An Architecture for Distributed EPON Access

A Technical Paper prepared for SCTE/ISBE by

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Introduction

Distributed Access Architectures (DAA), and Centralized Access Architectures (CAA), have been debated in the industry for many years. Over the last two or three years, though, the advantages of DAA have overshadowed centralized architectures. As a result, cable operators are beginning to deploy DAA for DOCSIS.

The technical aspects of DAA for DOCSIS have been well treated in standards and literature. Products implementing RemotePHY and RemoteMAC/PHY are available in the market today. Some suppliers have included in their designs an SDN-based system that virtualizes portions of the overall DAA-for-DOCSIS solution.

Similarly, the benefits and challenges of FTTx and EPON have been well treated in the literature. The result has been a move by many operators to strategically deploy FTTx and most have chosen to use EPON in those deployments. However, relative to DAA for DOCSIS, little attention has been given to deploying FTTx in a distributed architecture.

This paper will describe a disaggregated architecture for EPON in an MSO network using concepts from the widely discussed distributed access architecture. The architecture will include separation of the management plane and data plane components and describe how they interact. We will discuss required functionality and how SDN and NFV, and breakthroughs in EPON technologies are key enablers of a distributed EPON network.

Reference Architectures in the Industry

Network and system architectures are a dime a dozen in today's industry. Many claim to address network and system architecture in general, but usually we will find that each is focused on solving a specific set of problems. Nevertheless, it is wise to survey those architectures to ensure we don't duplicate prior works and to take advantage of the findings in those previous works. In this section, we survey some architectures that are widely covered in the literature.

1. DAA as a Reference Architecture

Distributed Access Architecture (DAA) is referenced frequently in the literature.

In 2013, (M. Emmendorfer and T. Cloonan, 2013) examined the need to convert from analog to digital modes in the optical portions of the HFC network. The natural conclusion was that a remote PHY or remote MAC/PHY device would be required. This is one of the earliest to note the need and propose the basic architecture for what is now referred to as DAA.

(Emmendorfer, Cloonan, Ulm, & Maricevic, 2014) is one of the first times that the term Distributed Access Architecture is used in the cable industry literature. The authors expanded the analysis of (M. Emmendorfer and T. Cloonan, 2013) by comparing DAA to Centralized Access Architectures (CAA) and further described the architectural foundations of a DAA for an HFC/DOCSIS network. Notably, the authors identify physical locations for various elements (Headend, Node, Subscriber Premises) and decompose the key network elements into their functional layers and components. The CCAP is described as a combination of Upper MAC (Policing Classification, Shaping), Lower MAC and Convergence (filtering, scheduling, framing), Upper PHY (PCS layer), Lower PHY (PMA layer), and the PMD layer. This decomposition makes possible the authors' proposals to relocate portions of the CCAP system to physical locations outside the traditional MSO headend.

Further, the authors' decomposition of the CCAP/HFC network into its functional components sets the stage for a generalized discussion of a disaggregated access network in the cable industry. Later papers and articles (for example (Bernstein & Ramakrishnan, 2015), (Torbet, Cloonan, & Aftelak, 2016; Torbet, Cloonan, & Aftelak, 2016)), discuss how the component functions of a traditional "big iron" CCAP/HFC network can be split between less complex hardware and software located in data centers, headends, and nodes. This marks the beginning of widespread acceptance of SDN and NFV concepts being applied in the DOCSIS/HFC network.

Even though common roots exist, there is no one definitive architecture that is DAA. In fact, throughout the literature, we find that DAA is more of a concept than a definitive architecture. There are, though, common threads throughout the literature and industry discussions. Key threads are decomposition of the CCAP/DOCSIS elements and relocation of the RF transmit/receive functions much closer to the subscriber than past HFC designs ever thought necessary.

Ultimately, we find that DAA is enabled by several other architectures. Namely, remote PHY, remote MAC/PHY and virtual CCAP.

2. Modular and Distributed Cable Architectures

In (Sundaresan, 2015), the author surveys the various modular and distributed architectures for cable networks. We will not duplicate that work here. Instead we will point out some key re-usable constructs from those architectures.

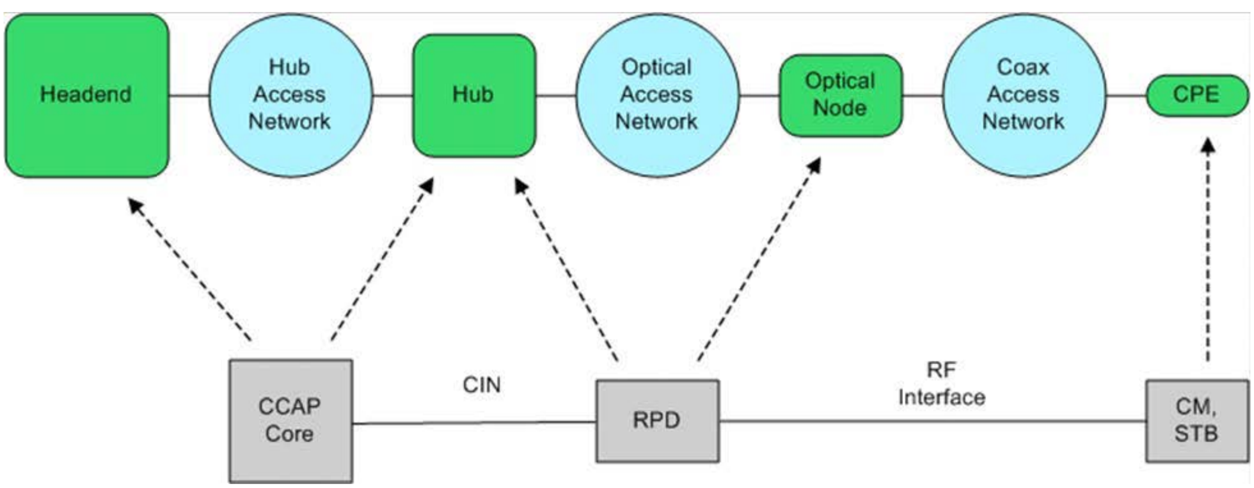

Figure 1 - Remote PHY System Diagram (Remote PHY Specification, 2017)

The R-PHY specification (Remote PHY Specification, 2017) formally describes the structure of a cable operators network and the relative location of the components as they are related to the R-PHY requirements. This foundation for the MHA and R-PHY architecture is shown in Figure 1.

The MHA/R-PHY architecture further describes the interfaces that have many similarities to what is required in the distributed PON network. For example, the Converged Interconnect Network (CIN), which is the network that connects the RPD to the CCAP Core, would need to have an equivalent in the distributed PON architecture.

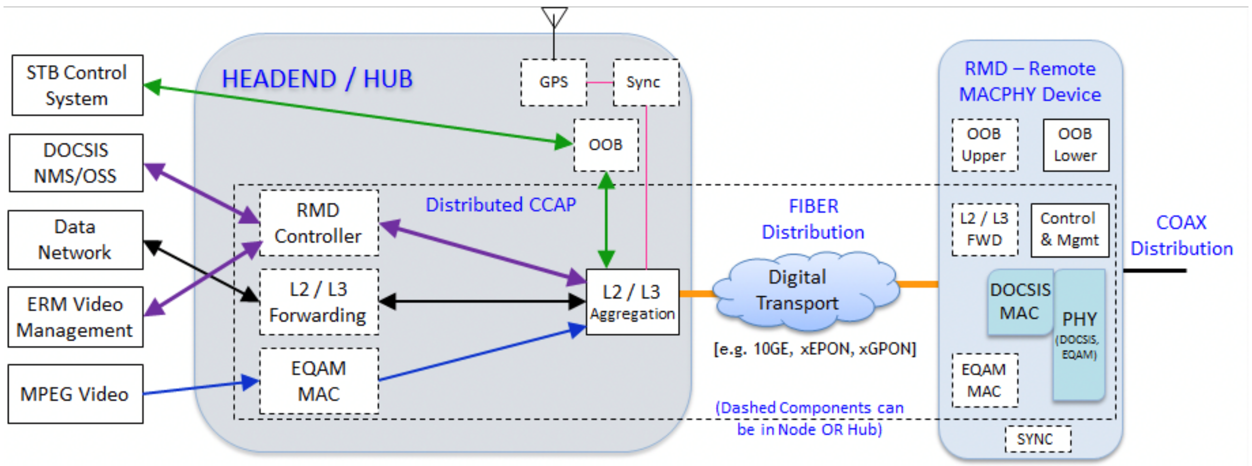

Figure 2 - Remote MAC/PHY System Architecture (Remote MAC-PHY Technical Report, 2015)

The Remote MAC-PHY technical report (Remote MAC-PHY Technical Report, 2015) describes a more complete model, shown in Figure 2, that aligns closely to what might be expected to support a remote PON.

