	Transmission Control Protocol
UDP	User Datagram Protocol
UEPI	Upstream External PHY Interface
US	Upstream

5 BASELINE ARCHITECTURE

Cable operators implement and deploy IP High Speed data, Linear Broadcast Video, Video on Demand, Voice, and various other integrated services to their end customers. The primary choice of access technology for this today is DOCSIS over a hybrid-fiber/coax (HFC) cable network.

5.1 Data

The DOCSIS system allows transparent bi-directional transfer of Internet Protocol (IP) traffic between the cable system headend and customer locations over the HFC network. The Cable Modem Termination System (CMTS) is the central platform in enabling High speed Internet connectivity over the Cable HFC network. The CMTS platform has evolved over time along with the DOCSIS Specifications. The CMTS provides the MAC and PHY layer connection to the Cable Modem (CM) at customer premise.

The CMTS consists of various logical functional components, at a high level these are as follows:

- DOCSIS PHY Layer
  - Upstream Receiver
  - Downstream Transmitter
- DOCSIS MAC Layer
  - Upstream MAC and Scheduler
  - Downstream MAC Processing
  - DOCSIS QoS
- Security
  - RF Output block
  - L2 forwarding block
  - L3 forwarding block
  - IP Processing for DHCP
  - SNMP agent / CLI, etc.

5.2 Video

The Video EdgeQAM is a key piece of equipment in any headend, hub site to enable video services including broadcast video, video-on-demand and switched-digital-video. The EQAM receives SPTS or MPTS streams over an UDP/IP unicast or multicast transport, multiplexes the streams, and generates an MPEG-compliant MPTS stream that is then reproduced on one or more RF outputs for transmission over the HFC cable plant. It performs a number of functions such as: demultiplexing, PID remapping/filtering, multiplexing, PSI parsing and re-generation, de-jittering, clock recovery and PCR restamping, NULL packet insertion, and encryption as described in [EQAM-VSI].

5.3 Modular Headend Architecture

Over time there have been many steps in the evolution of the CMTS platform. One of the first steps was the creation of the Modular Headend Architecture (MHA), which essentially separated the DOCSIS downstream PHY layer from the CMTS and moved it to a separate EQAM device.

A new interface called the DEPI (Downstream External PHY Interface) was defined to support sending the data from the CMTS Core to the EQAM. The idea was to reuse the EQAM to modulate the bits on to the wire for both downstream DOCSIS data as well as MPEG video. The video EQAM now becomes a universal EQAM, handling both video and DOCSIS data as inputs. The upstream receiver remains at the CMTS core. Since the DOCSIS MAC and PHY were separated in the MHA architecture, a new DOCSIS Timing Interface was introduced to keep the two devices closely synchronized. The Modular CMTS was essentially two separate platforms as compared to the fully integrated CMTS.

5.4 Integrated CCAP Architecture

The next big step in the evolution of CMTS platforms was the Converged Cable Access Platform (CCAP). The CCAP was intended to provide a new equipment architecture option for manufacturers to achieve increased Edge QAM and CMTS densities that MSOs require. The CCAP leverages existing technologies, including DOCSIS and newer technologies such as Ethernet optics and Ethernet Passive Optical Network (EPON). The CCAP unifies the CMTS, Switching, Routing, and QAM functions at the headend, so that all data, video, and voice functions can be handled over IP before conversion to RF or Optical signals. The CCAP eliminates the need for the combiner functionality in the headend.

5.5 DOCSIS 3.0 and DOCSIS 3.1

5.5.1 DOCSIS 3.1 Data

DOCSIS 3.1 is the next generation in the evolution of DOCSIS and it brings some fundamental changes to the technology. Backward compatibility with previous DOCSIS versions is part of the DOCSIS 3.1 standard. [DOCSIS3.1] introduces Orthogonal Frequency Division Multiplexing (OFDM) as the new PHY layer technology, and allows for wide channels from 24 MHz to 192 MHz wide, moving away from the legacy 6 MHz sizes. DOCSIS 3.1 introduces Low Density Parity Check (LDPC)-based Forward Error Correction (FEC).

DOCSIS 3.1 also introduces options for additional HFC spectrum by allowing for expansion of the US Split (Mid-split or High-split). It also allows expansion of the downstream spectrum at the higher end. DOCSIS 3.1 LDPC FEC allows data transmission approaching the theoretical limits, and this enables 50% more efficient modulations such as 4096-QAM, harnessing more capacity on existing HFC networks. In the long run, DOCSIS 3.1 could support data rates reaching 10 Gbps downstream and 1 Gbps upstream.

5.6 Areas to resolve for Distributed Architectures

Any DCA and remote solution will need to address the following areas, some of which were addressed above:

- Data plane versus Control plane considerations
- Video
- Security
- OOB
- Timing and Synchronization
- OSS considerations
- Video Considerations: DCA needs to solve and integrate with these other solutions.
  - DRM
  - RMI
  - SDV
  - EQAM Core: Need for an EQAM Core device with Ethernet output.

These areas will be covered in more detail in later sections of this technical report.

6 MIGRATION TO DCA

6.1 Operator Challenges

Cable operators today face numerous challenges. The customer and market demands for higher bandwidth are increasing at a fast pace, and the demand for data and video services is forcing operators to continuously upgrade the plant capacity. As bandwidth demand continues to grow, facility space, power, and other related factors start becoming a concern. Below are some issues that factor into the discussion.

6.1.1 Capacity increases / Performance

Moving the R PHY closer topologically to the customer premises will tend to improve performance as a function of the reduced attenuation and accumulated impairments that tend to accrue over the length of the physical medium. The net effects of a shorter RF paths are a reduction in bit error rates and improvements in SNR; these create opportunities for making use of higher modulation orders for DOCSIS 3.1 channels. MSOs are generally aware that increased aggregate capacity does not always translate into more capacity and that additional steps are needed to optimize the service.

One scenario is a selection of service groups that are approximately 50 kilometers from the headend with no intermediate hub site in a market about to launch a 1Gbit tier. In situations such as this, where capacity projections for the next 12 months may exceed 200% while the operating conditions are marginal for the existing tiers of service, a remote solution could meaningfully fill an architectural void and in fact be the technological tool needed to provide the service.

Distributed solutions offers additional performance beyond what would be possible with a very high performance cooled distributed feedback (DFB) laser with the necessary optical budget for a 50 kilometer link. A remote device, with a 10Gbit (and eventually 100Gbit) optical interconnect provides greater performance than a Dense Wavelength Division Multiplexing (DWDM) or ultra-high performance cooled (linear analog) DFB. The question of cost is an important one, but out of scope for this document.

6.1.2 Smaller Serving Group Size

There is a need to move to smaller service groups and to N+0 architectures to increase the bandwidth available to the user. The number of service groups needed might increase by a large factor with Fiber Deep HFC architecture and the question is if the current CCAP platforms can keep up.

The design of the remote system was intended to be adaptable to a variety of use cases that aid in reducing the size of the service groups, increasing the aggregate (but not necessarily the per user) capacity. While the actual reduction in service group size is highly contingent on the specific details of how the remote architecture is deployed for a given scenario and the total cost of deploying such a system, a remote device associated with a smaller serving area can greatly increase capacity for a given service grouping and allow for optimizations in the service to take greater advantage of the increased aggregate capacity.

6.1.3 SNR and Impact on Modulation Profiles Supported

A remote solution creates opportunities for using relatively little transmit power to obtain very high SNR due to the decreased attenuation and limited interference that very short RF networks can offer. This is important for cost competitive components, since each increase in dBs of power output increases noise as well. A remote solution might only have between several hundred meters and a few kilometers to reach the most distant end points on the network, dramatically reducing transmit power requirements while increasing SNR. With increased SNR, an operator can obtain more operating margin and/or additional operating head-room to compensate for diurnal changes in the plant as it heats during the day and cools during the night.

Additionally, a higher SNR allows the higher modulation orders offering higher bit per symbol performance to be used in D3.1 modulation profiles. Please refer to the table on CM Error Ratio Performance in AWGN Channel in [PHYv3.1].

Ideally, the distance between the Remote Device and the customer location is so short that ingress and physical defects causing leakage and micro-reflections are so well managed that the highest modulation orders could be used reliably. However, realities of plant materials and their oxidization rates, the inevitable "patchwork quilt" of network upgrades and extensions taking place over a timeframe of decades and practical issues such as the cost of dramatically changing the existing plant suggests a less idealistic goal would be advisable.

6.1.4 Headend Space Power Savings

Over the last few years MSOs have seen a significant increase in the number of SC-QAM channels used for narrowcast services. Most MSOs are intending to deploy DOCSIS 3.1 with SC-QAM channels and a small amount of spectrum for OFDM in order to support both existing high-speed data services, as well as new service types, such as IPTV, cloud-based DVR, home security and automation, connecting smart devices in the home (thermostats, light switches, appliances, etc.) in what has been dubbed the Internet of Things (IoT).

At the same time, MSOs continue to reduce the size of service groups. This trend, which has been going on for several years, is driven by the need to supply more bandwidth and improve service quality for existing services (smaller service groups have reduced plant impairments and allow for smaller failure groups and faster isolation of problems). The primary bandwidth drivers have been the success of DOCSIS and Video on Demand, with new, higher bandwidth services applying significant pressure.

To date, denser edge devices that converge services (i.e., CCAP) have been a solution; however, as the number of service groups grows, the number of RF ports on these devices must also increase. The physics that constrain the size of the interface connectors limits the number of connectors that can be implemented on a single board. Additional edge devices are therefore needed to meet service group growth. This need for additional edge devices puts a strain on headends and hub sites that are already space-and power-constrained. Many operators are quickly running out of rack space and floor space necessary to add more racks. Additionally, the cost of power and the practical limits imposed that are driven by these dense devices continue to grow.

Building out more headend and hub space, if it is practical to do so at all, is an operational expenditure that MSOs would very much like to avoid. It is for this reason that when total costs are factored in and compared objectively that solutions like DCA could provide an credible option.

6.1.5 Low Cost Deployments

In some global markets, the need for low-cost smaller-scope deployment options is important to enable the success of cable broadband. Chinese MSOs in particular face unique challenges. Their plant architecture consists of a digital optical packet network (using point-to-point, EPON, GPON, etc.) to the MDU (Multi Dwelling Unit) and coax within the MDU. A centralized CMTS and is not as economical in this architecture and market.

6.1.6 Flexibility and Other Benefits

Distributed architectures move portions of the CMTS functionality into nodes; this gives operators flexibility and another option in their tool belt for deploying DOCSIS. There are also various benefits of a high rate digital backhaul which can be used for other services, such as wireless backhaul, business fiber extensions, and so forth. See Section 11.9 for additional information. Long Nodes and No Hub Sites Scenarios also fit in with DCA.

