Software Revolution Of Field Meters Using a Field-Capable Measurement Device

A Technical Paper prepared for SCTE•ISBE by

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1. Introduction

Field meters have been on the first line of defense when determining if a cable plant is sufficient for installs, in need of repair, and for determining the quality of service. The original meters were expensive, heavy, and required a large amount of training. Contemporary meters are still relatively high-cost and in some cases require even more training to use than their predecessors. In order to get a tool in every technician's hands, the device needs to be light, lower cost, and use contemporary software to display and interpret the relevant data to help reduce the amount of training required.

In the past 20 years, improvements in cable technology have occurred often and at a larger scale. From the late 1940s through the mid-1990s, most cable plant was used to retransmit analog TV signals. This represents 45+ years of similar technology, with most advancements involving increasing the upper spectral boundary of the infrastructure to support a greater channel capacity. By contrast, and with the adoption of DOCSIS 1.0 (1997), 2.0 (2002), 3.0 (2006), and 3.1 (2013), the cable industry has experienced a major technology upgrade approximately every five years. With each upgrade in cable technology, testing devices needed to evolve in parallel, to keep technicians current and to provide more relevant information to perform their duties.

With the onset of COVID-19, which impacted both field upgrades and social guidelines, tools needed to evolve even more rapidly. New safety protocols for cable install and repair technicians resulted in new signal verification and testing processes. Recent increases in service bandwidth needs are forcing quicker deployments of multiple orthogonal frequency division multiplexing (OFDM) and orthogonal frequency division multiple access (OFDMA) channels. By developing a software-first, cloud-connected device, the operator can adapt to the current situation, access more technology and evolve it more quickly.

This paper discusses how cable modem technology was used to fulfill this role, evolving to be part of the operator's ecosystem and bringing tremendous value. The device we developed and characterize in this paper is referred to as a "field-capable measurement device," or "FCMD."

2. Historic Context

Original cable signal meters were very large and cumbersome. Ron Hranac, Technical Marketing Engineer in Cisco's Cable Access Business Unit, would know. He started as a technician in Idaho in the 1970s, working with up to seven other technicians, all of whom shared Jerrold Model 727 field strength meters (they also used smaller installation-specific meters). This particular meter was 13" x 8.5" x 8.5" and weighed 15 lbs. It was also very expensive. So expensive that after one of them was dropped from a telephone pole, instead of buying a new one, Hranac once spent 40 hours repairing it back into usability.

Figure 1 – Jerrold 727 Field Strength Meter

Newer field meters are much smaller, measuring around 6" x 10" x 3" and weighing about four pounds. This is an improvement of approximately a factor of three in both size and weight, compared to those very early meters available to cable industry technicians. One added benefit of the current meters is that they are battery powered and usually have a runtime of a couple of days, depending on usage patterns.

Until the advent of DOCSIS, the method to measure cable signals primarily involved measuring analog radio frequency (RF) signals. The process required the technician to properly adjust gain factors for a specific channel, measure, then repeat this process for the next channel frequency. It was a very time consuming and labor intensive process.

The arrival of the cable digital age dramatically changed how cable modems were used. Steve Zanetich, Executive Director of Technical Operations at Comcast, has seen more than a few signal level meters in his career, dating back to the times of manually tuning each frequency, through adjusting a series of pots and knobs. In the digital age, those same meters jumped light years ahead of their predecessors in terms of features, processing, and measurement accuracy. "In the past, we needed to change hardware and software, recalibrate regularly, and [perform] other costly routine maintenance in an effort to keep measurements accurate," Zanetich noted. With today's technology, by contrast, considerably more can be accomplished, at a fraction of the cost. "The days of manually writing down your levels at each job are gone," he said. They've been replaced with real-time remote management, integrated business and performance tools, and collaborative software development, "all inside a feature-rich device that is capable of measuring so much more than just the amplitude of a single carrier."

3. Problem / Opportunity Statement

Over the years, RF signal level meters (SLMs) have been made nearly indestructible, while being given the ability to make very accurate measurements. These requirements resulted in a meter with a significantly higher price point. The high price point, coupled with limited operator capital budgets, typically meant that most operators expected the meters to last between five and 10 years. With the rapid DOCSIS revisions, these meters can be obsolete before the cable operator can get a good return on investment (ROI).