The Remote MAC-PHY model includes elements for the RMD (analogous to a remote OLT), L2 aggregation in the hub/headend, a control function for the RMD, and digital transport (the CIN in R-PHY). The model includes security mechanisms that are critical for operation in a potentially hostile remote location and the model addresses distribution of synchronization and timing which are important for service offerings like wireless backhaul and other commercial and carrier services. This model could be a good example to follow for the physical topology of distributed EPON.

Missing so far, though, is an architecture that describes in sufficient detail the disaggregation and possible virtualization of the control-plane and management-plane functions.

3. DPoE as a Reference Architecture

No discussion of PON in a cable network would be complete without including DOCSIS Provisioning of EPON (DPoE). DPoE v1.0 is specified in a series of nine documents and DPoE v2.0 is specified in a second series of nine documents. Of interest to our analysis is the DPOE v2.0 architecture in (DPoE Architecture Specification, 2016). The DPoE architecture, pictured in Figure 3, is the first time that we find a virtualized network function – namely the vCM – in cable industry specifications.

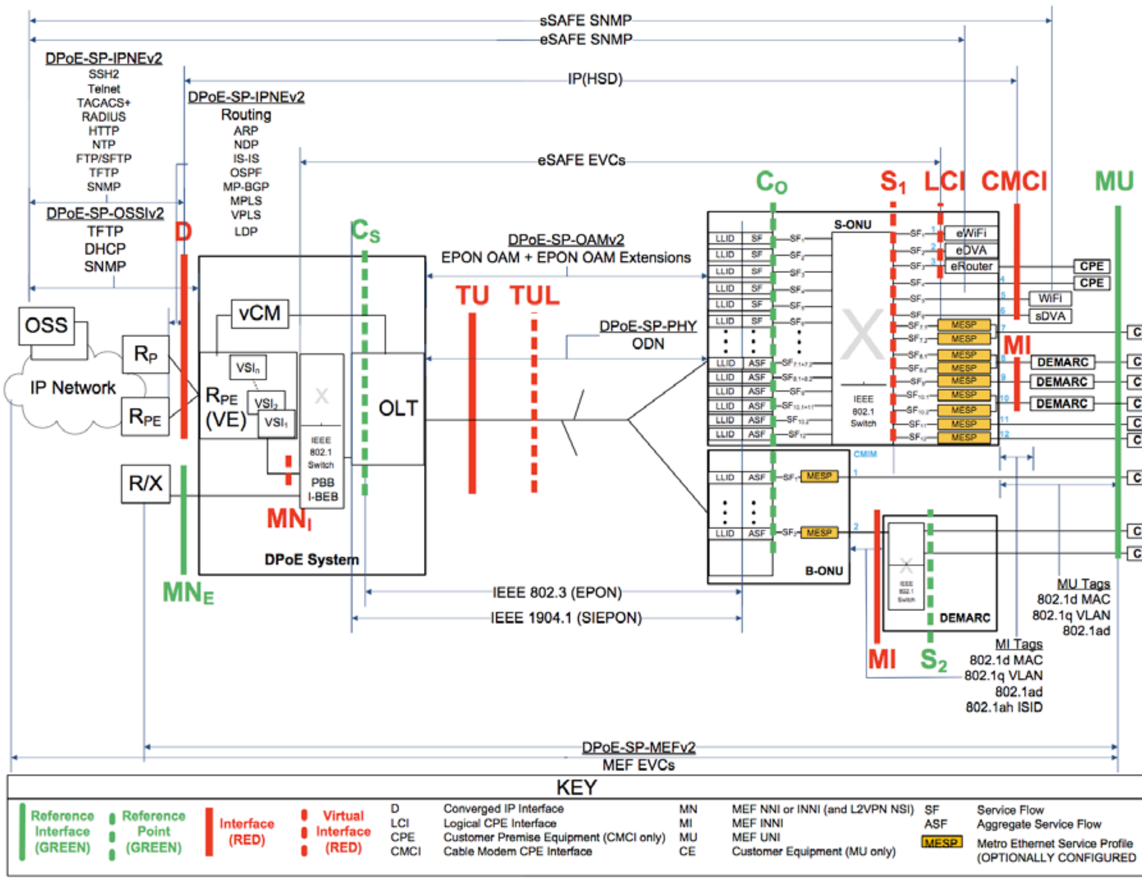

Figure 3 - DPoEv2.0 Reference Architecture, Interfaces, and Reference Points (DPoE Architecture Specification, 2016)

The DPoE specifications, however, do not describe a method by which the OLT can be physically disaggregated from the DPoE System (an extension of the Cs reference point definition). In other words, DPoE practically requires that the DPoE System (analogous to the DOCSIS CMTS) be a full-function system housed in a monolithic chassis. This means that DPoE cannot be an essential basis for the distributed EPON architecture.

It is, however, essential in our proposed architecture that DPoEv2.0 functionality be maintained. Therefore, we cannot dismiss the DPoE architecture from the list of considerations for the distributed EPON architecture.

In fact, a distinct possibility for developing a complete distributed EPON architecture could be to further define the interfaces that would enable the DPoE system to be disaggregated. This was one of the major topics of the Virtual Provisioning Interface Technical Report (VPI) (Virtual Provisioning Interfaces Technical Report, 2017). Section 9 of VPI describes this aspect of the DPoE architecture and calls out several possible solutions, but does not settle on any single solution. Nonetheless, VPI serves as a very good reference for defining our distributed EPON architecture.

4. Non-Cable Reference Architectures

It is important to recognize that the telecommunications and networking industry is a much larger community of which the cable industry is a subset. This means that the cable industry, and any proposal for new architectures, should survey non-cable specifications and standards with the expectation that we will find helpful input there. In this section, we look briefly at three architectures that are frequently referenced in the telecommunications and networking industry.

4.1. IEEE 1904.1

IEEE Std1904.1 (SIEPON) (IEEE Standard for Service Interoperability for Ethernet Passive Optical Networks (SIEPON), 2013) is very familiar to the cable industry because it was originally derived from the DPoE specifications. This adopts the interoperability mission that DPoE sought out in for the cable industry and expands on it by defining two other profiles for OAM messaging to the ONU. SIEPON adds additional requirements and features (such as service availability functions, and PON protection mechanisms) into the EPON system and does not concern itself with the DOCSIS-specific functions that DPoE defines.

