It's 10 PM: Do You Know Where Your Wavelengths Are?

Continuous and Pervasive Monitoring of Optical Assets in the Access Domain

A Technical Paper prepared for SCTE•ISBE by

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1. Abstract

Today, the access fiber plant carries large amounts of varied data content deeper into the network. Analog wavelengths support traditional Hybrid Fiber-Coax (HFC) plant, 10 Gbps wavelengths support Distributed Access Architecture (DAA) network segments and other MetroE applications, while newer Coherent Optics modules support "Switch on a Pole" (SOAP) [1] type architectures. As use of the fiber footprint grows, so too will the need for comprehensive monitoring, to optimize the efficiency of access optical assets with the ability to inventory bi-directional wavelengths. These optimizations aid with capacity planning and to locate fiber cuts and other impairments across the plant, in real time, while identifying effective mitigation options.

For too long, such monitoring has solely been the purview of long-haul networks, but recent innovations in optical technology pioneered in part at Comcast enable automatic, continuous and pervasive monitoring of access optical assets without active user intervention. These cost-effective, switched optical devices, comprising an optical spectrum analyzer and optical time domain reflectometers modules, are co-located with access headend optics and continuously scan links to detect fiber cuts or individual wavelength outages. These headend tools are augmented with the same cost-effective optical measurement technology implemented in handheld meters for field testing. Headend and handheld tools together provide real time optical data to the cloud for data-analytics. Locating an access fiber-cut in real time, and automatically guiding the Comcast response team to its exact location, results in exceptional uptime, which enhances customer satisfaction -- especially in periods of disaster recovery.

In this paper, we begin with a description of the optical innovations and powerful techniques that enable this extraordinary tool set. We then describe the infrastructure that was stood up to intake, visualize and "event" this data, and detail our preliminary experience using this technology in the COVID lock down period. We will then venture into the future of continuous pervasive monitoring of access optical assets, and the positive impact such next-gen monitoring has on network robustness, which, in turn, enhances the customer experience.

2. Introduction

Readers will perhaps remember the popular public service announcement "It's 10 p.m. Do you know where your children are?" intoned before the nightly news. This was memorably used in a 1996 episode of *The Simpsons*, when Homer Simpson responds to his TV, "I told you last night — no!" And so it was with our fiber plant for many initial years -- as the plant grew in density and reach, then added multiple wavelengths for each fiber, we were often in Homer's position, when it came to knowing where our wavelengths were, at 10PM or otherwise!

With improvements in technology and design, and as our long haul and back bone networks increased capacity and reach, we initiated programs to track and keep knowledge of wavelengths used, fiber cuts and impairments in the plant. With the advent of Remote Optical Add-Drop Multiplexers (ROADMs) and more sophisticated technology, this knowledge was now available, and in real time.

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Comcast is one of the largest broadband providers in the country. Our network reaches from coast to coast. In total, in the U.S., our network comprises ~150,000 miles of fiber route miles, as shown in Figure 1.

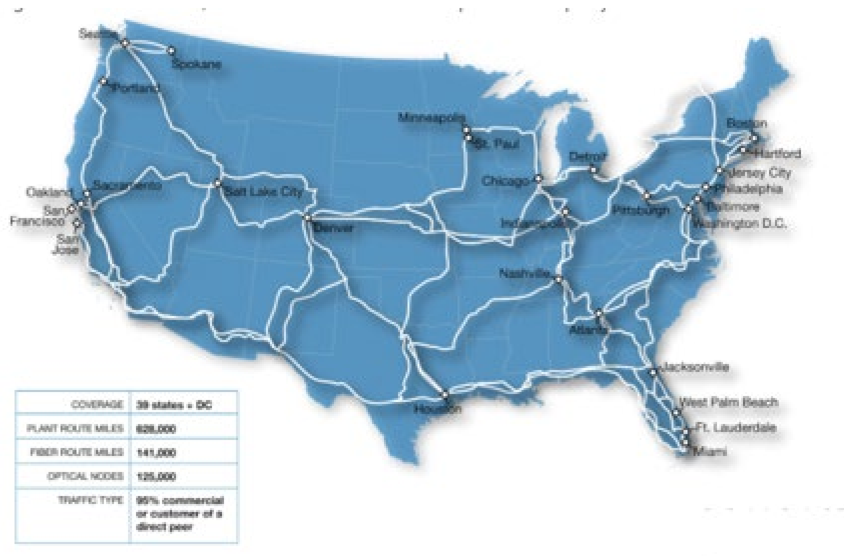

Figure 1 – Comcast Long Haul Fiber Network

Part of running a high-capacity backbone network is the ability to monitor and troubleshoot any outages and disruptions due to fiber cuts and/or equipment malfunctions. The larger the network, the more challenging this task.

Similarly, we run a very large footprint of Access Plant, covering ~55 Million Households Passed (HHPs), and illustrated in Figure 2. This access plant network (marked in dense Red points), also called Hybrid Fiber-Coax (HFC), generally has Cable termination to the end customers, but a vast majority of the access plant is also covered by Fiber, from the Primary headend (PHE) to the Secondary Headends/Hubs (SHE) to Fiber Nodes.

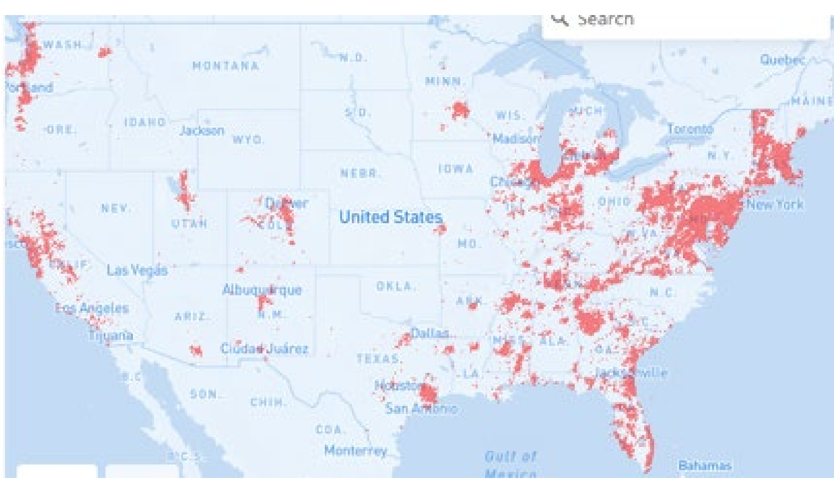

Figure 2 – Comcast Residential Network Areas

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With new Distributed Access Architectures (DAAs), we anticipate the fiber content of this network to grow exponentially over time -- and by over 10x in the coming few years. With this huge growth in our fiber assets, it is now imperative to more tightly monitor and secure our high-capacity access networks as well.

In the remainder of this paper, we describe our efforts to create a hardware and software infrastructure that continuously and pervasively monitors our optical assets. We also describe how such monitoring can come in very handy during the present COVID environment, and likely in perpetuity.

3. Access Architecture

Figure 3 presents a highly simplified connectivity model for our access architecture. In big markets, we typically have a high availability fiber back bone linking the Primary Headends (PHEs). These are typically connected to Secondary Headends (SHEs) via a redundant route. Often the SHEs themselves are arranged in a ring connected off of the PHEs, also with redundant fibers, which then connect to individual fiber nodes.

