Broadening the Reach of Broadband, Powered by Distributed Access Architecture

An Operational Practice prepared for SCTE by

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Introduction

1.1. Comcast History and Community Initiatives

For nearly 60 years Comcast has held to a consistent truth: The customers and the communities that we support are at the focal point of our decision making. In recent years, Comcast has created a multitude of programs to best support the diverse communities we serve. In 2011 Comcast introduced Internet Essentials. This program has delivered high-speed Internet to over 10 million Americans, bringing the technology required in today's world to be successful in education and work, and which now has also become social gathering space and center of entertainment. In 2020 the Lift Zone program was created. Additional sites are created every year, with over 1000 sites now available. This past year Comcast started to participate in the Affordable Connectivity Program, a government run program which has been able to help over 11.5 million households obtain reliable, quality Internet services through its partnerships with Internet providers[1]. These programs show that Comcast's commitment is more than simply providing broadband connectivity. The company prioritizes being a strong community partner as well. We have commitment to bridge the digital divide by partnering for these programs and creating additional grants which have supplied more than $16 million in grants and $75 million in-kind support to thousands of small businesses[2].

Comcast's commitment also spans into being a responsible steward of the environment, with various initiatives to hold ourselves accountable to specific environment-friendly target goals. A first of its kind recycling program for coaxial cables was established this year. With this program, approximately 70% of our coaxial cable waste will be recycled every year. We stand by our commitment to be carbon neutral by 2035 and have initiatives in place to drive to that outcome.

In this paper, we discuss how the landscape of rural broadband (RBB) is evolving quickly, and strategic network investments being made to serve these areas and help to close the digital divide in the years ahead. Today, over tens of millions of Americans do not have reliable high-speed Internet[3], and many are in these rural areas. With a foundation of virtualization and distributed access architecture (DAA) serving our coaxial footprint, Comcast is building on this to bring to life the DAA vision of a converged access infrastructure, and its introduction is timely and effective for RBB initiatives.

1.2. Technology Path Alignment

In 2020, the world was faced with a challenging situation. Having pioneered the deployment of a DAA beginning in 2017 combined with business-as-usual node segmentation that pushes fiber deeper into our network, Comcast was in an enviable position to handle the instantaneous pandemic-related capacity demands that 2020 presented[4, 5]. The pandemic shifted daily norms of work, education, and social interaction.

Comcast's DAA is based on the remote PHY specification[6], as shown in Figure 1. The introduction of DAA five years ago began the preparation for new processes, practices, tools and technology, starting with our most familiar and powerful workhorse – DOCSIS®. DAA was a fast follower to our prioritization of DOCSIS 3.1, which was deployed as soon as it was available. The launch of DOCSIS 3.1 represented yet another instance of recognizing the importance of building new capacity well ahead of demand. In 2020, this turned out to be very prescient, enabling Comcast and other operators to mostly absorb the COVID-induced traffic spike with loss of capacity margin as the primary impact – not customer issues as seen in **Figure 0**[4]. These investments not only allowed Comcast to meet the extreme capacity demands of the pandemic, but it validated the years of decisions based upon untapped potential of the HFC network and continuing to leverage that network and the coaxial connections to millions of homes.

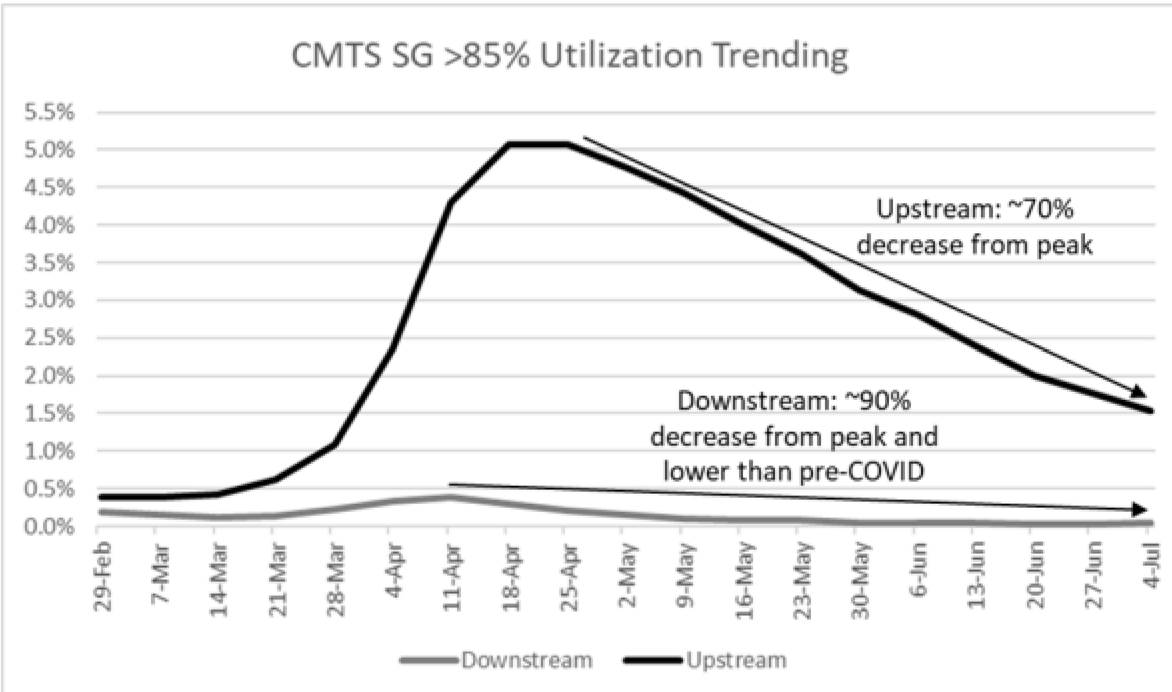


Figure 0 - Highly Utilized CMTS SG Trending[4]

As we continue to deliver on continuous capacity growth and demand for increased speeds, RBB highlights a renewed focus on the digital divide in rural America. We have evaluated the approaches to delivering on RBB requirements, which typically come in the form of request for proposals (RFPs). We have considered the underlay of the environment, needs and expectations of customers, and the growth projected for these areas in years ahead.

There is new technology being developed that is well-suited to deliver on RBB requirements in these RFPs. In this discussion, we highlight how Comcast's DAA and vCMTS foundation will enable us to drive the latest technology and capability into RBB by introducing a new remote OLT (R-OLT) that is particularly effective for RBB, as shown in Figure 2**.** The R-OLT and accompanying virtualized platform SW will enable efficient and effective delivery of fiber-to-the-home (FTTH) broadband services to the RBB customer base. Historically, to deploy passive optical network (PON) technology, companies used centralized optical line terminals (OLT). These are classic "big iron" chassis consuming significant power, space, and cooling capacity in headend facilities. Furthermore, with their proprietary hardware and software implementations and the large scale of users subscribed to a single chassis, they are relatively costly to deploy, operate, and upgrade.