The opportunity to use cable modems, which may not be as durable, but nonetheless make reliable and accurate measurements, was identified as a potential means to yield a better ROI.

After all, one element that is the same, between expensive spectrum analyzers and full-band-capable cable modems, is that they both thrive on the task that is demodulating signals. Developing a FCMD based upon a generic cable modem can help also achieve a good ROI.

4. Solution

The solution was to design a FCMD tool based on of a portable cable modem, using known hardware commodities to help reduce overall cost. Similarly, the software architecture was selected from well-known open-source commodities, to again save costs in the short and long term. Environmental and technological performance requirements were adjusted to achieve a desired price point.

In the process of achieving these goals, numerous additional benefits were identified that had not been originally anticipated. These include periodic software improvements to keep the devices reasonably current; cloud connectivity to "share the load" of processing, and to reference historical or informational data too bulky to be stored locally; and the development of "role-specific" user interfaces (UIs) such as "line technicians" and "install and repair technicians".

4.1. DOCSIS Based Cable Modem Gateway

The first SLMs could be considered high-precision near-laboratory-grade instruments that were ruggedized to handle the harsh outdoor field environments we frequently encounter. With the advent of DOCSIS and the use of microprocessors, SLMs transitioned to be high-end pieces of field test equipment. All DOCSIS cable modems (CMs) are required to perform measurements/tasks similar to current field SLM equipment, just to function. Example of these measurements include:

- Full bandwidth spectrum capture
- Downstream signal level measurements for automatic gain control (AGC)
- Quadrature amplitude modulation (QAM) measurement error statistics
- Upstream equalization coefficients
- Upstream transmit power
- Data throughput (speed test)

Since cable modems perform tasks equivalent to meters, and a goal was/is to reduce the overall cost per device, the decision was made to develop the field-capable measurement device using a known commodity. As a direct result, a DOCSIS 3.0-capable (to be followed by DOCSIS 3.1-capable) cable modem was selected as the hardware platform.

The cable modem housing was designed consistent with its consumer premise equipment (CPE) version, to minimize ruggedization costs.

4.2. Power Source

The development of a power source for the FCMD followed a similar methodology. Batteries have been used in our cable modem gateways for a long time, so the circuitry was extant. High capacity batteries have been around for a significant timeframe, and their technology is also proven. By selecting a generic form factor, we were able to decrease overall costs for the original product and any future battery replacements.

4.3. Graphical User Interface

Traditional SLMs are designed with a dedicated user interface as an integral component. This type of user interface usually touts benefits like being tightly coupled with the hardware, and ruggedized for daily field use. Those benefits can also represent drawbacks, however. Specifically, the drawbacks of an embedded graphical user interface (GUI) include:

- GUI is a possible point of failure requiring repair / replacement
- GUI software / GUI hardware is custom-designed on a per-product basis
- GUI hardware needs to be considered during power budget analysis
- GUI operating system includes licensing costs (sometimes but not always applicable)

At Comcast, technicians have been using existing network tools to interact with our cable modems for well over 10 years. Allowing them to interact with a portable cable modem, in the form of an FCMD, was an easy extension to those long-standing processes. The use of these tools brings additional benefits to the testing in the following ways:

- Cloud connectivity of the instrument (with consequent data ecosystem access)
- Common software development tools for application development
- Common operating system when mobile platforms are upgraded
- Global Positioning System (GPS) assistance with respect to application use
- Built-in, industry-standard accessibility features such as high contrast, large font sizes

Our technicians already use tools with adaptive and cross-platform form factors, suitable to their tasks, as depicted in Figures 2, 3, 4 and 5, which show the same ingress detection widget on a smart phone, small form factor tablet, large form factor tablet, and desktop computer, respectively:

Figure 2 – Ingress Widget on phone

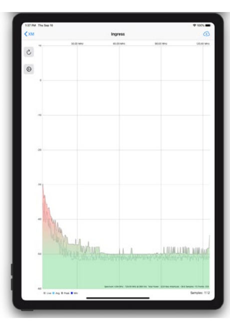

Figure 3 – Ingress Widget on Small Tablet

Figure 4 – Ingress Widget on Large Tablet

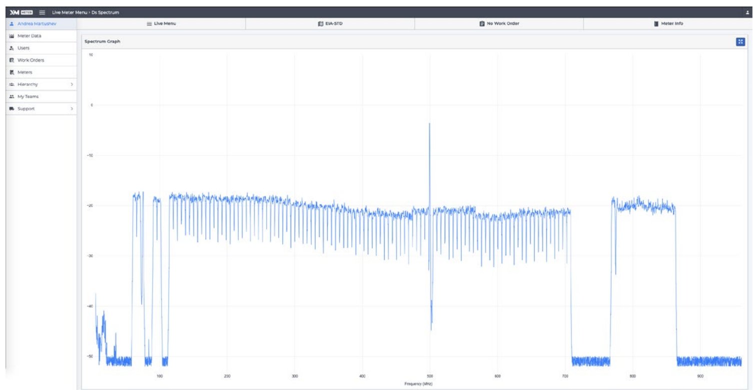

Figure 5 – Spectrum Widget on Desktop Computer

4.4. Performance Requirements

Environmental requirements for high-end signal level meters are developed with the overall price of the product in mind. This means being able to withstand a variety of weather, environmental and electro-magnetic interference (EMI) conditions. In addition, the RF front end of these meters is designed such that they have an extremely low noise figure, especially at low frequencies.

Based on over two years of field data, and despite fall-related ruggedization being a highly marketed feature of traditional SLMs, the truth of the matter is that product failures due to a drop are fewer than 0.1%. This is a very low calculated failure rate and was used as a consideration in the overall design. As a direct result, the FCMD was designed with the protection of an accompanying bag, designed to withstand a drop from a typical telephone pole height.

Environmental conditions, including rain, snow, heat and humidity, exemplify how cost reduction compromises carry some risks. For instance, temperature requirements required the addition of a fan on the second generation FCMD. The location of the ventilation holes, as well as the bag design, limited this risk. Over two years of data, the failure of this product due to environmental conditions is 0.2%. Again, with some mitigation in the design, the cost offset outweighed the risk.

Electrostatic discharge (ESD) and RF interference (RFI) issues are problematic for any cable field device. During initial development of the FCMD, multiple changes were made to minimize both internal and external issues which would affect performance.

High performance SLMs have an extremely low noise floor and a high dynamic range with respect to their input signal. A compromise was made during the design to accept and minimize the noise that is inversely proportional to the frequency common at low frequencies, 1/F noise. For a majority of technician tasks, the need is to see ingress about -30 decibel millivolt (dBmV) at 5 megahertz (MHz) – versus the ability to see ingress below 50 dBmV at 5 MHz. Specialized software was used to compensate for the front end design to achieve a sufficient dynamic range for ingress measurements, for both residential and line technicians.

5. Operator Benefits

The first generation FCMD device was based on DOCSIS 3.0 technology and was deployed in the fall of 2016. The second generation version was based on DOCSIS 3.1 and was deployed in fall of 2018. Beyond the lower cost, the benefits of the design were quickly realized over the past four years. By combining a non-proprietary software architecture with cloud connectivity, a number of features turned into benefits that were realized from this measurement device, versus a typical SLM. These feature/benefit pairings are bulleted below:

- *Reduced cost*. At a lower per-unit cost, the FCMD was and can be made available to more technicians, which translates into a higher adoption rate. It continues to increase employee satisfaction, and can be integrated into a larger tools and business metrics ecosystem within the company.
- *Cloud capable.* By linking the FCMD to cloud-based databases and processing functions, technicians gain immediate access to historic diagnostic data about a home or business, as well as performance metrics, remote diagnostics, and training opportunities.
- *Non-proprietary software architecture.* By taking an open-source, non-proprietary route to development, we were able to move in lockstep with agile software methodologies, which also reduced costs and improved employee satisfaction.