6.2 Evolution from Analog Fiber to Digital

6.2.1 Digital Fiber

For analog optical networks between the hub and the fiber node, the length of optical link can be a limiting factor in managing the Signal-to-Noise Ratio (SNR) performance. For DOCSIS 3.1 technology, capacity in the plant can be optimized when the analog optical noise floor is eliminated.

Digital optics promise reduced OPEX as compared to analog optics. For digital optics, MSOs can use low-cost small form-factor pluggable (SFP) lasers instead of high-priced DFB lasers used in AM fiber. In this manner, they avoid the operations costs of maintaining rigorous performance on AM links as plant conditions change. The increased reach of the technology can be used to reduce facilities expense.

Use of digital fiber increases SNR at the remote device and eliminates the optical noise generated by analog optics. DOCSIS 3.1 modulations and/or capacity can be increased with no linear optics noise and better SNR. It eliminates System Non-linearity.

6.2.2 Fiber Efficiency

Digital optics also provides a lower CAPEX for capacity growth. With a shift to digital optics, the throughput on the fiber becomes much greater (wavelengths can be packed much closer spectrally in the DWDM than with Wave Division Multiplexing spacing for analog optical signals. Typical spacing between wavelengths in AM mode is 100 GHz, which allows up to 40 wavelengths on a single fiber, whereas spacing for digital wavelengths is 25 GHz or less, which leaves room for 160 or more wavelengths.

6.2.2.1 Need Distributed for PON

Typical PON technologies, such as 1G and 10G EPON, defined by the IEEE, and GPON and BPON, defined by the ITU, use standard wavelengths for upstream and downstream transmissions. These wavelengths are fixed and hence each fiber can only support one PON wavelength of each type. ITU has developed a NGPON2 standard that allows wave division multiplexing, allowing multiple PONs to be multiplexed on a single fiber. To improve the efficiency of EPON and GPON, a distributed network element that aggregates multiple wavelengths is required. As MSOs transition to distributed architectures, it is hoped that significant synergies can be drawn out of multiple distributed access technologies

6.2.3 Use Cases for DCA and Linear Optics

Two use cases justify the use of a Remote solution. In both cases, economical scaling of analog linear optics, as the length of the link increases, is implicated as a key inflection point.

1. The connection of a remote location to a hub site that is in excess of 25 km distance. Such distances either require an EDFA repeater mid-span to amplify the signal, high fiber counts or both. This limits the utility of linear analog transmitters as distances increase. Even the latest generation of ultra-high performance upstream optics and/or DWDM optics can make future scaling expensive and/or difficult to accomplish.
2. Replacement of “blast and split” type overlay architectures where current DWDM narrowcast is being used and/or when the link is deficient in remaining fiber count constitutes the second important use case for Remote solution. DCA can use much higher capacity, repeatable DWDM 10 Gbps point-to-point optics, providing the scaling in a way that a “blast and split” overlay architecture cannot.

In situations where the hub location is situated within fewer than 8 kilometers (5 miles) from the customer premises location, the expectations for performance enhancement maybe considerably lower. The necessary signal power alone is not a deciding factor in this case.

6.2.3.1 Blast and Split

‘Blast and Split’ (also known as broadcast-narrowcast overlay) describes the downstream direction architecture only; various upstream architecture variants may be associated with it to form a bidirectional optical system.

Blast and Split is a somewhat colloquial term for an HFC architecture where a group of (typically broadcast) video RF channels and other common RF signals that are shared across a large number of customers are modulated onto a linear laser/modulator/EDFA system on one wavelength (typically 1550 nm) with high output power (the “blast” part), and transmitted over a (often long distance) fiber link to a remote location. At the remote location, the high-power signal is split (obviously the “split” part) into separate (subtended) fibers, each carrying an identical copy of the wavelength to the destination optical receiver locations (nodes). Each of those subtended fibers also carries narrowcast signals.

Those narrowcast signals are supplied on separate fibers to the splitter location. Each of those fibers carries a group of wavelengths produced by multiple linear laser transmitters. Each of those transmitters modulated with a unique group of (typically VoD, SDV, and/or DOCSIS) narrowcast RF channels and other narrowcast RF signals destined for an individual node or service group. The outputs of those transmitters are multiplexed into a fiber using optical filters. At the remote split location, each unique-content wavelength is separated (de-multiplexed) and combined with the “blast” (broadcast) light from each splitter output using optical filters. The resulting outbound fibers each carry a copy of the shared “blast” wavelength from the broadcast fiber, and a “narrowcast” wavelength with unique content from one of the narrowcast fibers. When the fiber carrying the combined light from these two sources is connected to a detector in the optical receiver (node), the light intensity adds, producing a sum of the modulation of the two wavelengths at the detector's electrical output. This RF signal is then amplified in a manner identical to a conventional HFC node.

Advantages of this architecture include longer reach and lower fiber counts. The longer reach is attained by a combination of transmitter characteristics; the high cost of the very high performance "blast" transmitter is shared across a large customer base, while the reduced channel loading on each of the narrowcast transmitters allows use of low-cost directly modulated lasers which can use high per-wavelength optical modulation indices, and in conjunction with the fact that they are not split, thus attain long distances. When all lasers operate at EDFA-friendly wavelengths, the link may also employ mid-span repeaters, further increasing reach. Since these EDFA-based repeaters simultaneously amplify multiple wavelengths, they are more cost-effective than single-wavelength EDFAs.

The use of multiple wavelengths, most recently in the "C" band, results in significant reductions in the initial fiber count requirements. A further advantage stems from the fact that the combined reach and fiber count reduction advantages make this architecture particularly well suited for service to widely-disbursed small communities, where each community may not be large enough to support a dedicated video and data re-processing facility (aka distribution hub).

Disadvantages of the architecture are: complexity, difficulty in node splitting without construction of additional fiber counts, difficulty in scaling to high-SNR linear optics, difficulty in scaling to higher narrowcast RF channel counts, and typical use involves distances that prohibit future use of passive optical networks, compared to the initially more costly hub construction and higher fiber counts.

7 DCA OVERVIEW

7.1 Overview

There are multiple distributed CCAP architectures emerging in the marketplace and being described in CableLabs specifications or technical reports. The basic idea in DCA is to distribute some or all of the functionality of the CMTS/CCAP down to a remote location, like the Fiber Node, MDU or remote hub.

7.1.1 Three DCA Approaches

There are three distributed architectures that have come forth so far. These are the Remote PHY, Remote MAC-PHY and the Split-MAC variations. The concept behind Remote MAC-PHY is to split the CCAP above the MAC layer and move the entire MAC and PHY into the Remote node. The idea behind the Remote PHY is to split the CCAP between the MAC and the PHY Layers and move the PHY layer to the Remote Node. The Split-MAC is in between the above two options, where some of the MAC functionality is defined and left at the headend and the remaining MAC and PHY functionality are moved to the Fiber Node. Further below, the D-DOCSIS II architecture is discussed as an example of a Split MAC distributed architecture.

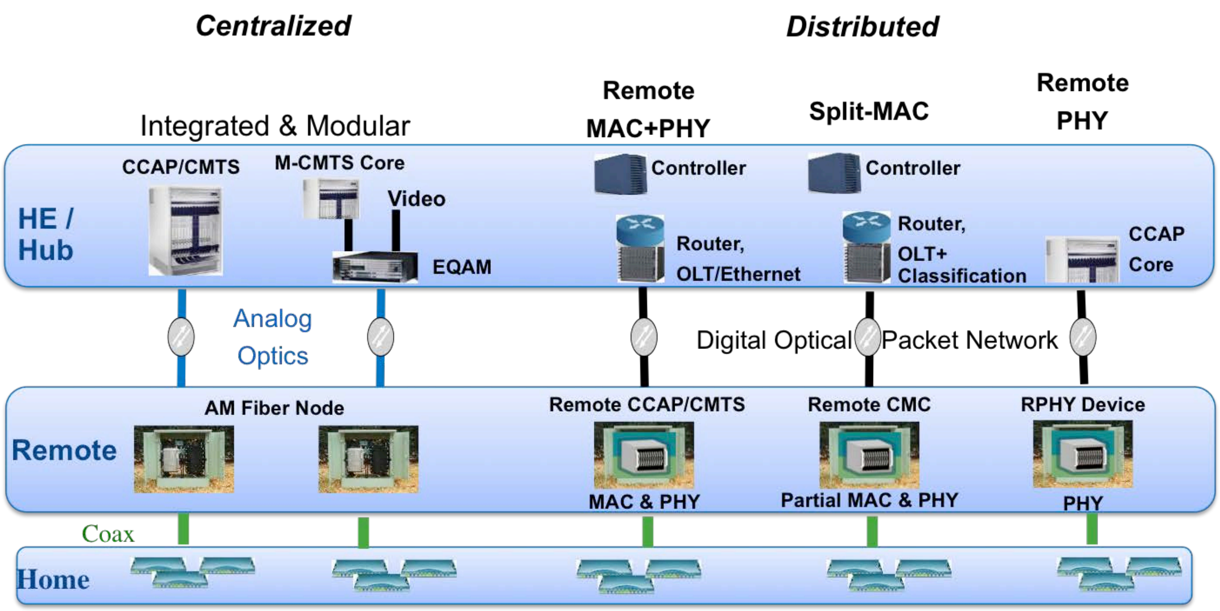

Figure 2 - Three Forms of D-CCAP Architecture

The foundation for Distributed CCAP Architectures is a digital optical plant, which essentially makes the connection between the headend and the fiber node a Layer 2 packet based connection. In a digital HFC plant, the fiber portion utilizes a baseband network transmission technology such as Ethernet, EPON (Ethernet over Passive Optical Networks), GPON (Gigabit Passive Optical Network), or any layer 2 technology that would support a fiber-based PHY layer.

7.2 RPHY Overview

The Remote PHY technology is also known as MHAv2 (Modular Headend Architecture version 2) as in many ways it builds on the original MHA architecture. MHAv2 uses a Layer 3 pseudowire to connect a CCAP Core and a set of Remote PHY devices over an IP network. One of the common locations for a Remote PHY device is the optical node device that is located at the junction of the fiber and coax plants.

In a Remote PHY System, the integrated CCAP is separated into two distinct components. The first component is the CCAP Core and the second component is the R-PHY Device (RPD). The CCAP Core contains both a CMTS Core for DOCSIS and an EQAM Core for Video.