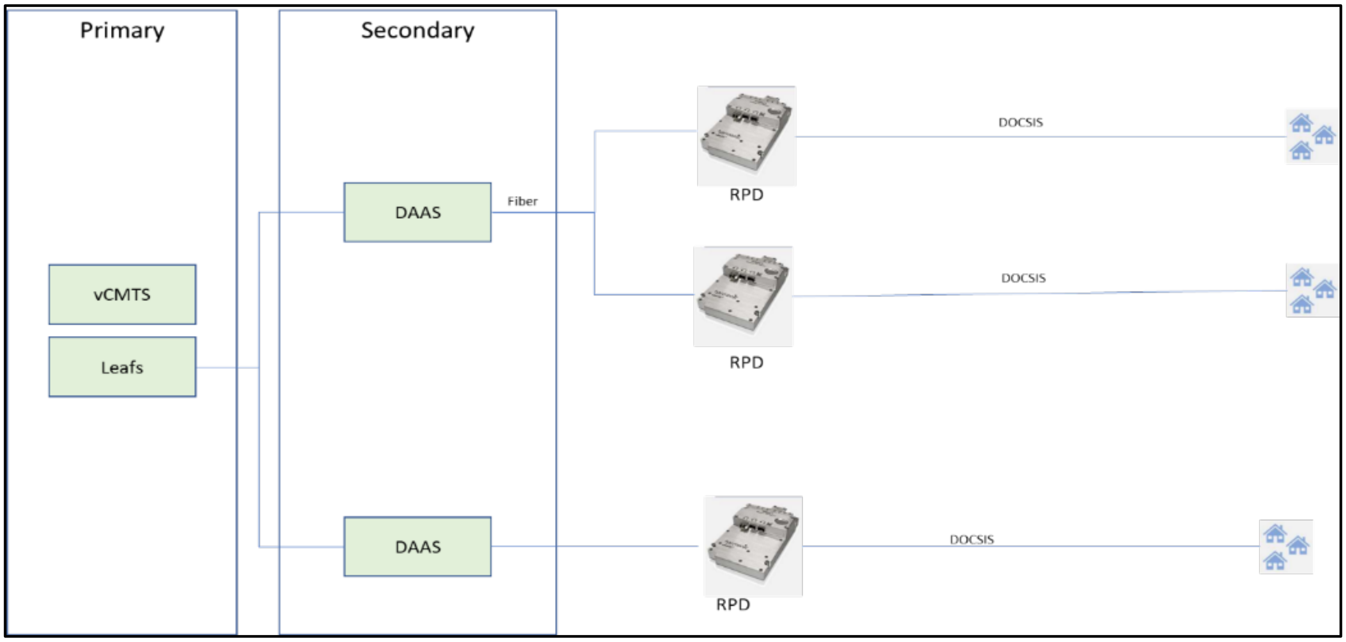


Figure 1 – Diagram of DAA Basic Infrastructure from Headend to Home

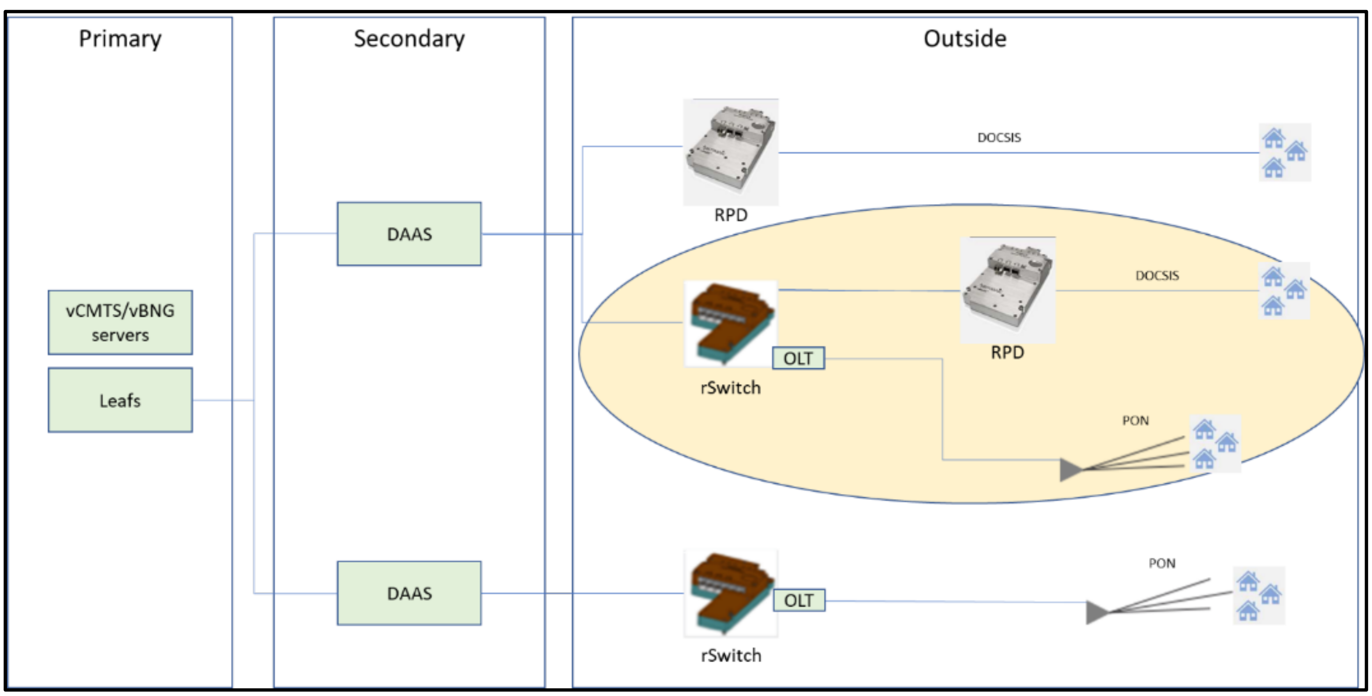


Figure 2 – DAA Basic Infrastructure Demonstrating Converged Access

The above description for PON chassis can also apply to DOCSIS, where "OLT" can be replaced with "I-CMTS" or "I-CCAP," where "I" is for integrated. However, as noted, Comcast began moving to vCMTS five years ago and continues to aggressively upgrade to vCMTS nationally. Nonetheless, most operators still have an integrated CMTS dominant footprint.

Working within the limitations of these integrated chassis platforms, major parts of budget strategies over the years have been focused on periodic SW upgrades and timing of procurements for growth and new features. In addition, while large scale chassis solutions do have efficiency advantages for supporting high density areas, they are not ideal for low density areas.

Other solutions have served and/or been proposed for these rural communities. Copper pair systems are simply inadequate – too slow – by today's broadband standards. Wireless-based systems can be impacted by poor weather and other factors, and not be able to deliver the consistent, reliable performance customers expect and deserve. Leveraging DAA investments with vCMTS and digital nodes is a pathway to efficiently deploy a R-OLT-based FTTH solution into RBB areas. This architecture provides the flexibility to implement PON service very granularly and on demand. It will enable reliable services to penetrate anywhere deep into the existing footprint, while also expanding the radius of reliable Comcast broadband service to rural customers.

2. The Foundation of Distributed Access Architecture

Because of persistent year-on-year compounded annual growth rate (CAGR) of downstream and upstream traffic, operators found it increasingly difficult to keep up with upgrades to the network and spectrum using business as usual (BAU) processes such as node splits and incremental adjustments to spectrum allocation. New processes and tools were needed to replace BAU approaches before the scale made it too challenging or costly to execute upgrades.

Among the most powerful tools developed to address this were the distributed access architecture specifications developed through CableLabs. These specifications were a collaboration among operators, vendors, and CableLabs subject matter experts (SMEs) to address many of the anticipated challenges for operators as data traffic and speed demands continued to grow year over year. Among the first to be published was the "Remote PHY" (R-PHY) specification in 2015[6]. Technology development had begun well before the completion of the specification, and Comcast embraced the transition to DAA using R-PHY as part of its network evolution plan in 2015.

Note that the CableLabs work continued to develop another version of DAA based on the flexible MAC architecture, or FMA. As part of its strategic planning for DAA migration, Comcast deeply evaluated both options to determine which would better position the Comcast network for the long term. In the final analysis, the R-PHY approach was selected as it better aligned to key network objectives such as centralization of high SW complexity, lightweight distributed compute for low-touch, high-reliability outside plant locations, and simplifying interoperability of ecosystem components.

Comcast began deploying R-PHY based DAA in 2017 and has over 30,000 remote PHY device (RPD) equipped nodes from multiple vendors in production today, and that number is rapidly increasing as a major network upgrade plan to digital nodes and vCMTS takes place. There is no large-scale deployment of the FMA architecture to date. The Comcast DAA network now exceeds the availability performance of our mature, standard HFC deployments, as was anticipated with the migration to DAA.