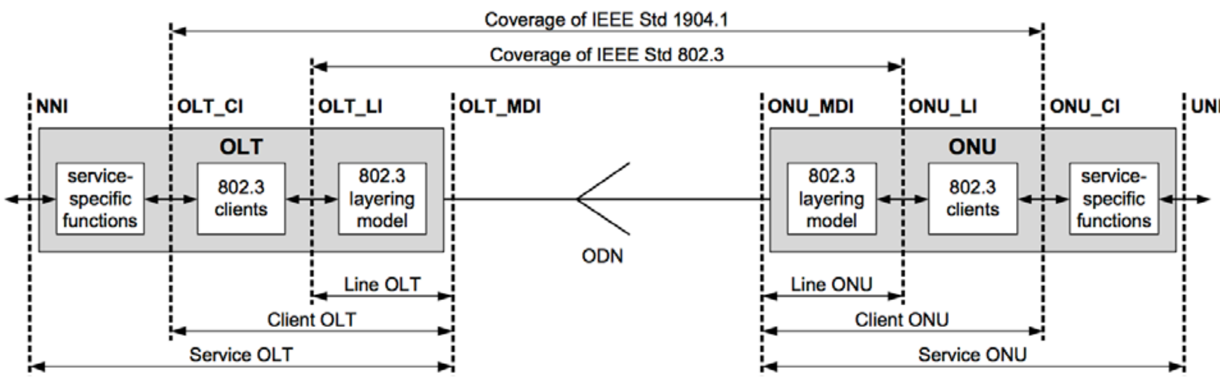

Figure 4 - SIEPON Target System Architecture with Service-Specific Functions (IEEE Standard for Service Interoperability for Ethernet Passive Optical Networks (SIEPON), 2013)

SIEPON also defines features and functions in much finer detail and structure than DPoE. In so doing, SIEPON defines a scope of the system being specified. Shown in Figure 4 is the scope of the SIEPON system architecture.

Note that SIEPON does not define service-specific or system-level functions like DPoE does (e.g. IP routing, DHCP relay, provisioning system interfaces, etc.). As can be seen in Figure 5, SIEPON focuses primarily on the functions and interfaces occurring at the MAC layer and the layers immediately adjacent to the MAC layer (OAM, Data Link, MAC Control, MAC Client).

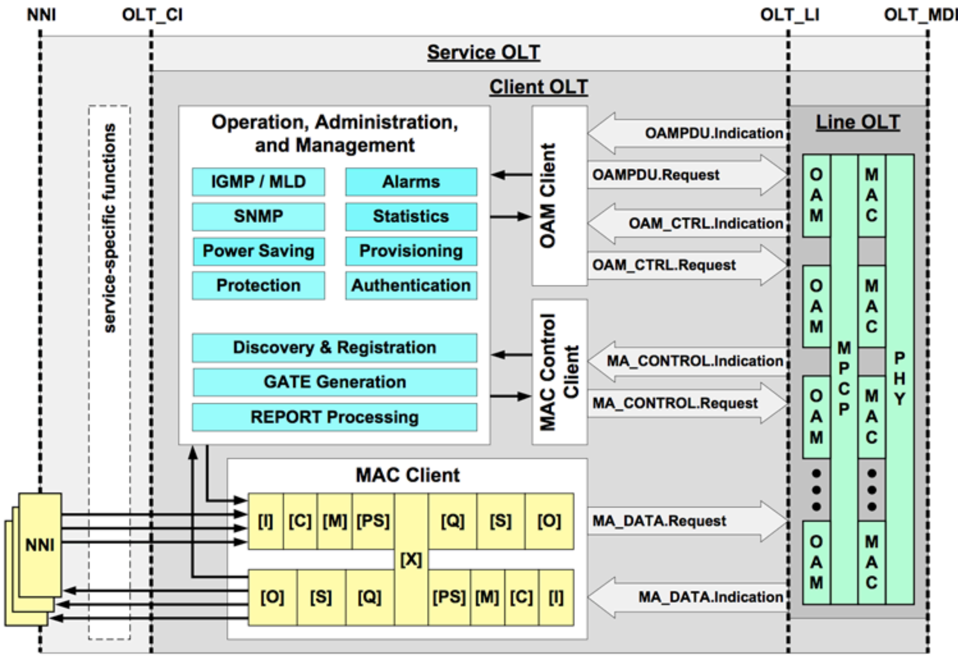

Figure 5 - SIEPON OLT Architecture with single L-OLT (IEEE Standard for Service Interoperability for Ethernet Passive Optical Networks (SIEPON), 2013)

We note from Figure 5 that SIEPON breaks the OLT system down to its basic function blocks required for operation and interoperability. This is of interest to the distributed EPON architecture as it can help guide the distributed EPON architecture in where and how functions can be physically and/or logically separated and still maintain the required functionality.

4.2. Broadband Forum

The Broadband Forum (BBF) has a long history of architecture for access networks. TR-001 (TR-001 ADSL Forum System Reference Model, 1996) the base architecture for an ADSL access network and included abstract definitions of an access node (AN), and the interfaces between each element of the access network, the subscriber and the upstream core networks. BBF documents that followed have adapted this architecture to accommodate changes in technology, additional features and requirements, and the maturing of broadband access networks in general.

What we find now, in TR-200 (TR-200 Using EPON in the Context of TR-101, 2011) is a well-defined architecture that includes EPON in the suite of supported access technologies.

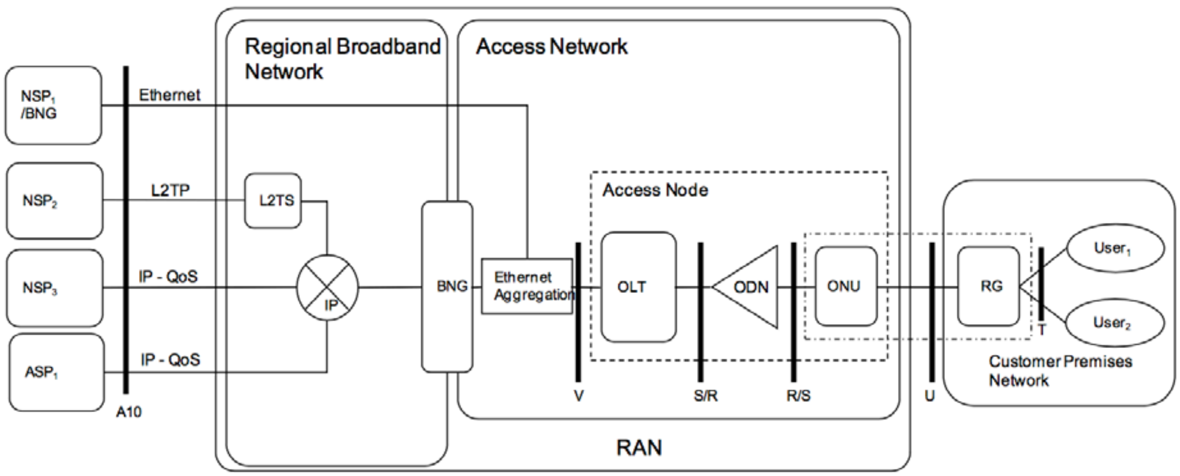

Figure 6 - TR-200 Network Architecture in the case of EPON Access (TR-200 Using EPON in the Context of TR-101, 2011)

The TR-200 architecture for EPON access, shown in Figure 6, inherits from TR-101 (TR-101 Migration to Ethernet-Based DSL Aggregation, 2006), TR-059 (TR-059 DSL Evolution - Architecture Requirements for the Support of QoS-Enabled IP Services, 2003), and their antecedents and successors, the definitions of the network elements like the Access Network, Customer Premises Network, BNG, Access Node, OLT, Ethernet Aggregation, Residential Gateway (RG), and the interfaces between these – the V, S/R, U and T interfaces.

Another line of development in the BBF that continues is a framework for virtualization of network functions in the BBF architectures. TR-345 (TR-345 Broadband Network Gateway and Network Function Virtualization, 2016) develops a framework under which the broadband network gateway (BNG) can be implemented in software as a virtualized network function (VNF) instead of as a monolithic system in hardware. TR-359 (TR-359 A Framework for Virtualization, 2016) moves a far step beyond by developing a framework in which any network function (NF) in the TR-178 (TR-359 A Framework for Virtualization, 2016) architecture can be virtualized. The TR-359 architecture is shown in Figure 7.

