# Fiber QAM vs RF QAM

## Demystifying Coherent Optics

A Technical Paper prepared for SCTE by

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## 1. Introduction

Quadrature Amplitude Modulation (QAM) transmission has been the mainstay of Radio Frequency (RF) networks for the better part of two decades. During that period, we have witnessed modulation complexity rise from 64-QAM to 4096-QAM. With each increase in complexity, we have adapted network configurations to higher SNR and spectrum to deliver higher and higher capacity. Similar is the case for optical transmission as operators move to higher modulation order Coherent Optics to keep up with the ever-increasing capacity needs in the transport, metro, and access networks. There is a need to get beyond contemplating the many similarities and challenges coherent optics are currently facing, however, and use the lessons learned in the RF domain for the journey with Fiber QAM.

100Gbps QPSK optics have been routinely used in different segments of Comcast's network and 800Gbps 32-QAM and beyond are not far on the horizon. In the access network, 100Gbps bi-directional optics have been instrumental in supporting different initiatives beyond capacity increases [1]. This includes fiber conservation, pushing Distributed Access Architecture (DAA) further down close to the node, and faster and lower-cost deployment and upgrades.

In this paper we first share our experience in preparing for higher order m-QAM modulation in terms of Coherent Optics terminology and tracing parallels with the steps the industry took during their m-QAM RF transition. Concerns about the fiber infrastructure, managing fiber non-linearity, and network architecture are then addressed with our recommendation to operators on how to get ready for Fiber QAM evolution. Lastly, as part of the envisioned evolution, the concept of Orthogonal Frequency-Division Multiplexing (OFDM) and Orthogonal Frequency-Division Multiplexing Access (OFDMA) in the optical domain leveraging the current cable operator experiences are explored. This includes a review of current industry initiatives and some predictions based on the uncovered parallels.

## 2. QAM is QAM

QAM is a technique that mixes both amplitude and phase variations in a carrier at the same time. This technique allows higher data rates within the same bandwidth. The higher the modulation order, the higher the spectral efficiency although higher signal fidelity is required to support such capacity gains. Figure 1 shows the constellation for QAM signals for different modulation orders.

The first observation about m-QAM signals and its detection process is that a constellation diagram is a geometrical problem that is valid for both RF and Fiber (Optical) QAM signals. Without getting into the mathematical details [2], the Bit Error Ratio (BER) can be estimated based on the symbol distance to the threshold levels defined by the boundary spacing. The received symbol being interrogated by the decision circuit will be a combination of the actual imperfect symbol and different noise sources, oscillator phase noise, system linearity, and other types of distortion. The probability of error for a symbol, assuming a Gaussian distribution, is estimated by computing the complementary error function of the effective (RMS) distance of the symbol to the boundary. Non-linear effects change the symbol cluster shape and the effective symbol distance to the boundary needs to be corrected for that. The energy (Power x Time) of the symbols in constellation affect the distance between the data points in the constellation. The higher the energy of the symbols the larger the distance between symbols.

The impact of such limitations and impairments are well known in the RF industry and can be identified in the constellation using the notorious HP/Agilent illustration [3] shown in Figure 2. This has been well documented [4,5] in the industry. The theoretical waterfall curves defining the minimum Signal to Noise Ratio (SNR) required for a maximum BER is well documented in the literature and in the industry.

 

