Exploring Multi-Access Edge Compute in Converging Access Networks

A Technical Paper prepared for SCTE by

Andrii Vladyka
Technical Product Manager, Cable Access
Harmonic Inc.
2590 Orchard Parkway, San Jose, CA 95131
+1 408 542 2559
Andrii.Vladyka@harmonicinc.com

Asaf Matatyaou
Vice President, Solutions and Product Management, Cable Access
Harmonic Inc.
2590 Orchard Parkway, San Jose, CA 95131
+1 408 542 2559
Asaf.Matatyaou@harmonicinc.com

Howard Abramson
Principal Architect, Cable Access
Harmonic Inc.
2590 Orchard Parkway, San Jose, CA 95131
+1 408 542 2559
Howard.Abramson@harmonicinc.com

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1. Introduction

Cable access networks and equipment has changed dramatically since the inception of high-speed data over hybrid fiber coaxial (HFC) networks. This evolution has enabled cable to become the dominant supplier of broadband access worldwide. The ongoing need for scale and operational efficiencies to maintain this lead is anticipated and will enable Multi-System Operators (MSOs) to meet subscribers' voracious appetite for bandwidth and internet-enabled devices while lowering the overall cost of ownership so that MSOs can stay competitive with alternate access providers.

A common element to cable access network evolution has been a focus on purpose-built hardware appliances, employing advances to information encoding (e.g., DOCSIS® 1.0, 1.1, 2.0, 3.0, 3.1, and 4.0), that operate on-premises at *carrier scale for a single service medium, DOCSIS*. These advances were complemented by the modularization and distribution of functionality to various portions of the operator's access network (inside and outside plant) using tightly coupled (industry standard) hardware appliances continuing to operate at carrier scale and including other service medium such as passive optical networks (PON). In recent years, the industry has acknowledged the utility and applicability of public (and private) cloud operator approaches to organizing, operating, and deploying massively scalable computational networks for the access network. These *cloud-native* architectures started by partitioning functions into software-based applications running on commercial off-the-shelf (COTS) servers and Ethernet switches to *virtualize* typical hardware-based network functions (VNFs). This approach to VNFs has evolved into the orchestration of *containerized* cloud-native functions (CNFs) that comprise a collection of disaggregated loosely coupled microservices that can operate in public, private and distributed portions of an operator's network to advance *carrier scale toward cloud scale*. Further evolution of these networks is now occurring along two dimensions to i) leverage elasticity of hyperscale cloud service providers' (CSPs) compute resources and ii) deep edge computing infrastructure to converge deployment and operations for a diverse collection of access technologies and services into a single multi-access, multi-service edge computing (MEC) platform. A paper presented last year focused on exploring the former aspect of access network evolution. This current paper focuses on the latter point — access service convergence.

This paper summarizes the role of CNFs and edge compute in access network convergence based on the practical experience of deploying distributed access architecture (DAA) DOCSIS networks and PON. This convergence is in a form of CNFs on a common cloud-native platform leveraging general purpose x86-based compute resources. Motivation and strategies for convergence, as well as its impact on network topology change and daily operations is considered. The concepts of cluster resource elasticity and horizontal scaling, along with the benefits of infrastructure resource sharing between access media (e.g., DOCSIS and PON) workloads in MEC deployments, are also analyzed. Finally, furthering DOCSIS and PON network convergence with other access technologies that provides a path for building CNF-based service agnostic networks will be described.

2. Terminology

The following interpretation of key industry terms is assumed throughout the paper.

Multi-access Edge Computing (MEC): applies to a system which provides an IT service environment and cloud-computing capabilities at the edge of an access network and contains one or more types of access technology that is within close proximity to its users [1].

Cloud-native Network Function (CNF): network functionality delivered in software via cloud-native development and delivery practices [2].

Cluster: a set of compute nodes that can be viewed as a single system. Cluster nodes are connected via a converged network (e.g., Ethernet-based) and managed by platform management software.

Multi-tenant cluster: sharing compute resources for infrastructure pods and workload pods serving different types of applications (e.g., DOCSIS, PON, wireless), while providing required levels of resources and components isolation.

Access network convergence: providing wireline and mobile services from a single flexible, programmable connectivity platform whose hardware, software and data storage resources spanning multiple geographic locations are shared across multiple access technologies. For operators, network convergence reduces the complexity and cost of providing multi-service offerings [3].

Pod: a group of one or more software containers, orchestrated by Kubernetes [4].

Container: an application that has its own file system, CPU, memory and process space. It is similar, but more lightweight compared to a virtual machine (VM), as containers have relaxed isolation properties to share the Operating System (OS) among the applications.

3. Historical Overview of Access Network Convergence and Virtualization in Cable

Historically, the telecommunication equipment market was dominated by hardware-based appliances tailored for a specific access layer technology, implementing one or more layers of the Open Systems Interconnection (OSI) model, from L1 to L7 [5]. Although such appliances employ industry standard protocols (e.g., SSH, Telnet, SNMP, NETCONF, etc.) each is built and managed using proprietary methods. The result has been economic and operational overhead that inevitably comes with the proliferation of disparate networking appliances on the same network.

The evolution of telecommunication equipment was (and remains) focused on the following.

1. Increased performance and capacity (e.g., throughput, network latency, and port density) facilitated by innovations in purpose-built, highly integrated application-specific integrated circuits (ASICs) and systems on a chip (SoCs).
2. Reduced construction cost and operations maintenance.
3. Increased availability, reliability, and security.
4. Improved network management and network operations.

Each of these advances has been mostly focused on individual network elements that each operate at *carrier scale and availability* rather than focus on the network as a converged system. Examples of these network improvements include the original Modular Cable Modem Termination System (M-CMTS) followed by the Converged Cable Access Platform (CCAP), later the Modular Headend and Distributed Access Architecture (MHAv2 and DAA), Remote PHY (R-PHY), and Flexible MAC Architecture (FMA) specifications; all of which were closely tied to advances in physical layer optimizations via the DOCSIS 2.0, 3.0, and 3.1 standards. Today, the cable industry recognizes challenges for taking networks to the next level, as described by CableLabs' vision of the 10G platform — a combination of technologies that will deliver symmetric multigigabit internet speeds [6].

As an alternative to optimizing individual network appliances, a new approach to meeting these challenges has emerged. This can be described by the following two points.