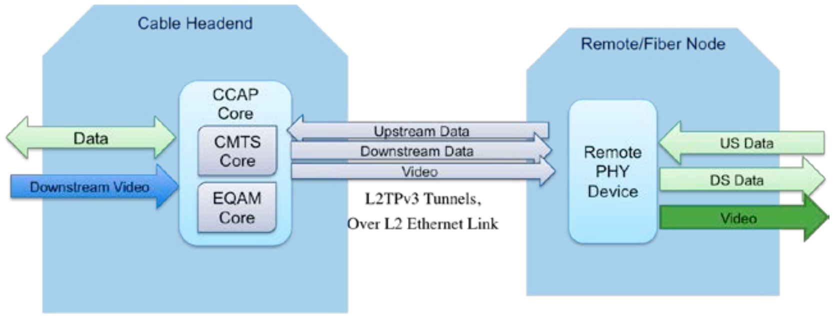

Figure 3 - Remote PHY High level Architecture

The CMTS Core contains the DOCSIS MAC and the upper layer DOCSIS protocols. This includes all signaling functions, downstream and upstream bandwidth scheduling, and DOCSIS framing. The DOCSIS functionality of the CMTS Core is defined by the existing DOCSIS Specifications. The EQAM Core contains all the video processing functions that an EQAM provides today.

The Remote PHY Device contains mainly PHY related circuitry, such as downstream QAM modulators, upstream QAM demodulators, together with pseudowire logic to connect to the CCAP Core. The RPD platform is a physical layer converter whose functions are:

- To convert downstream DOCSIS, MPEG video and OOB signals received from a CCAP Core over a digital medium such as Ethernet or PON to analog for transmission over RF or linear optics.
- To convert upstream DOCSIS and OOB signals received from an analog medium such as RF or linear optics to digital for transmission over Ethernet or PON to a CCAP Core.

7.3 Remote MAC-PHY Overview

The Remote MAC-PHY technology moves both the DOCSIS MAC and PHY layers down to the Remote/Fiber Node. The link between the Headend and the node is essentially a Layer 2 connection using Ethernet or various PON technology. There are two options for this, which are different based on how video is handled. In both cases the data forwarding CMTS functionality is at the remote node. A compact CMTS is deployed at the fiber node and the CMTS NSI connects through the digital optical network back to the cable headend. Based on where video EQAM functionality is placed, there are two options, as described below:

- Remote CCAP
- Remote CMTS+Divided EQAM.

Remote CCAP: The Remote CCAP term applies to an architecture where both the data and the video functions are moved to the Remote node. The CMTS functionality and the EQAM functionality are completely moved to the Fiber Node, and hence the term Remote CCAP. The video and data transit the L2 Ethernet link like any other IP traffic. The video and data need to be encrypted to protect from unauthorized access at the Remote node.

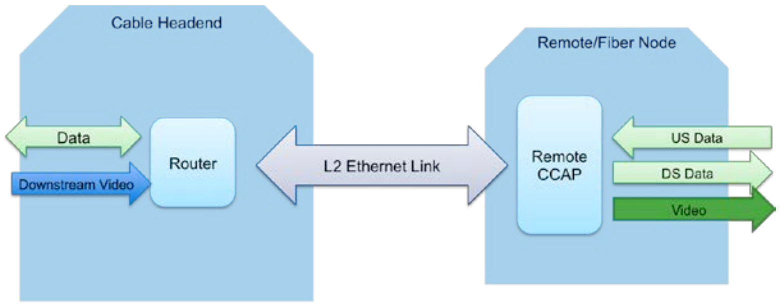

Figure 4 - Remote CCAP High level Architecture

Remote CMTS + Split EQAM: The Remote CMTS term applies to an architecture where only the data/CMTS functionality is moved into the remote node. The video/EQAM functionality is divided between the headend and the remote node, as in the Remote PHY architecture. The video MPEG packet processing is handled in the headend by an EQAM core device and the EQAM PHY inside the Remote CMTS handles the modulation of the video onto the wire.

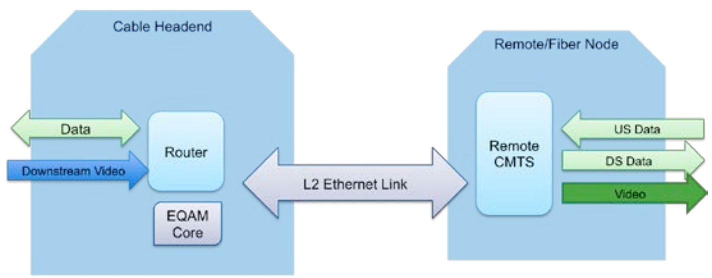

Figure 5 - Remote CMTS + Split EQAM High level Architecture

7.3.1 Remote MAC-PHY and Remote PHY: Video and OOB

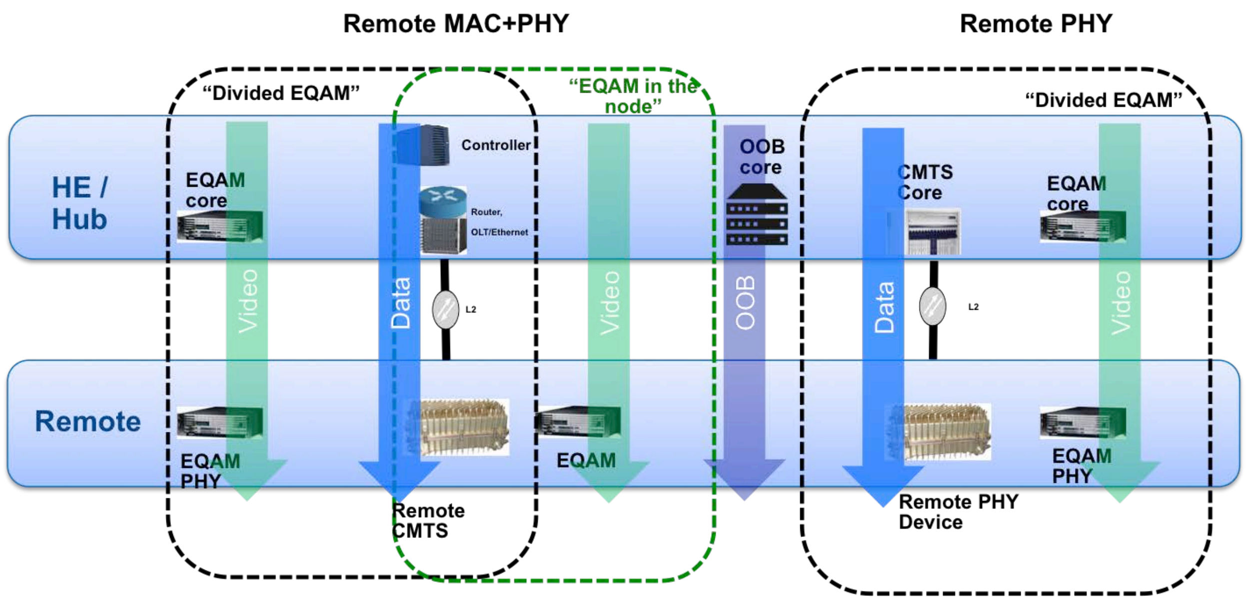

Figure 6 - Video EQAM Options for Remote MAC-PHY vs. Remote PHY

Figure ***6*** above illustrates options for the EQAM in an Remote MAC-PHY architecture and a Remote PHY architecture. For the Remote MAC-PHY architecture, the EQAM functionality can be "divided" between headend and the remote location ("Split EQAM") or can be completely located at the remote location ("EQAM in the node"). For the "Split EQAM" case, the EQAM core device is at the headend and EQAM PHY is at the remote location. For the Remote PHY architecture, the EQAM functionality correspondingly (to the CMTS functionality) has the EQAM PHY at the remote location and the EQAM Core at the headend. The Out-of-band (OOB) data for both architectures are handled similarly with an OOB core in the headend and the modulation of the OOB data at the RPD/RMD

7.4 C-DOCSIS II

The C-DOCSIS Architecture as specified in [CDOCSIS] describes a distributed CMTS architecture realized with a Coax Media Converter (CMC) and the CMC Controller interconnected via a layer-2 or layer-3 network.

In this architecture the lower layer functions are implemented in the node using a Coax Media Converter (CMC) with the upper layer functions implemented in a controller located in the headend or hub. The C-DOCSIS Type II CMC implements the data forwarding and RF PHY layer functions, and the Type II CMC controller implements the system management, configuration, and scheduling functions.

The CMC Controller is deployed in the hub to realize centralized system management, configuration, and scheduling, thus enabling the distributed CMTS to inherit the advantages of a centralized DOCSIS CMTS system. The CMC is deployed in the optical node, enabling the CMTS to introduce the space-division multiplexing on top of the time-division multiplexing and frequency-division multiplexing utilized by the centralized DOCSIS CMTS to achieve higher access bandwidth per user, which is highly desirable for the applications with large upstream bandwidth consumption. With the distributed deployment of CMC and coupled with the technical advantages of the digital optical packet network, the system can fully utilize the resources of the HFC network and existing CMs to realize a cost-effective system deployment and operation, reduces the return path noise and enhances the CMTS downlink channel SNR, and is thus able to implement a higher order modulation scheme to obtain higher bandwidth.

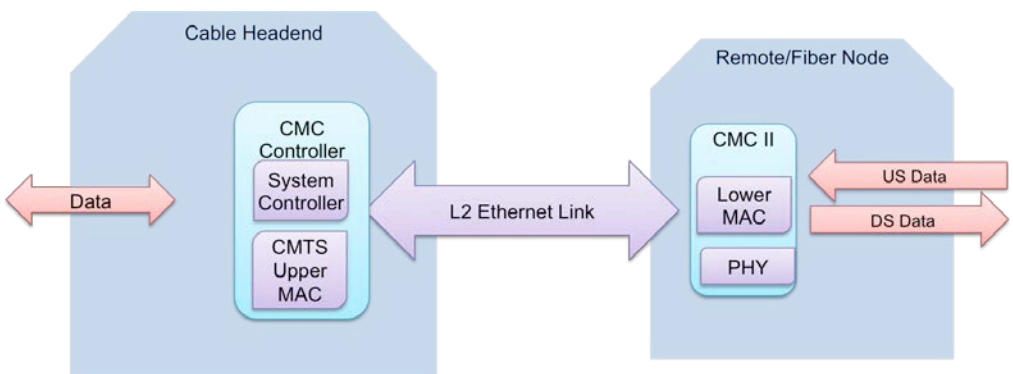

Figure 7 - Split-MAC (C-DOCSIS II) High level Architecture

8 REMOTE PHY

8.1 Overview

Remote PHY [R-PHY] is a modification of the current CCAP architecture in which the PHY component is removed from the CCAP platform and moved into a separate Remote PHY Device (RPD). The RPD is connected to the CCAP Core (CCAP minus the R PHY) by an IP network. The combination of CCAP Core and RPD provides the functional equivalent of the integrated CCAP. Essentially R-PHY takes the digital interface between the MAC and the PHY components in the CCAP and extends it over the IP network to the RPD using pseudowire technology as shown in Figure 8 and Figure 9.