5.1. Adoption Rate

Perhaps not surprisingly, the capital expense budgets for network service providers are tightly controlled. By introducing a lower cost measurement device, operators can increase adoption rates, because more devices can be purchased from the same fixed capital budget. The first generation FCMD was, as previously mentioned, introduced in 2016, and achieved a 98% adoption rate across the operator's install and repair technicians within 13 months. This initial device was DOCSIS 3.0-capable, and despite a high adoption rate, its functionality didn't meet the need for a DOCSIS 3.1-capable device, especially for maintenance technicians.

The second generation FCMD device (DOCSIS 3.1-capable) was deployed in January of 2019. It achieved a 95% adoption rate for maintenance technicians within 16 months. Graphs showing the uptake for the first and second generation FCMD are shown in Figures 6 and 7.

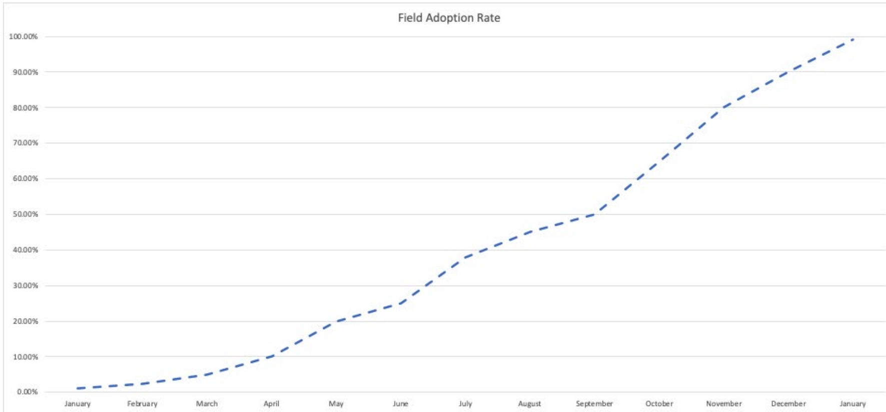

Figure 6 – 1st Generation Adoption Rate

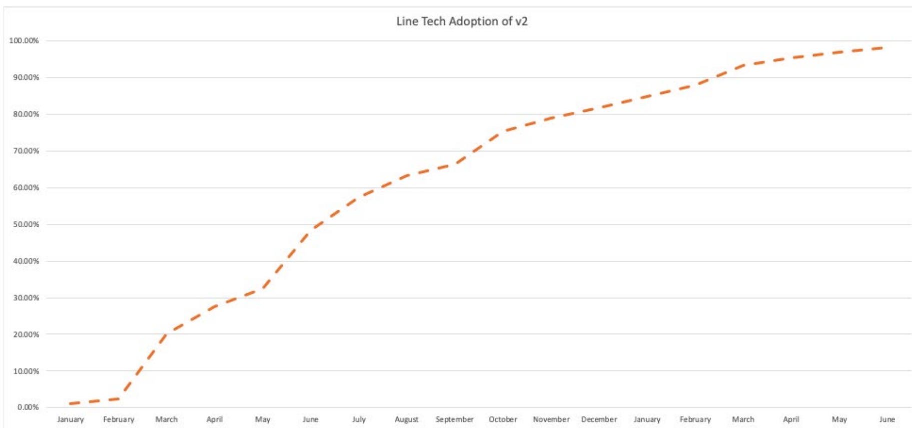

Figure 7 – 2nd Generation Adoption Rate

5.2. Employee Satisfaction

As mentioned previously, traditional SLM costs and functional lifetimes typically resulted in employees using the same meter for a minimum of five years. This can impact employee satisfaction, noted Tom Bach, Senior VP of Engineering for Comcast, who explained that employee morale can be affected, "especially when less-tenured employees are using the latest 3.0 DOCSIS-capable equipment, while long-term employees are still on DOCSIS 2.0-capable equipment." The ability to equip all technicians with the latest DOCSIS 3.1 technology quickly helped to improve overall employee satisfaction, he added.