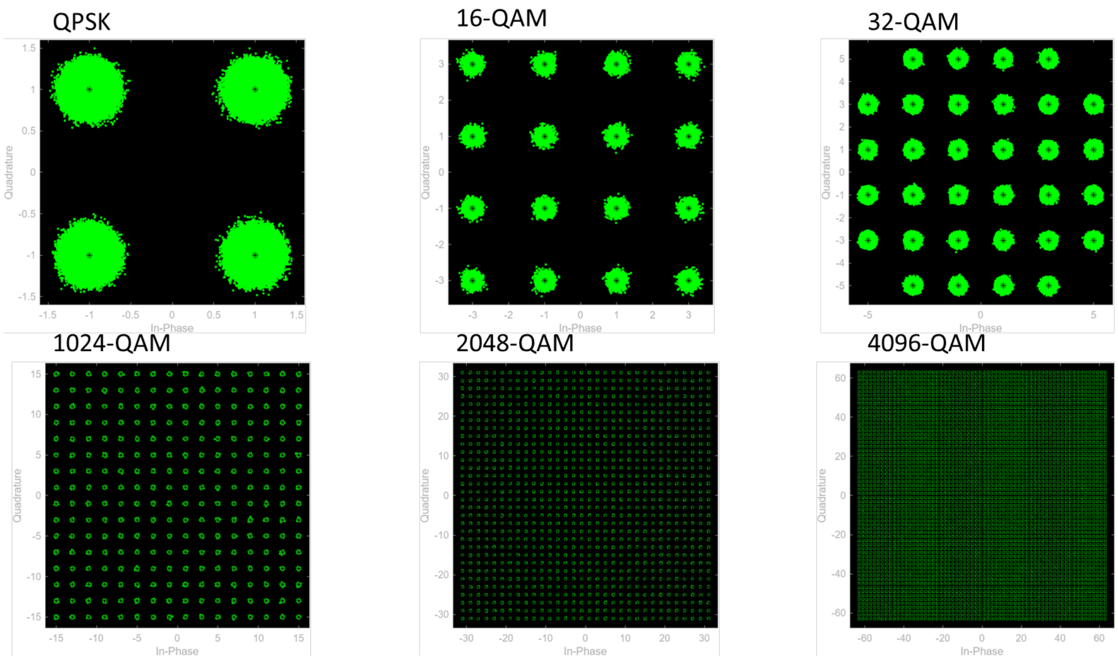


**Figure 1 – Symbol constellation for different Modulation Orders**

Also, for comparison purposes, Fiber-QAM state of the art is currently using 64-QAM, limited by the Baud rates the modules can handle. Meanwhile, RF-QAM is currently commonly using 4096-QAM on live networks, with the possibility of moving to 16k-QAM in the future.

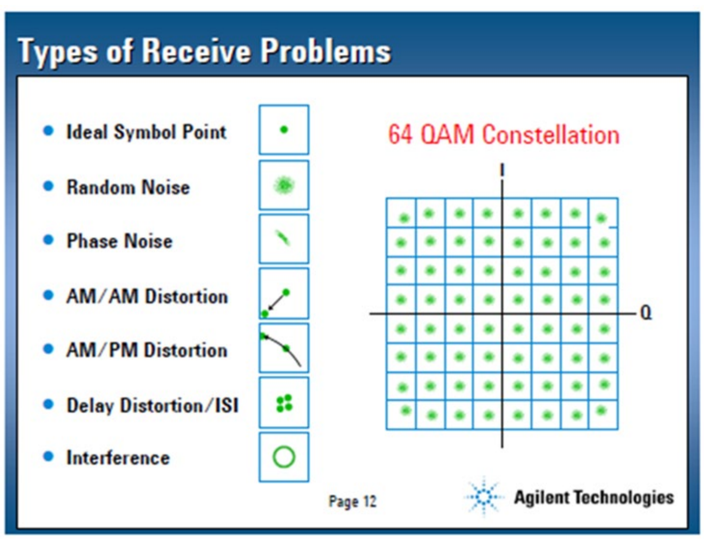


**Figure 2 – Residual BER Prediction [2]**

## 2.1. SNR vs OSNR

Figure 3 shows a few examples of BER vs. SNR curves for different modulation orders based on the geometric model [6]. The model applies to both RF and Fiber QAM, but as we will discuss next, there are some terminology differences particularly when the industry refers to SNR and Optical SNR (OSNR). Many of us would think that OSNR is simply twice the SNR but that is not the case. The optics industry defines OSNR as the SNR referenced to 0.1nm (or 12.5GHz @ 1550nm) optical resolution bandwidth. Therefore, an OSNR, an optical signal with 30 GHz bandwidth, needs to be corrected by 3.8dB with respect to the SNR value. For example, a QPSK signal with 30GHz baud rate would require 8dB SNR to produce a BER around 2e-2 which, as we will see in the Forward Error Correction (FEC) section, would lead to error free operation after Soft-Decision Forward Error Correction (SD-FEC). The OSNR correction factor for this condition is 3.8dB as indicated in the Figure 3, and would lead to a minimum 11.8dB OSNR.

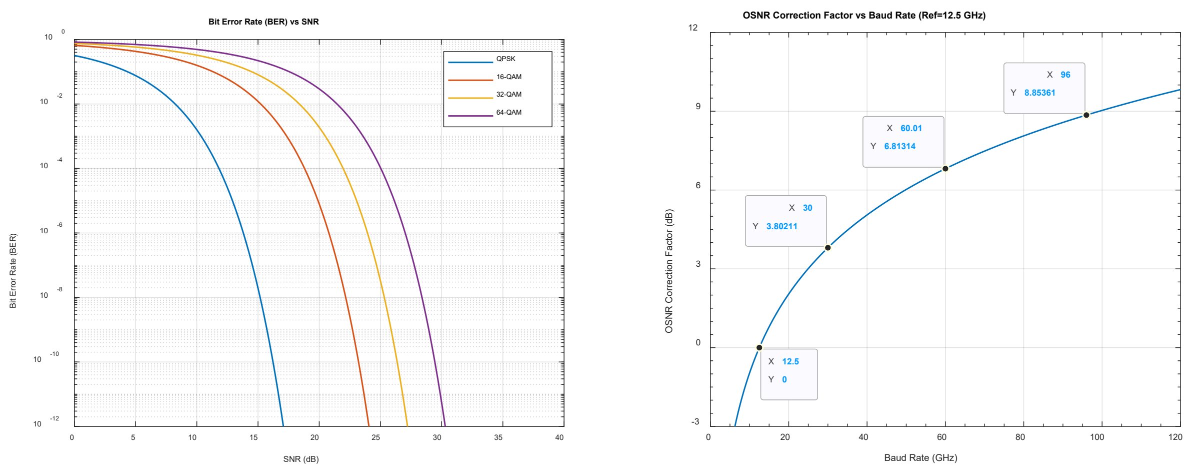


**Figure 3 – BER vs SNR and OSNR correction factor plots for AWGN & no FEC**

Further improvements in error rates are obtained in both RF and Optical QAM systems using different error correction techniques such as Low-Density Parity Check (LDPC) and other Shannon Capacity approaching codes and are discussed later in this paper.