1. Network and service convergence.

2. Network and service virtualization.

Network convergence and network virtualization has presented a convenient approach to solving these challenges given exponential growth of computational efficiency available in general-purpose processors using common design patterns and leveraging open source software libraries, tools, and network operating systems. The increased performance of general-purpose compute has enabled telecommunication equipment vendors to develop solutions that run on generic, compute platforms that can implement virtual network functions (VNFs) in software. By using COTS server hardware, operators are reducing variations and consolidating vendor proprietary hardware appliances that were deployed in their network. The transition from purpose designed hardware appliances to similarly capable virtualized functions running on COTS servers is illustrated below.

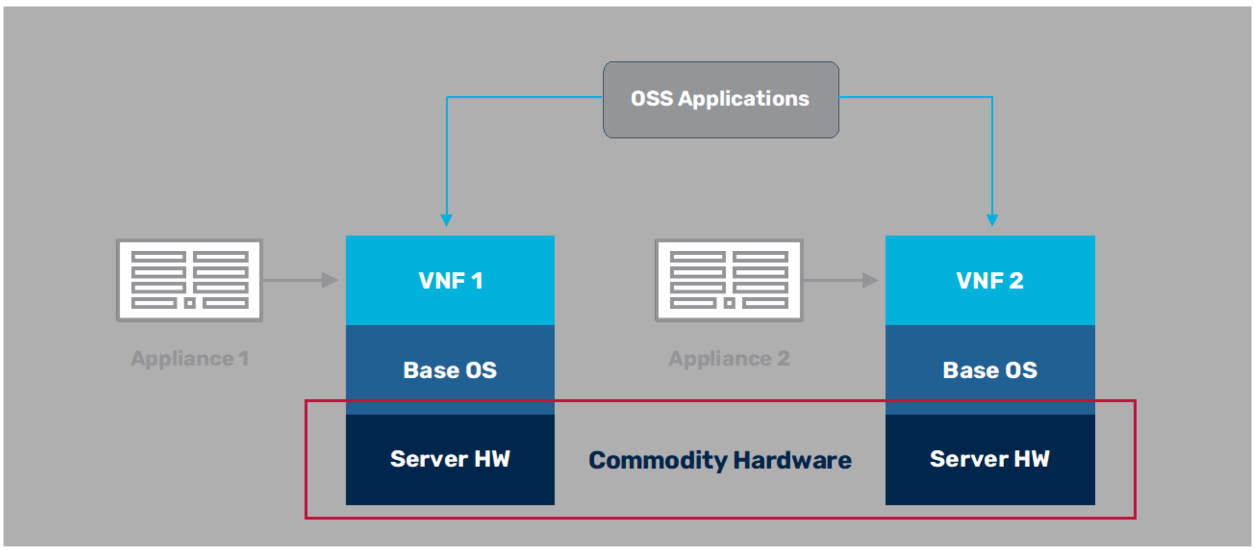

Figure 1 – Transition from Hardware-based Appliances to VNFs on Commodity Hardware

This first transition from hardware to VNFs remained *carrier scale and availability* of individual elements as it has been mostly focused on substituting network appliances with a better mouse trap [11].

Based on advances by the major hyperscalers, the next natural step in network convergence and virtualization has been the adoption of a new paradigm that operates at *cloud scale and availability*: the shift from VNFs to CNFs operating under the management and control of a container orchestration system (such as Kubernetes). This container orchestration system provides a time tested, scalable, de-facto standard for managing cluster resources (such as central processing unit (CPU), networking, memory, and storage), network function partitioning & abstraction, and operation of the network. Rather than managing individual appliances at carrier scale, this *cloud-native* paradigm creates an open environment where homogeneous general-purpose compute can be shared by networking applications from any vendor design deployed in the form of CNFs that is scalable and isolated from other vendor CNFs. The following diagram illustrates independent network functions (from one or more vendors or the operator themselves) operating as CNFs to provide an end-to-end network solution.

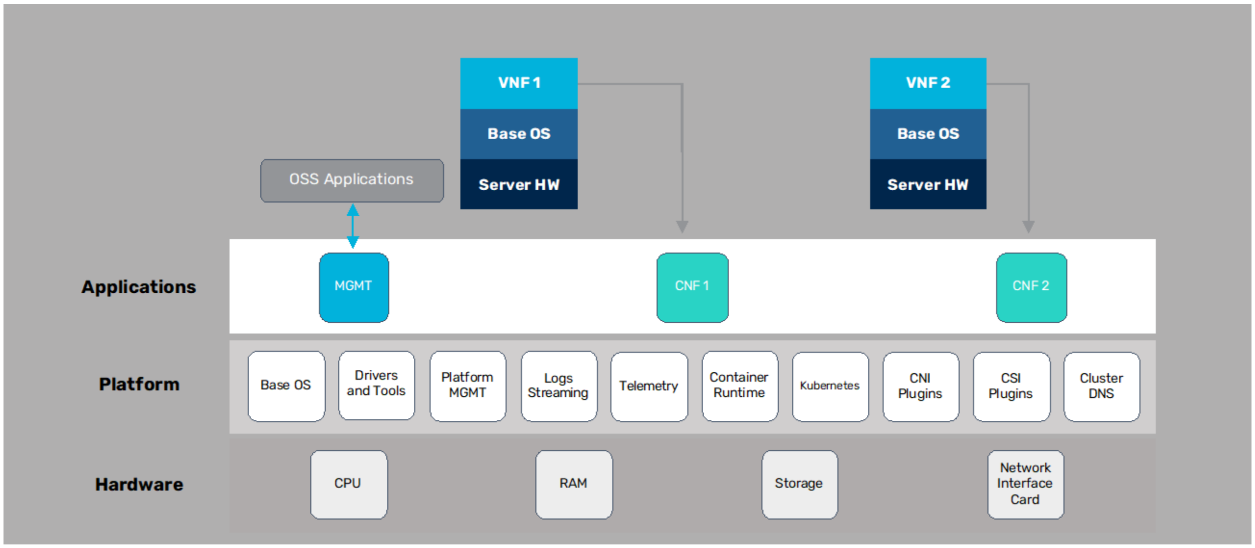

Figure 2 – Transition from VNFs to CNFs

To date, access network convergence and virtualization has helped cable operators to address the following challenges.

1. Sustaining ever-growing network performance requirements by leveraging a short and predictable cycle of increasing performance gains available in general-purpose compute.
2. Reducing network capex by riding economies of scale provided by commodity hardware.
3. Optimizing network opex by reducing the number of disparate devices deployed and maintained in the network.
4. Improving network reliability by employing native high availability (HA) facilities that come with the flexibility of network functions implementation in software, in general, and in particular with the use of Kubernetes-orchestrated CNFs.
5. Simplifying and unifying network management and operations by reducing the number of different systems to manage and leveraging service-based telemetry and logging for receiving and storing the information from different CNFs in a uniform way.
6. Advancing *carrier-scaled* applications that can grow or shrink both in terms of performance/capacity of an individual CNF (vertical scaling) and in terms of the number of deployed CNFs (horizontal scaling) at *cloud scale* one CNF and one server at a time.