5.3. Ecoystem

With the low cost and consequent high adoption rate across the company, the FCMD product could be designed to participate in the company's extensive and growing software ecosystem. All techs could be assigned identical devices, whether their primary roles involve installation and repair, maintenance, or headend tasks. This also allows data to be shared across functional groups. In turn, and over time, this improves the accountability and access to data across different populations of technicians.

The high adoption rate, coupled with being part of the company's overall data-driven ecosystem, and the availability of the cloud, allowed the FCMD product to go beyond a field measurement device, to a device that supports training opportunities, metrics, and even remote diagnostic capabilities.

5.4. Cloud-Capable

Existing SLMs do, of course, have the ability to work with a cloud infrastructure. However, access to proprietary cloud data can be cumbersome and cost prohibitive. By contrast, the FCMD became part of the operator's ecosystem, such that we were able to rapidly adapt its design to numerous cloud-capable applications.

Noted Larry Wolcott, Engineering Fellow at Comcast and a lead proponent of the industry's proactive network maintenance (PNM) efforts: "Because of the open nature of the software APIs, we were able to quickly attach this tool into our software ecosystem. Other systems had clouds, but they were not adaptable into the rest of the ecosystem."

5.5. Immediate Historic Data Collection

FCMDs have collected multiple terabytes of data over the past two years. The data collected include but are not limited to: ingress, full band spectrum capture, QAM channel signal analysis, OFDM signal analysis, and speed test performance. This information carries many long-term uses, including peer review, training, artificial intelligence (AI) and machine learning (ML) analysis, and system metrics. Figures 8, 9 and 10 depict different types of data collection using the FCMD:

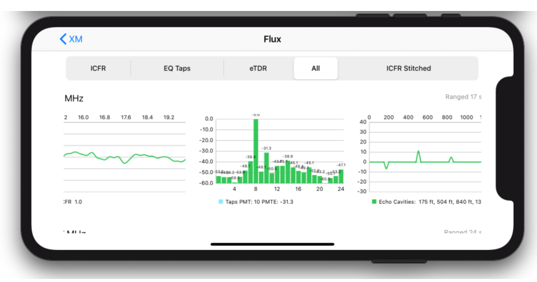

Figure 8 – Pre-Equalization Data Collection

Figure 9 – OFDM Data Collection

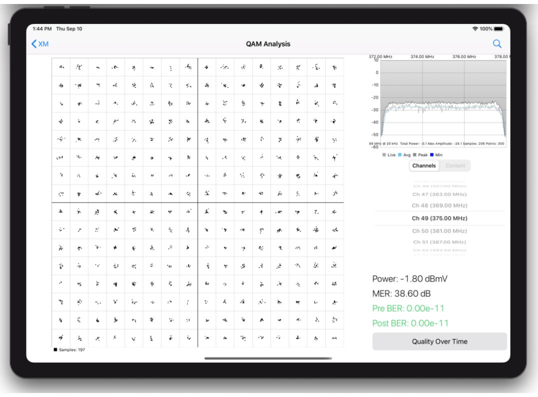

Figure 10 – QAM Data Collection

5.6. Peer Assistance

Many field problems are difficult to diagnose even by an experienced technician. Using the technician's tools as a medium to share data immediately to the cloud allows other technicians and supervisors to assist technicians remotely. The need for multiple truck rolls to diagnose and repair a difficult problem can be and was decreased. Figure 11 shows an example of a peer-assisted diagnosis, where a remote technician can assist the technician that is onsite by reviewing signal spectrum, DOCSIS and video channel powers, and DOCSIS locked signals statistics.