Note: we will be loosely equaling baud rate or symbol rate with signal bandwidth across this paper but understand that spectral shaping and roll-off factor need to be considered in this relationship.

## 3. RF QAM Brief Review

As a quick review of the RF QAM history, reference [2] provides a great review of all the work that was done with digital communication systems that started in the late 1950s where the concept of coherent and non-coherent detection schemes were devised. By the 1990s, coherent communications took off thanks to the availability of components driven by satellite communications initially followed by wireless/mobile communications. Topics such as optimum constellation, coherent vs. non-coherent detection, clock recovery, filtering, channel model, equalization, besides many others, were explored and lead to a wide range of products, as well as standards, enabling different applications. Those are the very same topics in the forefront of the Fiber QAM developments.

Particularly with respect to the cable industry, the adoption of digital communication followed the communications industry, benefiting from the devices being developed for wired and mobile communications. In fact, the cable and broadband industry was first using 16, 64, and 256 QAM in 1997 when the wireless industry was still using QPSK and GMSK. This initial use of QAM modulation included a variety of symbol rates in the upstream for DOCSIS to increase speeds. Now cable broadband has capabilities up to 16k QAM on OFDM, and 4k QAM on OFDMA when moving to DOCSIS 3.1 in 2013. These same capabilities exist today with spectrum used in both directions with Full-Duplex DOCSIS (FDX).

# 4. Fiber QAM Review

Fiber QAM has been following a similar path to the RF QAM development steps. The need for higher capacity has driven the industry to look for ways to increase spectral efficiency and symbol rate. Although there are many ways to increase capacity, one primary approach, particularly when fiber and wavelengths are scarce, is to use a higher order of modulation. That has driven the optical industry to develop a wide range of coherent optics modules in the last 10 years. For many years, coherent optics has been a topic with dedicated technical sections at the Optical Fiber Conference (OFC) since 2008 and at SCTE since 2017, and different standard driven efforts across the industry.

The main enabling technologies are the maturity of the optical manufacturing capabilities that are effectively moving optics from art to craft. The development of manufacturing capabilities is making it possible to, cost effectively, build more complex optical devices, particularly pluggable optics. A key technology particular to coherent optics is the development of powerful Digital Signal Processing (DSP) devices that makes these complex devices possible. 7nm, and now 5nm manufacturing resolution allows for higher density with more digital logic, higher speeds, and, potentially, lower power consumption devices.

## 4.1. The Form Factor Dilemma

Not long ago, coherent optics modules were only available in a line card form. Now, there are many form factors that have been proposed and standardized to a certain extent that allow for predictable integration efforts. Particularly in the coherent optics front, there are different form factors and applications currently available in the market. However, for the purpose of this paper, we will be focusing on two main contenders based on Comcast's current needs, the C Form-factor Pluggable type (CFP2) and Quad Small Form-factor Pluggable – Double Density (QSFP-DD), although the OSFP modules are also a potential option.

Figure 4 depicts the two modules while Table 1 provides a brief comparison of their main characteristics.

**Figure 4 – Pictures of the CFP2-DCO (left) and QSFP-DD-DCO (right)**

The CFP2 is the C form-pluggable and is the larger module with a larger area that can provide better thermal management for some of the Hybrid Fiber Coaxial (HFC) industry applications that Comcast started to investigate. These applications included outside plant (OSP) where the module is exposed to wider temperature ranges. Initial industrial operating temperature range (-40 to +85$^0$C) requirements were reduced to take into consideration the temperature rise in certain applications. However, cold start under this requirement is still a must.

QSFP-DD is the double-density quad small form-factor pluggable. Its main advantages are density, due to its compact size, and lower power consumption. However, power consumption may be also reduced to other form factors by careful selection of features that the device supports.