In subsequent sections of the paper, we describe different aspects of the current state of cable access networks convergence and virtualization.

4. Access Networks Convergence in Cable: The Current State

Network convergence can be viewed by considering three different access technologies employed in cable. Looking at cable's HFC, it becomes clear that the same fiber carrying analog and digital wavelengths for video and data can be used for Ethernet and PON. In fact, DOCSIS, Ethernet, and PON are three edge technologies that have been used in cable networks for years. These access technologies are typically applied for different subscriber categories and managed by different personnel using unique operations. For example, it is often the case that DOCSIS is reserved for residential and small medium businesses (SMB), Ethernet is used for enterprise and mobile xHaul, and PON is used for managed property and multidwelling unit (MDU) subscribers. Although provisions were made for designing hardware appliances with support for multiple edge access technologies in the CCAP specification, it is typically the case that DOCSIS, Ethernet, and PON are provided by different vendors using quite different approaches to managing and operating the network. The impact is a non-uniform and disparate collection of point products that must be managed by cable operators. The result is a lack of convergence and economies of scale that come from modern approaches to deploying and managing cloud-native networks. Alternatively, when considering access solutions based on virtualization, it becomes possible to consider workloads for two or more of these access technologies within the same converged platform.

Key factors that contribute to access networks virtualization include the following.

1. Growth in general-purpose CPU performance capable of software implementation of network functions in the form of CNFs with the same or better performance as of field-programmable gate array (FPGA)/ASIC-based hardware appliances.
2. Maturity of software frameworks that accelerate packet processing workloads running on a wide variety of CPU architectures [12].

The trigger for virtualization of the CMTS (vCMTS) was the release of the DOCSIS Remote PHY Specification [10], that partitions the DOCSIS PHY from components responsible for MAC and upper layer protocol functions. This separation of the lowest layer of the DOCSIS protocol enables the repartitioning of upper layer software-only implementations. In this way, virtualization of the CMTS was achieved and brought into operator's facilities [11]. Using general-purpose compute resources for running DOCSIS vCMTS workloads makes it possible to consider workloads for other access technologies on the same cluster of compute resources.

The following diagram illustrates an example of how access workloads, operating on general-purpose COTS servers, can be applied to DOCSIS and PON.

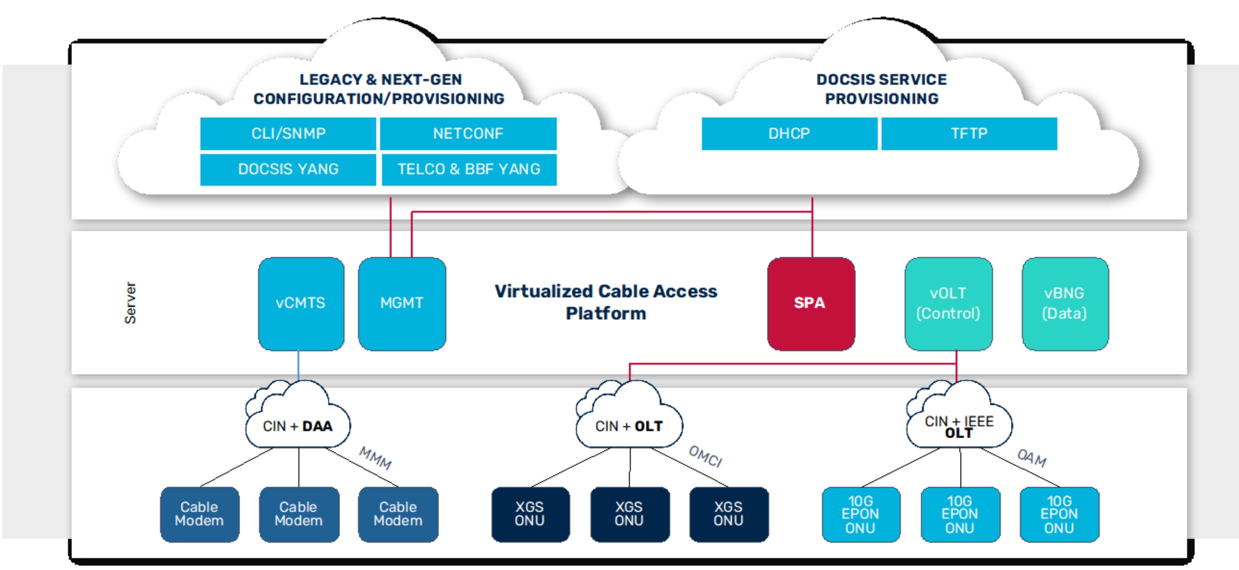

Figure 3 – Access Network Convergence and Uniform Service Provisioning for Any Access

This is explained by the following.

- vCMTS — DOCSIS workloads are provided by CNFs that virtualize the CMTS upper layers serving DAA-based PHY devices.
- vOLT— PON workloads are provided by CNFs that virtualize the control of external physical OLTs
- vBNG — upper layer functions typically provided by hardware appliances for PON are provided by CNFs performing subscriber management and user plane operations
- MGMT and SPA — OSS/BSS, fault, configuration, accounting, performance, security (FCAPS) is provided by Management and Service Provisioning Application CNFs to complete the convergence

In this way, not only are different access technologies and protocols converged on common COTS servers, but they are presented to the operator's network with a uniform and scalable platform that can share and load balance available resources.