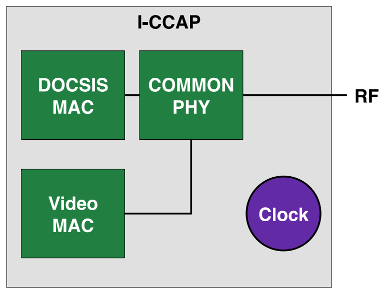

Figure 8 - Integrated CCAP

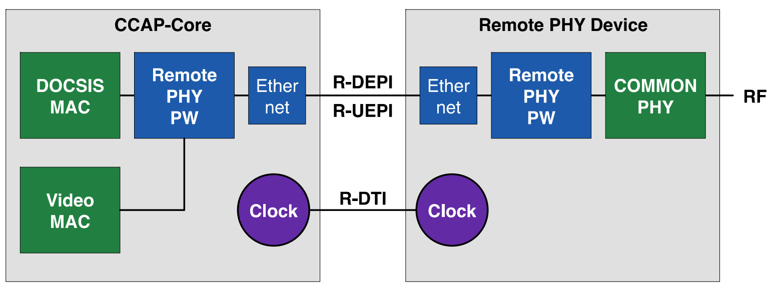

Figure 9 - Remote PHY

This has the effect of moving the digital to RF conversion from the CCAP core, located in the headend or hub, to the RPD located deeper in the network, such as in a fiber node. Standard digital optics (e.g., Ethernet) can be used for the CCAP to RPD link in place of the analog optics previously used. RF over coax or analog fiber is used for the RPD to CM link, which is now much shorter. This extends the all-digital IP network deeper into the plant providing advantages in lower cost, simpler operation and better performance. The migration of the physical layer from the CCAP to the RPD is transparent to the external DOCSIS infrastructure and CPE so that this can be used unchanged as shown in Figure 10.

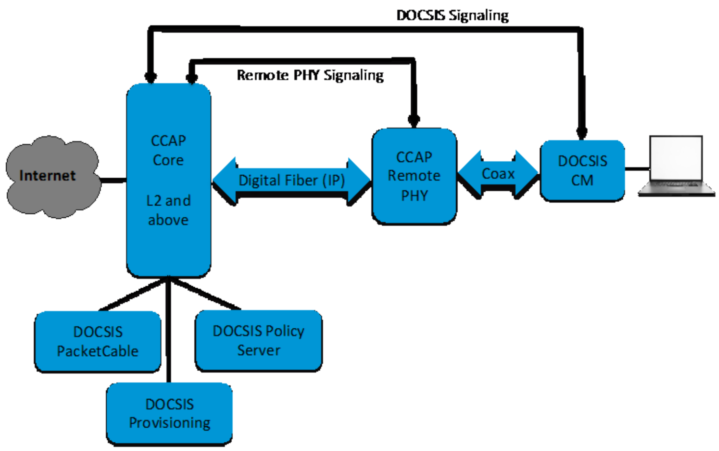

Figure 10 - RPD Deployment

For a more in-depth view of R-PHY refer to [R-PHY].

8.2 Data plane

The R-PHY data plane consists of a set of pseudowires linking the CMTS cores with the RPDs. These are implemented as a DEPI tunnel overlay on top of an L2 or L3 interconnect network.

DEPI is an IP Tunnel that exists between the DOCSIS or MPEG Video MAC in the CCAP-Core and the PHY that exists in the RPD. It takes either formatted DOCSIS frames or MPEG packets, transports them through the network and delivers them to the RPD for transmission.

The base protocol that is used for the DEPI is the Layer 2 Tunneling Protocol, version 3, or L2TPv3 for short. L2TPv3 is a standard IETF protocol for creating a pseudowire.

8.2.1 R-DEPI

R-DEPI, the Downstream External PHY Interface, is the downstream interface between the CCAP-Core and the RPD. It is an IP pseudowire between the MAC and PHY that contains both a data path for DOCSIS frames, video packets, and OOB packets, as well as a control path for setting up, maintaining, and tearing down sessions.

The control path allows for signaling messages to be sent between the CCAP-Core and the RPD. Typical control messages will set up a "control connection" between the CCAP-Core and the RPD, and then set up multiple data sessions (one for each downstream and upstream QAM or OFDM channel). Each session can be marked with different Differentiated Services Code Points (DSCPs) and can support different encapsulation protocols.

There are two main data pseudowire techniques defined by R-DEPI with each main supporting a variety of subtypes:

- MPEG Transport (MPT) mode transports multiple 188-byte MPEG-TS packets by placing them into the L2TPv3 payload. The encapsulation of DOCSIS frames into MPEG-TS packets is performed in the CCAP-Core.
- Packet Streaming Protocol (PSP), transports DOCSIS frames directly in the L2TPv3 payload. The DOCSIS frames are then encapsulated in MPEG-TS packets within the RPD. PSP mode allows DOCSIS frames to be both concatenated, to increase network performance, and fragmented, in case the tunneled packets exceed the network MTU size.

MPT mode is generally used for single carrier QAM systems such as DOCSIS 3.0 and video, while PSP mode is used for downstream OFDM channels and for the DOCSIS upstream.

8.2.2 R-UEPI

R-UEPI, the Upstream External PHY Interface, is the upstream interface between the RPD and the CCAP-Core. Like R-DEPI, it is an IP pseudowire between the PHY and MAC that contains both a data path for DOCSIS frames, and a control path for setting up, maintaining, and tearing down sessions.

It uses the same control plane structure as R-DEPI with a different set of encapsulations in the upstream direction.

R-UEPI takes DOCSIS frames that have been received and demodulated by the DOCSIS upstream PHY in the RPD and transports them to the CCAP-Core for processing. The RPD does not provide any upstream DOCSIS processing; with one minor exception, the RPD will extract the bandwidth request frames from the DOCSIS stream and send them in a separate pseudowire so that bandwidth request frames can be given a higher priority than data frames.

8.3 Control plane

The RPD operates as a slave device from the CCAP core. It is controlled from the core using the GCP (Generic Control Plane) protocol.

8.3.1 GCP

GCP is a generic control plane protocol that exists between a master entity and a slave entity. The GCP master (CCAP Core) initiates reads and writes to the GCP slave (RPD). The GCP slave can initiate a notify message to get the attention of the GCP master entity. This is shown in Figure 11.

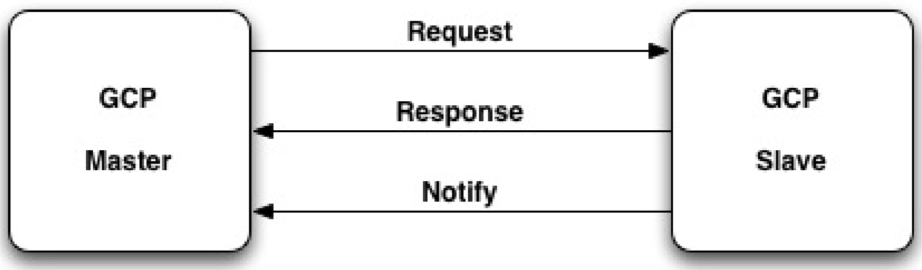

Figure 11 - GCP Block Diagram

GCP also has a peer-to-peer mode that permits both endpoints to simultaneously be both masters and slaves. The peer-to-peer mode is really just two independent master-slave nodes, in opposite directions, on the same port number.

When used in R-PHY GCP uses TCP/IP as its transport to provide a reliable connection that is independent of the connection network.

8.4 Video

In the R-PHY architecture the CCAP-Core performs the vast majority of the EQAM functions and the RPD perform minimal functions. Thus the CCAP-Core receives SPTS or MPTS streams, multiplexes the streams, and generates an MPEG-compliant MPTS stream that is then transported over R-DEPI to the RPD. The RPD performs de-jittering to handle any jitter that the intervening network has introduced and transmits the MPEG frames to the HFC.

8.4.1 CCAP-Core Video Functions

The CCAP-Core receives SPTS or MPTS streams and outputs MPTS streams. It performs the classical EQAM functions such as: de-multiplexing, PID remapping/filtering, multiplexing, PSI parsing and re-generation, de-jittering, clock recovery and PCR re-stamping, NULL packet insertion, and encryption. After performing all these functions, the CCAP-Core outputs a constant bit rate multiplex output and transports the multiplexed stream over R-DEPI, with up to 10 MPEG packets in one R-DEPI packet.

8.4.2 RPD Functions

The RPD receives constant bit rate MPTS streams which themselves may contain streams for VoD/SDV/Broadcast applications. The RPD is unaware of any individual video sessions, or their setup and teardown. The rate of the incoming MPTS stream is signaled to the RPD from the CCAP-Core via the control plane.

The incoming MPTS stream is de-jittered to remove any jitter that was introduced in the intervening network and any lost packets are detected. There are two potential operating modes:

- The RPD may be synchronized to the CCAP-Core in which case lost packets are simply replaced by NULLs.
- The RPD and core are not synchronized in which case the RPD adjusts the PCR timestamps to account for any NULL packets added or deleted.

8.5 Security

The R-PHY architecture requires MSOs to deploy a large number of IP networking devices (the RPDs) into inherently unsecure portions of the network, such as pole mounted nodes and remote cabinets. This extension of IP deeper into the plant exposes the network to a number of security threats such as unauthorized network access, loss of customer privacy, theft of service and denial of Service attacks on the network itself.

To mitigate these threats, R-PHY specifies a number of security options for:

- Authentication of the RPD prior to access to the network
- Mutual authentication of CCAP Core and RPD
- Protection of control and data paths between CCAP core and RPD.

8.5.1 Network Access

When an RDP boots up, it must try to authenticate to the network using 802.1x. 802.1x is a port based access mechanism used with Ethernet switches. Each port on the switch may be either fully open, fully blocked or allow a subset of packets only, e.g., for device management. When the RPD is first connected to a switch port it may receive restricted or no access to the trusted network (depending on switch configuration). 802.1X messages are exchanged to identify the RPD. Identification is based on digital certificate credentials issued from the Cablelabs public key infrastructure (PKI) which are securely installed during RPD manufacture. When the switch confirms that the RPD is authorized for the network it will unblock the port. As part of the 802.1x exchange the switch may require the use of MACsec (a link layer encryption protocol) between the switch and the RPD.

8.5.2 Core to RPD Security

After the RPD gains access to the network it connects to the CCAP Core. As a first step in this process the CCAP Core and the RPD perform mutual authentication based on Cablelabs PKI certificates. The CCAP core configuration determines the level of security that will be applied to the control session to the RPD. Control plane security uses IPsec and may be authenticated, encrypted or left in the clear.

In the R-PHY architecture DOCSIS BPI+ processing occurs in the CCAP Core. Thus the data plane traffic is encrypted from the core to the cable modem and no further protection is needed.

8.5.3 S/W Download

Remote PHY architecture supports downloading code to RPDs. The methods used for secure software download have been based on the [SECv3.1]. Broadly speaking, with respect to secure software downloads; the RPD assumes the functions of a DOCSIS cable modem. The RPD code is signed with a certificate from the Cablelabs PKI and then validated by the RPD. It is envisioned that such an approach will allow the operators to reuse the majority of the OSS infrastructure deployed for CM software and security certificate management to perform equivalent functions for RPDs.