**Table 1 – Coherent Optics Pluggable Comparison**

| | CFP2 | OSFP | | QSFP-DD | |
|---|---|---|---|---|---|
| Form Factor | C Form-Pluggable | Octal Small Form-factor Pluggable | | QSFP Double Density | |
| Specification | OIF-CFP2-DCO | OIF 400ZR | OpenZR+ | OIF 400ZR | OpenZR+ |
| Main Application | DCI, Metro, regional/long haul | Metro | Long Haul | Metro | Long Haul |
| Line Rate (Gbps) | 100/400 | 400 | 100-400 | 400 | 100/400 |
| Baud Rate (Gbaud) | 28 | 32 | 60/63 | 60 | 30/60 |
| Modulation Order | QPSK, 8QAM, 16QAM | 16QAM | QPSK-16QAM PCS | 16QAM | QPSK, 8QAM, 16QAM |
| FEC | SCFEC, SDFEC | SCFEC,GFEC | oFEC | cFEC | oFEC, CFEC |
| Target Reach (km) | | <120 | >120km | <120 | 450@400Gbps |
| Dimensions (mm) | 41.5×12.4x106 | 22.6x13.5x108 | | 18.4x8.5x89.4 | |
| Power Consumption (W, max) | 24 | 18 | 22 | 18 | 22 |

It would be ideal if interoperating different form factors were possible. In that way operators would be able to use high-density form factors in controlled environments, such as head-ends, while more thermally robust devices could be used in the OSP. Currently, that is far from reality due to the somewhat immature state of coherent optics.

### 4.2. Coherent Optics Implementation

DSP has been used in the CATV industry for a long time. Cable modem equalization, digital return, and edge QAM channel generation are all good examples of how the technology can help us to cost effectively deliver services to our customers. The semiconductor industry, driven by a wide range of technological innovations, has developed very high-density (5nm process), low-cost computing power, ADC performance, and higher electrical speeds. This 5 nm technology also results in a power reduction of 20% by reducing core voltages thus reducing leakage power.

Coherent optics is a complex communication system whose performance is degraded by a range of linear and non-linear distortions. These distortions include transceiver limitations such as frequency response, E/O and O/E non-linearity, and even manufacturing tolerances. There are also optical channel distortions such as Chromatic Dispersion (CD), Polarization Mode Dispersion (PMD), fiber non-linearity (XPM, SPM, FWM), optical filtering, and noise.

In general, most of the DSP to compensate for these challenges is done on the receiver side with the goal of improving system performance. The compensation is done in the form of equalization at different points of the coherent optical receiver for each of the optical polarization components. The length of the equalizer (number of taps) defines the compensation range. The wider the required compensation, the larger the device is with higher power consumption. Defining and limiting the requirements for the application is key. Figure 5 shows a generic block diagram for a coherent optical receiver indicating the DSP algorithms.

Digital equalization of chromatic dispersion is straightforward and understood. Applications such as Access and Metro optical links, with typically 80 and 120km, require relatively short tap lengths since the required compensation is under 1920 ps/nm, which can be accomplished with 256 taps up to 60 Gbaud rates [7].