2.1. Benefits of DAA

Distributed access architecture delivers multiple powerful advantages. It represents one of the most powerful technology upgrades to cable, nearly as powerful as the introduction of fiber itself to all-coaxial RF systems decades ago.

Among the benefits that can be attributed to the move to digital optics, and specifically Ethernet-based digital optics, in place of cable-specific analog optical (AM) technology are:

1) Optical wavelength efficiency

With increasing node splits and deeper fiber migration, significant numbers of new nodes are installed every year. The use of wavelength division multiplexing (WDM), where multiple links to RPDs can share a fiber, maximizes the use of the existing fiber infrastructure. The use of digital optics means up to 80 dense wavelength division multiplexing (DWDM) wavelengths/nodes can be aggregated on a single fiber (or more). Standard HFC AM optics are restricted typically to 16 wavelengths to manage the nonlinear effects on modulation error ratio (MER) for typical HFC optical links lengths. This means a more cost-effective deployment and less fiber needed to support the nodes.

2) Reach of digital optics vs AM optics

As noted above, longer optical links from headend transmitter to node historically meant that fewer wavelengths can be used on that fiber to meet a given end-of-line MER. Digital optics eliminate this dependency in practice for common HFC optical links. In fact, a DAA-based CMTS core, outfitted with digital optical outputs, could be moved closer to the core if headend consolidation is an objective.

3) SNR and MER performance improvement of eliminating the DS and US AM HFC optics

DOCSIS 3.1 and DOCSIS 4.0 enable higher order modulation profiles, increasing the bandwidth efficiency by up to 50% over DOCSIS 3.0 in the downstream and up to 100% in the upstream. In standard HFC, the end-of-line (EOL) MER is dominated by the performance of the AM optics. The CMTS RF ports provide an extremely high MER of 48 dB (set by the DOCSIS Downstream RF Interface Specification, or DRFI) for DOCSIS 3.1, which gets degraded by the AM optical link to the node in the field to below 40 dB, depending on optical link length and other variables and that is *before* the RF amplifier cascade acts to degrade it further.

With DAA, the digital link to the node eliminates the AM optics, and the MER degradation caused by it. Instead, the DRFI requirement is met at the node RPD port, gaining back the lost fidelity of the AM optics nearly completely. This maximizes the capacity possible for DOCSIS 3.1 DS output and US input signals.

4) Space, power, cooling efficiencies in the hubs and headends

Moving some of the CMTS functionality to the node leaves less behind in the hub or headend to power, cool, and consume space. The density of RF connectors and isolation requirements on a typical CMTS tend to set the density of these chassis. With the RF ports of the CMTS distributed into the plant, the density of the core can now be redefined since the density of optical connectors is much higher. Also, integration of digital infrastructure for video and data services allows for the elimination of large RF combining networks.

5) Alignment with virtualization of the CMTS, and more broadly towards convergence into a common virtualized platform serving multiple last-mile coaxial and fiber access technologies

This is discussed in the next section.

2.2. Virtualization

Cable operators' inside plant equipment and networks historically have been based on a collection of purpose-built video, voice, and data platforms of integrated hardware and software. This has been a successful formula for over 30 years of service introduction and service growth including digital video, high-definition (HD) video, voice, data, and video on demand (VOD) and FTTH implementations of the same services.

Unfortunately, with these monolithic platforms, in particular DOCSIS CMTS platforms, it is difficult to keep pace with exponential traffic increases. Also, considering the construction aspect of splitting nodes, typical network augments – node splits – cannot accelerate to match the trajectory of traffic growth.

Network function virtualization (NFV) and software defined networking (SDN) are enablers of cost effective, efficient, exponential network and service change velocity. Historically, the continued growth in traffic and mounting node splits to support that growth meant the addition of CMTS RF ports and line cards.

Bringing this concept down to operational practice, in a DAA implementation, these RF ports are distributed into the field. However, supporting line cards of the CCAP core would still be necessary if the digital node is connected to an existing I-CCAP.

In a virtualized implementation, however, this purpose-built hardware core, designed to be tightly coupled to the output RF interfaces, is instead implemented in commercial off-the-shelf (COTS) server hardware. This is made possible simply through Moore's Law. The compute power and resources needed are available in standard processors today, allowing CMTS functions to be executed in such platforms. This approach is shown in Figure 3.

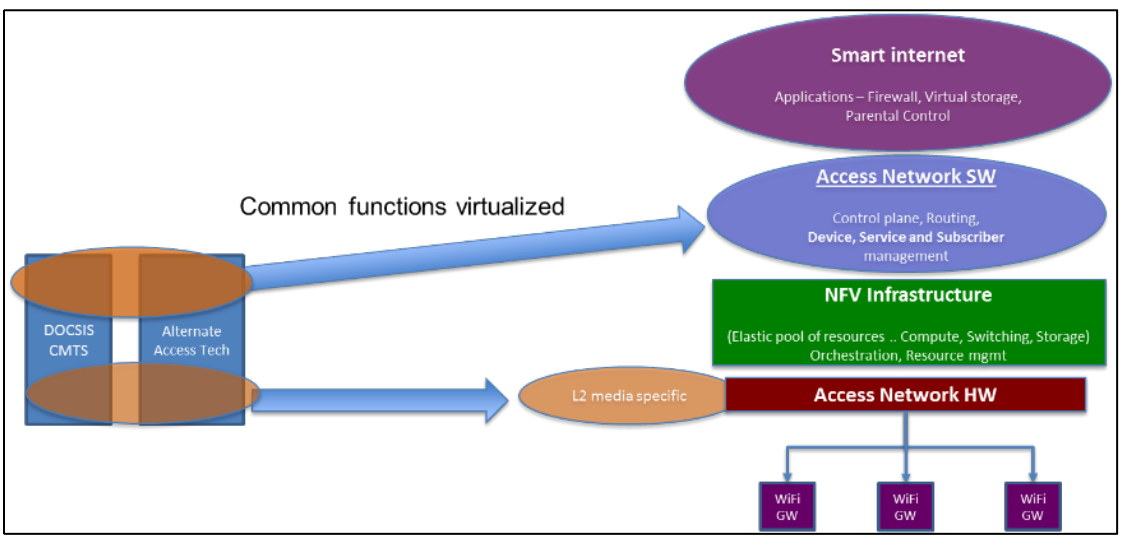


Figure 3 – Virtualization of Edge Access Platforms

The potential to create SW-based CMTS on standard server platforms has enormous implications for cost, space and power savings in facilities, and service velocity. As with DAA nodes, the advantages of a migration to virtualized edge platforms are so compelling that figuring out this transition from integrated architectures to distributed architectures, and to virtualized *and* distributed is essential. At Comcast, every RPD node is connected to a vCMTS core. Traffic growth and new product speeds now revolve increasingly around compute power, which scales with Moore's law, and spectrum re-allocation, which no longer involves massive re-wiring inside plant because it is empowered by automated RPD configuration for channel line-up changes.

In summary, the Comcast DAA implementation is based on an Ethernet switch fabric feeding R-PHY-based DAA nodes. The previously purpose-built CMTS hardware core is instead virtualized in COTS platforms. This architecture is shown in Figure 4, envisioned here as migration of existing HFC architecture – I-CMTS and analog fiber node to vCMTS, digital infrastructure, and digital nodes (RPDs). Not pictured here for simplicity is the substantial RF and analog optical headend equipment in the secondary that exists between the I-CMTS and analog node.

A significant item to note is that with DAA the vCMTS location is consolidated back to the primary – a benefit of the digital optics and scalability, with the switching infrastructure deployed into the secondaries rather than the CMTS itself.