8.6 OOB

A number of OOB mechanisms are defined to support any traffic that is not DOCSIS or MPEG video. This includes primarily set-top control traffic based on SCTE55-1 and 55-2 but can also support other traffic such as generic analog signals. The OOB data path uses L2TPv3 tunneling to isolate the OOB traffic from the DOCSIS and MPEG Video traffic.

8.6.1 NDF

Narrowband Digital Forward (NDF) digitizes a portion of the downstream analog spectrum at the headend, sending the digital samples as payload in DEPI packets to the RPD, and then re-creating the original analog stream at the RPD. This approach works with any type of OOB signal as long as the signal can be contained within the defined pass bands.

8.6.2 NDR

The Remote PHY narrowband digital return (NDR) is the upstream equivalent of NDF. In this case the RPD digitizes a portion of the upstream analog spectrum, sending the digital samples as payload in UEPI packets, and then re-creating the original analog stream at the headend.

8.6.3 SCTE 55-1

SCTE 55-1 support in RPDs is implemented using the NDR and NDF mechanisms.

8.6.4 SCTE 55-2

For SCTE 55-2 support the existing SCTE 55-2 modulator/demodulator hardware and RF combining circuitry deployed in legacy headends are replaced with small-scale SCTE 55-2 modulator/demodulator functions embedded in each RPD. The high-level MAC functionality resides in an external server. L2TPv3 tunnels transport the data between the server and the RPD.

8.7 Timing and Synchronization

The Remote DOCSIS Timing Interface [R-DTI] is the timing specification standardized for R-PHY architecture

The CMTS Core and the RPD are two entities located in separate chassis, and potentially in different physical locations. The DS PHY and US PHY are located on one assembly—the Remote PHY Device—controlled with a common clock. The upstream scheduler/MAP builder is part of media access control (MAC), and is located at the CMTS Core. The DOCSIS time described by the MAP needs to allow correct burst reception at the RPD. Therefore the CMTS Core and the RPD need to have a common knowledge of the DOCSIS time. R-DTI supports both the basic synchronization between the CCAP-Core and Remote PHY Device required for DOCSIS/video/OOB services and the precision time synchronization required for emerging services such as wireless backhaul.

R-DTI leverages IEEE1588v2 Precision Time Protocol (PTP) to replace the DTI infrastructure used for M-CMTS. IEEE 1588v2 is a hierarchical, master-slave architecture for clock distribution using a packet-based two-way message exchange protocol for synchronizing clocks to enable accurate time distribution over a network. Timing signals from a Grand Master (GM) clock are propagated through the network to the slaves. The protocol provides for timing adjustments to compensate for transmission time.

R-DTI can operate is several modes.

- The RPD may be the clock master with the core operating as a slave
- The CCAP Core can act as a clock master with the RPD as a slave
- Both RPD and core may operate as slaves to an external clock master.

8.8 OSS Considerations

This section outlines some key points relating to OSSI for the RPD. A detailed description can be found in [R-OSSI].

8.8.1 RPD as Slave to CCAP Core

In an integrated CCAP the PHY devices are integral with the system. With R-PHY these PHY devices are now remote but continue to operate under control of the CCAP core. Thus the normal mode of operation for the RPD is that it is a slave device to a controlling CCAP core. This master slave model is also used for OSS operations. The back office systems interface with the CCAP core using existing interfaces such as CLI scripts, XML configuration files, NETCONF or SNMP. The core then uses GCP to communicate with the RPD to set or get the data needed to complete the operations. The data model for the CCAP core is extended with additional RPD parameters RPD as required, but existing CCAP management infrastructure and practices continue to be used. This allows a CCAP core to serve as the single point of configuration for the resources (e.g., RF ports and channels) on all the RPDs connected to it.

8.8.2 Initial Configuration

It was a design goal that the RPD should operate “out of the box” with no pre configuration required. To achieve this it uses DHCP to obtain its IP address and the address of a controlling CCAP core. It then establishes a connection to the core and retrieves configuration information via GCP. Thus, operator configuration of the RPD is performed indirectly via configuration of the CCAP-Core.

8.8.3 Authentication

As the RPD may be located in an unsecure location all OSS operations are subject to authentication and security measures as described in Section 8.5.

8.8.4 Directly Managed RPD

The RPD is an IP networking device and as such may be managed directly. This is expected to be the exception rather than the rule, e.g., when a connection to the controlling core cannot be established. Two mechanisms are proposed for direct access:

- CLI via a local console or SSH connection
- An embedded SNMP agent and a set of MIBs as described in the RPD OSSI specification

9 REMOTE MAC-PHY

9.1 Overview

There are multiple ways to build an R-MACPHY distributed CCAP solution. Figure 12 highlights the common components of all the options. The distinguishing element in this architecture is the R-MACPHY Device (RMD) which could replace the traditional analog fiber node, or be located elsewhere deeper in the HFC network.

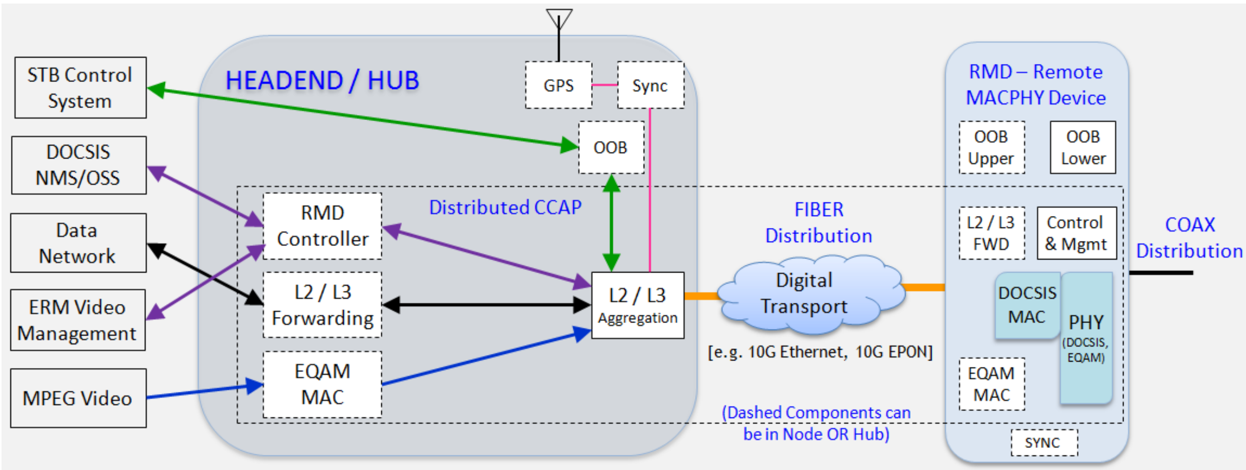

Figure 12 - Remote MAC-PHY System Architecture

The Remote MAC-PHY architecture moves both the DOCSIS MAC and PHY layers out to the RMD. The connection between the Headend and the RMD is essentially a Layer 2 Ethernet connection.

From a downstream perspective, an RMD accepts data from a hub-located L2 aggregation device. This includes data, video and also digitized signal sequence from an external OOB converter. From the upstream perspective, RMD collects data from the associated cable modems (CM) and STBs, and forwards it to the hub aggregation device and STB control system via the OOB channel. Within this architecture, the exact partition and functionalities for configuration and management, video, data, security and OOB are discussed in more detail in later sections.

The DOCSIS MAC and PHY layer functionality is integrated and located within the RMD. The various approaches to R-MACPHY differ in the additional functions that are included in the RMD. Functions that are candidates to be included in the RMD, or which may be located in the hub, are shown in dashed boxes in Figure 12.

9.2 Data Plane

The typical first point of contact for the RMD in the Hub is an L2 and/or L3 aggregation device.

The normally expected Layer 2 digital transport connection from the Hub to RMDs are via optical fiber. The access distribution architectures that are most likely to be implemented to backhaul RMD traffic are xEPON (EPON, 10G-EPON), xGPON (GPON, NG-PON2), optical Gigabit Ethernet (GE) and optical 10G Ethernet.

The DOCSIS MAC + PHY functionality is always located in the RMD, with the direct coupling between the DOCSIS MAC and the DOCSIS PHY contained within the RMD. The number of supported downstream and upstream channels and the upstream/downstream split frequency may vary between different implementations. In many cases, these key features are likely to be configurable over the allowed upstream and downstream frequency ranges, as defined in the [PHYv3.1] and related DOCSIS specifications.

The RMD may or may not support the CMTS L2/L3 forwarding component. If it does not support it, then all data traffic may be tunneled to the L2/L3 component in the Headend/Hub where the forwarding decisions are made.

If the forwarding component is in the RMD, it could be L2 only, L3 only or a combination of L2/L3 Forwarding.

If the entire CCAP functionality is pushed out to the RMD, then this variation is referred to as Remote CCAP (R-CCAP).

In all the RMD architecture variations, since the MAC and PHY are collocated, there is no difference in QoS from a traditional centralized CCAP environment operating the DOCSIS network. All current QoS mechanisms of CCAP/CMTS are directly applicable to the RMD architecture in the Coax-Access segment.

9.3 Control Plane

All R-MACPHY devices are expected to contain a management entity to allow control of various configurable features and to report maintenance and diagnostic information back to the DOCSIS management system in the Hub. Currently, there is no standardized management interface to control RMD devices unless the RMD management interface complies directly with the current DOCSIS 3.1 and CCAP OSSI suite for data control and for video control.

Currently the management objects and commands to control mechanism between hub and RMDs uses vendor specific management objects and protocols. The standardization of this management interface has been discussed as a possible future CableLabs specification project.

9.4 Video

Video EQAM service can either be delivered via analog fiber or digital fiber or hybrid mode within the Remote MAC-PHY architecture.

In analog fiber, all video signals, including analog and digital video signals, can be delivered to remote node via an analog fiber or analog wavelength (i.e., RF overlay).

In hybrid mode, analog and digital broadcast video signals are delivered to the remote node via an analog fiber or analog wavelength (i.e., RF overlay), while digital narrowcast video services are transmitted in IP packets and through digital fiber to Remote MAC-PHY Device.

There are two options in terms of digital video delivery for R-MACPHY:

1. Remote EQAM: where the entire EQAM MAC and PHY for both narrowcast and broadcast video services is embedded in the remote node.
2. Split EQAM: where EQAM MAC functions are in the Headend/Hub and EQAM PHY (e.g., QAM modulator) is in the RMD.

Another essential element of the Distributed Architecture is broadcast conditional access scrambling, which is used to encrypt broadcast video. Conditional access is deployed in order to secure both service and content from theft or unauthorized viewing. Operators are strongly encouraged to work with their current CAS vendors to provide a commercially feasible adaptation for DCA.