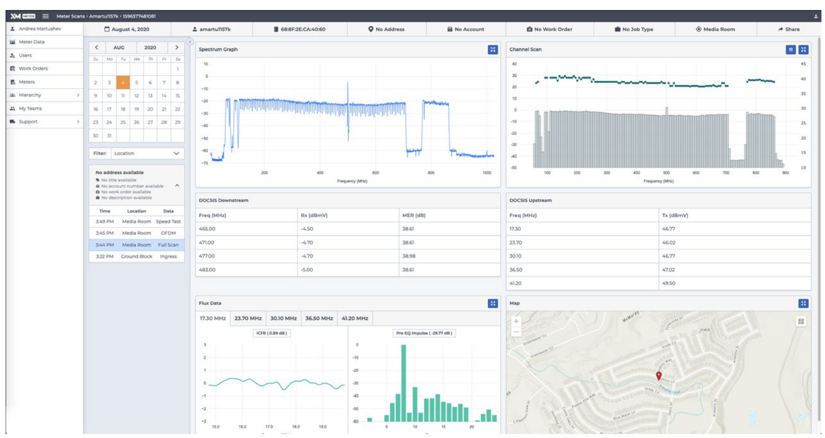

Figure 11 – Peer Assistance Example

5.7. Training

Post-job analysis of historic data per technician provides an opportunity to design individualized training, per employee, to improve overall cable plant health in the short and long term. For example, supervisors routinely review employee ingress measurement metrics and work with each technician to identify what would likely cause the ingress seen on their jobs and possible solutions for future reference.

5.8. Real time analysis and feedback

Measurement data, at the time of collection from the FCMD, is flowed into data streams that serve multiple purposes: overall company consumption; real time analysis for network performance; and adherence to employee metrics. The data is also stored for post processing and long-term data mining.

5.9. Metrics

For field technicians, metrics collections can simultaneously represent tremendous value and occasional contention – the latter because the addition of the cloud allows those metrics to be collected and validated on a per-job basis, which ultimately decreases the potential for obfuscation by the technician.

On the other hand, the ability to collect and analyze anonymized per-customer/per-incident performance data, over time, gives the operator the ability to document performance and determine possible customer improvements. These metrics help to improve the overall quality of the plant. In numerous cases, when we implemented a required set of metrics, a measurable decrease in repeat calls was seen.

Beyond per-technician or per-customer metrics used for diagnostics, the ability to collect meter application metrics has also been beneficial to identify the application usage statistics, which assist in application design. With the data available, the operator can understand which application widgets are being used and how much time it takes. Such metrics give opportunities to improve the widgets and employee training.

The collection of metrics into the ecosystem can also improve construction build-out processes. Upon completion of construction, the mobile measurement tool and ecosystem in the FCMD is able to document the RF performance of the new plant construction prior to operator acceptance – a capability deemed invaluable to building out plant infrastructure.

Metrics about various tasks can also be validated, by collecting demonstrated plant performance improvements that were observed on a job. One example might be when a speed test improves from 500 Mbps to 1 Gbps.

5.10. Remote Diagnostics

The addition of the cloud and Wi-Fi connectivity also allows for remote control and remote diagnostics through the FCMD. A technician can now connect the device to the ground block, establish a DOCSIS connection, and, through a remote application, move around the premises, fixing issues and receiving immediate feedback from the device, still out by the ground block.

In addition, the cloud allows the FCMD to become a short-term piece of diagnostic equipment. Through the ecosystem, many of the technician's applications have been re-hosted in the cloud and can be controlled remotely.

5.11. Software Architecture

A non-proprietary software architecture also enabled short-term product improvements that helped to improve overall acceptance and performance. Technicians have suggested numerous areas where the technology could be improved. Including technicians in the design feedback loop translates into quick product improvements. It also increases employee morale, by not only giving technicians a say in how they would like the gear to work, but also by rapidly implementing those suggestions.

"We get to make it do exactly what we want," said Patrick Stephens, a Senior Business Technician at Comcast, who also noted that "it makes honest technicians."

5.12. Reduce Development Costs

DOCSIS 3.0, DOCSIS 3.1, and high-split (5 MHz to 204 MHz upstream) cable modems have an underlying software architecture and operating system that is almost identical. Adding mid-split or high-split capability to an SLM is primarily a hardware (HW) upgrade and only requires minimal software upgrades. The jump to a DOCSIS 4.0-based cable modem will require additional software upgrades, but the backwards-compatible nature of DOCSIS indicates that a large amount of the existing development will be reusable.