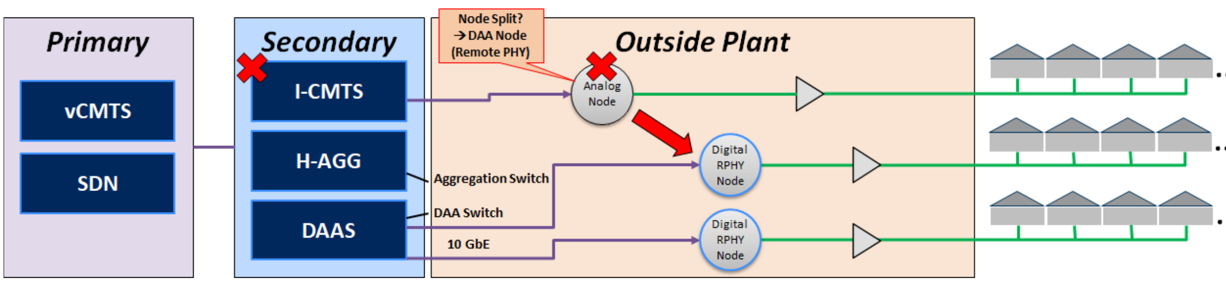


Figure 4 – Comcast DAA Architecture based on Remote PHY Node and vCMTS

3. DAA Extensibility and the Access-Agnostic Last Mile

DAA benefits extend beyond the considerable advantages it provides to cable systems. Most operators within their strategy also build and operate FTTH systems, consider the role of FTTH as HFC network upgrades take place, and think about how to efficiently transition to it where and when it makes sense to do so.

As the HFC architecture takes fiber deeper and builds out DAA based on vCMTS, the power of deep network Ethernet connectivity comes to the forefront. Ethernet is a Layer 2 foundation of global scale, and the workhorse of modern fiber and copper WAN and LAN communications. Virtually any last mile access technology will interface to an Ethernet-based system. Furthermore, by terminating these links in OSP in a fiber node, the node platform becomes a multi-purpose platform of plug-in modules supporting various last-mile options. For cable systems today, the most obvious next scenario and fast-follower of DOCSIS into DAA is EPON FTTH. Unfortunately, HFC architectures are not built to the physical standards of optical reach, homes passed per fiber, and wavelength plan of a "classic" EPON architecture. Because of these differences, a key component of the existing EPON solution is a "PON extender" module in a node housing, which solves both fiber utilization and distance constraints of classic PON system overlaying HFC. This node location now serves as the perfect place to instead utilize an R-OLT. As part of a node housing, the node platform itself now becomes a multi-access last mile, architected for dual use in this case as shown in Figure 5**.**

The basis for both last miles is similar – deliver 10 gigabit Ethernet connectivity to an access module inside of the node. Current nodes support RPD modules already. A node of the future for FTTH last miles now includes the addition of an EPON R-OLT. The PON portion of network (where the PON protocol lives) then extends from the R-OLT port to business and residential customers, based on the same PON optical budget standards that exist today. These PONs are standard-compliant for optical link budget, as the PON is being served from that deeper physical location closer to FTTH customers, just as with the PON extender.

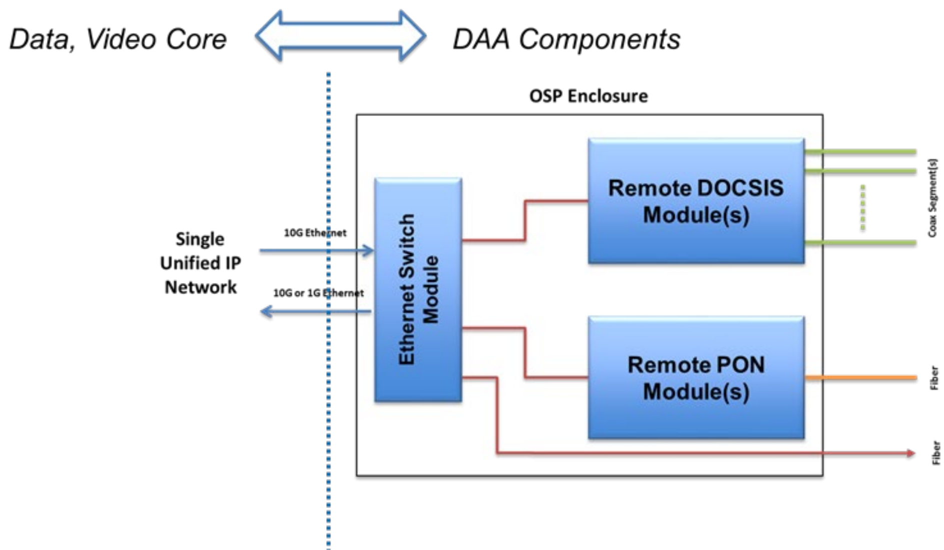


Figure 5 – DAA Enables Access-Agnostic IP Network Architecture Convergence

3.1. Integration of EPON FTTH into DAA Infrastructure

Last-mile access convergence does not end with an R-OLT HW module, however. Today's R-OLTs are simply smaller, hardened versions of centralized OLT platforms. Those were designed to support thousands of customers in large FTTH build-outs, such as the telcos have been doing in targeted ways for about 20 years. Cable operators generally deploy FTTH more tactically. Specific properties and developments built as FTTH are sprinkled about a ubiquitously deployed coaxial network. As mentioned, the R-OLT approach allows for ease of granularity of adding a single PON port at a time to manage growth most efficiently in the fashion it is deployed by most cable operators.

Aside from the properly sized HW platform, and as indicated previously, the virtualized infrastructure built and matured for DOCSIS DAA can be leveraged now for EPON, rather than operating DOCSIS and PON as two independent, parallel systems that happen to share the same optical infrastructure and switches. This introduces the virtual broadband network gateway (vBNG) platform SW component to the ecosystem

Consider Figure 6, which compares cable and telco implementation models for deployment of PON services, Open Systems Interconnection (OSI) alignment, and networking configuration. The telco PON architecture was developed to drop into existing DSL architectures, with a Layer 2 OLT taking over the role of the digital subscriber line access multiplexer (DSLAM).

Similarly, cable operators developed PON to drop in-line with existing DOCSIS deployment models, which has a more intricate integration of Layer 2 and Layer 3 functionality at the edge router (CMTS) for historical reasons. The more flexible EPON standard was used, and an SW abstraction layer called DOCSIS provisioning of EPON (DPoE) developed to accommodate the technology within a DOCSIS end-to-end system. DPoE assigns each ONU as a virtual cable modem (vCM) inside of the OLT, allowing operation and management of it via DOCSIS tools and back-office systems. This is what is commonly used in most EPON systems today in the cable operator community.

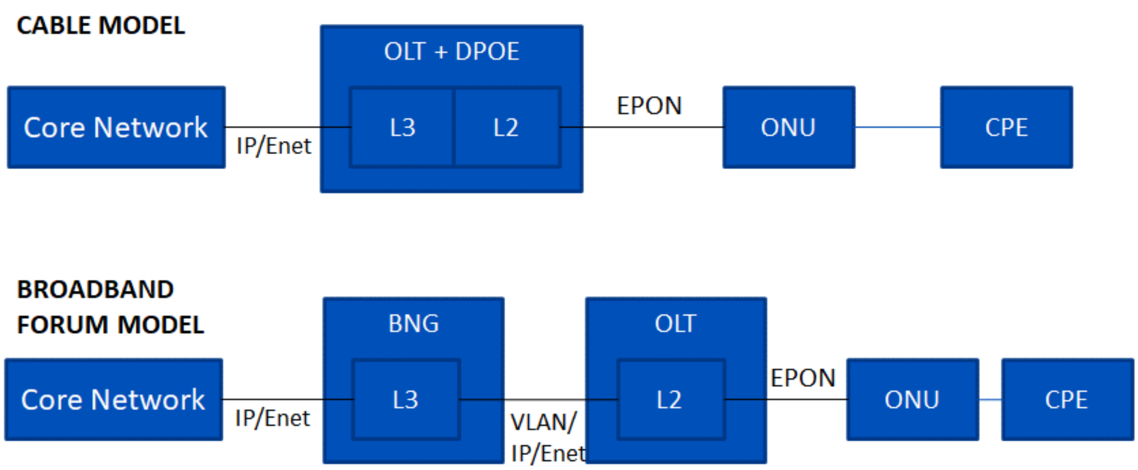


Figure 6 – Cable and Telco PON Network Models

For vBNG, however, this emulation of DOCSIS functionality in the R-OLT is eliminated. Rather than remotely deploying complex OLT SW with DPoE, the R-OLT is simplified, becoming more of a wavelength, scheduling/multiplexing, and protocol converter that integrates directly to subscriber management SW in the vCMTS platforms alongside DOCSIS. The vBNG data plane can be run in the network processing unit (NPU) of today's COTS server platforms, while the control plane can be run in the cloud.