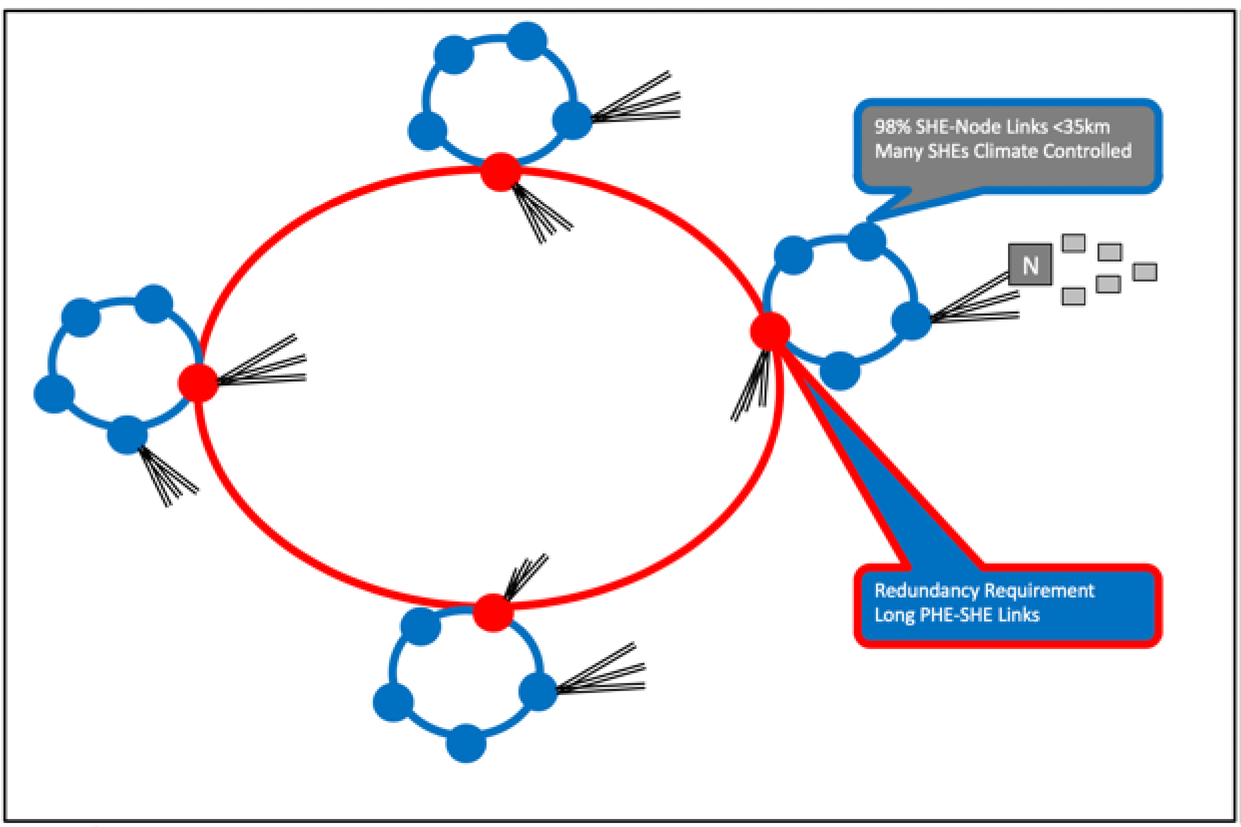

Figure 3 – Simplified Connectivity Diagram

Typically, the PHE network is supplied by high speed (such as coherent 100G-400G) links which have levels of monitoring for all optical wavelengths in use, and capabilities for locating fiber cuts or impairments.

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As can be seen, for each PHE, there are several SHEs -- and for each SHE, there are a lot of nodes. While the SHEs are connected directly to the PHE with redundant routes, the nodes are directly connected to the SHE with straight fiber connections. Thus, the access plant has a lot more optical connections. Even considering the coaxial plant exiting the fiber nodes, the sheer amount of fiber links in the access plant is much greater than what exists in the long-haul plant.

With the Distributed Access Architecture (DAA), each of the parent nodes is now connected via fibers to multiple nodes within its footprint. We anticipate that the fiber plant will grow exponentially in the access domain.

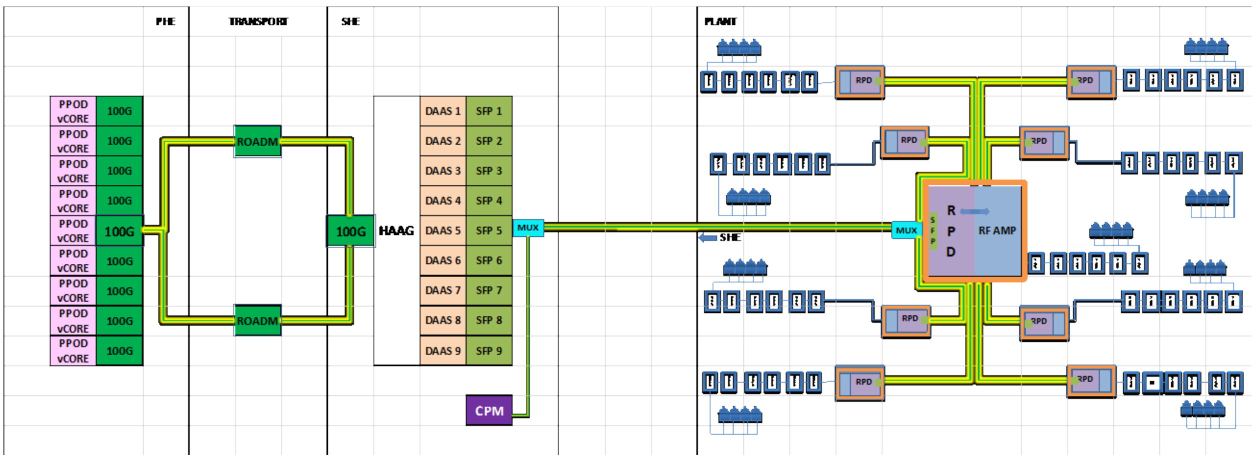

Figure 4 – End to end DAA Architecture DIagram

In the DAA architecture shown in Figure 4, PHEs would contain all of the virtualized CMTS (vCMTS) cores, connected to the SHEs through redundant routes to DAA Switches, and then via SFPs to the individual Remote PHY Device (RPD) nodes. These RPD nodes are connected to individual homes across coax. The return circuit is connected back via the RPD node to DAA Switch (DAAS) and then through to the vCMTS in the PHE.

Several other vCMTS-based architectures are in the process of being deployed and worthy of mention here. In one instance, the RPD is itself within the SHE and an analog link connects to the fiber node in the field. In this case, the trunk fiber would use Dense Wave Division Multiplex (DWDM) wavelengths on the 4 Wave Mixing mitigated plan (aka the "Full Spectrum" [FS] plan.) The reverse path typically uses baseband digitized return links (BDR links). In this case, the monitoring requirements would not change, but rather move to monitoring the analog links that have thus been established.

In other variations, the RPD node would still be in the field, but would encompass additional passings. This could be because of an internal split (such as 1x2 or 2x4), or due to RF amplifiers that exist in the plant. In this case, we have a need to monitor the digital links as described earlier.

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In yet other variations, we may have analog nodes deeper into the plant with no RF amplifiers. These would have the downstream (DS) on analog FS plan described earlier but would have separate fibers for the upstream. What complicates the situation further is that these links have asymmetric US and DS wavelengths per fiber, thus resulting in asymmetric DS and US fiber counts. And the need is still to monitor these fiber links with a view to know individual node connectivity and inventory fiber capacity.

The vast majority of nodes, though, are the regular HFC nodes that are connected to the headend with either a single WL, or with multiple WLs on the FS plan, with US WLs sometimes on the same fiber, and sometimes on other fibers. All in the need of fiber monitoring for connectivity.

It is easy to see here that the sheer number and the variety of links present a unique opportunity for operators like us to improve further on our network availability to the node and prepare for the future. The difficulty has thus far been the cost of getting said monitoring developed and in place, plus the intensive manual nature of troubleshooting, which is discussed next.

4. Fiber Connectivity and Inference

An outage, particularly a suspected fiber cut, instantly calls attention to a wide variety of resources in Comcast. With advanced internal tools like National Watchtower (NWT), we are able to know within minutes that individual Cable Modems have lost touch with the CMTS. The inference engine in the NWT can identify a problem node, to which trouble tickets are then generated for workforce management. If the whole node is out, then chances are high that a fiber may have been cut, heavily impaired or involved in a utility power outage. An optical time domain reflectometer (OTDR) is pressed into service to determine fiber connectivity, after a quick check that the return light is absent at the headend. The OTDR reveals a fiber cut, which is then located using a Geographical Information System (GIS) and fiber plant data. Then, a crew is sent to the spot for repair. When they get there, the restoration duration depends upon the number of fibers to be re-spliced.