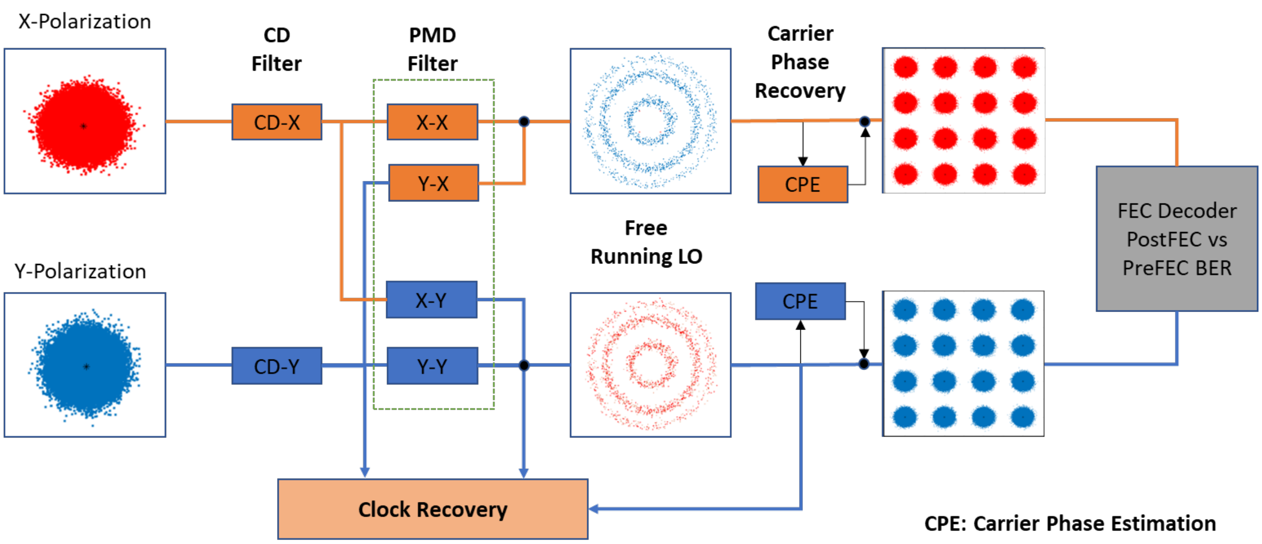


**Figure 5 – Generic Coherent Optical Receiver Block Diagram (after [7])**

It is important to note that Fiber QAM takes advantage of its powerful DSP capabilities to use the X and Y polarizations to double the channel capacity, something RF QAM should consider as well. Differential Group Delay (DGD) is produced by the optical fiber refractive index variation along their principal optical axis, typically denoted as X and Y. The refractive index variation, termed birefringence, is a random physical phenomenon that is temperature and wavelength dependent, and present in all fibers. As a note, most communication fibers are designed to introduce low birefringence, but some fibers are purposely made as highly birefringent, as in the case of the Polarization Maintaining (PM) fibers. The term DGD is sometimes exchanged with the related Polarization Mode Dispersion (PMD). However, DGD is a statistical representation of the random variations while PMD is its average value. The butterfly configuration of the PMD Filter shown in Figure 5 provides the means for tracking polarization variation. There are many DSP algorithms that were developed for such a purpose, using time or frequency domain implementations capable of compensating a wide range of dynamic environmental caused by temperature variation (rad/s) and vibrations (krad/s) and even lightning (Mrad/s) [7].

Carrier phase recovery algorithms in the optical domain are necessary to minimize the phase and frequency mismatch between Tx and Rx lasers in a coherent system. The process is the same as in the RF domain where laser-integrated phase noise needs to be minimized to minimally impact the system performance. Besides the Tx and Rx laser phase noise, channel impairments such as Self-Phase Modulation (SPM) and Cross-Phase Modulation (XPM) also need to be considered. There are many carrier phase recovery algorithms used for this purpose.

Although we focused here on these three main DSP components, we should also mention that non-linear compensation and timing recovery are also part of the channel compensation. The main trade-offs to keep in mind are that the longer the filters used, the higher the latency and power consumption. Also, for the short-reach applications we are concerned with in the cable access network (<120km), we can optimize cost based on the shorter distances. Also, since the potential solutions exceed the required link budget for such application, designers could consider absorbing some of the power penalties imposed by such distortions. That is due in part to the powerful Forward Error Correction (FEC) currently used in the industry and that will be reviewed in the next section.

### 4.3. Forward Error Correction (FEC)

Forward Error Correction (FEC) is a method or algorithm whereby the original signal is encoded with error detection and correction redundant information. With this approach, RF or Optical receivers can detect and correct errors that occur in the transmission path and dramatically lower the BER and extend the distances that signals can be transmitted without regeneration. FEC is also commonly considered as an attractive, cost-effective tool to recover the lost sensitivity due to the transition to higher data rates.

There are several FEC algorithms to choose from that vary in complexity, strength, and performance across the industry. The most common and standardized first-generation FEC is Reed-Solomon (255, 239) that adds slightly less than 7% overhead and provides approximately 6 dB net coding gain.

Second and third-generation FECs became a reality as cost-effective computer power became more readily available. Second-generation FEC includes LDPC (Low Density Parity Check) used in DOCSIS 3.1 and Ultra FEC (UFEC) and Enhanced FEC (EFEC) in 10 and 40Gbps optics. These algorithms still use 7% overhead, but implement stronger, more complex encoding and decoding algorithms, which provide an additional 2–3 dB coding gain over Reed-Solomon.

Third generation FEC extends the performance and overall optical distances even further. Based on even more powerful encoding and decoding algorithms, iterative coding, and SD-FEC. The concept of SD-FEC is illustrated in Figure 6.

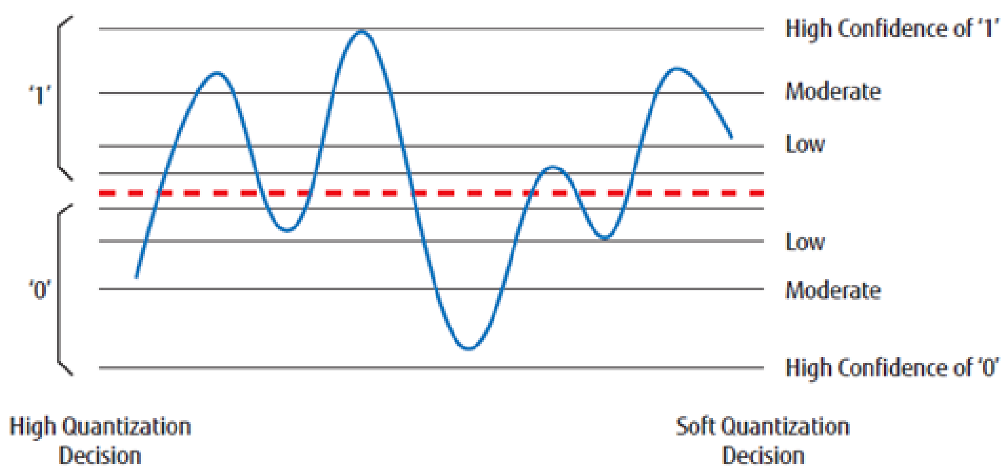


**Figure 6 – Soft Decision concept (after [8])**

Reference [9] provides a comprehensive review of FEC algorithms being currently used in coherent optics. It includes the definition of the metrics, Net Coding Gain (NCG), Coding Overhead, and the Pre-FEC BER threshold. Another metric that is not covered in this reference and that has become more important nowadays is latency, which became a key design parameter for operators due to stringent end-to-end design guidelines.