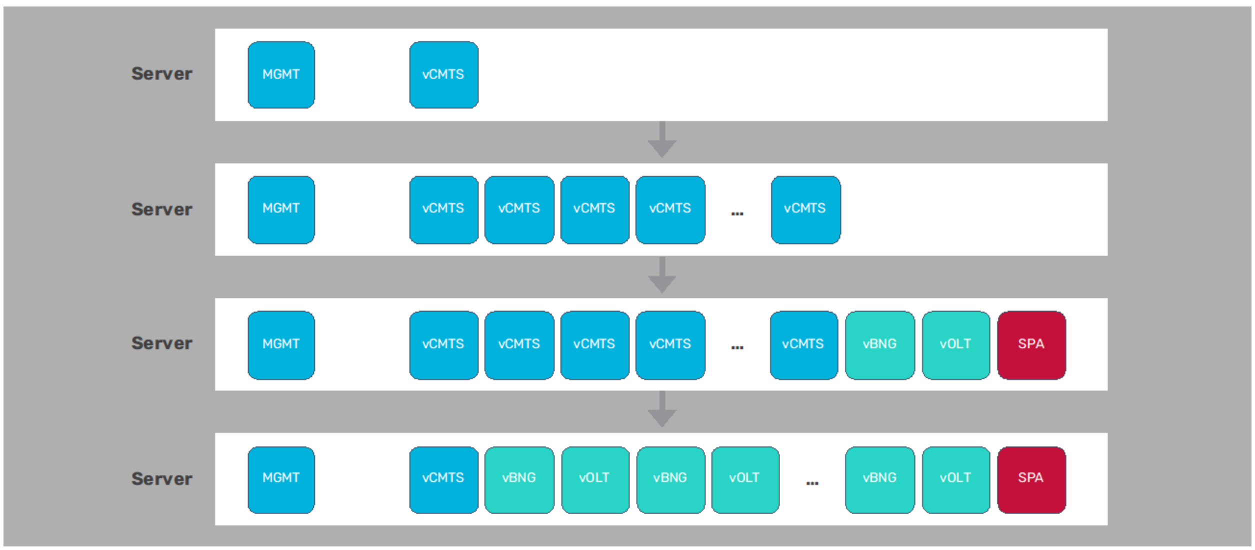

Figure 4 – Horizontal Scaling of CNFs on a Converged Access Platform

Figure 4 illustrates the example of horizontal workloads scaling on a converged access platform.

1. The deployment starts with a relatively small number of DOCSIS service groups (SGs) connected to one CNF instance that implements vCMTS functions.
2. As the number of connected DOCSIS SGs grows, the number of vCMTS workloads increases proportionally.
3. With the introduction of a new type of access technology (PON), CNFs implementing vBNG, vOLT, and SPA functions are instantiated on the same cluster resources.
4. Over time, the number of CNFs implementing different types of access technologies may change. For example, some of the DOCSIS SGs may be converted to PON SGs, which is reflected by the proportional change in the number of CNFs of a certain type running on the platform.

As a converged access platform, the solution now offers common interfaces for managing and operating the entire network. One example of this convergence is the presentation of traditional DOCSIS service provisioning.

Cable operators have long benefited from a simple and standard method of provisioning individual subscriber services. The utility of this basic approach for defining individual subscriber connections and service level agreements (SLAs) was recognized and applied in the DOCSIS Provisioning of EPON (DPoE) standards [17]. While originally defined and qualified for 1 Gbps EPON, this same DOCSIS-based method for defining subscriber connections, when partitioned as a collection of CNFs, can be applied to any media, including ITU-T (GPON and xGPON), IEEE (10G, 25G, and 50G EPON), and Ethernet. Further, by separating provisioning and management CNFs from the media-specific CNFs, adoption of other methods becomes far more flexible and scalable. As an example, by applying cloud-native APIs within Management and Service Provisioning Applications, use of CLI, SNMP, NETCONF, and of course virtualized cable modem (vCM) methods specified in DPoE, are all available and of little consequence to the vCMTS, vOLT, and vBNG CNFs that they serve.

While this is one way of converging an access network, it is but one example. The point is that the impact of access network convergence in the cable industry results in the following benefits.

1. Increased service agility.
2. Reduced operational cost.
3. Simplified and uniform network operations.
4. Increased network reliability, availability and security.

Next, we will explore the connection of cable access network convergence with the MEC concept.

5. Multi-access Edge Computing in Cable

The ETSI definition for Multi-access Edge Computing enables the implementation of applications as software-only entities that run on top of a virtualization infrastructure, which is located in or close to the network edge [7]. The MEC framework represented in the diagram below shows the general entities involved. These can be grouped into system level, host level and network level entities.

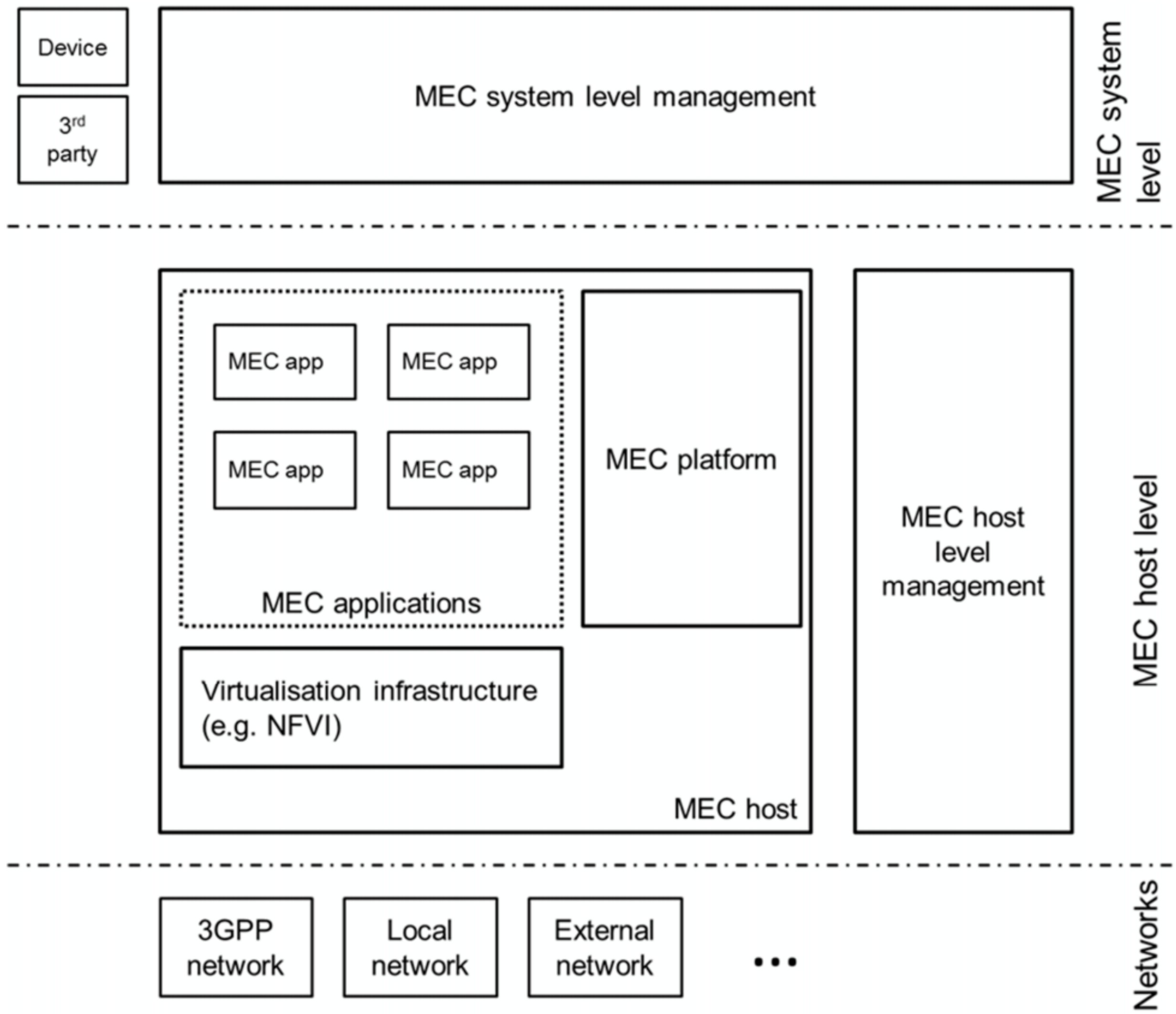

Figure 5 – ETSI Definition of Multi-access Edge Computing Framework [7]

The framework for Multi-access Edge Computing consists of the following entities.