9.5 Security

The security architecture for R-MACPHY is the same as R-PHY and uses a lot of the same mechanisms. The security features and functions that are specific to Remote MAC-PHY and are different from R-PHY are summarized below:

- The BPI+ protection of user traffic occurs only between the CM and remote device (RMD). This is because the CMTS MAC layer functionality has been moved from the CCAP Core to the RMD. Therefore, the data link between the RMD and CCAP Core will need to be secured to protect user traffic.
- A digital certificate public key infrastructure (PKI) is used to authenticate devices when setting up secure connections. R-MACPHY uses the same PKI as R-PHY.
    - The certificates used for securing the BPI+ link between the CM and RMD (effectively the CMTS) are defined in the [SECv3.1]. These certificates are also issued from the same root CA and intermediate CAs

(Device CA and CVC CA) as R-MACPHY certificates. When the RMD receives CM certificates it will validate them according to the DOCSIS 3.1 Security specification.

- Certificates are exchanged when authentication occurs between the Headend/Hub, AAA server, and RMD. The receiving entity will verify that the certificates have been issued by a root trust anchor using Basic Path Validation procedures defined in RFC 5280. During the certificate validation process revocation status is checked to see if a certificate has been revoked before it has expired. If certificate validation fails, the secure connection attempt will be rejected with an error message returned. When authentication fails the RMD will periodically re-attempt establishing a secure connection using a random interval.

- To protect user traffic across the data link between the RMD and the headend/hub, this link will need to be secured. IPsec is used to protect both user data traffic and L3 management and control traffic between the L2/l3 aggregation device in the headend and R-MP device.
- Since L2 management may be used to manage R-MP device, MACSec can be used to protect L2 management traffic between the headend and R-MP device.
- If entities such the controller and DOCSIS OSS/BSS exist outside the headend/hub trusted domain, their interface connections to the Headend/Hub should be secured using a protocol such as TLS, DTLS or IPSec.

9.6 OOB

When RMDs are deployed in certain regions (particularly North America), support for the downstream and upstream legacy set-top-boxes (STB) RF control channels are required. This is often referred to as OOB, or Out-of-Band, since these narrow-band RF channels normally lie outside of normal QAM video or DOCSIS data RF channels. These signals are commonly distributed over the coaxial networks, which include:

- STB two-way communication – SCTE 55-1, SCTE 55-2
- HFC outside plant status monitoring – SCTE 25
- Broadcast FM radio
- Specialized test signal injection

The implementation for each of the OOB signals in a Remote MAC-PHY system follows the same general philosophy as used with the Remote PHY distributed access architecture as detailed in [R-OOB]. R-OOB specifies the following mechanisms:

- Narrowband Digital Forward (NDF) – transport of streams of digitized samples of narrowband downstream signals suitable for all OOB signals with some constraints for SCTE 55-2.
- Narrowband Digital Return (NDR) – transport of streams of digitized samples of narrowband upstream signals suitable for all OOB signals with some constraints for SCTE 55-2.
- SCTE 55-1 native mode – implementation of PHY modulation and demodulation functions in the RMD.
- SCTE 55-2 native mode – implementation of PHY modulation and demodulation functions in the RMD plus some low level time-critical MAC functions due to the unique timing constraints in the protocol.

In the case of NDR/NDF approach, OOB signals are transported using UDP or RTP is discussed.

The native mode approach is contingent on further development in corresponding R-PHY specification.

9.7 Timing & Synchronization

Since the DOCSIS MAC and PHY are both co-resident in the RMD, there is no hard requirement for distributed synchronization and timing for DOCSIS data services.

The typical Customer Premise Equipment (CPE) requirement for network level frequency and phase synchronization is for Mobile Backhaul (MBH) applications, where some level of frequency or phase traceability is needed for virtually all the current cellular standards. As a side benefit, the delivery of high-quality network-traceable frequency/phase synchronization to the RMD could also be used, if needed, for any EQAM retiming requirements.

One of the desired use cases for the RMD is for backhauling traffic from connected eNodeB-type cellular terminals connected to the RMD via Cable Modems. One key requirement of all known Mobile Backhaul (MBH) equipment is the ability to provide network-traceable frequency synchronization to connected eNodeBs, and in many cases, depending on the cellular standard, to also provide a precise phase synchronization reference to the cellular equipment. The precise phase reference most often used is UTC-traceable timed to a very high precision.

The most popular way to transport both frequency synchronization and precise phase/time over an L1/L2 network is via IEEE1588 protocol. Thus, it is likely that the RMD contains an IEEE1588 slave clock, and be required to transfer the received precise frequency and phase reference to the connected CMs using the DOCSIS Time Protocol (DTP) The RMD may also support a northbound Synchronous Ethernet [SyncE] interface for enhanced frequency and phase synchronization performance.

9.8 OSS considerations

R-MACPHY Devices need to be configured and managed, and report maintenance and diagnostic information back to the DOCSIS management system in the Hub. Currently, they can comply directly with [CCAP-OSSI].

There are two ways to manage R-MACPHY devices:

- Direct management using NMS/OSS. In this case the R-MACPHY device needs to have an IP address for management. It also needs to comply with DOCSIS OSSI requirements.
- Management using a centralized controller. The controller intercepts OSS/NMS messages and converts them to the L2/L3 messages that R-MACPHY device can handle. The main advantage of using a controller is that it alleviates the need for the R-MACPHY device to support all DOCSIS OSSI requirements.

The first approach is geared toward the Remote CCAP architecture, where highly integrated small scale CCAP is desired. The second approach is for those who want to maintain centralized control and management entity.

9.9 RMD – Example Configurations

Section 12 of the Remote MAC-PHY Technical Report includes the following examples of distributed architecture variations:

- RMD Minimal Configuration
- RMD with Embedded EQAM
- Remote CCAP (R-CCAP)
- Remote CCAP with Centralized Controller

Each of these example D-CCAP architectures is similar, but differ in the location of the functional blocks between the Hub and the remote location.

10 C-DOCSIS II (SPLIT-MAC) ARCHITECTURE

10.1 C-DOCSIS Introduction

C-DOCSIS is specified by Cablelabs [CDOCSIS] specification. C-DOCSIS presents a logical architecture of distributed deployment and centralized management for the cable broadband access system. C-DOCSIS defines the CMTS with a Coax Media Converter (CMC) and the CMC Controller to achieve the DOCSIS CMTS functionality, as shown in Figure 13. The CMC Controller and CMC can be interconnected via a layer-2 or layer-3 network, such as digital optical packet network.

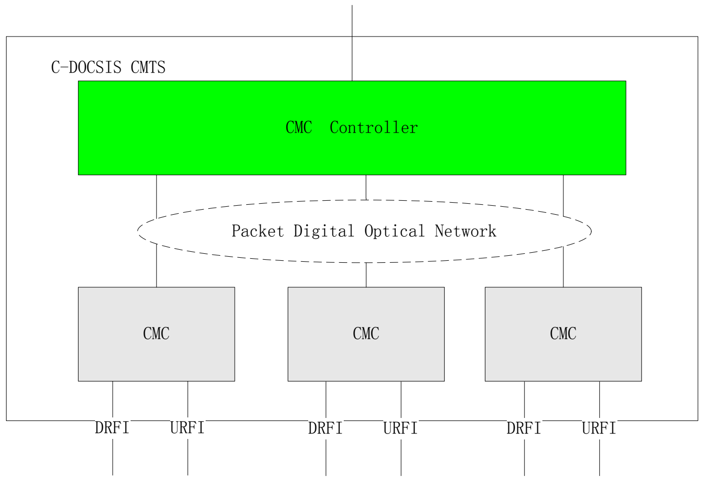

Figure 13 - Components of a C-DOCSIS Distributed CMTS Architecture

The CMC implements the RF interfaces specified by the Annexes titled "Additions and Modifications for Chinese Specification" in [MULPIv3.0]. The CMC Controller is deployed in the central office or headend to forward upstream and downstream service data and realizes the centralized system management, configuration, and scheduling, thus enabling the distributed CMTS architecture. The distributed CMTS connects to a metropolitan area network (MAN) through the CMC controller device, which can be an optical line terminal (OLT), an Ethernet switch, or a router.

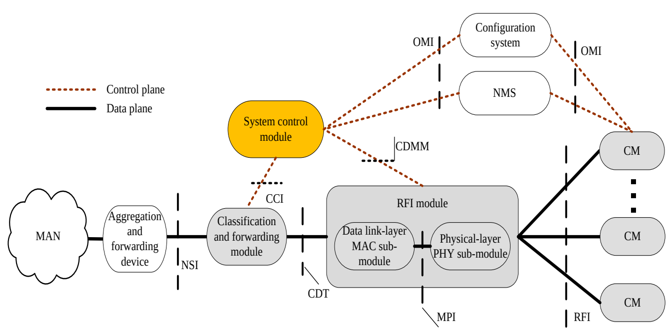

Figure 14 - Functional Modules of a Distributed CMTS Architecture.

The **RFI module** implements the functions of the data link-layer MAC sub-module and the physical-layer PHY sub-module.

The **System control module** is responsible for Configuration and management of the RFI module and the classification and forwarding module. This module can be part of the CMC, CMC controller or run in a virtual machine in the data center.

The **Classification and forwarding modul**e classifies downstream traffic based on header fields and inserts C-DOCSIS Data Tag (CDT) to identify service flow for the RFI module. For upstream data flows, the RFI module inserts a CDT into the Ethernet frame header in the data packet to identify the service flow. The classification and forwarding module MUST be able to map the CDT to the service flag, such as S-VLAN or MPLS tag, IP ToS, and Ethernet LLID of the aggregation network and forward data to the network side.

There are three types of CMC devices:

The CMC type I device contains the classification and forwarding module, the RFI module, which includes the data link layer MAC sub-module and the physical layer PHY sub-module, and the system control module. CMC type I is the same as Remote MAC-PHY See Section 8.

The CMC type II device contains the DOCSIS MAC and PHY and the CMC controller contains the classification and forwarding module and the system control module to implement the following functions: service flow classification and forwarding, configuration and management of CMC II devices, and configuration and control of services. Figure 15 shows the C-DOCSIS architecture which uses CMC type II device. This architecture is called Split-MAC architecture since the classification and forwarding module is not collocated with the MAC sub-module in the CMC device.

The CMC type III device only contains the DOCSIS PHY. CMC type III is the same as Remote PHY. See Section 8. The CMC Controller III device contains the classification and forwarding module, the data link-layer MAC sub-module, and the system control module to implement the following functions: classify and forward service data, implement data link-layer MAC framing, control system protocols, configure and manage services, and manage the system and devices.

10.2 C-DOCSIS II (Split-MAC)

The C-DOCSIS II system [CDOCSIS] consists of the CMC Controller II device, CMC II devices, and CMs. The CMC Controller II device works with the CMC II devices to implement CMTS functions. In this architecture, the CMC Controller II device contains the classification and forwarding module and the system control module to implement the following functions: service flow classification and forwarding, configuration and management of CMC II devices, and configuration and control of services. The CMC Controller II device is deployed at the hub site. The CMC II device contains the RFI module, including the data linklayer MAC sub-module and the physical-layer PHY sub-module, to implement the data link-layer MAC framing as well as data modulation and demodulation on the physical layer.