Developing the architecture for incorporating FTTH into the production DAA system brought to light opportunities for synergy between DOCSIS and PON. The first obvious area of synergy is simply that the remote switch (rSwitch) and R-OLT are connected to already existing DAA infrastructure. This produces a very low barrier to entry to deployment time and saves on construction costs. It also allows the reuse of field processes that technicians have become accustomed to when installing RPDs. With this experience combined with experience from also having deployed EPON in scale in production, the learning curve is significantly reduced, and less new training needs to be developed.

Other major benefits to the sharing of the physical infrastructure include:

1. Transit fiber feeding DAA components in the field is efficiently used and shared between the access networks either through high-speed switch networks or via multiplexer combining of the Ethernet wavelengths to the RPD and rSwitch devices.
2. Routing infrastructure is combined, so the IP infrastructure costs are made to be as efficient as possible. This means that PON customers and DOCSIS customers will utilize the same IPv4 and IPv6 scopes and all the same security risk management practices.

3.2. The Road to RBB Is Through vBNG/R-OLT

One of the most powerful advantages of the DAA-based EPON implementation is the ability to take advantage of over five years of production deployments of DAA with vCMTS for DOCSIS customers, and leverage that knowledge for PON customers over that same DAA infrastructure with vBNG (instead of vCMTS) and R-OLT (instead of RPD). In the vCMTS, the core of the software is all built into a single Kubernetes "pod," which is a tight knit group of containers. For PON, the software is built in three primary pods, identified in Figure 7: the vBNG itself, the access controller, and the service activation pod. Splitting these functions allows us to separate the complexities of service provisioning and device control away from the compute-intensive but relatively simple function of the vBNG to pass the customer's traffic.

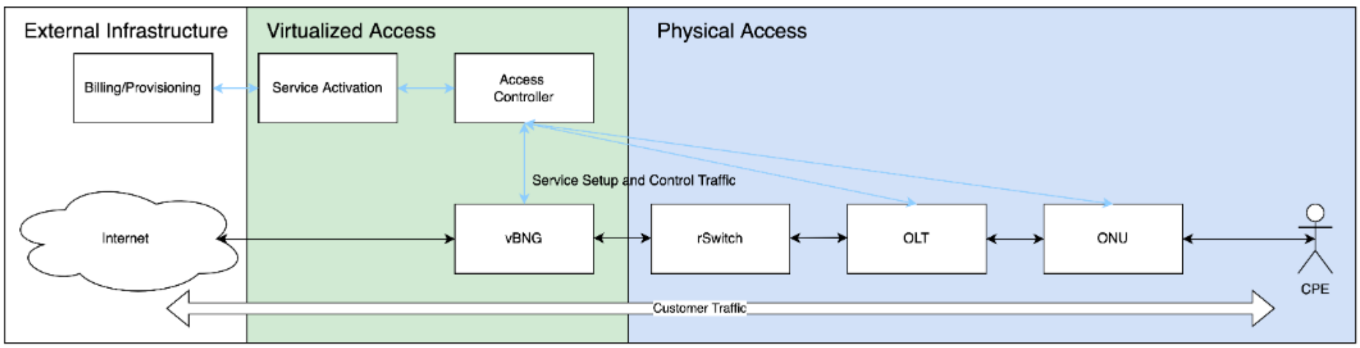


Figure 7 – vBNG-Based PON: Service Components and Traffic Flow

Let us detail further the functionality of these components:

<u>Service Components</u> – vBNG – This is the most familiar component in the system. The job of the vBNG is to guarantee the quality of service (QoS) parameters associated with the customer's services, enforce security policies, provide basic IP services such as Address Resolution Protocol (ARP) and neighbor discovery, and to consistently pass the customer's Ethernet frames to and from the Internet. This component has a high CPU resource requirement and must be highly available with a maximum downtime, counted in a handful of seconds. Simplicity and consistency are the primary operational considerations.

<u>Access Controller</u> – This component is primarily responsible for the configuration and monitoring of the R-OLT and ONU. It also provides service level configuration to the vBNG for its consumption. The PON interfaces and the service definition can become quite complex necessitating close adherence to both standards documents and actual implementation details within the R-OLT and ONU. This complexity does not impact the availability of customer services. However, for customer services, the access controller is only needed during initial provisioning in that the vBNG, R-OLT, and ONU will continue to provide the services they were configured with even if the access controller is down. It is still preferred that the controller be available if only for monitoring purposes, but the acceptable downtime can be measured in minutes. While the service activation and vBNG components will largely be common to all Ethernet based access technologies, the access controller must be replaced or redesigned significantly to support other technologies.

<u>Service Activation</u> – This component is responsible for all per subscriber service level configuration. Today for most cable operators that means that it will create a vCM to interface with a DOCSIS compliant back office. However, unlike a DOCSIS cable modem, information about the ONU devices can

be provided through telemetry rather than being polled via Simple Network Management Protocol (SNMP). This greatly simplifies the vCM itself, essentially becoming a DHCP emulator with a means of downloading configuration files and translating them into a common API to communicate with the access controller. The superpower of the service activation component, however, is that it is not tied to the DOCSIS back office. Having this component as part of the system allows the operator to add to, change, or replace this mechanism with the newest and/or most convenient APIs for back-office integration. This is an ability that is difficult to take advantage of in the short term but encourages movement in that direction just by existing. Much like the access controller, this component is only necessary at initial provisioning and the acceptable downtime can be measured in minutes.

The final critical and strategic attribute that should be highlighted about the DAA-powered PON architecture, founded upon the rSwitch, R-OLT, and vBNG components is not just the value it brings today, but also its value for future evolution. This system is constructed of six independent sets of services, as shown in Figure 8: management, provisioning, service fulfillment, routing, backplane, and access technology. These services can and are being improved upon without impacting the other services. The ideal future state is one where we have the best in breed services in each of these areas which can then be continually optimized within their own technology domains. By doing this, we will also be continuously improving network capability, services offered, and the customer experience while increasing network reliability for all commercial and residential customers. We can even consider third and fourth last mile access technologies to integrate in the future.

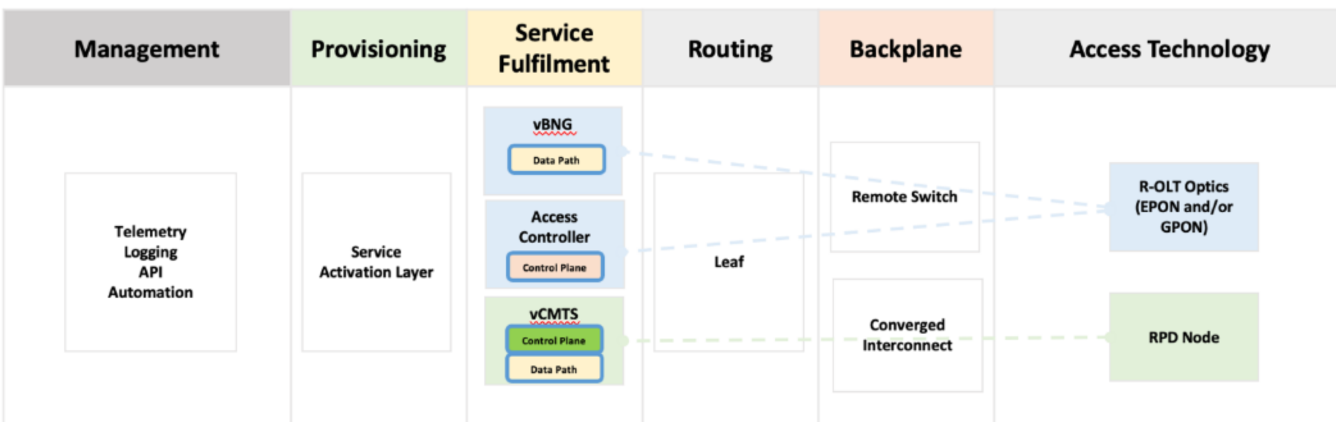


Figure 8 – Abstract Layers of DAA System

3.3. Distance Matters

Deployment of traditional HFC plant in very low-density has been limited historically. The cost of large-scale network construction has to be balanced against the number of customers that will be reached. Signal attenuation of the coaxial cable is a major factor in low density due to longer runs of cable, requiring long RF amplifier cascades and more power to run them.