1. **MEC host** – an entity that contains a MEC platform and a virtualization infrastructure that provides compute, storage, and network resources for the purpose of running MEC applications.
    a. **MEC platform** – the collection of essential functionalities required to run MEC applications on a particular **virtualization infrastructure** and enable them to provide and consume MEC services.
    b. **MEC applications,** instantiated on the virtualization infrastructure of the MEC host based on configuration or requests validated by the MEC management.
2. **MEC system level management** that includes the multi-access edge orchestrator as its core component. The orchestrator is responsible for the following functions.
    a. Maintaining an overall view of the MEC system.
    b. Application packages on-boarding.
    c. Selecting appropriate MEC host(s) for application instantiation based on constraints, such as latency, available resources, and available services.
    d. Triggering application instantiation, termination, and relocation.

3. **MEC host level management** which handles the management of the MEC-specific functionality of a particular MEC host and the applications running on it.

While the MEC concept originated in the context of mobile/wireless networks, the general definition of the MEC concept and framework has a lot in common with the real-world architecture of the current generation of the virtualized cable access platforms deployed today [8].

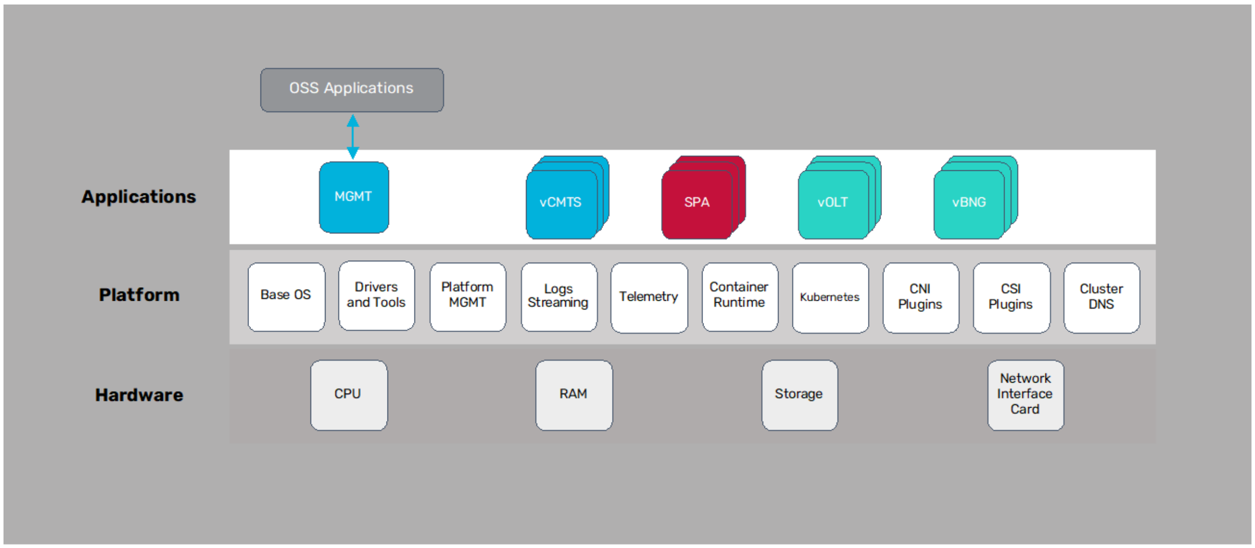

Figure 6 – A Host of a Virtualized Cable Access Platform

As can be seen from the figure above, the implementation of a virtualized cable access platform is like the generic ETSI definition of MEC compute framework. This includes the following similarities.

1. The role of the platform layer of the virtualized cable access platform is equivalent to those of the MEC platform and virtualization infrastructure entities.
2. Applications running on a virtualized cable access platform are equivalent to MEC applications. Examples of applications running on top of the virtualized cable access platform are:
    a. Virtual cable modem termination system (vCMTS).
    b. Virtual optical line terminal (vOLT).
    c. Virtual broadband network gateway (vBNG).
    d. Service provisioning application (SPA).
    e. Management (MGMT) applications implementing “northbound” interfaces toward operations support systems (OSS) as well as “southbound” API calls toward platform and CNFs.
3. MEC system level management in a virtualized cable access platform is partially covered by the OSS applications, and partially implemented by a set of tools for deployment automation and monitoring.

In fact, the cable industry has been leveraging the MEC concept for years [9] without calling it “MEC.” Future directions for the application of the MEC framework within cable may include the following.

1. Further network convergence and proliferation of the applications running on top of the virtualized cable access platform:

   a. Adding new types of broadband access applications on the virtualized cable access platform.
   b. Adding applications specific for the hospitality industry (e.g., digital signage and targeted advertising applications).
   c. Converging applications implementing 5G CU/DU/cCore components with other broadband access applications.
   d. Exploring new business models with healthcare applications. This use case also covers more generic list of applications dealing with sensitive customer data, where application data is not allowed to leave the perimeter of the organization.
2. Integration with hyperscalers and offloading certain types of workloads traditionally deployed in CSP infrastructure to the network edge.
3. Adopting CI/CD practices on the organizational level to accelerate the development and deployment of edge compute applications.

6. Dealing with Transport Matters in a MEC Era

As shown on Figure 5, the MEC framework is generally agnostic to the networks connecting MEC hosts. Luckily, the current state of the virtual access networks convergence doesn't leave many variations for networking technologies connecting applications running on the edge compute hosts with their consumers. To explain the concept and why it's perceived to be a positive way of network evolution, we need to take a step back and state the challenges attributed to the networks of the past.

Consider the following diagram showing a typical legacy DOCSIS network with analog fiber going from the hub to the field.