Personal computer devices (desktops, laptops, tablets) continually evolve, yet the underlying operating system is usually 90% or more backwards-compatible. Similarly, a GUI that uses an operating system that has not significantly changed over the past five years can also dramatically decrease ongoing development costs. Additionally, with the mobile cable modem and control-plane in the FCMD being separate, either can be upgraded with minimal impact to the overall system.

5.13. COVID-19 Opportunities

Along the way, we've been able to identify and implement a quarterly improvement program to modify the FCMD's functionality, through software, to meet changing needs of the technicians.

One example of such dynamic adaptation, attributable to a non-proprietary software architecture and a cloud-based ecosystem, is the changes required to work in the physically distanced COVID-19 conditions that occurred in early 2020. Employee safety was crucial during this time, and required the development of new testing methodologies. Using existing and available field meters, processes would need to be identified and appropriate training would need to be developed and implemented. Additionally, there was no practical way to ensure that the process would be properly followed.

Our tools software architecture allowed us to build new signal processing algorithms to validate performance at taps, residential ground blocks and internal CPE -- without endangering employee safety by entering a premise containing potentially infected residents.

This is not the only use case where the software architecture has afforded us the ability to improve the product between hardware improvement cycles. We were able to rapidly build other tools, as well, to measure downstream alignment, improve speed test diagnostics, and log DOCSIS information.

6. Field Feedback

The integration of the SLM into our overall data ecosystem provided a number of time-saving and performance benefits. Todd Szuter, Director, Preventive Maintenance at Comcast, contributed this short-list of benefits:

- Old methods of collecting per-channel data on plotting paper, to see a standing wave, are gone.
- Instant cloud access dramatically decreased configuration headaches for residential technicians. No longer were techs using outdated channel maps, resulting in invalid refer to maintenance (RTM) requests.
- Third party SLMs have cloud capabilities but are not integrated into our software ecosystem. The data may be recorded but it was rarely used.
- This cloud-enabled device keeps technicians honest by making data available. Those who want to succeed embrace the device.

- This capability has great value in validating new construction prior to marking the effort as complete. Performance metrics and pictures, including GPS data, can be recorded and validated prior to company acceptance
- Cloud metrics helped improve the plant by enabling all technicians to reduce issues at all jobs.

Szuter also identified some negatives and resistance with introducing new technology to the workforce. Many technicians, he noted, just don't want to switch, because embracing a new technology and/or paradigm can be difficult. Also, with the addition of cloud metrics, "even though we dramatically increased network health, reduced repeat rates and improved the overall customer experience, in some cases a job that used to take 10 minutes may take 50 minutes," he noted.

When asked about the challenges and rewards of pushing new technology so deeply into the field, Comcast's Zanetich, quoted earlier, reiterated that good design yields good usage. "I think with anything new, you will experience challenges, and the deployments of this platform were no different," he said. Specifically, encouraging technicians to embrace the idea of a portable FCMD, and trust its readings, takes time, but not that much time: "It didn't take long for our technicians to see the value of the powerful platform that we placed in their hands, which they themselves can iterate based on what they need," he continued. "It's amazing to see the changes in the field, that can now happen overnight with a software update – changes that used to require us to purchase a new device and spend months distributing."

Clearly, the adoption of new technology, especially test equipment, always comes with its challenges. With the introduction of the FCMD, technicians were able to find issues faster, improve rework metrics and optimize the customer experience. Gone are the days of hunting-and-pecking, from a troubleshooting perspective; as a result, technicians appreciate the platform and as a means to pinpoint what needs to be done to optimize product and services delivery. "As I talk to our technicians," Zanetich concluded, "they appreciate the investment the company is making to ensure they have the best equipment available."

7. The Future

When measurement tools are cloud-based, remote signal analysis can be done to reduce truck rolls – in some cases, truck rolls that weren't necessary in the first place. Eventually, the same software can be embedded in CPE like set-tops and gateways, because they all ultimately use the same DOCSIS underpinnings. The network becomes the test apparatus – and it runs constantly, finding problems, and self-healing when possible, via PNM, dynamic channel changes, and related adjustments: Informing customers so that they can help themselves, such as about loose connectors or too many splitters, or automatically creating outage information that can inform operations centers and network techs.