To illustrate the trade-off between FEC gain, implementation latency, and power consumption, Table 3 shows the performance for a 100Gbps module operating with some different FEC modes [7, 10]. The table shows an increase of 19us in latency and ~2.5% in power consumption for a 2.1dB code gain, when moving from EFEC to oFEC. That corresponds to approximately 10km additional reach with a modest power consumption increase.

**Table 2 – Metrics for standardized FEC in optical fiber transmission systems**

| Mode | Type | Coding Overhead (%) | Estimated NCG | Pre-FEC BER Limit | Latency (us) | Est. Power Consumption Variation |
|---|---|---|---|---|---|---|
| 100G GFEC (Generic, RS) | HD | 6.7 | 6.2 | 8.5E-05 | 11 | 0 (ref) |
| 100G EFEC (Enhanced) | HD | 12.3 | 9 | 4.5E-03 | 26 | ~+10% |
| 100G oFEC (open) | SD | 15.3 | 11.1 | 2.0E-02 | 45 | ~+12.5% |
| 100G CFEC (Concatenated) | SD | 14.8 | 11.2* | 1.2E-01 | 45 | ~+15% |

There is also proprietary FEC implementations in the industry that is part of the maturity concern of the coherent optics industry. As an example, XR optics, a sub-carrier based coherent optics technology for point-to-point and point-to-multipoint topologies, has data rates ranging from 25Gbps up to 400Gbps. Such technology has great potential in moving coherent optics to fulfill the potential of using coherent optics in the access networks by providing flexibility to operators to adjust capacity to their HFC, P2P Ethernet and PON customers, on demand. With the intent to address the proprietary concerns in the industry, the Open XR Forum [14] was formed in 2021 to promote open, standards-based adoption of XR optics.

## 5. Plant & Operations Implications

One of the most basic tasks of a cable operator's daily activities is the upkeep of their coaxial network. The reason for that is quite simple - the cleaner the HFC network is, the higher spectral efficiency is attained. That leads to a wide range of benefits including service experience and CAPEX deferral, among others. Addressing ingress, distortion, and micro-reflection issues is key to a well-run operation. However, RF-QAM is extremely adaptable and forgiving, with features such as DOCSIS Profile Management Application (PMA).

### 5.1. Plant Optical Return Loss

The very same concerns apply to the fiber network as well. Attention is needed to make sure the optical plant supports a higher order of modulation. The quality of the optical network needs to be monitored and managed as the coaxial plant. As operators start moving to a higher order of modulations, it is necessary to manage the optical reflections from the components used in the network, active and passive. When specifying the Optical Return Loss (ORL) of these devices, careful consideration should be taken, similar to what is done for the ORL of HFC analog optics in the not-so-distant past. Numbers in the 60 dB RL in the RF domain would translate to 30 dB ORL, which may be an issue if an Ultra Physical Contact (UPC) port is left unterminated and producing ~ 14 dB ORL. Keep in mind that losses before unterminated ports could improve ORL though that needs to be evaluated for each case.

Reflected light in an optical system, as we learned from our analog days, can create unwanted feedback to the lasers, adding non-linearities by changing frequency or modulation responses, degrading system performance in terms of Relative Intensity Noise (RIN) optical frequency variations, and even laser line-width variations. The system performance degradation can be expressed as power penalties, which can be as high as 2 dB depending on the number of reflection points. Figure 7 shows ORL power penalty for a 100Gbps Bi-Directional (BiDi) system. The expectation is that even higher power penalties could be produced at higher data rates and higher modulation orders.