Fiber optic cable has a much lower attenuation per mile compared to coax, so is better suited to cover very long distances efficiently. As such, the R-OLT and vBNG bring an opportunity to support rural deployments very effectively, as well as streamline the deployment of Comcast's EPON FTTH network by converging it with the existing DAA infrastructure.

In addition to the last-mile distance to homes in low-density areas, another challenge to serving these rural communities is the distance from Comcast's core network and primary facilities to these areas. A conventional chassis OLT requires deployment in a secure and environmentally controlled environment and access to the core network. From that centralized location the standard PON deployment can reach commercial and residential customers as far as 20 km of fiber away, assuming the 128-split ratio of the PON standard. Unfortunately, as noted previously, these parameters are not well-aligned to an implementation to cover a distant rural footprint. A proprietary PON extender solution developed by a technology partner enables the PON network to extend up to 80 km from the conventional OLT. In this implementation, the EPON network is transported from the OLT using conventional 10G DWDM transport to a node-type housing. Up to eight fiber link modules (FLMs) are contained in the node housing, making up to eight 10G EPON networks possible, supporting up to 1024 passings. This technology breaks up the optical transportation from OLT to ONU network into two parts, the OTL (optical transport link) and the ODN (optical distribution network) as shown in **Figure 9**.

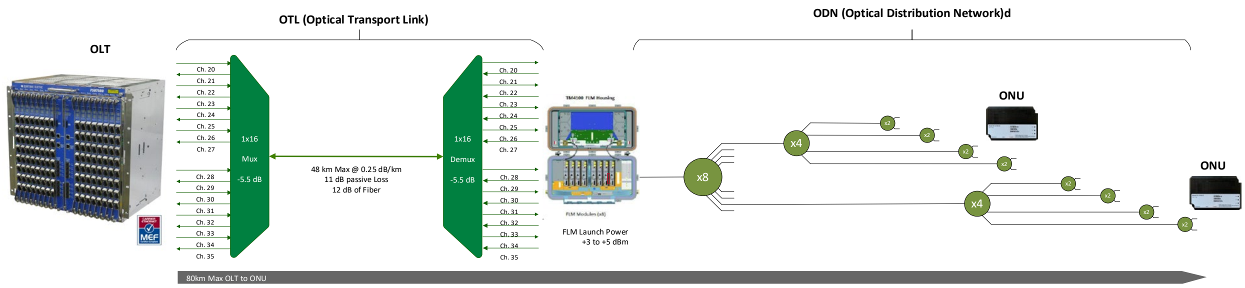


Figure 9 – PON OLT, OTL and ODN Architecture

As effective as PON extenders are to FTTH deployments, they represent a bandage to a fundamental architecture incompatibility that exists between telco-based PON standards and cable network principles. The R-OLT, by contrast, aligns PON technology to how HFC technology has evolved, in particular with DAA – use of Ethernet-based optical infrastructure feeding flexible, modular, multi-use platforms.

An example R-OLT is shown in Figure 10, in this case developed by Harmonic, one of Comcast's DAA business partners. The deployment is made up of three parts, the housing ("Ripple"), rSwitch "Jetty-1", and the single-port R-OLT itself, the "FIN-1".

This node housing for the R-OLT can also support an RPD, simultaneously. The Jetty-1 is a remote switch that connects to the distributed access architecture switch (DAAS) through a standard 10G DWDM link. The switch could support additional application, but for this paper we will focus on EPON. The Jetty-1 contains six SFP ports, two designated as uplink ports and four multipurpose ports. Up to two rSwitches can be mounted in this housing.

The FIN-1 enables simple plug-and-play 10G PON capability from rSwitch. Up to four FIN-1's per Jetty-1 are expected to typically support EPON deployments.

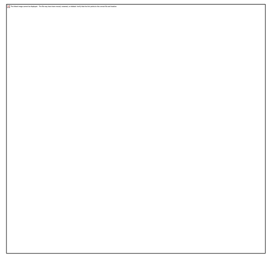
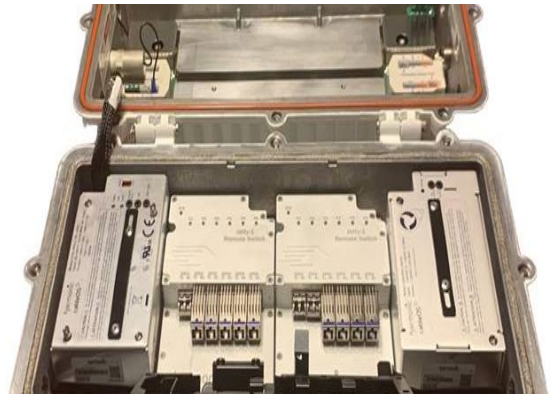
 **FIN-1 R-OLT**	 **JETTY-1 REMOTE SWITCH**	 **RIPPLE-1 Housing with PHUM, JETTY-1 and FIN-1 Modules**

Figure 10 – Remote OLT (R-OLT) Hardware Components

Standard fixed or tunable 10G SFP+s are deployed to provide connectivity from the DAAS port and the rSwitch port. 12, 24 or 48 port DWDM 4.0 optical filters provide multiwavelength connectivity on a single fiber from the DAAS facility to the R-OLT housing. This is shown in **Figure 11.**

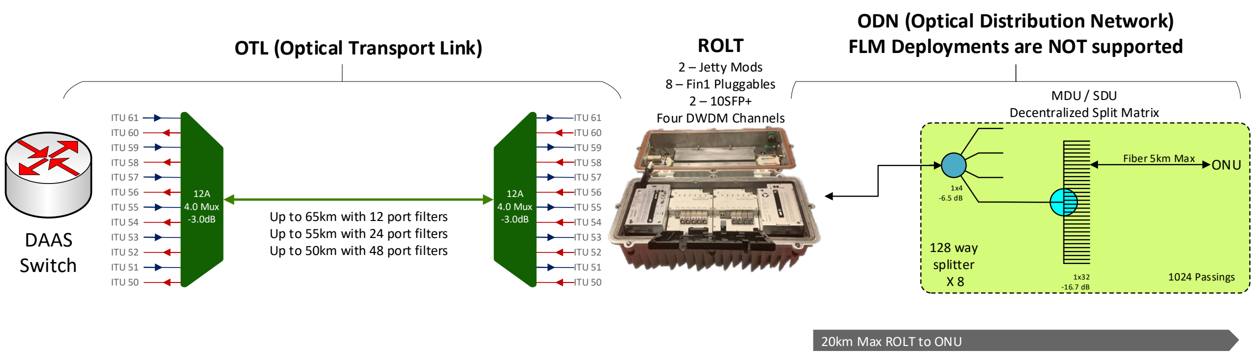


Figure 11 – DAA-Based PON – Optical Connectivity

The engineering and design of the ODN does not change with the deployment of the R-OLT when replacing an FLM-based EPON deployment. Of course, the OTL becomes standardized across the DAA deployment footprint including access to production tools and provisioning developed during the vCMTS rollout. The overall distance from the DAAS port to the ONU increases by 5 km reaching a maximum of 85 km from the DAAS to the ONU, enabling a solution that enables the deployment of EPON into the rural markets that is much simpler and faster – and where most of the end-to-end mileage is already built!