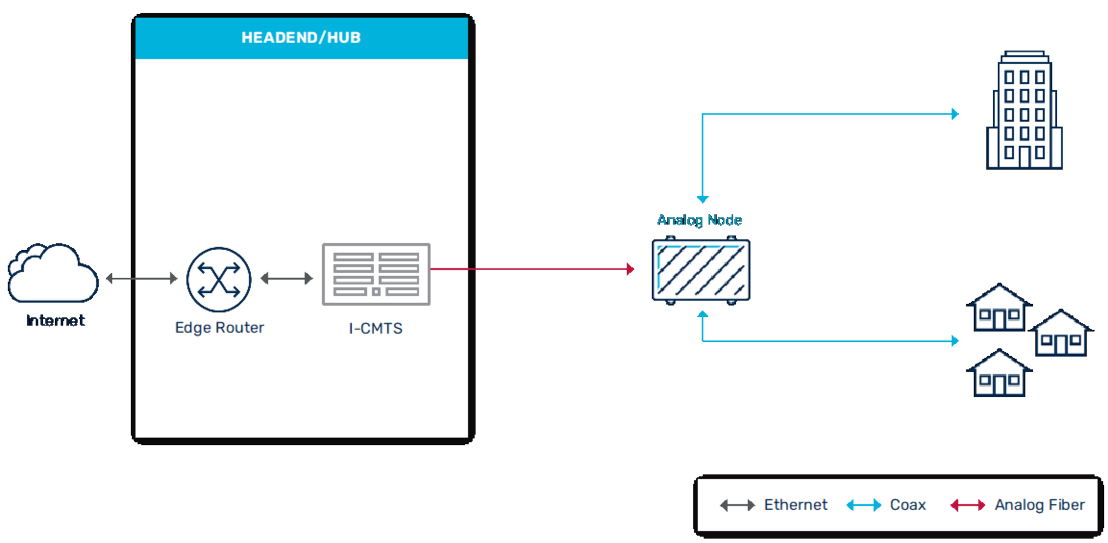

Figure 7 – Legacy DOCSIS Network

Analog connectivity between headend/hub and fiber node doesn't leave options for choosing the connectivity type for the end subscribers. If, for example, a business subscriber is looking for a speed tier that cannot be provided by a DOCSIS network, then it would require the cable operator to lay a dedicated optical fiber line from the headend/hub to the customer's facility. The cost of such work and the time it would take to do the construction makes the business case not economically viable. Similarly, delivering high-speed internet connectivity using Ethernet as a last mile technology would require adding more physical appliances (e.g., access switch, BNG) to the operator's facility and integrating them with the service provisioning systems. The alternative, of course, is to use the same fiber with different digital wavelengths that can carry a variety of access protocols. This is a key concept of the DAA.

With DAA, Ethernet transport becomes a universal means of transporting broadband access applications running on top of the compute resources (wherever they are) to the devices implementing physical layer connectivity. The result is a converged multi-access network as shown below.

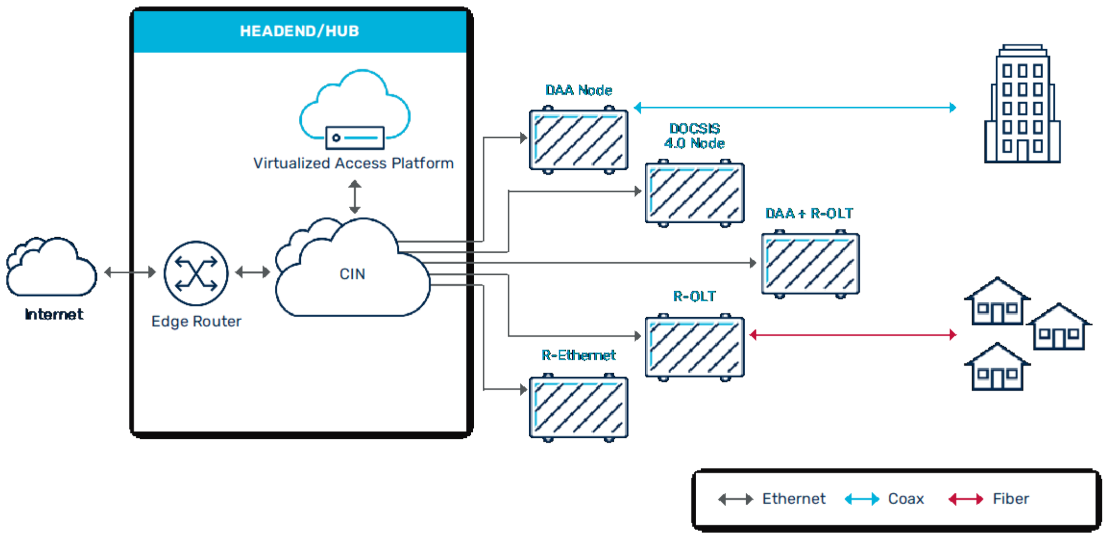

Figure 8 – Converged Multi-services Cable Access Network

The benefits of this converged multi-service cable access network include the following.

1. "Standardization" of the outdoor plant, with Ethernet links (via the converged interconnect network, CIN) connecting DAA nodes with headend/hub equipment that in turn may be connected to off-premises resources *in the cloud.*
2. *Stretching* the CIN closer to end users with outdoor digital fiber segments extending reach, aggregation, and overall network capacity.

It's worth mentioning that while current DAA deployments are based on 10G Ethernet connectivity between distributed access architecture switches (DAAS) and DAA nodes, the industry is looking into adopting higher rates (25G, 100G and higher speed Ethernet).

Using the same example of an enterprise business customer connected over a DOCSIS network looking for a higher speed tier, let's look at how a virtualized access platform enables instantiation of new services.

6.1. Use Case: Adding New Services On Virtualized Access Platform with DAA

6.1.1. Outside Plant Work

The scope of the outside plant work includes installation of a digital fiber from the DAA node closest to the customer's facility to enable 1G or 10G Ethernet or PON. Rather than the expense and complexity of a headend/hub trunk connection, the scope of required construction to reach the customer's facility is far smaller.

6.1.2. CNF Instantiation

A vBNG CNF workload is deployed on the virtual cable access platform's compute resources that are closest to the customer's facilities. Generally speaking, the exact location of the compute resources serving a specific customer is flexible: location of the CNF can be anywhere in the network and can change over the time based on commercial and operational needs.

6.1.3. Topology Discovery

The logical connectivity (session) is established between CPE and the corresponding vBNG instance using automation tools or statically.