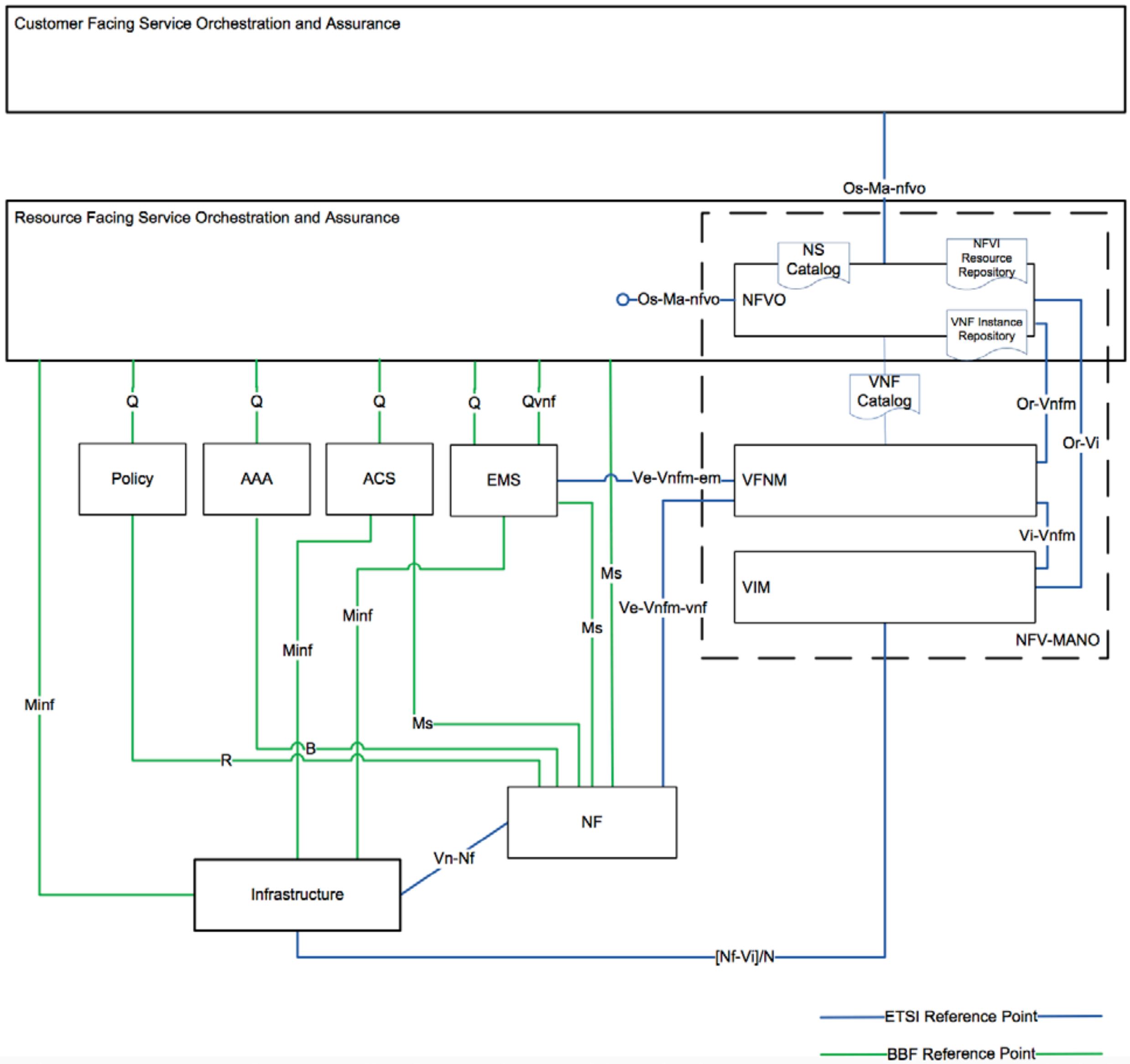

Figure 7 - BBF and ETSI-NFV reference model for service management and control (TR-359 A Framework for Virtualization, 2016)

4.3. Central Office Re-Architected as a Data Center (CORD)

All the reference architectures discussed so far have focused on the physical network elements and network functions required to deliver service to the subscriber. With the notable exception of TR-345 and TR-359, what has not been well covered is the framework for and implementation of software-defined networking (SDN) and network function virtualization (NFV) in a broadband access network.

In 2015, AT&T published a whitepaper entitled *Central Office Re-Architected as a Datacenter* which has been updated in (Central Office Re-architected as a Datacenter, 2016). The whitepaper proposes a major re-think of how a telco's central office (CO) is architected and used. The whitepaper proposes that the CO be considered a data center that houses general purpose computing hardware that runs in software what previously would be housed in application specific hardware occupying many square feet of space, consuming more energy than necessary, and taking too long to develop and deploy new features. Variations on the CORD architecture have been documented and are under development in the open-source community – namely Residential CORD (R-CORD), Enterprise CORD (E-CORD), Mobile CORD (M-CORD) and others.

The CORD architecture replaces the application specific hardware with virtualized functions running as a service in the cloud infrastructure. An example of this is found in the R-CORD architecture (Figure 8), in which the access network (EPON, GPON, DSL, etc.) is abstracted away from the control and management layers to present a single network architecture to be managed.

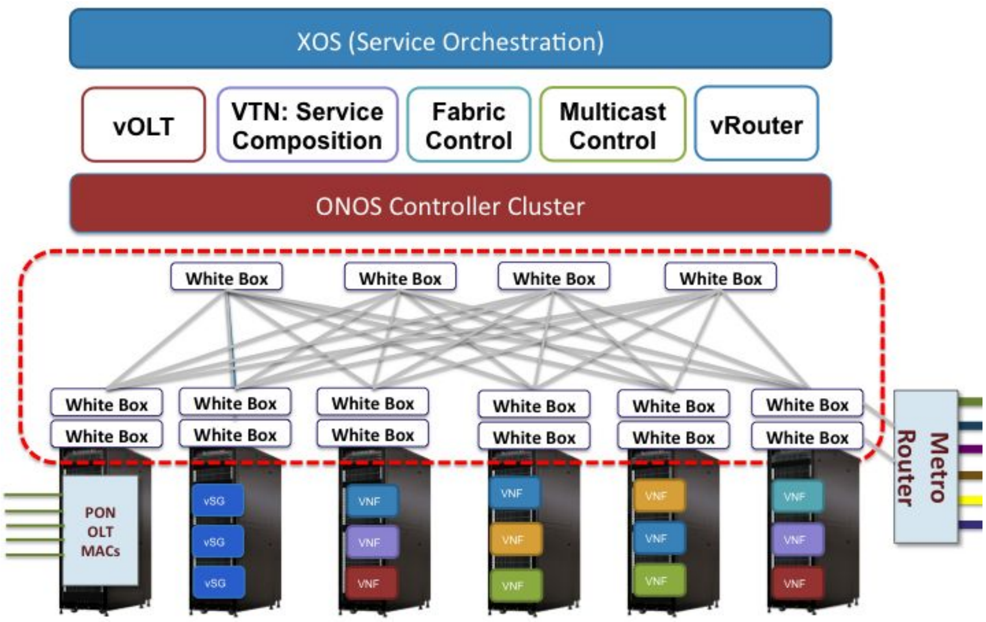

Figure 8 - R-CORD Architecture (Das, et al., 2016)

The virtual OLT (vOLT) which was described in (Al-Shabibi & Hart, 2016) and being developed under the OpenCORD project (VOLTHA Wiki, n.d.), is very relevant to the present distributed PON architecture proposal. The vOLT whitepaper (Al-Shabibi & Hart, 2016) describes an architecture that consists of a simple I/O blade that contains only the PON OLT MAC and a software module running in the cloud that implements all the PON control functions and protocols. Some of the many advantages this architecture brings is the ability to minimize the cost of the hardware by making it a simple media conversion and, by abstracting the control functions, removing many of the interoperability challenges that delay deployment of new PON OLTs and ONU/ONTs.