In such cases, it is quite possible that the fiber sheath that is cut could also house a number of fibers, some of which could serve multiple non-residential services, such as Metro Ethernet (Metro E) or other business services, all managed by Service Level Agreements (SLAs.) Sometimes, especially if the fiber cut location is inconclusive, field technicians have no choice but to OTDR the fiber backwards, to further attempt to locate the cut. This adds both time and frustration. After the cut is restored, fiber plant is put back and the ticket cleared.

If, however, the node is affected, but it is not due to a fiber cut (which is known after an OTDR shot is taken), or if other nodes known apriori on the same fiber are unaffected, then, without a power outage, the dispatch instructions for the node would be to replace its optics/RF components. All of this information is available in multiple places, and the amount of time effort and energy it takes to communicate effectively when responding to such incidences continues to improve, steadily, as tooling and integration improve. However, this is still a logical step in addressing the above need and improve the customer experience further.

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5. Current State of the Art

Although technology has improved in major ways, and costs have come down, the current state of the art in mobile optical spectrum analysis and fiber connectivity is still quite expensive and localized. It is not unusual to see major equipment at headends and equipment moved around as needed. In an effort to lower cost, optical channel checkers have proliferated that enable us to measure individual WL power values. But these do not have integrated OTDRs. Many in the optical equipment manufacturing community now offer modular OSA and OTDR models -- but adding too many modules make the equipment bulky, and having fewer slots requires module swaps, which can be an issue in the field.

Since most of our access network footprint is in the 1550 nm region, using a standard 1550nm OTDR would not enable live scoping of the fiber plant since the OTDR light pulses could interfere with the smooth functioning of signals if the wavelengths coincide. Thus, this becomes used only in known or suspected fiber cuts or impairments. Mobile tunable 1550 nm OTDRs are a great innovation and could be used in live plant on unused channels, but we would need to apriori know that those channels are not in use. In addition, care must be taken in their use, to avoid damaging connected SFPs at the far end, because of damage or impairment to Avalanche Photodiode (APD) receivers in SFPs.

While channel checkers built with a filter/photodiode combination would track power levels, they will not be able to track wavelength movements, which can sometimes occur in the plant. Furthermore, it is not uncommon to use non-ITU wavelengths in the plant, such as when a broadcast transmitter is deployed in an overlay system. Comcast developed an architecture option for grey optics aggregation (GOA) that, as the name implies, uses Grey Optical Transmitters, where the transmitters are in the 1550 nm region without them being on any one specific ITU wavelength. In such cases a channel checker is insufficient and an OSA function is needed.

In a different paper [3], we discuss a more general convergence model at Comcast, where multiple services are all combined together on the same single fiber bidirectionally. In that model, analog DS WLs along with BDR signals of varying speeds, 10G RPD node connections, 10G Metro E connections, and 100G connections are all multiplexed on the same fiber.

6. Pervasive Monitoring Paradigm

Our thought process for continuous and pervasive monitoring began with three fundamental insights:

1. Use of commercially available components to cost effectively monitor individual wavelengths and to detect fiber cuts across the access plant
2. Continuous monitoring of all optical assets, using only test ports, without impacting the fiber reach of the access plant
3. Pervasive monitoring of optical assets in a cloud-based environment is essential to efficient correlation and problem resolution (as opposed to targeted stand-alone solutions.)

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To elaborate further, it is observed that OSA chips are widely used in ROADM applications. Cost effective and plentifully available, these chips used in ROADMs in the test port path could enable us to view optical wavelengths in real time. Many of these chips have a ~500ms scan time for the entire C-Band, and function from ITU 14 thru ITU 62 range, which makes them capable of detecting and showing WLs regardless of being on the ITU spectrum.

Selecting an OTDR of 1611 nm enables cost effective fiber connectivity information over live plant. Furthermore, 1611 nm Coarse Wavelength Division Multiplexing (CWDM) optical passives are cost effective and plentifully available. Additionally, single mode optical fiber is weakly guided and much more sensitive to micro and macro bending losses at 1610 nm (than it is at 1550 nm), so that "fiber choking" described earlier is seen much earlier than on the signal. 1310 nm is much stronger guide and has higher losses over fiber, thus is less suitable than 1611 nm for this purpose. We also selected 1611nm vs. 1620 nm due to the more widespread availability of optical passives at this region, and the fact that we generally do not use the 1611 nm window in the access plant (except in FTTH/RFoG deployments). We have already indicated that a standard 1550 nm prevents live channel OTDR and violated our rules of pervasive and continuous use, thus deeming it unsuitable. A DWDM Tunable OTDR would be much more expensive and require spare ports, and therefore that option was also not selected at this time.

Even with cost effective and capable OSA and OTDR options, we still required additional insight into making this technology pervasive in general operating conditions. That insight led to the use of an optical switch, to enable a "round robin" perpetual scan of the multiple fibers in the access plant. As described earlier, the fibers from SHE to the node are multiplexed at the SHE and demultiplexed at a field location, then feed individual nodes. Several such links exist in the SHE -- typically one may see up to 128 fiber links in each SHE. Therefore, the ability to have a 48-port switch that can connect to the test ports enables us to cost effectively deploy the OSA and OTDR functionality over up to 48 links. This concept is shown in Figure 5.

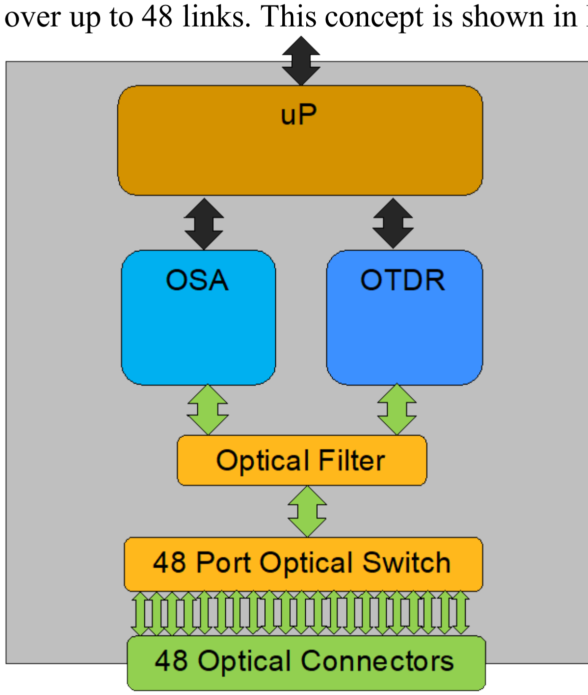

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Figure 5 – Highly Simplified view of the Continuous Pervasive Monitoring Tool

As an aside, it is common to see fiber counts in multiples of 12 as opposed to in powers of 2, perhaps because 12 has many factors that make it convenient to divide a fiber's route after the fact. In any case, we extended this number of wavelengths available on optical passives to up to 48. Therefore, it is possible that one OSA, OTDR combination behind the 48-port optical switch to survey 48x48 = 2304 WLs, which can translate to 1152 optical WL pairs or nodes.

With this background, a pervasive monitoring tool was built, as described next. We began by selecting an appropriate OSA chip currently used in ROADMs with sufficient resolution (say 6.25 GHz). Typically, these are built using temperature-sensitive elements with a calibrated receiver that has a well-established relationship between temperature, wavelength passed and photodiode responsivity. This way, the whole C-Band is scanned, and power at each step classified within ~500ms. Tying up the OSA component to ROADMs gives us a reliable and sustainable way to ride their wave of cost effectiveness and performance enhancements. OTDRs function by sending out a series of pulses, receiving echoes, then analyzing the delay in the echoes to estimate the points of reflections. There is a fair amount of ambient reflection in fiber, due to Rayleigh scattering, and OTDR sensitivity is typically improved by higher laser power. The higher the laser power, the more the reach and the better the echo received back that enables one to estimate reflections. Sensitivity also improves with using an APD receiver vs. a PIN receiver. Finally, care must be taken to reduce any immediate initial attenuation, and therefore it enhances the launch power into the fiber and consequently improves sensitivity. It must be noted that all OTDRs have an initial dead zone that prevents identification of specific fault locations in close proximity to the OTDR itself. In our case we typically set fiber monitoring after about 250 m of the OTDR, which comfortably exceeds our dead zone.