6.1.4. Services Provisioning and Activation

This step implies provisioning of the selected speed tier and SLA for the customer premises equipment (CPE) and applying the corresponding configuration to the vBNG application running on the virtual cable access platform. As noted earlier, using uniform MGMT and SPA CNFs permits common tools and workflows to be applied for services provisioning over different access networks.

6.1.5. Monitoring

At this point, services are up and running and an operator performs routine monitoring of the subscriber connectivity and availability using cloud-native telemetry and logging.

The advantage of this approach for adding a new subscriber or introducing a new type of access technology is that it does not require installation of any new equipment within the operator's facility or change in workflow and tools. Connecting a subscriber to the desired access technology (e.g., DOCSIS, Ethernet, PON) to the nearest DAA node becomes more plug-and-play. Such deployment flexibility and service agility are enabled by the introduction of the digital fiber all the way down to DAA nodes, on the one hand, and leveraging MEC for broadband access applications deployment, on the other.

7. Network Operations in a Converged World

The change in network operational practices for access networks convergence can be viewed through the prism of network virtualization. The move from hardware-based networking appliances towards CNFs running on a common virtualized access platform implies changes to the following network operations properties.

7.1. Separation of Platform Management from Applications Management

The virtualized access platform provides standard resource units, such as CPU cores, memory, storage, and network share, to applications (CNFs). The platform considers CNF resource needs, as well as other requirements, such as locality and high availability (HA) preferences. As a result, operators need only to operate a single Kubernetes-based platform that is responsible for multiple CNF workloads in a consistent way. In comparison, legacy access networks typically require at least one element management system (EMS) or network management system (NMS) dedicated to each class and vendor provided networking appliance. The result is oftentimes complex and expensive software systems that attempt to orchestrate this collection of appliances.

7.2. Ubiquitous Automation

CNF deployment automation provides a declarative configuration model and single configuration interface for managing the configuration of different CNFs. Automation in cable access networks leverages standard network management protocols, such as NETCONF, and data models, such as DOCSIS YANG [19].

1. Operator builds configuration template(s) using standard data model.
2. Operator applies configuration to a virtualized access platform via NETCONF.
3. CNFs are instantiated on a platform to accommodate services configuration provided by the operator.

Using services-oriented configuration data models allows an operator to focus on services requirements while corresponding CNFs instantiation and resources allocation are handled by the platform.

7.3. Deprecation of Legacy Monitoring Interfaces in Favor of Modern Telemetry-Based Protocols

In the current context, SNMP and IPDR fall into the category of legacy protocols providing data to external monitoring and billing systems.

In short term, the usage of service-based telemetry is not mutually exclusive to legacy protocols. In fact, the current state of access networks convergence is characterized by the simultaneous and compatible use of modern and legacy monitoring/billing interfaces and protocols. The long-term vision is that legacy protocols will be deprecated in favor of the scalability and deployment flexibility requirements available in virtualized converged access networks. Figure 9 provides an example of a telemetry streaming pipeline from CNFs running on top of a virtualized access platform. The pipeline is highly scalable, provides updates with short time intervals, and can be incorporated into operator's automated analytics and machine learning (ML) applications.

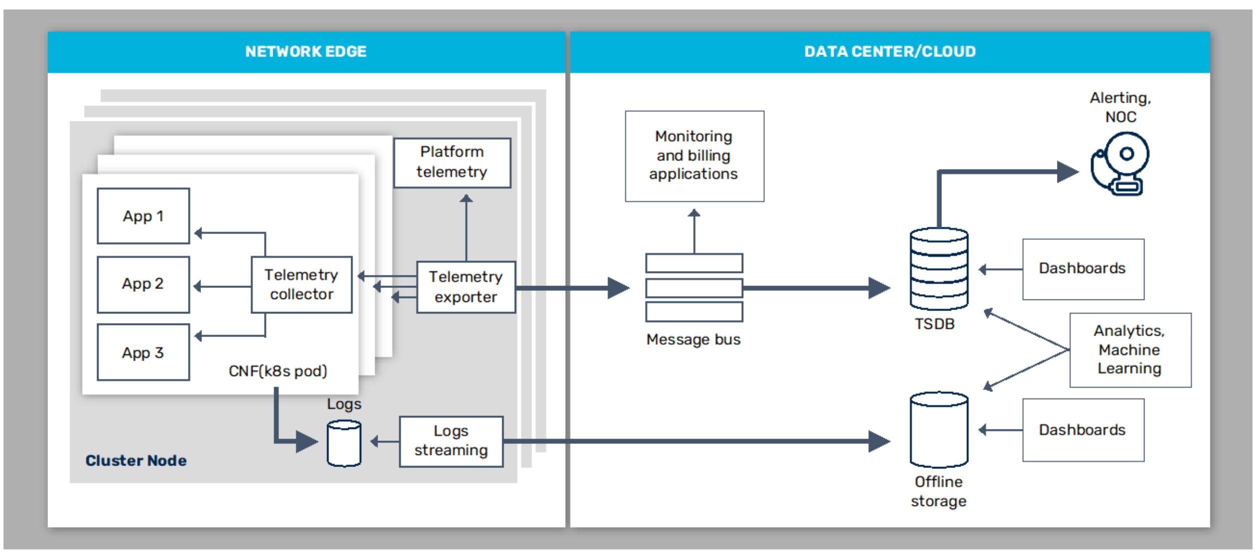

Figure 9 – Telemetry Streaming Pipeline

The result of telemetry data processing by automated analytics and ML applications can be then applied back to the access platform in a form of closed-loop automation.

7.4. Introduction of The New Software Distribution Models and Adoption of CI/CD Methodologies at The Organizational Level

In legacy networks, an upgrade of a networking device is typically executed in a form of transferring a software image file(s) to the target device and activating a new software version accompanied by the reboot of the device. In virtualized converged access networks, CNF software is released in the form of containerized images. This approach is characterized by the following.

a. The virtualized access platform is always connected to a container image registry, facilitating simultaneous software distribution and installation at *cloud scale*.
b. An upgrade of a CNF can be performed in a way seamless to the services provided to end users (in-service software upgrade, ISSU), with minimal service interruption. No host (server) reboot is required for a typical CNF upgrade cycle.
c. Individual CNFs running on a converged platform can be upgraded independent of each other.
d. The same virtualized access platform can host CNFs of the same type running different software versions. This enables *candidate or canary* upgrades and A/B testing on a per-service group basis for final field acceptance prior to networkwide updates.

8. Conclusion

Cable access network convergence and virtualization were developed as a general solution for the challenges and opportunities the cable industry has experienced over the years.

- Meeting and exceeding ever-growing network capacity and performance requirements.
- Network construction and operations cost reduction.
- Improving network reliability, availability and security.
- Managing the complexity of network operations to incorporate new services and access technologies.