The CORD architecture is being adopted by telco operators worldwide and has now become a work effort in the BBF. This is exhibited by the sponsors listed on the OpenCORD website (OpenCORD Members, n.d.) and by the efforts going on in the BBF's CloudCO (Broadband Forum Cloud Central Office (CloudCO), 2017)work stream which is seeking to document a formalized architecture.

Architecture

After surveying the industry specifications and standards from which our proposed architecture might benefit, we want to develop the proposed architecture.

Since we are operating in the cable industry, conformance with DPoE is a key requirement for operating EPON. However, we know from the beginning that the distributed EPON architecture cannot fully comply with DPoE because DPoE does not currently support distributed functionality like we are proposing. We offer a compromise in this architecture – this architecture will conform to DPoE by:

1. Exposing the same interfaces to the OSS/BSS;
2. Maintaining the interoperability requirements of DPoE (by using DPoE OAM to the ONU);
3. Exposing the same interfaces to the operator's backbone networks as required by DPoE.

Prior to explaining the proposed architecture, it is necessary to explain how the existing DPoE and related functions can be split apart, or disaggregated. After that is accomplished the proposed architecture can be explained. We, in fact, propose two similar architectures in the interest of showing how an operator might migrate their network over time.

5. Disaggregating DPoE and SIEPON

There are two key areas of required discussion when we decide to create a distributed EPON network based on DPoE. The first is how to disaggregate the DPoE System (the DPoE ONU is not affected by disaggregation) and maintain the same functionality that is specified in DPoE.

According to (DPoE Architecture Specification, 2016), the DPoE System is made up of the following elements and interfaces:

- ***vCM*** – The virtual cable modem which translates all the operations, administration, maintenance and provisioning (OAM&P) messaging between the DOCSIS-based OSS and the OAM protocol used by DPoE ONU.
- ***OLT*** – The EPON Optical Line Terminal as defined by IEEE 802.3 and contains the PMD/PHY, MAC, MAC Control, and OAM functions.
- ***Ethernet Switch*** – The 802.1d Ethernet switch is a connection point and switching matrix for traffic moving between the OLT, R_{PE}, and the MN_E interface.
- ***IP Router/Provider Edge Router (R_{PE})*** – The R_{PE} provides the internal IP routing function, subscriber management, and MPLS PE router functions.
- ***TU and TUL Interfaces*** – The TU interface is the Optical Distribution Network (ODN); the TUL is a MAC domain that exists on the DPoE network.
- ***C_S Interface*** – The C_S interface is the downstream classifier that exists inside the OLT.
- ***D Interface*** – Is the interface between the DPoE System and the operator's network. It has varied functionality that includes bearer traffic (IP only), OAM&P functions and protocols, and MPLS traffic intended for Metro Ethernet (MEF) services connected to the DPoE System.
- ***MN_E Interface*** – Is a raw IEEE 802.3 interface acts as a MEF INNI and/or L2VPN NSI.

The functionality of each of these is detailed in (DPoE Architecture Specification, 2016).

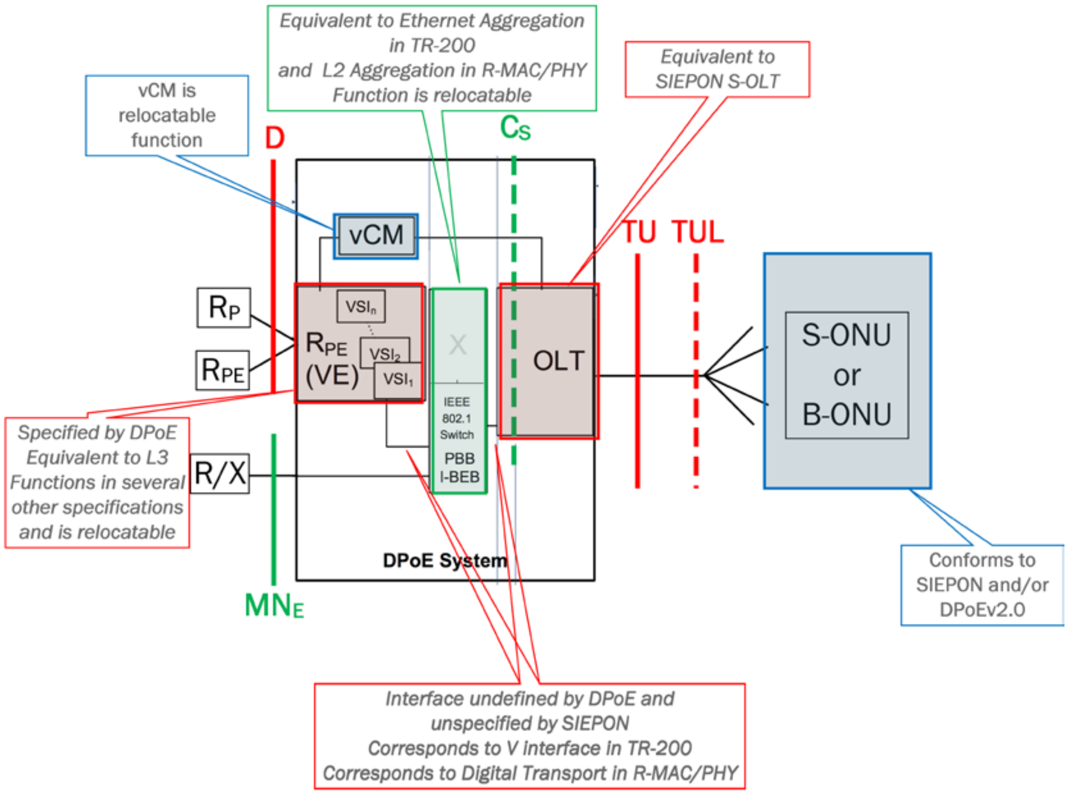

Figure 9 - Disaggregated DPoE System

Each of the elements listed are shown in Figure 9. Missing from the list is the interface between the OLT and the Ethernet switch and the interface between the Ethernet switch and the R_{PE}. These two interfaces must be defined if we are to separate the OLT from the physical DPoE System. These interfaces are similar in function to the V interface in TR-200 (TR-200 Using EPON in the Context of TR-101, 2011) and the Digital Transport described in R-MAC/PHY (Remote MAC-PHY Technical Report, 2015), so our architecture will look to those documents for guidance on their definition.

Figure 9 also shows the mapping between each element and interface and other standards or specifications.

As mentioned earlier, the DPoE ONU (S-ONU or B-ONU) and its functions and requirements are defined in the DPoE v2.0 suite of specifications and in IEEE 1904.1 (SIEPON) (IEEE Standard for Service Interoperability for Ethernet Passive Optical Networks (SIEPON), 2013).

The Ethernet switch is equivalent to the L2 aggregation block shown in R-MAC/PHY (Remote MAC-PHY Technical Report, 2015). It is also equivalent to the Ethernet Aggregation block shown in TR-200 (TR-200 Using EPON in the Context of TR-101, 2011). These two documents will guide our definition of the functions required in this switch.

The vCM is a relocatable function defined in the DPoE v2.0 suite of specifications. *Relocatable* means that the function does not need to be co-resident with its adjacent functional blocks.

The R_{PE} is specified in several industry specification documents. While our architecture will require only the functions defined in the DPoE v2.0 suite of specifications, individual implementations may support additional functions as required by the operator. The R_{PE} is a relocatable function.

In this architecture, we choose to use the SIEPON Service-OLT as the model for the OLT contained in the DPoE System. This choice eases the effort required to define the functions required in the OLT, and which functions can be separated/relocated.