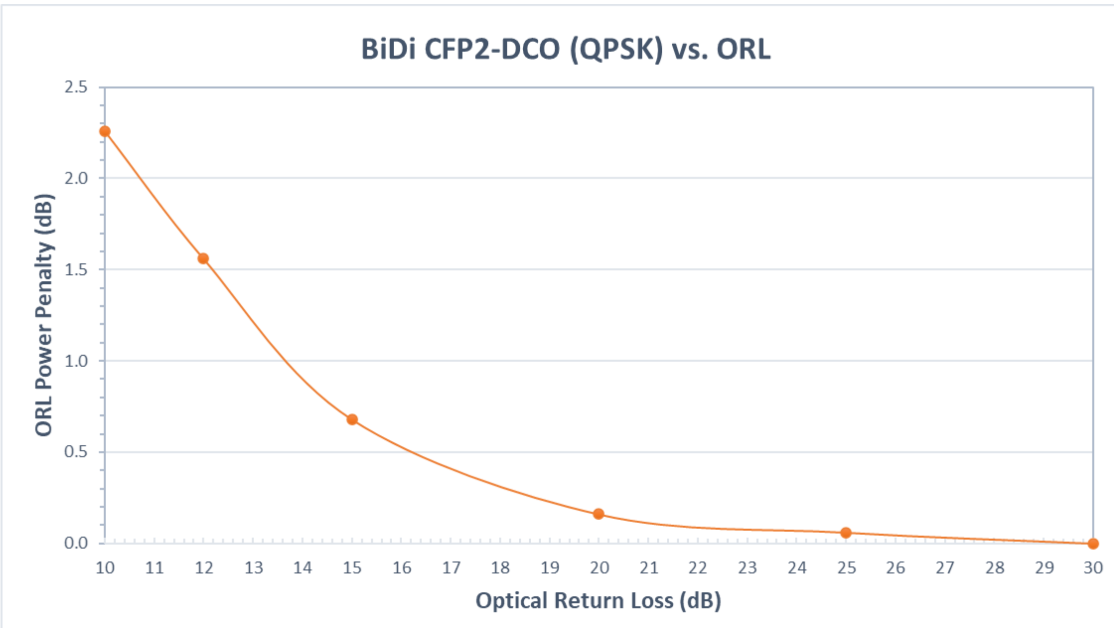


**Figure 7 – Power penalty caused by the ORL in a 100Gbps QPSK BiDi system**

It is strongly recommended to use Angled Physical Contact (APC) connectors instead of the UPC connectors commonly used in digital systems. That is again another parallel with the analog days of the industry when SC/APC connectors were a must. Lesson learned. It is important to note that current coherent optical modules do use a UPC connector and that is fine for the concerns above since they will always be terminated.

Another reflection phenomena that APC connectors will not address is Rayleigh Backscattering produced by the fiber. Light propagating in one direction is scattered by fiber imperfections (scatters) in the fiber core as one of the loss mechanisms in fiber. Part of the scattered light is coupled back in the fiber, but in the reverse direction. The level of Rayleigh Backscattering is very wavelength dependent (inverse fourth power), being more severe at shorter wavelengths.

### 5.2. Cascaded WDM Power Penalty

As we increase the data rates by increasing the baud rate, there is a concern that the interaction of wider bandwidth and the passband of passive optics like muxes and demuxes along the link may start to impact the performance. That impact could be quantified as a power penalty, which defines how much margin we need to add to a system to guarantee error free operation. Figure 8 illustrates the modulated linewidth of different types of pluggable devices at different data rates: Pink line for a10 Gbps SFP+, Yellow for 100 Gbps QPSK, Purple for 200 Gbps 8-QAM, and Green for 400 Gbps 16-QAM.

To verify the impact of the muxes as we increase the bandwidth and/or the modulation order of the transceivers, we measured a system-sensitivity change with no muxes, with a pair of muxes, and, finally, with 2 pairs of muxes. The measurements were done with 100Gbps/QPSK, 200Gbps/QPSK, 300Gbps/8QAM, and 400Gbps/16QAM signals and the results are summarized in Figure 9.

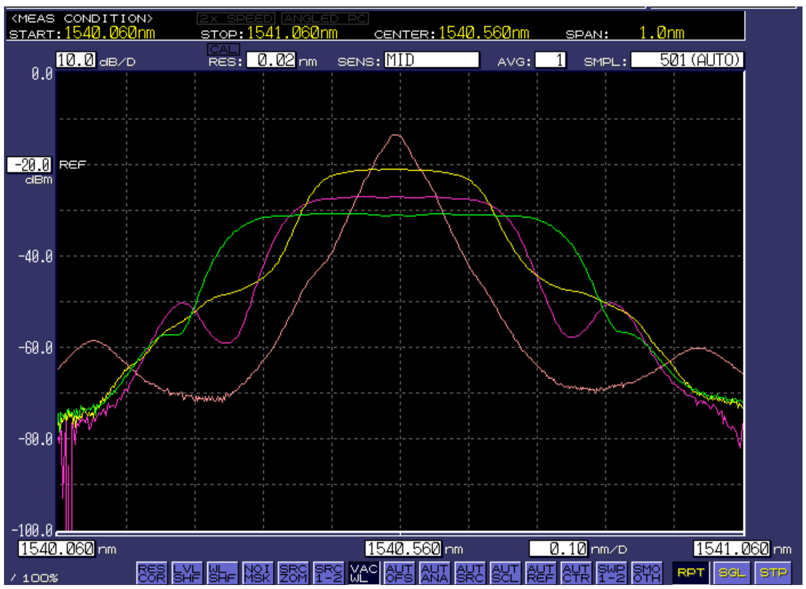


**Figure 8 – Modulated linewidth at different data rates and modulation orders**

Since the signal bandwidths, shown in Figure 8, are narrower than the WDM pass band, 100GHz, we don't see conclusive indication of WDM impact in the system performance, perhaps at higher data rate.