The cable industry is taking advantage of concepts defined by MEC by applying hyperscale cloud methods to DAA with CNFs. These concepts help to accelerate the convergence of cable access networks. These innovations enable cable operators to take advantage of the following converged network benefits.

- Elasticity of cluster resources and infrastructure.
- Automation and service instantiation at high velocity.
- Horizontal scaling capabilities and ability to change capacity on demand.
- Visibility of the platform and service.
- Faster time to market for deployment of new applications and repair.

Standard Ethernet-based connectivity between MEC infrastructure and devices in the field becomes a key enabler for many access technologies.

Moving forward, future directions of MEC development in access networks may include the following.

1. Adding new types of broadband access technologies and services, with the end goal of deploying an access agnostic network.
2. Unifying service provisioning processes for multiple access network types.

3. Integration with hyperscalers, that may be executed in two directions:
    a. Moving certain types of CNFs from on-premises compute resources to hyperscaler infrastructure.
    b. Moving some of these workloads, traditionally operating in hyperscaler infrastructure to on-premises clusters or deep edge compute resources.
4. Adopting CI/CD practices and modern software distribution and management practices to further improve service agility.

Abbreviations

ASIC	application-specific integrated circuit
CAPEX	capital expenditures
CCAP	converged cable access platform
cCore	converged core
CD	continuous deployment
CI	continuous integration
CIN	converged interconnect network
CMTS	cable modem termination system
CNI	container network interface
CNF	cloud-native network function
COTS	commercial off-the-shelf
CPE	customer premises equipment
CPU	central processing unit
CSI	container storage interface
CSP	cloud service provider
CU	central unit
DAA	distributed access architecture
DNS	domain name server
DOCSIS	Data Over Cable Service Interface Specification
DPDK	data plane development kit
DPoE	DOCSIS provisioning of EPON
DU	distributed unit
EMS	element management system
EPON	ethernet passive optical network
ETSI	European Telecommunications Standards Institute
FCAPS	fault, configuration, accounting, performance, security
FMA	flexible MAC architecture
FPGA	field-programmable gate array
GPON	gigabit passive optical network
HA	high availability
HFC	hybrid fiber-coax
HW	hardware
IEEE	Institute of Electrical and Electronics Engineers
ISSU	in-service software upgrade
IT	internet technology
ITU-T	International Telecommunication Union Telecommunication Standardization Sector
MAC	media access control

M-CMTS	modular CMTS
MEC	multi-access edge computing
MDU	multidwelling unit
MGMT	management
MHA	modular headend architecture
ML	machine learning
MMM	MAC management message
MSO	multi service operator
NETCONF	network configuration protocol
NMS	network management system
NOC	network operations center
OAM	operations, administration, and management
OLT	optical line terminal
OMCI	ONU management and control interface
ONU	optical network unit
OPEX	operating expenses
OS	operating system
OSI	open systems interconnection
OSS	operations support systems
PHY	physical layer
PON	passive optical network
RAM	random-access memory
RPD	remote PHY device
RPS	remote PHY shelf
SG	service group
SLA	service level agreement
SNMP	simple network management protocol
SMB	small medium businesses
SoC	system on a chip
SPA	service provisioning application
SSH	secure shell protocol
TSDB	time-series database
vBNG	virtual broadband network gateway
vCM	virtual cable modem
vCMTS	virtual CMTS
VNF	virtual network functions
VM	virtual machine
YANG	yet another next generation

Bibliography & References

[1] ETSI GS MEC 001 V2.1.1 (2019-01): Multi-access Edge Computing (MEC); Terminology. ETSI Industry Specification Group (ISG) Multi-access Edge Computing (MEC)

[2] CNCF Cloud Native Networking Preamble. Web. https://github.com/cloud-native-principles/cloud-native-principles/blob/master/cloud-native-networking-preamble%20(1).md
[3] CableLabs Network Convergence. Web. https://www.cablelabs.com/network-convergence
[4] Kubernetes. Web. https://kubernetes.io/
[5] ISO/IEC 7498-l Information technology – Open Systems Interconnection – Basic Reference Model: The Basic Model. International Organization for Standardization and International Electrotechnical Commission
[6] 10G: The Next Great Leap in Broadband. CableLabs; Web. https://www-res.cablelabs.com/wp-content/uploads/2019/08/26064924/10G-The-Next-Great-Leap-in-Broadband1.pdf
[7] ETSI GS MEC 003 V2.2.1 (2020-12): Multi-access Edge Computing (MEC); Framework and Reference Architecture. ETSI Industry Specification Group (ISG) Multi-access Edge Computing (MEC)
[8] Matatyaou, Asaf. 10G Technology Network Virtualization. February 19, 2020. Web. https://broadbandlibrary.com/10g-technology-network-virtualization/
[9] Matatyaou, Asaf. Real-World Deployment of a Virtual Cable Hub. Publication. San Jose: Harmonic, 2017. Web. https://www.nctatechnicalpapers.com/Paper/2017/2017-real-world-deployment-of-a-virtual-cable-hub
[10] Remote PHY Specification, CM-SP-R-PHY-I15-201207. December 7, 2020. Cable Television Laboratories, Inc.
[11] Matatyaou, Asaf. Transforming the HFC Access Network with a Software-Based CCAP. Publication. San Jose: Harmonic, 2015. Web
[12] DPDK. Web. https://www.dpdk.org/about/
[13] CableLabs Distributed Access Architecture. Web. https://www.cablelabs.com/technologies/distributed-access-architecture
[14] CableLabs DOCSIS® 4.0 Technology. Web. https://www.cablelabs.com/technologies/docsis-4-0-technology
[15] ITU-T Recommendation G.9807.1: 10-Gigabit-capable symmetric passive optical network (XGS-PON). June, 2016. International Telecommunication Union
[16] IEEE Standard for Information technology 802.3av-2009: Local and metropolitan area networks; Specific requirements; Part 3: CSMA/CD Access Method and Physical Layer Specifications Amendment 1: Physical Layer Specifications and Management Parameters for 10 Gb/s Passive Optical Networks. Institute of Electrical and Electronics Engineers
[17] DPoE Architecture Specification, DPoE-SP-ARCHv2.0-I07-190213. February 13, 2019. Cable Television Laboratories, Inc.
[18] Flexible MAC Architecture (FMA) System Specification, CM-SP-FMA-SYS-I02-210526. May 25, 2021. Cable Television Laboratories, Inc.
[19] DOCSIS YANG Model. Web. http://mibs.cablelabs.com/YANG/DOCSIS/. Cable Television Laboratories, Inc.