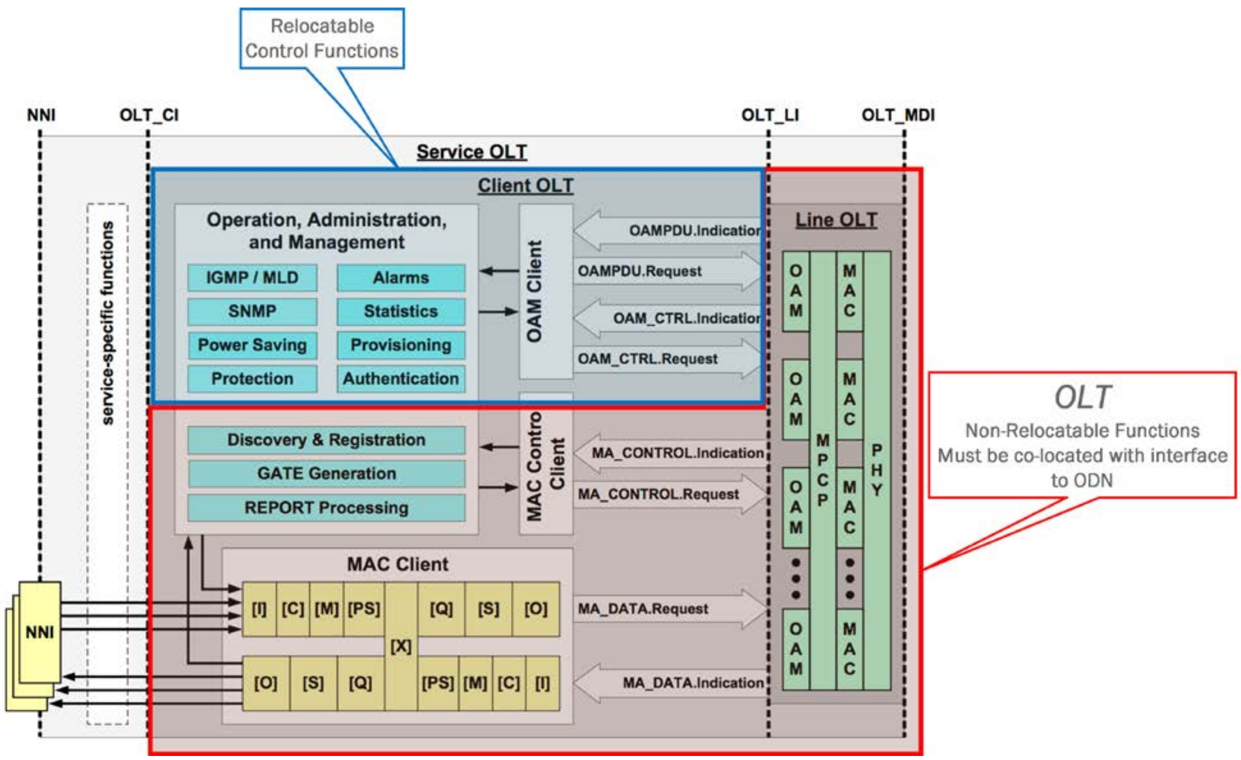

Figure 10 - Disaggregated SIEPON S-OLT

According to the SIEPON architecture, there are three types of OLT:

- Line OLT – is the element that provides the physical connection to the ODN and contains the fundamental functions for MAC, MAC Control (MPCP) and OAM.
- Client OLT – is the element that implements higher-layer functions that control the Line OLT's functions, establishes and manages connectivity with the ONUs, and sends/receives subscriber frames.
- Service OLT – is the element that contains one or more Client OLTs, and provides connectivity to external entities via a Network-Network-Interface (NNI), and may supply additional higher-layer functions such as L3 routing or others as defined in DPoE.

The relationship between these three entities is shown in Figure 10. Annotated in Figure 10 are the elements of the SIEPON architecture that can be separated and/or relocated in a distributed architecture. The Line OLT and a portion of the Client OLT functions cannot be separated because they are intimately involved with the basic functions of the PON and separating them would have negative impacts on performance (performance impacts are explored in (Boyd, Noll, Rahman, Nandiraju, & Villaruel, 2015)).

In the architecture proposals that follow, the OLT element will correspond directly to the combination of Line OLT and the portion of Client OLT functions that are outlined in Figure 10.

6. Reconnecting the Parts – Near Term Architecture

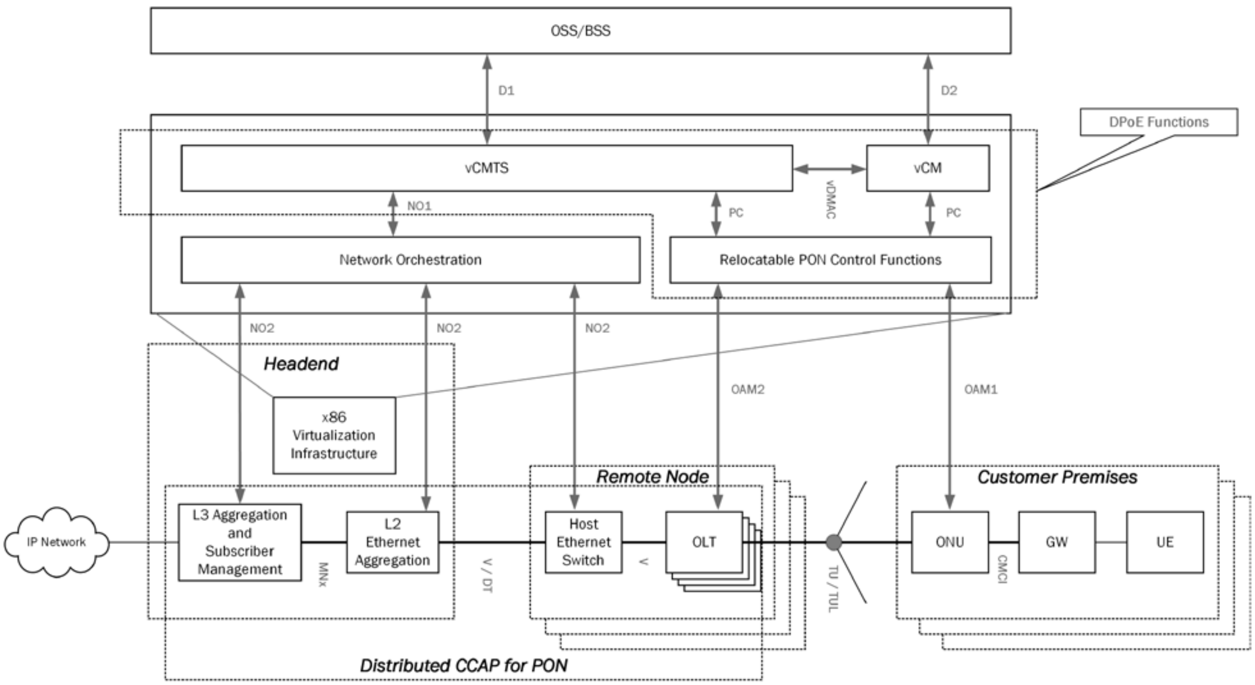

Figure 11 - Near Term Distributed EPON Architecture

The near term distributed EPON architecture is an example of how an operator could deploy distributed EPON today with little disruption to the existing operations. This architecture maintains the existing hardware-based routing and BNG functions, but replaces the OLT system chassis (though it is not necessarily incompatible with this architecture) with an inexpensive OLT that is supported by software elements. Those software elements exist in a virtualized environment and implement the PON control functions and DPoE OAM&P functions.

Key to making this architecture complete, functional, and interoperable is to define the interfaces and elements that are not defined by DPoE. The following sections do this.