Figure 6, reproduced with permission from Corning, shows the relationship between wavelength of operation and its effect on micro and macro bending losses for standard G.652 fiber (lower macro and micro bending losses are achievable using the ITU G.652D compliant fiber). Notice that the macro bending losses are low when the wavelengths are below 1400 nm due to exceptionally well guided light there. Also, notice how the losses are higher at 1550nm, but the losses increase dramatically past the 1550nm area. The micro bending losses also increase with wavelength, but the delta is rather limited.

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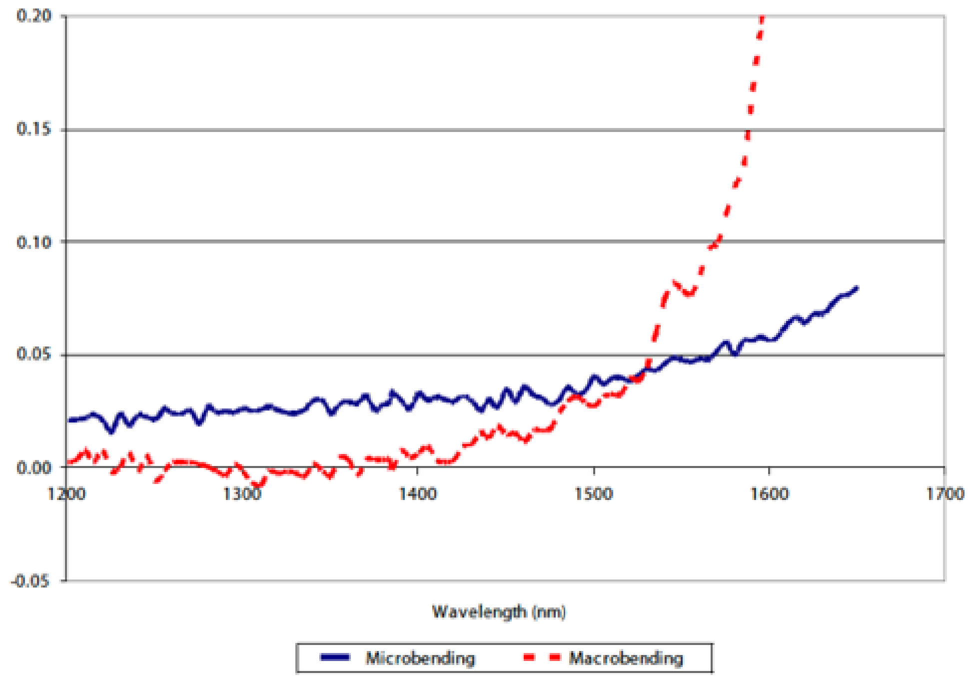

Figure 6 –Micro and Macro Bending Losses for ITU Rec G.652 Fiber

A typical New England winter brings with it a freezing cold followed by a thawing cycle repeated over several months. Over time, many of the splice boxes get filled with water and “choke” the fiber when frozen. This can attenuate fiber significantly, sometimes disabling a link. Unfortunately, this usually happens at inopportune times, the weather being bad and all, and resolving this issue has been a bugbear. Fortunately, the selection of 1611 nm enables us to see the drop in light levels as an event far earlier than we would have seen on the signal itself. This is because the fiber weakly guides 1610 nm and more strongly guides 1550 nm. In fact, it guides 1310 nm much more strongly, which is why it is a poor candidate for OTDRs wavelengths -- besides the fact that the fiber loss is much more at 1310 nm, and for that reason also has poorer sensitivity and reach.) Higher sensitivity in the OTDR not only enables one to scan longer reaches, but also to make out individual losses in the fiber path, attributable to bad splices or micro- and macro-bending.

The time required for OTDRs to declare a fiber length is typically dependent on pulse widths, anticipated fiber lengths and the number of averages needed to get a clear idea of the fiber distance. This computationally intense process could easily exceed one minute and sometimes takes several minutes. Since we need to be able to scan in round robin fashion through 48 individual ports, the dwell time in each port would need to be multiplied by 48 in order to calculate the maximum time before a fiber break is identified (for sticklers of accuracy, one must also take into account the switch time, which is ignored for the moment.) Even a 1-minute dwell time would require 48 minutes before a fiber cut could be declared. In fact, this is a major difficulty that limits very drastically the number of ports realistically used.

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For the pervasive monitor, we set up a target of declaring a fiber cut within 3 minutes for any one of the 48 ports. Our effort began with a commercially available OTDR module that offered the right set of optical specifications for our application but required more time than we had budgeted for our polled-scan method of monitoring the optical links. After some consideration of the OTDR requirements, it was clear that moving some of the digital signal processing from the original FPGA-based soft-CPU, to the high performance ARM used in the CPM, and increasing the data transfer rates at a key point in the OTDR module, yielded significant speed-up in the scan time. Only minor rework of the OTDR hardware was needed to implement this. Systematically understanding the computational requirements, the time of exporting the data for calculations, and then to convey the computed result, along with any events (more about that in a bit) enabled us to reduce the dwell time to just under 3 seconds! Furthermore, the OSA and the OTR could run simultaneously and independently on live plant. Thus, we are able declare any wavelength outage or fiber cuts within a maximum of 3 minutes across the plant. This massive and substantial improvement truly enables us to understand our plant in real time.

As described above, enabling the OSA and the OTDR to operate independently requires a new set of optical passives that have sufficient isolation and minimal insertion loss to enhance sensitivity across the board. This is described next.

7. Role of Optical Passives

Architecting a pervasive monitoring infrastructure requires one to follow the fundamental rules laid out in earlier sections. It requires not only the ability to accommodate existing, set optical passives and access architectures, but also to define reference optical passives and architectures that can be better served. To this end, we have specified new sets of optical passives with consolidated test points.

Typical optical passives have had multiple filtered ports that either take in or put out ITU WLs. Then they have a COM port that combines these to launch on the optical fiber. WLs within the ITU range but that are not used in the Mux are typically available in the Upgrade port (UPG), whereas wavelengths outside of the ITU band are available in the Express (EXP) port. Typically, a test point for forward wavelengths is available (TPF) as well as a test point for reverse WLs (TPR).

Use of optical passives of this kind typically is less than optimal for pervasive monitoring. To peer in the network at 1610 nm, one would have to use the whole of the EXP; to check on outgoing WLs, one would have to use all of the TPF, and for the return WLs, the whole of the TPR. Doing this would require 3 ports on the monitoring tool, but more importantly it eliminates the future ability to add out-of-band wavelengths to the link, and requires manual troubleshooting, should the need arise, by the using TPF or TPR, since they are all connected to the tool. While this already considerable base of passives can also be monitored subject to the limits discussed, we opted to define a new set of optical passives to improve on this efficiency in a significant way.

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Furthermore, optical switches are typically used for one WL at a time, and typically to direct light from one end to the other. Since all but one port is active, interactions between ports that are not in the optical path are generally not taken into account to build inexpensive switches. In our case, however, ALL ports that are lit on the switch are lit, which can cause unintended interaction between unrelated ports that are not in the intended light path. This is a fairly complex subject and not discussed further, but fortunately, optical passives can be designed quite easily to avoid this crosstalk issue altogether.