4. Operational Benefits

4.1. Software Over Hardware

As noted, Comcast has been investing in DAA for years. As part of the architecture development, decisions were made to drive to a more software-centric solution wherever possible. What does this mean when talking about the access network? In many cases it means having the ability to upgrade software features and capabilities instead of requiring physical replacement of deployed elements in the network.

The large-scale deployment of vCMTS / RPDs demonstrates this, and the same vision, capability, and intelligence in the network is part of the vBNG / R-OLT design. Through DAA, we have never-before available visibility into the network, in real-time. We are leveraging the cloud and machine learning to create intelligent automation and configuration of components error-free and in-scale, all in SW. As an example, the process of increasing speeds and change spectrum allocations on the plant is a few clicks that can ultimately touch hundreds or thousands of production nodes.

Maximizing use of software in the architecture enables flexibility to, for example, push new speed tier offerings throughout the network in months rather than years. By designing a more intelligent outside plant, we are able to push configuration changes via software, obviating the need for a technician to go into the facility to perform re-wiring and/or into the field to make configuration changes. It opens the doors to automation that drives rapid scalability. With that scalability comes the need for improved network resiliency and visibility. Figure 12 is an example of a dashboard showing real-time information related to activation of OFDMA as part of a mid-split network upgrade. Currently, approximately 90% of updates and configuration changes introduced into the DAA footprint are delivered via automated tools, with a goal to increase this to 99% by the end of 2022.

Figure 12 – Real-Time Network Stability

Increased intelligence means substantially more telemetry available to observe and manage the network. Data can be processed and filtered into dashboards focusing on performance, availability, and capacity management in real-time. These data sets will be available in R-OLT through the DAA investments, just as they are in DOCSIS RPD deployments. With metrics and real-time traffic data, new RBB deployments can be optimized very efficiently as the understanding of network characteristics and traffic dynamics associated with these new environments is learned. Available information includes operational data at each component of the network. This is an unprecedented amount of data compared to traditional HFC systems. The challenge then becomes how best to use this deep, real-time information. How should this data be managed? Who can use it effectively? Are there new tools that we must develop to convert this data into actionable information?

4.2. Network Telemetry – Breadth and Depth Across the Ecosystem

We break down the information and the benefits of this capability across equipment and serviceability elements below:

- **Platform**
  This includes the base level hardware and software of the virtualized system that support the microservices, and the infrastructure to instantiate and maintain them. Invaluable information that speaks to the health, efficiency and workload within this view includes memory utilization, CPU load, Kubernetes state and host state.
- **Software deployment**
  Deploying software in a non-customer impacting way – in-service upgradeability – is extremely important when there are hundreds of independent microservices that all rely on each other. This allows us to upgrade code and augment features with maximum flexibility and without traditional operational practices focused on customer care management. Current versioning, downtime, error notifications, and level of impact in case of a failure are all important metrics in this view.
- **Service Orchestration**
  Bringing up the right software instances at the right time to the right customers is vital for success. How do we coordinate data from the field with information such as location, network devices, and physical connectivity of construction and network maintenance with the delivery of vBNG or vCMTS-based services? Automation and scripting are vital to doing this effectively at scale and without human error. This enables the efficient, widescale activation of services quickly as network builds such as RBB take place in parallel across the footprint.
- **Outside Plant**
  With the distribution of smart components in the field, we have access to new and valuable data closer to the customer pertaining to their experience. This data can be analyzed via machine learning algorithms to trigger preemptive repair before a customer notices a problem. For DOCSIS, this includes RF data from the RPD and future smart amplifiers. For either DOCSIS or FTTH, real-time information on fiber impairments, fiber cuts, and power supply health and status provides important telemetry to preempt network outages or improve MTTR.
- **DAA Network**
  As we push Ethernet out into the field via connectivity to the rSwitch and RPDs, we create increased connectivity complexity compared to traditional HFC, but also a much better opportunity to manage and monitor capacity, utilization, and scalability. Traditional network monitoring must be augmented to work effectively in a cable operator's physical network where an out of band connection cannot always be relied upon.
- **Customer Services**
  This view of the network most directly impacts the customers. Who is impacted by a physical outage? Are the devices working in a degraded state? What are the network services that the customer is entitled to? This is the most traditional and vital view of the network for cable operators. Being able to observe real-time ONUs and CM behavior via streaming telemetry of the virtualized platform is an opportunity to address device issues before a customer notices service issues, which has a huge positive customer experience impact.

There are many other great ways that the system can be viewed, but this gives us a reasonable cross section to make some important observations.

The virtualized core and DAA infrastructure are very similar, no matter which last mile access technology is being used. Beyond the nuances of PON and DOCSIS, the system is run the same way using the same hardware with very similar, if not the same, software. Much of information gathered is similar, with some obvious differences in the specific last mile RF data vs FTTH data. Most importantly, the information coming from this data is operationally transformative, creating significant efficiencies of scale while simultaneously adding deeper diagnostic value. They lend themselves to leveraging cloud services and infinite possibilities of dashboard views that can be spun up quickly and iterated upon to maximum effectiveness by users, as seen in Figure 13, showing a dashboard view of CM online status.

General / vCMTS Summary Landing Better [redacted] View

Site All

CM Status Per Site

site_name	Online	Unregistered	Offline	Partial
cc[redacted]	156,629	54	749	9.25 K
ca[redacted]	133,416	42	421	5.48 K
wa[redacted]	126,933	24	491	12.90 K
nh[redacted]	115,936	26	339	7.04 K
fl0[redacted]	108,666	66	1,521	8.00 K
co[redacted]	105,931	42	803	3.61 K
ca[redacted]	103,996	31	1,356	4.37 K
nm[redacted]	103,614	51	1,013	6.74 K
fl[redacted]	96,197	50	522	6.62 K
fs[redacted]	85,945	33	498	5.30 K
fl[redacted]	84,415	27	450	6.01 K
i[redacted]	83,041	48	1,515	3.70 K
fl[redacted]	79,430	23	386	5.43 K
t[redacted]	78,923	36	434	4.76 K
ma[redacted]	78,826	21	292	5.28 K
az[redacted]	76,643	27	264	3.78 K
mn[redacted]	76,526	17	312	4.23 K
cal[redacted]	76,355	34	317	4.68 K
al[redacted]	74,483	119	458	4.83 K
nj80cc100	72,071	34	323	5.61 K
gampcc100	71,632	18	416	4.53 K

1 2

Figure 13 – Real-Time Customer Cable Modem Telemetry

With the amount of new and possibly overlapping data, algorithms using machine learning are needed to transform this data into actionable intelligence. For example, with new data comes new thresholds for alarms and triggers. If there are multiple alarms going off, how do we ensure they are correlated with one another? Do they have the same root cause? Can the system help direct the people managing the network to the source of the issue faster? Can the system learn enough to be able to correct itself when it is possible? This is a key part of the operational ecosystem under development.

5. Operational Impacts

5.1. Sustainability

Sustainability has been at the forefront of Comcast practices for many years. Whether it is proactive decommissioning for a network upgrade project, reducing energy use or managing customer network traffic most efficiently, Comcast is considering the impact on our environment. As we build out our network for RBB and continue to upgrade our HFC footprint, we are committed to being environmentally responsible.

5.1.1. Fiber

For RBB, and more generally for all EPON FTTH deployments going forward, integration of PON into existing production DAA system – re-using already built infrastructure for FTTH services – provides construction-related savings, and outside plant power savings.

In addition, because of the significant difference in the signal attenuation of fiber compared to coaxial distribution the PON distribution network is approximately 90% more power efficient than the typical HFC network that would be needed to cover the same low-density footprint. Thus, for RBB, the vBNG with R-OLT represents a significant advantage in terms of sustainability.