6.1. The Elements

- ***User Equipment (UE)*** – Is the equipment that is used directly by the user and is not involved in providing the network connection. Examples: PC, Set Top Box, WiFi access point. This element is out of scope for this architecture.
- ***Gateway (GW)*** – Is the element that provides service-specific features and connectivity functions at layers above that provided by the ONU (e.g. Layer 3 and above) at the customer premises. The GW may be operator owned or customer owned.
- ***Optical Network Unit (ONU)*** – In this architecture the ONU is a SIEPON Client ONU and is equivalent to a DPoE Bridge ONU. This device provides basic layer-2 bridging between the PON

and the GW. The ONU contains all the necessary PON OAM&P functions to operate on the EPON.

- ***Optical Line Terminal (OLT)*** – In this architecture the OLT is a combination of the SIEPON L-OLT and a portion of the SIEPON C-OLT functions. Specifically, the OLT contains the L-OLT functions, MAC Client functions (bridging, cross-connect queueing, VLAN tagging, etc), and MAC Control functions (GATE generation, REPORT processing, Discovery and Registration).
- ***Host Ethernet Switch*** – Is the element to which the OLT connects directly through the V interface (defined below). It provides basic layer-2 switching and VLAN tagging functions. It is desirable to minimize the cost of this device; therefore it is desirable for this device not to contain significant queueing and shaping/policing features.
- ***L2 Ethernet Aggregation*** – Is the element to which one or more Host Ethernet Switches connect for aggregating traffic from many OLTs and many remote nodes. This device implements the functionality describes in R-MAC/PHY for the L2/L3 aggregation (L2 functions only in this architecture) and the Ethernet Aggregation block in TR-200.
- ***L3 Aggregation*** – Is the element which provides L3 routing and service functions. The functions of this element are well summarized in (Emmendorfer & ZorluOzer, 2016) as IPv4/IPv6 Router (and related forwarding and control-plane functions), DHCP relay, MPLS PE, VPLS, VPWS, etc.
- ***Subscriber Management (BNG)*** – Is the element at which (borrowing the definition from TR-101 (TR-101 Migration to Ethernet-Based DSL Aggregation, 2006)) bandwidth and QoS policies are applied to subscribers' flows. This function is defined by DPoE as residing inside the DPoE System.
- ***Virtualization Infrastructure*** – Is an infrastructure of computing platforms (typically x86-based) on which software implementations of network functions can be executed.
- ***Relocatable PON Control Functions*** – Is the upper half of the set of functions described in SIEPON's Client OLT. These functions are highlighted in blue in Figure 10, and include Authentication, Provisioning, Statistics, Alarms, Power Saving, Protection, IGMP/MLD, SNMP (the latter two are implemented in the vCM and vCMTS for DPoE).
- ***Network Control and Orchestration*** – Is an abstract function that controls certain lower-layer network elements and coordinates activities between all the various elements so that all required "system" functions are achieved. In other words, Network Control and Orchestration is required to coordinate all the disaggregated functions into a system that completely meets the requirements of the operator.
- ***vCM*** – Is the virtual cable modem defined in the DPoE v2.0 suite of specifications.
- ***vCMTS*** – As the name implies, the vCMTS is a virtual CMTS. This element is not currently defined explicitly in any specifications. However, the functions are implied in the DPoE v2.0 suite of specifications. Its functions include CLI access to manage the DPoE System configuration, SNMP, DOCSIS MAC-layer emulation, etc. In this paper, we leave this function vaguely defined due to lack of space. Future development of the proposed architecture could further define the vCMTS.
- ***OSS/BSS*** – Is the set of Operational Support Systems and Billing Support Systems used by the cable operator. These systems interact with current DPoE Systems via the D interface as defined in the DPoE v2.0 suite of specifications.

6.2. The Interfaces

- ***D1*** – Is the interface between the vCMTS and OSS/BSS. This interface is a subset of the D interface defined by the DPoE v2.0 suite of specifications. The subset includes SNMP (CMTS-specific MIBs, only), Command Line Interface (defined in the DPOE IPNE specification), policy control (currently undefined in DPoE, but could conform to the PacketCable/COPS suite of specifications for DOCSIS), etc. For lack of space, this paper will not attempt to fully define this interface.
- ***D2*** – Is the interface between the vCM and OSS/BSS. This interface is a subset of the D interface defined by the DPoE v2.0 suote of specifications. The subset includes TFTP (for vCM configuration file download), DHCP, SNMP (vCM-specific MIBs only), etc. For lack of space, this paper will not attempt to fully define this interface.
- ***NO1*** – Is the interface between the vCMTS and the Network Orchestrator. This interface is likely to be RESTCONF or NETCONF/YANG as suggested in (Virtual Provisioning Interfaces Technical Report, 2017) and (SDN Architecture for Cable Access Networks Technical Report, 2015). In this architectural model (architecture 1 in this paper), the vCMTS would be responsible for translating function calls from the D1 interface to the necessary function calls on the NO1 interface.
- ***PC*** – Is the interface to the PON Control Functions element. As exemplified in this architecture, the PC interface exists between the vCM and the PON Control Functions and between the vCMTS and the PON Control Functions. There are two prime candidate protocols for this interface: RESTCONF or NETCONF/YANG and OpenFlow. RESTCONF seems to have more favor in the cable industry, but a combination of RESTCONF and OpenFlow could be a superior solution.
- ***vDMAC*** – Is the interface between the vCMTS and the vCM. This interface is intended to emulate the minimum set of DOCSIS MAC protocol and messaging necessary to achieve DOCSIS-like functionality on the EPON network. A structured specification of this interface (whether public or proprietary) could enhance the existing DPoE v2.0 functions to bring it closer to full DOCSIS capabilities (for example, addition of dynamic service flows via emulated DSX messaging).
- ***NO2*** – Is the interface between Network Orchestration and lower-layer network elements – L3 Aggregation, Subscriber Management, L2 Ethernet Aggregation, and the Host Ethernet Switch. This interface is similar in function to NO1 and is likely to be implemented as RESTCONF or NETCONF/YANG. Network Orchestration would be responsible to translate the directives sent by the vCMTS to corresponding directives sent to the lower-layer network elements for implementing the features and functions required by the DPoE v2.0 suite of specifications and any additional or alternate requirements the operator might impose.
- ***OAM1*** – Is the interface between the PON Control Functions and the ONU. This messaging protocol for this interface is entirely defined by the DPoE v2.0 OAM specification (DPoE OAM Extensions Specification, 2017) and/or the SIEPON OAM specifications (IEEE Standard for Service Interoperability for Ethernet Passive Optical Networks (SIEPON), 2013). What is missing from those specifications is a transport for the OAM messages to be sent across a non-PON network to the OLT and then to the ONU. IEEE 1904.2 (IEEE 1904.2 Task Force, n.d.) is a work in progress that is intended to provide just such a transport.
- ***OAM2*** – Is the interface between the PON Control Functions and the OLT. This messaging protocol for this interface is not currently defined in an industry standard or specification document. This architecture proposes that this interface adopt the same messaging protocol,

message formats and message content as is defined in DPoE v2.0 OAM specification (DPoE OAM Extensions Specification, 2017) and/or the SIEPON OAM specifications (IEEE Standard for Service Interoperability for Ethernet Passive Optical Networks (SIEPON), 2013). There is much overlap between what is needed to program an ONU and an OLT, but clearly there are instances where the OLT will require new message content. This paper does not attempt to specify the required additional message content, but calls out the need for that work to be done in the industry. Like OAM1, this interface could use the proposed IEEE 1904.2 (IEEE 1904.2 Task Force, n.d.) standard to provide transport between the PON Control Function and the OLT.