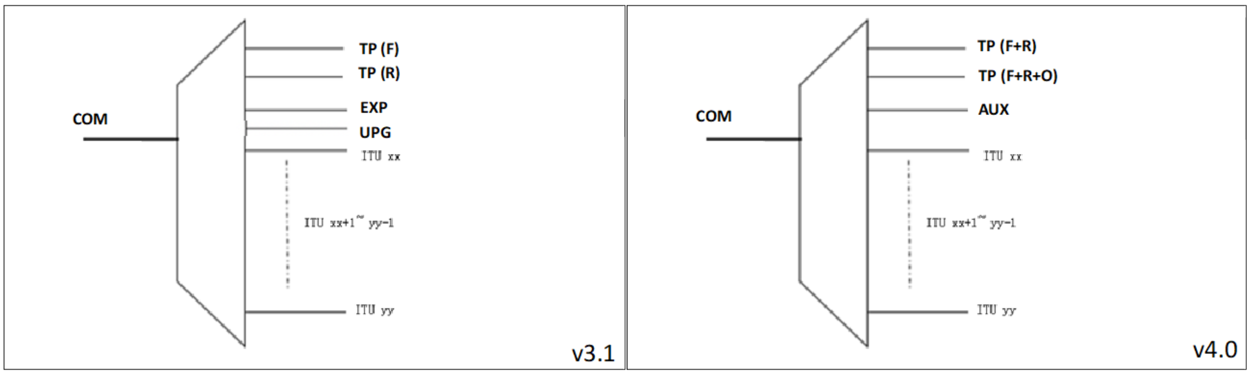

Figure 7 – Optical Passives Old and New in Comcast

The new standard of optical passives in Comcast today have consolidated test ports so that manual troubleshooting, if needed, can occur independently of pervasive monitoring. This is accomplished through an innovative optical filter design that consolidates the forward, reverse and 1610 nm part of the optical spectrum in one test port called TPFRO. The manual troubleshooting port is a consolidated forward and return test port called TPFR. The remaining optical wavelengths in EXP and UPG are all together combined into one consolidated Auxiliary port (AUX), which extends from 1260nm to 1598 nm (excluding the water peak WLs). This patent-pending concept is shown in Figure 7.

To enhance density as we prepare for the access growth, we have moved towards very small form factor (VSFF) connectors. These connectors can enhance deployment density, which is always useful in cramped PHEs and SHEs, thereby making space for pervasive monitoring tools.

8. Infrastructure Evolution

The Continuous Pervasive Monitoring tool (CPM) is implemented as a 1RU box that comprises the OSA, OTDR, 48-port optical switch and associated power supply and processors. As discussed, the processor must be fast enough to process fiber lengths, put out events, process the OSA and analyze wavelength information within the dwell time. The high reliability 48-port optical switch typically switches from port to port within 100ms. Therefore, within about 3 minutes (180 seconds), one can process up to 48 optical links, confirm their integrity as well as process up to 2034 wavelengths and confirm their well-being. It's a good time to be a fiber wavelength.

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Figure 8 – Actual Comcast Installation of the Continuous Pervasive Monitor

As shown in Figure 8, the CPM is connected to the headend optical passive test points, which are then connected to DAAS ports. Figure 9 shows a typical SHE layout that accommodates the CPM.

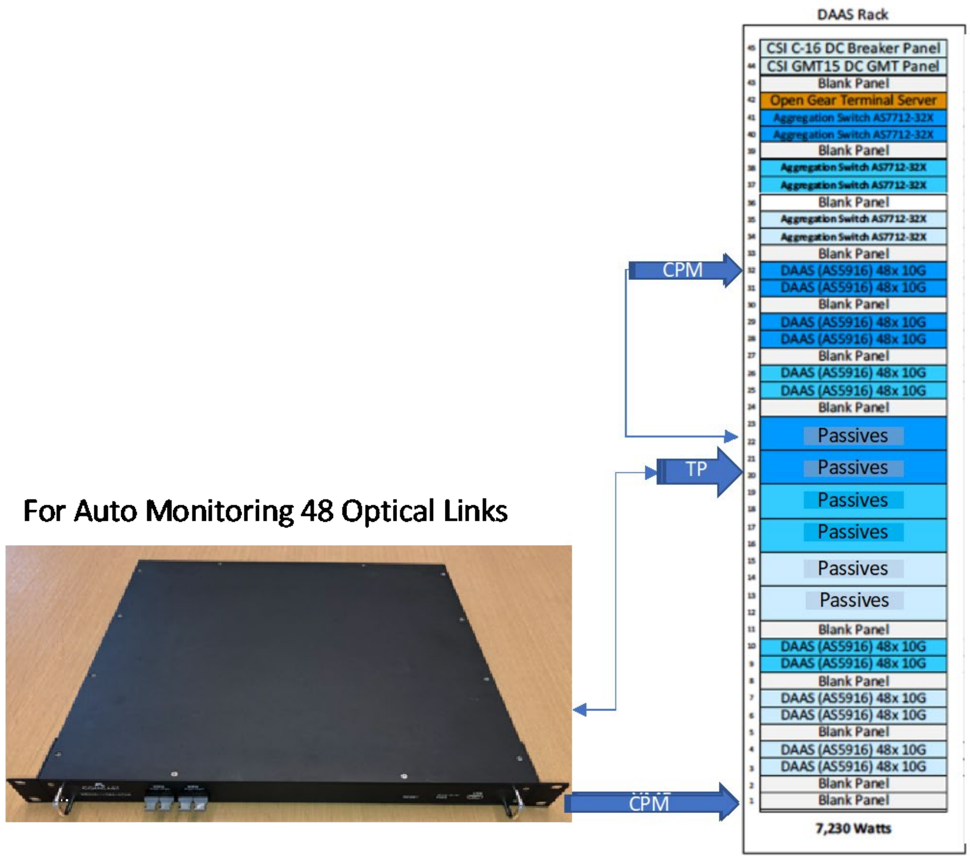

Figure 9 – Describing the DAAS Pod and the Monitor

As indicated in Figure 9, the (Continuous Pervasive Monitor) CPM is typically set up in the SHE alongside the DAAS pods. These pods were well defined and have their own power supply panels, aggregating switches if needed, and DAAS switches, along with optical passives, in one compact location. The DAAS pods connect to the vCMTSs that are typically located in the PHEs. From 192 to 576 service groups (SGs) may be served with one DAAS Pod. The CPM is thus exceptionally well suited to monitor each of these DAAS pods and additionally handle any additional service that may be typically lit up in the SHE.

Typical SHEs may contain DAAS pods, many MetroE service groups, some traditional analog links and the incoming high capacity coherent links. Some SHEs are co-located with the PHE (they are called direct feed links), while many are small, single room discrete locations within the footprint. Some of the SHEs could be smaller and be accommodated in large air conditioned cabinets.

Widespread use of CPMs in the system will also help with SLAs in MetroE links and enable us to enhance the customer experience for both residential and business services. As such, even though the CPMs are never in the signal path, they still undergo a stringent Physical and Environmental (PnE) evaluation process, to assess their suitability of existing in SHEs and

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meeting the demanding standards of our field equipment. Furthermore, as will be seen in the following section, and since they are going to be connected to our network, they undergo a rigorous security audit to ensure that there are no open ports, and that their connections are secure. It was surprising to see how quickly open ports are pinged by untrustworthy IP addresses, within hours of installation, making one feel glad about the security process in place.

9. End-to-End Optical Architecture

We have so far described the process of building innovative and cost-effective monitoring equipment, and some of the infrastructure, such as optical passives, that enhance its usefulness. Creating a physical infrastructure is one thing, but creating an end-to-end software infrastructure based on the third insight -- to take the promise of pervasive monitoring -- and turning it to reality is another substantial endeavor, and demonstrates the great opportunity to bring complex ideas into existence.