The CMC II devices and the CMC Controller II device use the CDT and CDMM specified in C-DOCSIS to mark service flows and to control and manage services. The CMC II device communicates with CMs through the RFI interface to implement HFC network communication. The CMC Controller II device connects to the aggregation networks through the NSI to forward data flows and map services. The CMC Controller communicates with the configuration system and the NMS through the OMI interface over IP channels provided by the aggregation network to configure services and manage the network. The CMC Controller II device communicates with the policy server to perform operations on dynamic service flows.

In a system implementation, the CMC Controller II device can be either a separate device or a component integrated in an aggregation and switching device, such as a router, a switch, or an OLT.

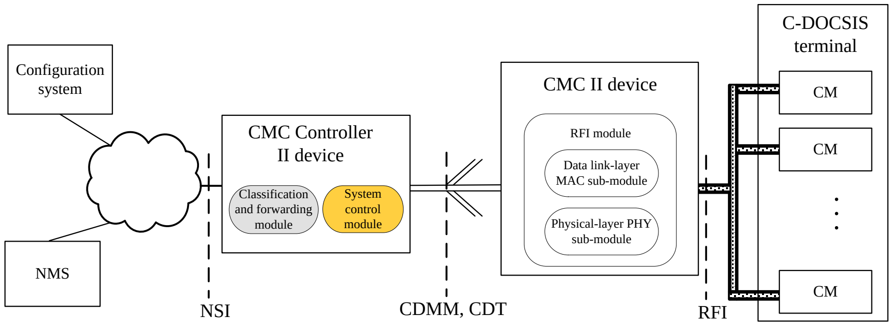

Figure 15 - C-DOCSIS II System

10.2.1 C-DOCSIS II Variations

There is a variation of C-DOCSIS architecture that can be used to create a R-MACPHY system. In this variation the system control module is implemented by the CMC controller and the classification and forwarding module is located in the remote CMC device. See Section 9.

In this R-MACPHY architecture CMC controller contains the system control module, and the classification and forwarding module is collocated with the MAC sub-module in the CMC device.

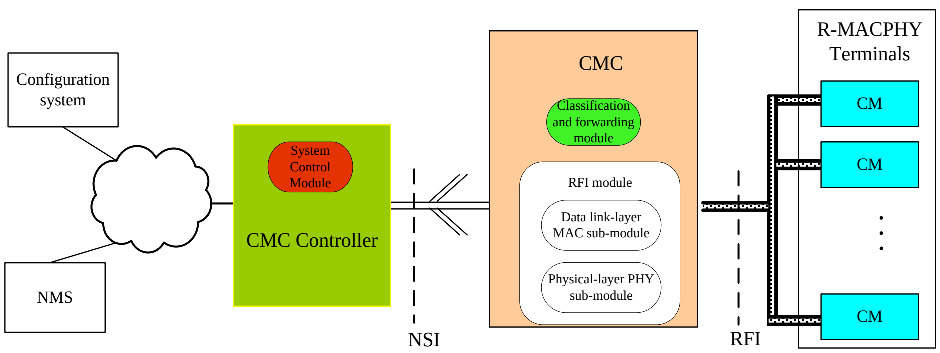

Figure 16 - R-MACPHY Architecture based on C-DOCSIS Specification

The CCI is the control interface between the system control module and the classification and forwarding module. The C-DOCSIS spec does not define the message format for this interface because these two modules are always built within the same device, either in a CMC device or a CMC controller. Since this is not the case in the configuration shown in Figure 16, and because CDMM as defined in this spec does not define the CCI message format, vendors who support this configuration do not use CDMM; instead they use their own proprietary protocol between the system control module and CMC.

11 OPERATIONAL CONSIDERATIONS

This chapter focuses on the new challenges DCA brings to an operator network.

11.1 DCA Operational Considerations

Deployment of distributed CCAP architectures shifts equipment, traditionally managed and serviced in the hub, to locations on the plant traditionally serviced by field technicians that are accustomed to working with outside plant equipment (nodes, amplifiers, taps, power supplies, etc.). Minimizing the knowledge required by those field technicians to install, replace and service distributed access devices is crucial to minimizing operational expenses and preserving the division of labor and responsibilities.

The installation, provisioning, troubleshooting and maintenance procedures for distributed CCAP devices should factor in the following considerations:

- Focus field technician tasks on installation, replacement and basic troubleshooting of plant electronics, avoiding software configuration or troubleshooting in the field
  - Hardware installation – mounting, cabling, powering, network connectivity, and RF signal adjustment
  - Hardware troubleshooting – identifying and replacing failed components, or entire device when service could not be restored using remote software management tools
  - Hardware upgrades –swapping modules or components as required for performance or capacity upgrades
- Focus headend/hub technicians on software configuration and troubleshooting of the device using remote management tools
  - Initial configuration and provisioning of distributed devices
  - Troubleshooting faults and issues related to software operation or configuration issues, including low level direct access to the remote device
  - Software upgrades or configuration updates as required for performance or capacity upgrades

11.2 OSS Considerations

The centralized CCAP architecture includes northbound OSS interfaces specified in [CCAP-OSSI]. Distributed CCAP architectures are also expected to support the same northbound OSS interfaces but there are some subtle differences in implementation:

- Extensions to the CCAP-OSSI data models including items such as those included in [R- OSSI]: additional parameters needed for splitting functions across multiple physical devices, additional RF configuration items suitable to nodes, OOB functions, etc.
- Northbound interfaces for various functions may be distributed across multiple devices (independent CCAP Cores for Remote PHY).
- Direct connection to many remote devices (some Remote MAC-PHY implementations).
- Abstraction of the OSSI northbound interfaces through a centralized Controller (some Remote MAC-PHY implementations).

The nature of distributed CCAP architectures will include a substantial increase in the number of physical devices being managed to serve the same number of subscribers, even without decreases in number of subscribers per service group. OSS interface abstractions provide a way to more effectively manage this larger quantity of devices.

11.3 Direct Communication with Device

Distributed CCAP architectures utilize remote devices deployed deep within the outside plant and require a truck roll to gain physical access to the device. Quick restoration of service during unintended outages may require additional considerations including:

- Ensuring that remote devices are accessible via IP connectivity with the MSO management network
- Inclusion of SSH-based CLI for secure manual mechanism to initiate remote resets and software upgrades while also providing for vendor-specific troubleshooting tools to minimize the need for physical debug and truck rolls
- Potential inclusion of a local direct communication interface accessible with housing open (console/debug interface). Any local direct interface may provide benefit in identifying HW or network connectivity faults but has the potential to pose a significant security risk if attackers gain physical access to the unit.
- Clearly documented indicator LEDs to assist field technicians with identifying particular fault conditions and status of the bootup and provisioning process.

11.4 Fault Diagnosis

Remote fault diagnosis depends on the quality and quantity of information available about the node. Compared to an analog fiber node, the DCA allows an MSO much greater remote fault diagnostic capabilities. An analog fiber node provides almost no information about the health or state of the node. Newer smart nodes improve on the situation by including a transponder that provides monitoring and possibly alarms on critical parameters within the node. The R-PHY and R-MACPHY provide much more detailed information on both the node and the communications to and from the node, and allows some interactive access to additional information when needed.

The DCA provides significantly more status information about the node, allowing a more detailed assessment of the node state. The very fact that the node is configurable and responds with errors when a configuration is unsuccessful reveals differences between the actual and expected hardware configuration. Detailed monitoring of the digital communications links to and from the node helps separate network and node problems.

While the quality and quantity of information about the node is dramatically increased, much of it is not organized to simplify remote fault diagnosis. Additional work is needed to maximize the value of this information for the task of remote diagnosis. While additional standards work will extend this capability, vendor development will provide the greatest increase in diagnostic capability. As the MSOs make diagnostic capabilities a priority, the DCA provides a framework for advances in remote diagnostics.

Also for a technician in the field, Line of sight diagnostic tools to get debug info from device (e.g., hanging on a pole) will be needed.

11.5 Considerations for PacketCable and PCMM

The PacketCable project defines interface specifications that can be used to develop interoperable equipment capable of providing packet-based voice, video, and other high-speed multimedia services over hybrid fiber coax (HFC) cable systems utilizing the DOCSIS protocol. PacketCable leverages and builds upon the data transport and Quality of Service capabilities provided by DOCSIS. PacketCable Multimedia defines a means for IP-enabled services to request QoS from the DOCSIS network. PacketCable defines how QoS can be provided for NCS or SIP-based services via PacketCable Multimedia and DOCSIS. The DOCSIS HFC access network includes the following functional components: the CM, the Multimedia Terminal Adapter (MTA), and the CCAP or CMTS.

In the PacketCable architecture, the CCAP is responsible for the following functions:

- Providing the required QoS to the CM based upon DOCSIS requests which are checked against policy;
- Allocating upstream bandwidth in accordance with CM requests and network QoS policies;
- Classifying each arriving packet from the network-side interface and assigning it to a QoS level based on defined filter specifications;

- Policing the TOS field in packets received from the cable network, in order to enforce TOS field settings per network operator policy;
- Altering the TOS field in the downstream IP headers based on the network operator's policy;
- Performing traffic shaping and policing as required by the flow specification;
- Forwarding downstream packets to the CM over the DOCSIS network using the assigned QoS;
- Forwarding upstream packets to the network-side devices using the assigned QoS;
- Converting QoS Gate parameters into DOCSIS QoS parameters;
- Recording usage of access network resources per call using PacketCable Event Messages

In general, implementing a DCA architecture is intended not to impact these functions. However, the QoS provided over the access network and towards the network side needs to be appropriately maintained to meet service standards for PacketCable services.

Two of the critical QoS parameters are latency and jitter. Scheduling over the coax link and the digital fiber link in a DCA will need to maintain latency and jitter to acceptable bounds. The specification for a specific DCA will discuss considerations and requirements such as to maintain the necessary latency and jitter.

11.6 L2VPN and Service OAM

The L2VPN feature on a DOCSIS CMTS allows cable operators to offer a Layer 2 Transparent LAN Service/ MEF services such as Ethernet Private Line, Ethernet LAN etc. to commercial enterprise locations.

Support for the L2VPN feature also requires support for Service OAM **(**Operations, Administration, and Maintenance**)** functions which allow an MSO to monitor and troubleshoot end-to-end Ethernet services. SOAM also ensures that SLA for the given Ethernet service is met and provides key indicators such as availability, packet loss, delay and jitter. SOAM consists of a series of techniques for fault management and performance management. Fault management techniques such as continuity check message allow operators to monitor the end-to-end circuit of an Ethernet service and re-route the traffic as needed. Other fault management techniques such as loopback and linktrace can be used by the operator to further troubleshoot the fault in the network. Performance management technique such as frame delay, frame delay variation and frame loss allow operators to monitor the end-to-end Ethernet services and to ensure that SLAs are met.