- ***MNx*** – Is the interface between the L2 Ethernet Aggregation and the L3 Aggregation and/or Subscriber Management elements. This interface should follow the specifications for the MN_E interface define in the DPoE v2.0 suite of specifications. This architecture does not simply call for the MN_E interface because the MN_E is a subset of functionality required. The MN_X interface must also implement the bearer plane functions of the DPoE v2.0 D interface. This can be accomplished by using the functionality of the MN_E interface to move traffic to the L3 aggregation and Subscriber Management functions.
- ***V/DT*** – Is the interface between the Host Ethernet Switch and the L2 Ethernet Aggregation. It is expected to be a simple fiber-based IEEE 802.3 and IEEE 802.1-based interface and corresponds to the Digital Transport interface called out in R-MAC/PHY and the V interface called out in TR-200. This architecture proposes that the V/DT interface be specified as a combination of requirements from these two industry documents.
- ***V*** – Is the interface between the Host Ethernet Switch and the OLT. It is expected to be a simple IEEE 802.3 and IEEE 802.1-based interface and corresponds the V interface called out in TR-200. This interface is expected to be short-hop fiber or other IEEE 802.3-compliant physical interfaces. This architecture proposes that the V interface here adopt the TR-200 V interface as a basis for its definition.
- ***TU/TUL*** – The TU interface is the same TU interface between the OLT and the ONU, as defined in the DPoE v2.0 suite of specifications. The TUL interface is the same TUL interface (a MAC domain) between as defined in the DPoE v2.0 suite of specifications with the subtle difference that the TUL interface will extend across the physical network to the L3 aggregation function.
- **CMCI** – Is the interface between the ONU and GW (or UE). This is the same CMCI interface that is defined in the DPoE v2.0 suite of specifications.

7. Reconnecting the Parts – Long Range Architecture

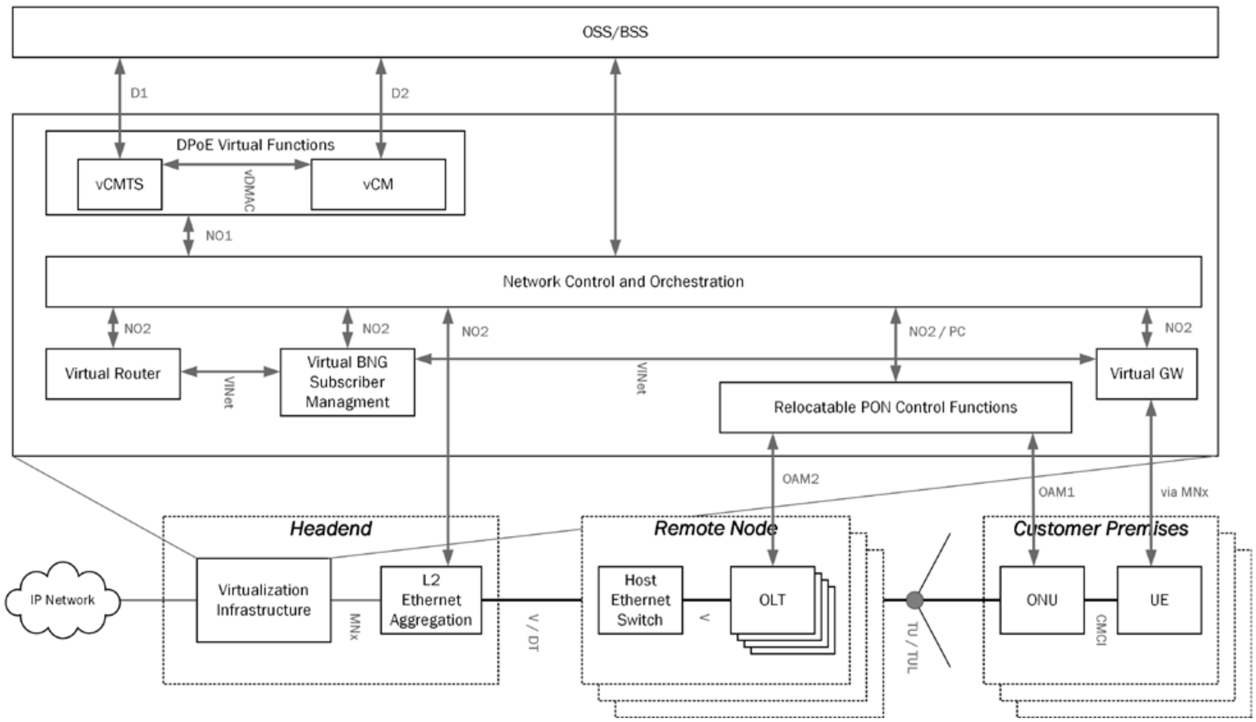

Figure 12 - Long Range Distributed EPON Architecture

The long range distributed EPON architecture is an example of how an operator could deploy distributed EPON with full SDN and NFV control while maintaining a migration path from DOCSIS-based provisioning. This architecture does away with traditional "big iron" application-specific systems and replaces them with virtualized network functions (VNF) running in software on a generic computing platform.

This architecture is a simple extension of the near term distributed EPON architecture proposed above, therefore most of the elements and interfaces are the same. Avoiding duplication, this section will discuss only the elements that are different between the two architectures.

7.1. The Elements

- ***Gateway (GW)*** – In this version of the architecture, the application-specific hardware GW is removed and replaced by a virtual GW running on the Virtualization Infrastructure.
- ***Virtual GW (vGW)*** – Is the VNF that implements the functions defined for the GW. It runs as a software module in the Virtualization Infrastructure and benefits from lower cost, due to the lack of application-specific hardware, and faster time to market with new features and functions due to the ability to develop and deploy software faster in the virtualized environment. The vGW must conform to the same feature/functional specifications as the GW, with the clear exceptions that are made for a device running as a VNF (for example, physical interfaces are not required).

- ***L3 Aggregation*** – In this version of the architecture, the application-specific hardware L3 Aggregation is removed and replaced by a virtual router running on the Virtualization Infrastructure.
- ***Virtual Router (VR)*** – Is the VNF that implements the functions defined for the L3 Aggregation Function. It runs as a software module in the Virtualization Infrastructure and benefits from lower cost, due to the lack of application-specific hardware, and faster time to market with new features and functions due to the ability to develop and deploy software faster in the virtualized environment. The VR must conform to the same feature/function specifications as the L3 Aggregation Function with the clear exceptions that are made for a device running as a VNF (for example, physical interfaces may not be specified for the VR, but instead would be specified for the Virtualization Infrastructure).
- ***Subscriber Management (BNG)*** – In this version of the architecture, the application-specific hardware BNG is removed and replaced by a virtual BNG running on the Virtualization Infrastructure.
- ***Virtual BNG (vBNG)*** – Is the VNF that implements the functions defined for the Subscriber Management function. It runs as a software module in the Virtualization Infrastructure and benefits from lower cost, due to the lack of application-specific hardware, and faster time to market with new features and functions due to the ability to develop and deploy software faster in the virtualized environment. The vBNG must conform to the same feature/function specifications as the Subscriber Management function with the clear exceptions that are made for a device running as a VNF (for example, physical interfaces may not be specified for the VR, but instead would be specified for the Virtualization Infrastructure).

7.2. The Interfaces

The only new or different interface in the long term architecture is the VINet interface.

- ***VINet*** – Is the interface between virtualized network functions running on the Virtualization Infrastructure. This specification does not attempt to define this interface and leaves it to be implementation specific based on the operator's architecture for the Virtualization Infrastructure.

Conclusion

In this paper, we have developed the framework for Distributed EPON Access in the cable industry. In the interest of reusing as much as possible from existing work, we surveyed the industry for standards, specifications and example implementations. This survey informed much of the proposed architecture and found that all elements and all interfaces, with one exception, have a basis in existing standards and specifications. By reusing the existing body of work, the work required by the industry is reduced significantly if it desires to write a complete specification for a distributed EPON architecture.

The proposed architecture fully supports the cable industry DPoE v2.0 suite of specifications and provides a migration path from current DOCSIS-based provisioning and operational models to SDN-based and NFV-based models that are currently being specified by industry consortiums and standards bodies and being implemented by non-cable telecommunications operators.

It will be important to the cable industry to adopt similar SDN-based and NFV-based models to stay competitive in the telecommunications market. The proposed architecture provides a framework for cable operators to use as they develop their own SDN and NFV architectures.

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