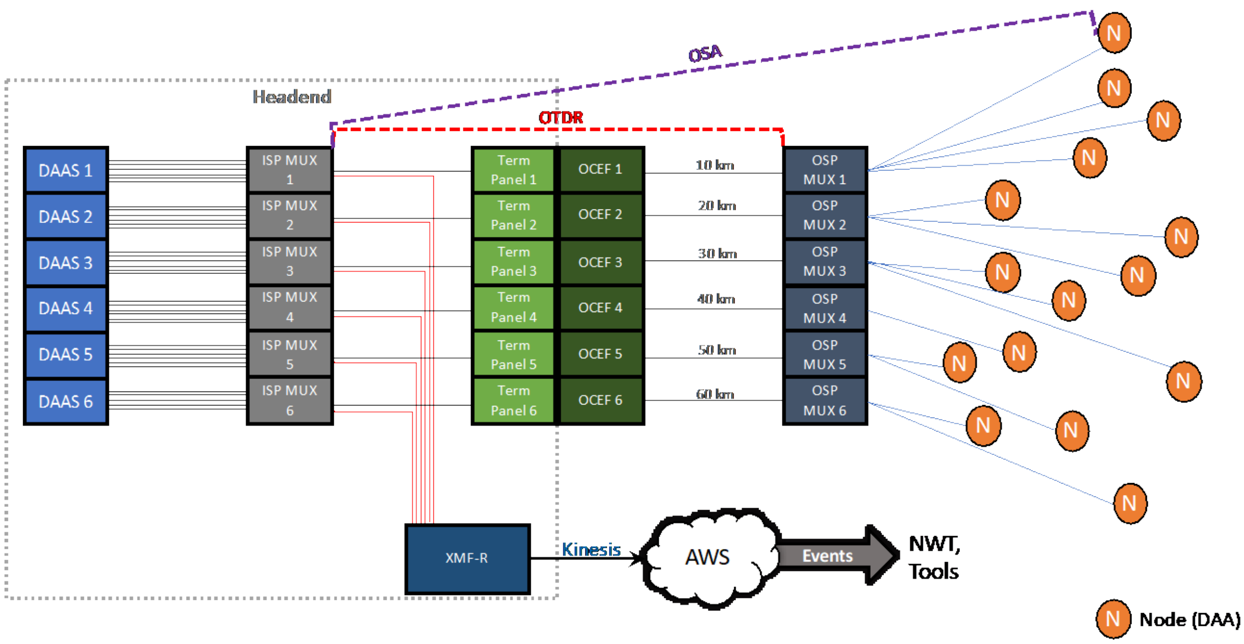

Figure 10 – End-to-End Software Paradigm

Figure 10 shows an end-to-end architecture in the context of our DAA architecture. As explained earlier, in the SHE, DAAS ports are connected to respective optical passives. Each DAAS port is logically connected to one optical node in the field and comprises two wavelengths, one downstream and one upstream. We also now use tunable SFPs in DAA applications that are typically spread from ITU 14 thru ITU 61. The light from multiple DAAS ports is multiplexed at the optical passives and is then connected to a termination panel in the SHE. This termination panel is the demarcation point between the SHE and the outside plant. Each fiber that goes to the outside plant has one optical connector on the termination panel. The termination panel fiber then passes thru a large conduit, called the Optical Cable Entrance Facility (OCEF) to the outside plant. Once outside, fibers are distributed according to plan to the various nodes. In our DAA

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architecture, we use only one single fiber for US and DS operation. This makes the process of keeping track of fiber easier. With modifications, architectures that envision separate US and DS fibers can also be similarly monitored.

Typical Comcast links could be as long as 60 km, although the vast majority of our links for this type of architecture are around 30 km. After traversing the distance from SHE to node thru several splice enclosures, the fiber reaches the outside plant (OSP) mux. The fiber route is contained within our GIS systems, in special software entities such as SNET or Bentley.
As the fiber makes it way to the OSP Mux, we recognize that its weight causes the fiber to sag between poles in aerial plant. And, every 1,000 feet or so, about 150ft of slack cable is maintained to aid in fiber cut restorations. Finally, as the fiber is lashed, the lashing wire envelops the strength member in a helix pattern. Combined together, these three factors contribute almost 20% extra linear fiber, as compared to the ground distance on maps. Many GIS systems take this into account, however there is an opportunity to re-verify and fine tune these numbers using the CPM devices.

In the OSP Mux enclosure, the individual wavelengths are brought out and fibers connected to support each node. Since the OTDR is a 1610 nm OTDR, once we reach the Mux, and the individual wavelengths are separated, that also ends the OTDR's ability to peer any further into the network. Therefore, the OTDR system provides continuous monitoring from the Inside Plant (ISP) Mux to the OSP Mux. Farther from the Mux to each individual node are set two fibers, one for US and one for DS, and these are terminated in the node to the SFP. This SFP receives the optical input from the DAAS port SFP and sends out light to be received by the DAAS SFP, thus completing the circuit. Notice, however, that unlike the OTDR, the ability of the OSA to view DS and US wavelengths is unaffected. It is able to record all wavelengths that traverse the fiber. Thus, a combination of OSA and OTDR provide a continuous and end-to-end view of the entire DAA network.

In keeping with our objectives, the CPM is connected to the TPFRO test point of the ISP Mux. The CPM is thus in a great shape to dwell on each one of its ports, measure the input and output wavelength values and their power values, independently measure the fiber link, and record any events on the fiber link. Using the fast processor with the unit, any event information can be uploaded to the cloud.

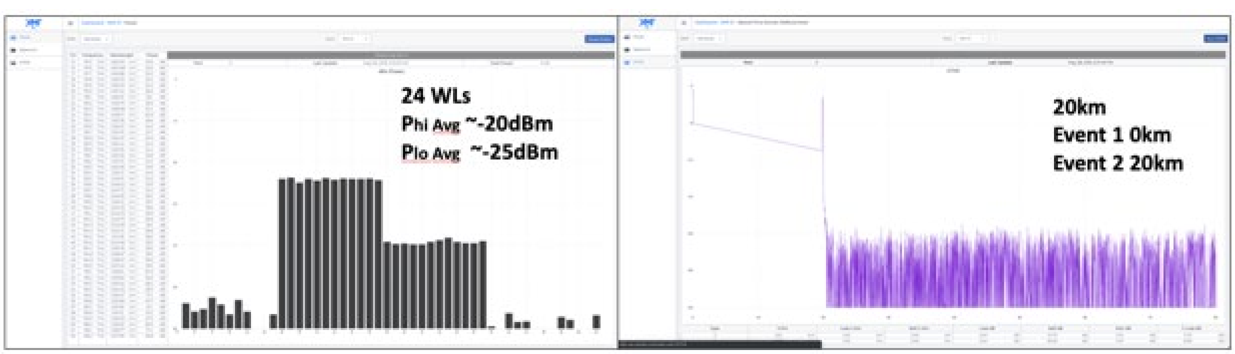

Figure 11 – Sample view of the OSA and OTDR Output for each port

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10. Praemonitius est Praemunitious (Forewarned is Forearmed)

While information is uploaded to the cloud continuously, it is also used to train the monitor. This step is described later in the paper. Any changes to the optical levels or to fiber events are then reported via the automatic feed (called Kinesis) to an eventing engine that connects to a sophisticated internal resource called the National Watchtower (NWT).

Since outage information from various sources arrive at the decision engine with various minor delays, if the decision engine begins reacting immediately, it will have reacted with insufficient information. Thus, to avoid this “race” condition, the decision engine “soaks” or stores all incoming information with various minor delays to look at it holistically [4]. Then they are brought up as one unified ticket with actionable data and sent to respective locations. Ideally, if the contents indicate a fiber cut, these are also laid out on the GIS, and a street address location is also provided, in which case the repair crews also have a specific location to head out to. For this reason, slack/sag/helix and other such parameters are estimated from the appropriate databases to ensure a level of accuracy.