These features are detailed in [L2VPN] and the same features need to be supported by a remote device for an operator to enable and offer business services. Any remote device solution may need to support L2VPN and SOAM functions in order to support business service offering from the operator. In the case of RemotePHY, the RPD will not terminate DOCSIS L2VPN tunnels and just like the integrated CMTS case these tunnels will be terminated at the CCAP core. On the Remote MAC-PHY case, the L2VPN tunnels will be terminated at the RMD, just like it is at a CMTS.

11.7 High Availability

With the introduction of Distributed CCAP Architectures, new points of failure are introduced into the MSO network, while others are modified or removed. Service reliability is dependent on more components than previously and the redundancy/backup model changes.

The following are factors to be considered for high availability of services with a DCA deployment:

- Digital links to the remote device can be implemented with link redundancy.
- The number of subscribers impacted by the failure of a given component can vary greatly: failure of a remote device may only impact a small service group, while failure of a critical headend component could impact a number of users greater than what would be seen with the failure of a line card in a CCAP.

- The move to a DCA enables the virtualization of headend components, as discussed in Section 11.10. Virtualization requires alternative high availability strategies. These are typically based on the reduction of failure group size and horizontal scaling, as multiple small components replace a single large platform (e.g., a virtual CMTS per serving group rather than an integrated platform serving many). When implemented correctly it can provide additional availability and stability.

11.8 Power Requirements

RPHY and R-MACPHY Devices (Nodes) will, in the vast majority of cases, will utilize a connection to the coaxial network as a power source. From a power source perspective, no changes are expected compared to powering of conventional HFC node devices. Coaxial network powering is well understood, and consists of a line-frequency 60VAC or 90 VAC sources with or without battery standby reserve. In some cases, power consumption will change, and may require modification of the capacity (but not other characteristics) of the power source in the case of installation into pre-existing HFC networks.

11.9 Network Requirements to Support DCA

The DCA architecture splits the CCAP platform into a lower layer component resident in the fiber node and a higher layer entity resident in the headend or hub, which are connected by a packet network referred to as the Converged Interconnect Network (CIN). The different DCA options impose somewhat different requirements on the CIN but in all cases it is expected to be a managed network with the following characteristics.

11.9.1 Throughput

The CIN must provide sufficient throughput to support the advertised level of service to the subscribers. The most obvious way to ensure this is for the bandwidth available on the CIN to be greater than that available on the HFC link. This allows the current “rules” for DOCSIS utilization and overprovisioning to be applied to both DCA and conventional architectures. This is easily achieved when point-to-point connections (e.g., 10G Ethernet) are used for the CIN. If the CIN is constructed using shared media such as PON then oversubscription may be used to reduce cost but this must based on traffic engineering models as for HFC oversubscription.

11.9.2 Packet Loss

Both the DOCSIS protocol and (most of) the applications running over it are resilient to packet loss but it does have significant performance impacts on both. Under normal conditions the packet loss rates on the CIN due to transmission errors should be much lower than on the HFC due to the technologies used. However, even short periods of congestion on the CIN will result in packets being dropped as modern switches have very small buffers relative to their switching capacity. Priority based forwarding can ensure that protocol messages are not dropped during congestion but applications will be impacted as protocols such as TCP compensate by reducing throughput. The CIN network should be engineered such that congestion is avoided.

11.9.3 Latency and Jitter

The latency in the CIN results from transmission delays and switching delays. The transmission delay in fiber is approximately 500us per 100km. The delay and jitter introduced in modern switches are minimal when the network is not oversubscribed (<2 us for 1518 byte packet in 10G switch) and is thus negligible compared to transmission time. For user data the distance between the data source (e.g., a server located in the internet) and the user does not change in moving from integrated CCAP to DCA architectures so there should be essentially no impact on latency and jitter. If the CCAP core is located in the same headend location as the integrated CCAP there will be similarly be no significant difference for the DOCSIS protocol (same transmission distance, limited switch delays). If the CCAP core is moved to a more distant location the latency impact on the DOCSIS protocol (and especially on the request-grant delay in the scheduling loop) becomes more significant but even this has minimal impact below 500km and can be easily mitigated well beyond this.

11.9.4 Timing

A DCA based network requires timing to support DOCSIS operation and to provide timing services using DOCSIS Timing Protocol (DTP). The different DCA architectures require different levels of timing support but all must be able to support DTP, which has much more stringent timing needs. Thus in all cases the CIN must be able to provide timing to the remote devices using a protocol such as PTP [IEEE 1588].

11.9.4.1 Impact of Network Jitter on Timing

A moderately or heavily loaded network can have a significant impact on the ability of the PTP slave to synchronize to the PTP master, both in terms of settling times and offset ppm tracking accuracy, as established in various studies of PTP servo algorithms.

To mitigate the impact of network loading, the following options may be considered:

- Use of managed network elements that handle traffic prioritization and can deliver the PTP messages with low latency.
- Intervening network elements that function as IEEE 1588 transparent or boundary clocks, thereby compensating PTP timestamps for network jitter.
- Synchronous Ethernet capable devices in the network to allow quick initial settling times.

11.9.5 Redundancy

The CIN may be constructed to provide redundant paths with fast fail over between them, or with multiple paths for load balancing. In these cases the impact of different path options on jitter must be considered.

11.9.6 Multicast

The CIN should be able to support IP multicast to enable efficient transmission of broadcast and multicast services such as video.

In summary, the CIN should be a high-speed managed network operated at less than full capacity to minimize packet loss, latency and jitter.

11.10 DCA, SDN, and NFV

11.10.1 SDN/NFV Synergies

Vendors and MSOs are exploring the benefits of incorporating Software-Defined Networking (SDN) and Network Function Virtualization (NFV) into their operations. See CableLabs SDN Architecture TR [SDN-ARCH] for a more detailed description of how SDN technologies can be incorporated into the access network. Complex and business critical functions now performed by edge devices could be moved to virtual platforms where specialized applications run and manage these functions, increasing quality and reliability. This also makes management more centralized and streamlines the provisioning of services.

As traditional headend equipment is analyzed in order to determine what can and should be virtualized, there is an opportunity to consider and combine it with a Distributed CCAP Architecture. Virtual implementations still require a hardware device to provide the physical layer transmission functions such as RF modulation so that some form of DCA is a prerequisite for NFV. Distributed CCAP Architectures are an initial step towards virtualization. Access network functions can be virtualized, all the way from some of the DOCSIS MAC layer functions to applications which control the access network to the network services delivered by the Cable Operators on top. Together these technologies enable fast deployment of new services, increased flexibility for Cable Operators and reduced operational expenses. SDN/NFV can help facilitate and enhance DCA; the technologies have a lot of synergy.

In addition, MSOs are increasingly deploying multiple access technologies in their footprint to provide services. This mixed environment further strengthens the desire to adopt a flexible NFV infrastructure to converge all technology specific functions on a virtual physical platform.

11.10.2 SDN – DCA Tie-ins

The SDN Reference architecture depicted below describes the following layers:

At the top is the Services and applications layer can include applications OSS/BSS and NMS. The next is the SDN controller layer which is used by applications to support end-to-end configurations of network elements, to provide the required services. An example of SDN controller is the OpenDaylight controller. The Northbound Interface (NBI) between the applications and SDN controller may be in the form of an Application Programming Interface. The South Bound Interface from the controller to the network devices can be implemented by various protocols such as NETCONF, RESTCONF, SNMP, PCMM, etc.

The DCA controller is shown in Figure 17 below. It is only used for R-MACPHY systems to provide the CCAP Management Abstraction (CMA) layer which makes the R-MACPHY system looks like I-CCAP for management applications. In R-MACPHY systems, the CMA/DCA controller can be implemented in L2/L3 aggregation device or in a VM in the operator data center. The control protocols between the CMA/DCA controller and R-MACPHY device are usually left to vendor implementation. The CMA/DCA controller allows using the existing management applications without modification. Just like a CMTS or a CCAP, the CMA/DCA controller is a client of the SDN controller and can interface with it using a variety of protocols such as SNMP, NETCONF, and PCMM. When CMA/DCA controller is not used, the RMD is managed directly as shown in the diagram below.

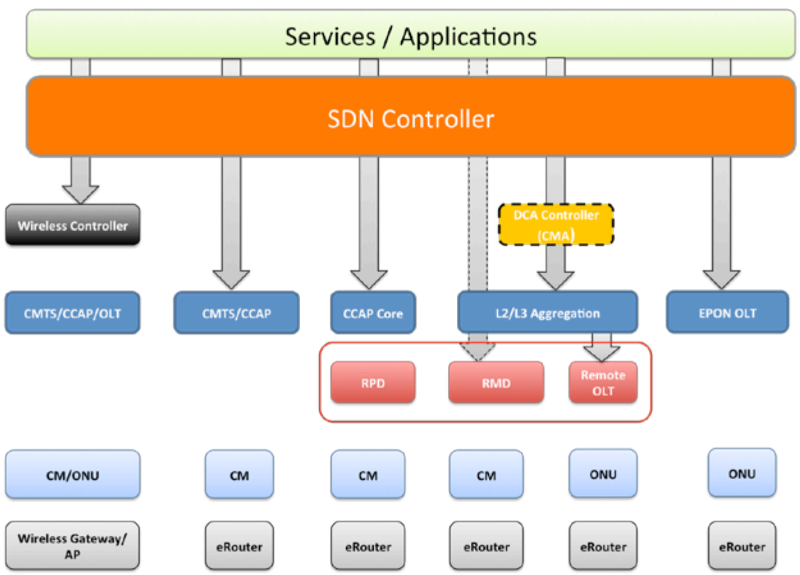

Figure 17 - SDN Architecture for MSO Access Network

*Based on Diagram from the CableLabs SDN Architecture TR [SDN-ARCH]

The infrastructure layer consists of the actual network devices which can be implemented using the centralized or distributed architecture.

11.11 Other Distributed Access

As noted in Section 6, cable operators today are facing numerous challenges to provide higher bandwidth and data rates. As bandwidth demand continues to grow, facility space, power, and other related factors start becoming a concern. The implementation of a distributed access system allows for an opportunity to provide additional service and hardware integration.

11.11.1 The addition of PON to DCA

The location of the RMD or RPD at the remote node offers additional opportunities for distributed access enhancements using a shared DWDM or CWDM standardized Ethernet digital fiber uplink. A key example is the addition of OLT functionality at the remote node as shown in the red box in Figure 17 above.

DCA not only provides a path to a shared digital uplink, but it also enhances the ability to implement CCAP Management Abstraction (CMA) and an SDN management model, which can be extended to include PON functionality at the node.

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