5.1.2. Coaxial Cable

As we continue to upgrade the HFC footprint, there are sustainability opportunities available also. Comcast uses thousands of miles of coaxial cable every year. New partnerships are strengthening our recycling programs for coax. Earlier this year Comcast launched an enhanced recycle program for coaxial cables that have reached their end of life. In partnership with Echo Environmental, we can now break down the cable to create new raw materials that can be reintroduced, resold, and reused.

Here is how it works: Coaxial cables are multi-layered "cords" that consist of 27 different polymers, all of which need to be separated to make them usable in new products. Traditional recycling efforts can recover the metals contained within the wires, but not the insulation and jacketing around them. Echo Environmental created a solution to address this issue, all without the use of hazardous chemicals or incineration – and now, thanks to their technology, 70% of our coaxial waste can be recycled for reuse each year, significantly reducing landfill waste. The remaining 30% of our cable waste will still be recycled, as it is now, with plans to recycle 100% for the purpose of reuse in the future.

"It is incredibly gratifying to develop sustainable solutions for underserved market products," says Brian Hays, Echo Environmental Project Developer. "Our unique process combines traditional recycling systems with methods from other industries, resulting in the ability to extract target polymers cleanly. This outside-the-box thinking not only sets us apart in our industry, but also enables us to deliver meaningful, real-world solutions for our clients and our environment."

5.1.3. HFC

Comcast has hundreds of thousands of nodes and millions of amplifiers in our HFC network, and all of these devices require power to operate. To support this infrastructure, Comcast has one of the largest power distribution networks in the United States. Operation of this power network with a high level of efficiency is a high priority.

As Comcast upgrades HFC plant, there is major focus on the power efficiency of the network and the health of the grid to make sure it is operating efficiently. The simple act of upgrading 20-year-old amplifiers introduces significantly more efficient amplifier technology – so much so that we can extend the bandwidth to 1 GHz, launch that additional power downstream with a tilt, and still come out approximately neutral on total power consumed, or even slightly ahead. The bps/Hz/W has improved dramatically as families of power amplifiers – silicon-based, gallium arsenide (GaAS), gallium nitride (GaN), and iterations of each, have evolved over the last 20+ years.

New technologies aimed specifically at power savings are now also available, such as digital pre-distortion (DPD), envelope tracking, and automatic bias adjustment for RF load. These technologies are reflected in our specifications, as are recommendations for power-factor corrected (PFC) supplies inside of our actives. PFC enables the AC supplies feeding the network to operate efficiently.

With historical efficiency gains over time and new technologies aimed at power savings we believe that today's HFC power grid is well-suited to support migration to 10G within the bounds of today's power grid. The perspective here is less about the absolute savings of power, but doing much more for the customer with the available existing power.

5.2. Workforce

As the vBNG and R-OLT solution moves into the field, we will be able to assess the actual implications to the field and to sustainability as identified previously. Another important aspect is how the solution will impact internal teams and field technicians. In 2017, Comcast launched the industry's first large-scale initiative to deploy DAA using RPDs and vCMTS. We did this expecting a bumpy road at the outset as the new technology and practices slowly matured. With vBNG and R-OLT, the advantage of lessons learned from that experience is with us and embedded into practices, documents, and the knowledge base. The deployment plan accounts for the change impacts to these downstream teams. Back-office and XOC support teams are working with this new technology in their labs to determine how it fits into existing processes and what potential impacts it would have to current staffing trends to ensure seamless deployments.

Previous PON solutions were so different than DOCSIS that the thought of having common staff maintain and manage both was a challenge, and at a minimum required technicians supporting both to augment existing knowledge with the "new" skills needed to support PON. Some of this is unavoidable in the last mile, of course. However, by aligning the architecture, platform, tools, and processes, and pushing the fiber and intelligence of the network further into the field, we've significantly converged the access network and correspondingly reduced the need for excessive additional training.

Our field technicians have become DAA experts with over five years of learned experience behind them. Training was developed internally and strong partnerships built between headquarters technologists and the practitioners in the field who would be called upon to operate the network. The smarter components themselves of DAA have played a role also, providing our technicians better insight into the network than they have ever had before once they have learned to use the tools. This commonality benefits the vBNG/R-OLT operational model, reducing the need for substantial new training. At the same time, the new DAA tools, processes, and converged technology offers growth opportunity for these technicians, much like technicians of prior years had in the vCMTS roll-out, further back in time, during the analog-to-digital video conversion.

6. Conclusion

Comcast has been building and operating DAA systems that virtualize CMTS platforms for over five years. We have gotten really, really good at it and have the network performance metrics to prove it. We are in the midst of rapidly scaling this foundational network upgrade across the vast majority of the footprint. The benefits have been enumerated herein – performance, scalability, availability, automation, deep telemetry, flexibility, sustainability… the list goes on. As we make our way along the path to 10G, DAA and virtualization are the most important pieces of the puzzle. Layering on DOCSIS 4.0 is the next step for the HFC network, a high priority strategy being executed to ready the network for multi-gigabit symmetrical speeds.

Exploding onto the scene in the midst of this very active cycle of HFC initiatives is the RBB initiative. Fortunately, having embraced the capability and vision of DAA, leading us to invest heavily in the baseline architecture, Comcast is in an excellent position to deliver best-in-class services to RBB areas using efficient architectures, align with operational simplification and sustainability objectives, and continue growth of our EPON footprint in areas where it makes the most sense to deploy FTTH.

We are not just bridging the digital divide as we turn up RBB – we are installing a 10G-enabling highway that will be maintained and managed with the power of proven DAA tools, back-office monitoring and automation, and deliver that best-in-class experience we strive for all of our customers, from the most dense high rise to the now-farther reaches of the Comcast plant.

Abbreviations

AC	alternating current
AM	amplitude modulation
API	application programming interface
ARP	Address Resolution Protocol
BAU	business as usual
bps	bits per second
bps/Hz/W	bits per second per hertz per watt
CAGR	compounded annual growth rate
CCAP	converged cable access platform
CM	cable modem
CMTS	cable modem termination system
COTS	commercial off-the-shelf
CPU	central processing unit
DAA	distributed access architecture
DAAS	distributed access architecture switch
dB	decibel
DHCP	Dynamic Host Configuration Protocol
DOCSIS	Data-Over-Cable Service Interface Specifications
DPD	digital pre-distortion
DPoE	DOCSIS provisioning of EPON
DRFI	[DOCSIS] Downstream RF Interface [Specification]
DS	downstream
DSLAM	digital subscriber line access multiplexer
DWDM	dense wavelength division multiplexing
EOL	end-of-line
FLM	fiber link module
FMA	flexible MAC architecture
FTTH	fiber-to-the-home
EPON	Ethernet passive optical network
GaAS	gallium arsenide
GaN	gallium nitride
GHz	gigahertz

HD	high-definition
HFC	hybrid fiber/coax
HW	hardware
I-CCAP	integrated converged cable access platform
iCMTS	integrated cable modem termination system
IP	Internet Protocol
km	kilometer
LAN	local area network
MER	modulation error ratio
NFV	network function virtualization
NPU	network processing unit
ODN	optical distribution network
OLT	optical line terminal
ONU	optical network unit
OSI	Open Systems Interconnection (the standard's full name is "ISO/IEC 7498-1 Information technology – Open Systems Interconnection – Basic Reference Model: The Basic Model – Part 1")
OSP	outside plant
OTL	optical transport link
PFC	power-factor corrected
PHY	physical layer
PON	passive optical network
QoS	quality of service
RBB	rural broadband
RF	radio frequency
RFP	request for proposal
RPD	remote PHY device
R-PHY	remote physical layer
R-OLT	remote optical line terminal
rSwitch	remote switch
SDN	software defined network(ing)
SFP	small form-factor pluggable
SNMP	Simple Network Management Protocol
SW	software
US	upstream
vBNG	virtual broadband network gateway
vCM	virtual cable modem
vCMTS	virtual cable modem termination system
VOD	video on demand
WAN	wide area network
WDM	wavelength division multiplexing

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