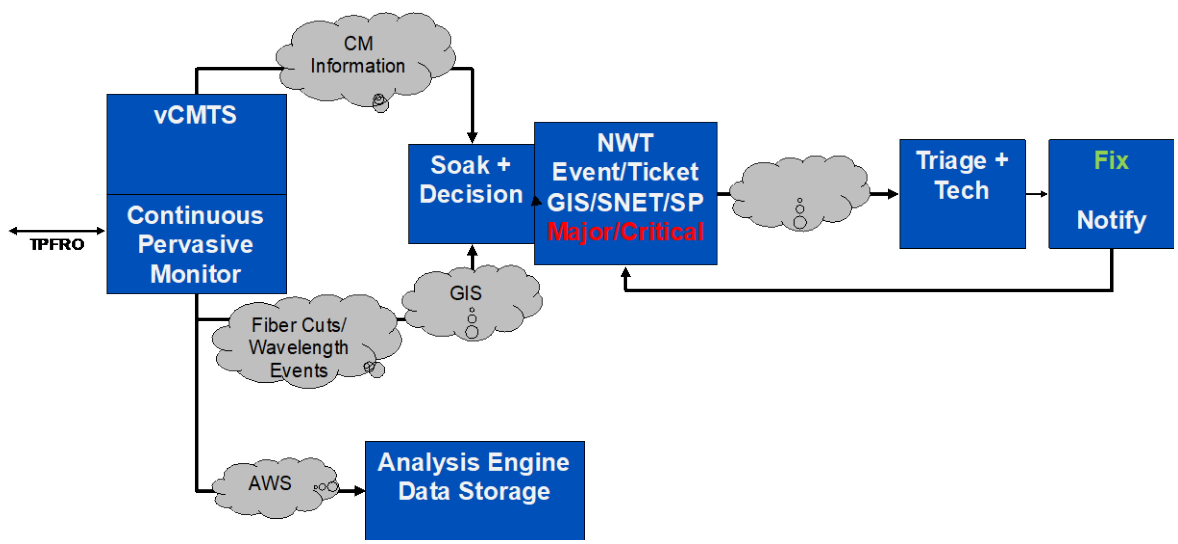

Figure 12 – Sample view of the OSA and OTDR Output for each port

We began this paper by noting the energizing effect of a suspected fiber cut. This process not only establishes the said cut, but also provides a specific location in almost real time. In Figure 12, it can be seen that the events are sent to the decision engine for handling related to ticketing from the CPM. To aid in fiber cuts, we also estimate the distance of the fiber cut and its relative location based on sag/slack/helix and compared to the GIS. At the decision location, this information is soaked and compared to other information also flowing, to avoid race conditions. At the NWT the ticket is generated with an appropriate alarm level, and the location of the fiber cut/node location is then sent to triage and to the technician. The problem is then fixed, and the tech clears the issue.

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While events are sent to a decision engine, the periodic data collected is sent to the cloud continuously. This data is curated and available for deeper analysis. For example, this data may be examined to compare various links at locations at the same time, or to compare data from the same link during different parts of the years, for weather-related impacts. Over time, this data will be a treasure trove for a machine learner to sift thru for various patterns in optical preventative network management.

If, on the other hand, wavelengths disappear on the OSA, but the fiber link on the OTDR shows strong, the inference is that the node is individually affected. This could mean that the node has an electrical, RF or optical issue inside of it, or that the fiber between the node and the OSP Mux is cut. In this case, after a soak period, the affected node is identified, and the technician can easily figure out the node status. If the node is fine, then the fiber cut between the OSP Mux and the node is easily identified by an OTDR (this will require a handheld OTDR, which is a mobile equivalent of the rackmount CPM). One other option, which is a bit manual, requires disconnecting the headend DAAS port of the affected node and shooting the fiber with a tunable OTDR, but this process requires a fairly good view of the ISP optical connections.

Establishing and then maintaining end-to-end connectivity for all elements in the network is as complex as it is important. The OSP plant that begins from the OCEF is typically overlaid on the GIS, as described earlier. This can span several 10s of km of plant. Also, such connectivity must be maintained within the PHE or the SHE, which is considerably difficult. This is because equipment may be periodically rearranged, revamped and swapped out, sometimes in phases. Therefore, an auto discovery process for all field entities is the most optimal path, which begins with a robust provisioning process.

Because the data is stored in an efficient format in the cloud, this data can be compared year to year to understand how each of the fiber links perform in different weather conditions. The role of machine learning in this type of an effort cannot be overestimated. Through a systematic comparison of events and fiber profiles across the fiber lengths, not only can link performance be flagged, but weaker splice enclosures prone to fiber fills can be replaced to shore up the fiber availability. In a natural disaster, having access to multiple fiber cuts and their location in real time will enable a far more efficient dispatching of resources. Since optical passive information is stored along with the current usage of optical wavelengths, and available at any given time, capacity on each fiber link can be estimated in real time. This helps us to understand which links can handle additional wavelengths. Furthermore, some of our limits on optical level differentials and wavelength plans to accommodate analog, coherent and 10G wavelengths on the same fiber can not only be viewed but also enforced.

The CPM is deployed in all three divisions at Comcast. The cloud-based infrastructure component, with respect to its provisioning and continued use, is described next.

11. Provisioning and Training the Monitor

When the CPM is first deployed, the MAC is discovered, an IP address given, and a name established. In the provisioning process, the ports are assigned to each of the ISP Muxes, by

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name, and each of the Wavelengths of each of the ports is connected to its respective node. Additionally, each port is also assigned to its terminal panel. Thus, by way of discovery of the DAA and OSP engines, auto discovery and alignment can occur to create an end-to-end connectivity diagram.

Figure 13 – View of the Provisioning page in for the Monitor

Once this is established, then the CPM is left alone until it has acquired, by the port dwelling process described earlier, a baseline of its fiber length and the wavelengths. Once the baseline is verified to be correct according to the maps, the baseline values are set, and then subsequent values are compared to the baseline in perpetuity. This is indicated by the green color of the OSA wavelength representation. In a typical day, each link is verified 480 times (or more per 24 hours), at three minute intervals. Thus, any change in the current vs. baseline situation is immediately flagged and sent to the NWT for ticketing.

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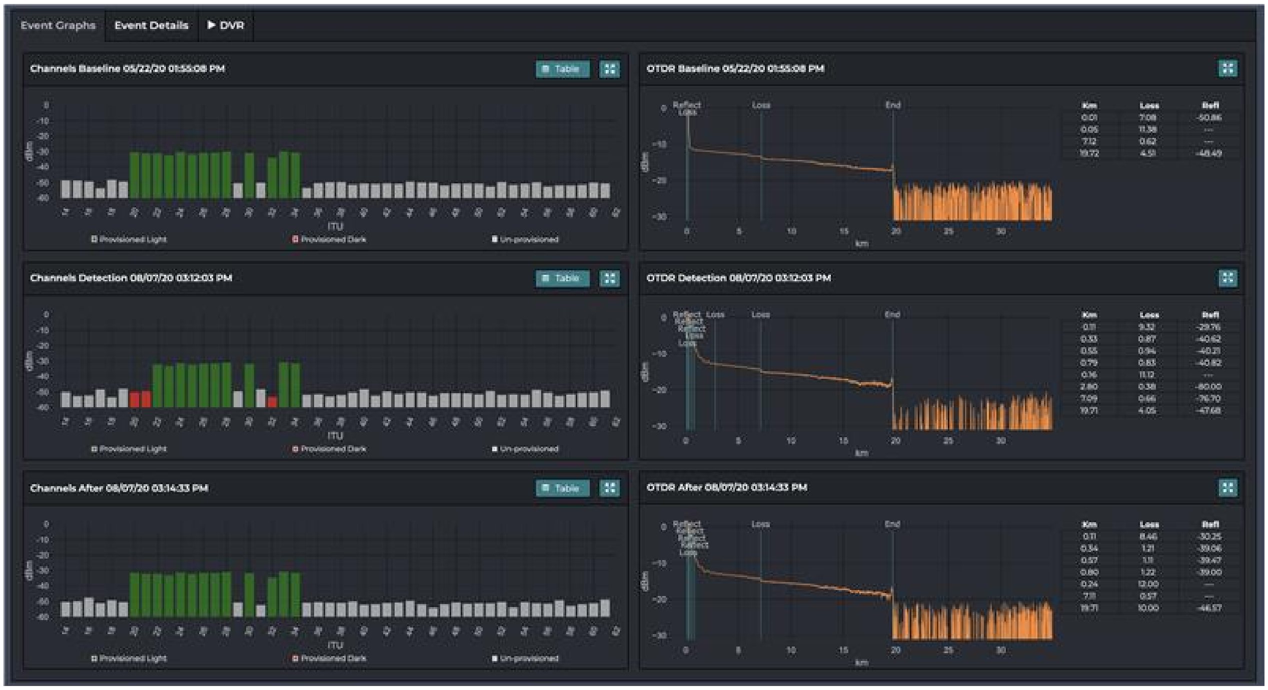

Figure 14 – Fully Provisioned Port (notice the green and red WL colors)

Figure 14 shows a case where the baseline has been set, as can be seen with all of the green ITU wavelengths. In the middle, we see that a power outage has taken out three nodes. Because in this case the CPM is monitoring the US ITU wavelengths, we see three of the green wavelengths are now in red. However, a quick check at the OTDR confirms that the trunk fiber is not cut -- it shows no events. We would be able to verify thru Continuity (an internal "source of truth" dashboard that indicates power continuity in the network) about the power outage. Once the power is restored, the wavelengths come back on-line and compare favorably to the baseline. In this case, this outage was resolved without the need to visit the node. However, if the power had been on, then the next step would have been to understand if there was a fiber cut between the OSP Mux and the nodes (although this is unlikely, given that more than one node was affected). In that case, a technician would resolve the issue by means of more sophisticated tools, described in the next section.