When asked for his opinion about adding more PNM features into CPE, Cisco's Hranac was enthusiastic. "I love it – the more information from premises equipment, the better, including what full band capture brought to cable modems, and PNM brought in DOCSIS 3.1-based cable modems."

Virtually all of the FCMD's functionality is based on software commonly found in all DOCSIS 3.1 compliant cable modems. The opportunity to add the underlying functionality to STBs and other CPE allows a large percentage of current truck roll analysis to be done via the cloud or autonomously. Currently, full band spectrum analysis is being performed on more than 85% of all deployed cable modems at Comcast. The ability to add constellation analysis on all channels beyond those representing the currently bonded channels, per modem, could yield additional insights about Moving Picture Experts Group (MPEG) video statistics, again to potentially prevent unnecessary truck rolls.

Meanwhile, DOCSIS 4.0 is coming. In order to be able to not limit the technology because of hardware limitations, the hardware should be overdesigned to allow options to be considered in software. As DOCSIS 4.0 evolves, there will likely be differences and improvements – and, as a result, any field tool should have the ability to accept over-the-air (OTA) updates to keep the devices in step with technology.

As a general rule, technician tools are continually getting smaller, faster, lighter and less expensive. Cable operators started with a field meter that was 25 pounds and required an external power source. Similar devices now are the size of a small loaf of bread. With the addition of software defined radios (SDRs) and system on a chip (SOC) designs, devices like cable modems and FCMDs at some point could be the size of a USB-connected Ethernet dongle.

The addition of AI/ML on all premise devices may improve troubleshooting. Cable modems and STBs can report network events at the premise level, between themselves. The aggregation of multiple events across devices sharing the same ground block can determine, for instance, if an issue is a single device issue, or one that affects the entire premise.

8. Conclusion

The software revolution of the FCMD has shown great benefits. The change to the ecosystem and returns on investment have so far outweighed the risks of this endeavor.

With the unanticipated adaptations to COVID-19 in the Spring of 2020, we demonstrated that the FCMD can quickly acclimatize to a new world, through software improvements and OTA updates, which brought tremendous value to the field.

This “cable modem as an analysis tool” paradigm, embodied in the FCMD, could apply to STBs and broadband gateways, as well. The ability to continuously innovate on this platform, depending on the needs of the operator, removes the hardware-based and proprietary constraints of the past. The software adaptability of the meter has accelerated innovation, improved employee and customer experiences, reduced cost and removed risk in our DOCSIS upgrades.

9. Acknowledgements

Much of the material within this document was sourced from interviews and written contributions of many Comcast leaders and industry experts. The authors would like to thank Ron Hranac from Cisco, and Tom Bach, Larry Wolcott, Stephen Zanetich, Todd Szuter, Rob Gonsalves, and Patrick Stephens from Comcast.

Abbreviations

AGC	automatic gain control
AI	artificial intelligence
CM	cable modem
CPE	consumer premise equipment
dBmV	decibel millivolt
DOCSIS	Data-Over-Cable Service Interface Specifications
EMI	electromagnetic interference

ESD	electrostatic discharge
FCMD	field-capable measurement device
Gbps	gigabits per second
GPS	Global Positioning System
GUI	graphical user interface
HW	hardware
Mbps	megabits per second
MHz	megahertz
ML	machine learning
OFDM	orthogonal frequency division multiplexing
OFDMA	orthogonal frequency division multiple access
OTA	over-the-air
PNM	proactive network maintenance
QAM	quadrature amplitude modulation
RF	radio frequency
RFI	radio frequency interference
ROI	return on investment
RTM	refer to maintenance
SDR	software defined radio
SLM	signal level meter
SOC	system on a chip
STB	set-top box
UI	user interface

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Tom Bach, Comcast SVP Engineering

Stephen Zanetich, Comcast Executive Director, Technical Operations

Todd Szuter, Comcast Director of Preventive Maintenance

Rob Gonsalves, Comcast Senior Director Product Development & Engineering

Patrick Stephens, Comcast Senior Business Technician

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