Occasionally, it becomes necessary to interrupt the automatic process to troubleshoot or verify performance. In these cases, the software also lets one SSH into the CPM to direct it to specific ports, out of the order for immediate real time view. In these cases, the CPM understands the legitimate request and pauses the auto view.

This level of automation and remote capability was especially helpful in the COVID environment, when folks from multiple locations were suddenly able to get on a conference call to view, inspect and troubleshoot specific links. In one specific instance, we were perplexed by a rather high loss appearing in the dead zone of an OTDR. The CPM was provisioned, by alerts that were not yet firing. Perplexed by this, and by good, old-fashioned process of elimination, we figured out that because of the unusually short fiber length, and to protect the APD of the SFPs, a rather large attenuation pad had been placed in the COM port of the ISP passive -- thus

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contributing to the dramatic attenuation increase on the OTDR and the OSA. Thus, it is rather important to understand the role of attenuators (commonly used to attenuate light levels) and their effect on OTDR resolutions and OSA power levels.

12. Handheld to the Cloud

Thus far, we have described the role of continuous and pervasive monitoring of optical assets. However, many impairments in the system require human interaction and experience in order to reach a resolution. In these cases, we rely on the considerable acumen and insights of our headend and fiber technicians. We also outfit them with an array of sophisticated optical equipment. These could be full featured optical spectrum analyzers, high sensitivity and/or high input optical power meters, 1550 nm tunable OTDRs and SFP programmers. We have previously mentioned that the optical passives have been designed to enable manual as well as pervasive monitoring.

In the example in the previous section, if only one node was affected, the technician would have disconnected the port to the affected node and used a tunable OTDR to verify whether there was a fiber cut, as it can peer beyond the Mux. Alternatively, a technician would have been dispatched to the node location for troubleshooting.

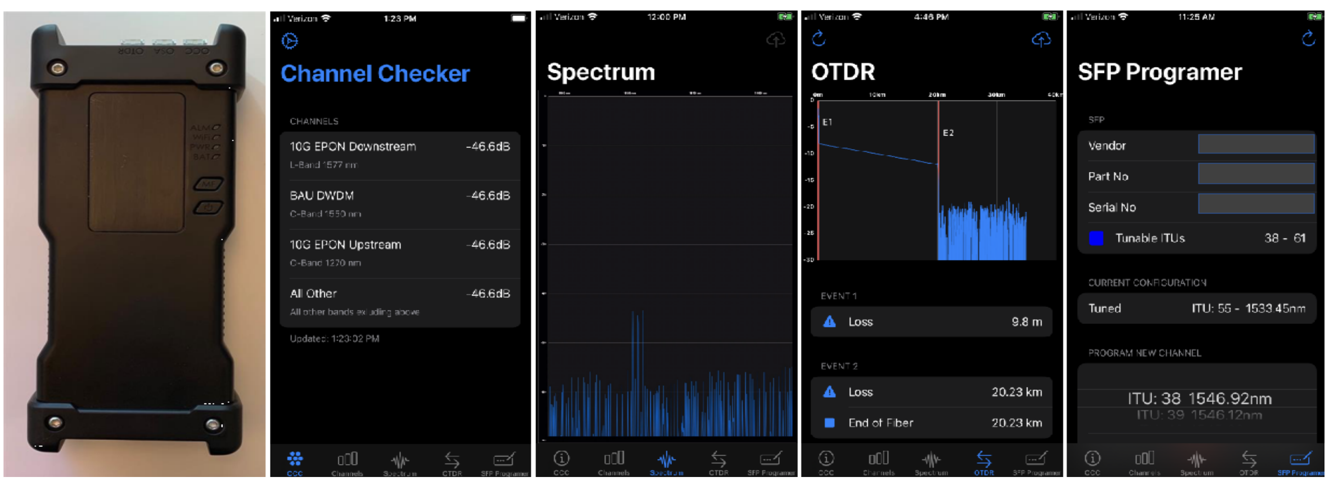

Figure 15 – Handheld unit with a Mobile Application and Cloud connectivity

The previously mentioned handheld equivalent of the CPM is also potentially useful for field technicians. This device has a C-Band OSA, the 1611 nm OTDR, an SFP Programmer and a Channel Checker/Power meter to aid in PON deployments. Designed with a long battery charge (a full shift) and WiFi hotspot, this device enables field technicians to troubleshoot a variety of fiber cuts, and SFP installations, along with routine troubleshooting. Based on popular RF meters of the same type, this device has impressive cloud capabilities, with a UI designed in-house. Because all of our technicians carry iPhones, the UI and display is adapted to the iPhone and shown in Figure 15. A device of this kind allows the technicians to troubleshoot and upload their observations to the cloud and helps round out our optical asset monitoring.

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13. Conclusions

We began this paper with a description of the access footprint and our substantial efforts to address continuous and pervasive monitoring of our optical networks. An innovative mix of technology, in use in other areas of optical communications, including innovations in optical passives was critical in standing this system up. As important as the hardware is, the software infrastructure is even more so.

Being able to remotely and automatically get notifications of fiber cuts, with appropriate overlays on GIS maps, is extremely useful in reducing the time to repair. It is especially helpful to not only DAA and HFC links, but also to the MetroE links in the access domain. The hand-held unit offers an extra layer of efficiency across the board and helps fulfill the promise of continuous and pervasive monitoring of access optical assets. The benefit of CPM during the COVID pandemic has been rather positive and can potentially be generalized further to enable remote monitoring and mitigating capabilities across the network.

14. Acknowledgements

It is a pleasant duty to acknowledge the entire team within Comcast that has been working directly and indirectly on the Continuous Monitoring project. A project of this magnitude benefits from the dedication of diverse expertise from hardware and software at the Operations and technology team, the reliability and functionality testing of the Physical and Environmental test team, the ticketing and alerting of the NWT team and the functional rules for deployment from the access engineering team. Our thanks are especially due to our vendor and partner II-VI for their insights. We sincerely thank the Senior Leadership Team at Comcast NGAN in supporting this project and for their support in deploying it in all the three divisions at Comcast.

Abbreviations

4WM	Four Wave Mixing
APD	Avalanche Photodiode
BDR	Baseband digital receiver
CMTS	Cable modem termination system
CPM	Continuous Pervasive Monitor
CPU	Central Processing Unit
DAA	Distributed Access Architecture
DAAS	Distributed Access Architecture Switch
DS	Downstream
DWDM	Dense Wave Division Multiplexing
EXP	Express port
FPGA	Field Programmable Gate Array
FS	Full Spectrum
GIS	Global Information System
GOA	Grey Optics Aggregation
HFC	Hybrid Fiber Coax

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HHP	Households passed
ISP	Internet Service Provider
ITU	International Telecommunications Union
MAC	Media Access Control
NWT	National Watch Tower
OCEF	Optical Cable Entrance Facility
OEM	Original Equipment Manufacturer
OSA	Optical Spectrum Analyzer
OSP	Outside Plant
OTDR	Optical Time Domain Reflectometer
PHE	Primary Headend
PON	Passive Optical Network
RF	Radio Frequency
ROADM	Remote Add-Drop Multiplexor
RPD	Remote PHY Device
SFP	Small Form Factor Pluggable
SG	Service Group
SHE	Secondary Headend
SLA	Service Level Agreement
SOAP	Switch On A Pole
SSH	Secure Shell
TPF	Test Point Forward
TPFR	Test Point Forward and Return
TPFRO	Test Point Forward, Return and OTDR
UPG	Upgrade Port
US	Upstream
VSFF	Very Small Form Factor
WL	Wavelength

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