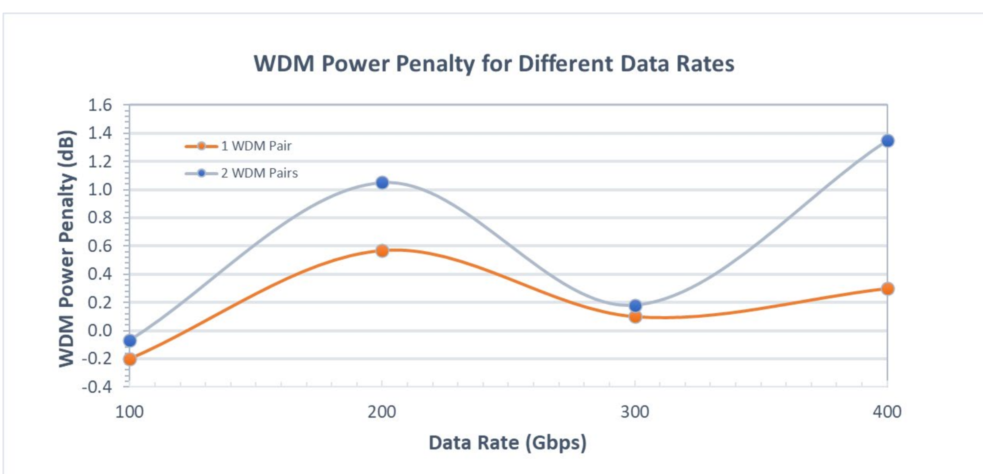


**Figure 9 – Sensitivity Power Penalty caused by the WDM passband**

We expect the impact would be more evident at higher data rates such as 800Gbps/64-QAM with expected 120GHz linewidths unless we keep increasing the modulation orders as it was done with RF-QAM. Another option is Probabilistic Constellation Shaping (PCS) where, by modifying the distribution of the data symbols to match the channel, the modulated linewidth takes a more Gaussian shape, which better endures the impact of channel bandwidth limitations. This technique also has the potential to conserve energy by using low-energy symbols more frequently, reducing signal distortion and allowing lower voltage operation. That may be an opportunity for RF-QAM as well.

### 5.3. Fiber Characterization

Comcast already has a wide range of tools to monitor their fiber infrastructure, both lighted-up (active) and dark (unused), using tools such as XMF-R and Link-It. However, as we start to use a higher data rate there is a higher modulation order.

We briefly discussed chromatic dispersion (CD), Differential Group Delay (DGD, and Polarization Dependent Loss (PD) in the DSP section. The impact of such parameters is due to the light-to-fiber interaction. The impact of such interaction, such as CD and DGD, are intrinsic to the fiber and can be managed by limiting the fiber length. Since Comcast has a wide range of legacy fiber in their networks, there is a need to keep track of such parameters. The same applies to PDL, but depending on how the fiber is installed, it may be necessary to make sure fiber birefringence produced by bending pressure points varying with temperature are not creating PDL issues.

## 6. Fiber QAM Industry Initiatives

There are currently many initiatives related to the adoption of coherent optics in the cable industry. That includes many CableLabs' specifications described in Table 3 below.

**Table 3 – Current CableLabs Coherent Optics related Standards**

| Title | Published | Version | ID |
|---|---|---|---|
| CPON Architecture Specification | 05/03/23 | I01 | CPON-SP-ARCH |
| Coherent Optics Termination Device OSSI Specification | 01/27/23 | I03 | P2PCO-SP-CTD-OSSI |
| Coherent Termination Device Requirements Specification | 06/09/21 | I01 | P2PCO-SP-CTD |
| P2P Coherent Optics Physical Layer 1.0 Specification | 05/01/20 | I03 | P2PCO-SP-PHYv1.0 |
| P2P Coherent Optics Physical Layer 2.0 Specification | 05/01/20 | I02 | P2PCO-SP-PHYv2.0 |

Besides that, CableLabs has been sponsoring other activities such as the CableLabs Point-to-Point (P2P) Coherent Optics Interoperability Event that took place in December 2018 and July 2022, in addition to periodic optics-related calls (CableLabs Envision Vendor Forum: FTTP & Optical Day). It is important to note that interoperability efforts have been focused on the line side but the same should be done on the client side.

 

Meanwhile, Comcast started developing and deploying their own coherent optics-based solutions. The next section briefly describes those initiatives.

### 6.1. Application Scenario

One pressing issue that operators are facing is the lack of fiber available in the access networks for capacity expansion across its extensive access networks. The capacity expansion includes activities such as new installs, expansion, and node-splitting initiatives. That drove the Comcast Connect engineering team to consider new solutions. At the same time, there was a need to address some limitations of the Distributed Access Architecture (DAA) that Comcast has embraced, particularly in long-reach systems served by small secondary hubs.

Initial analysis comparing the deployment cost and deployment time for laying new fiber compared with the cost of adding a coherent optics solution was carried out. The comparison included the design, construction, licensing, and deploying of new fiber compared with the deployment of a 400Gbps system aggregating up to 40 x 10 Gbps links serving up to 40 optical nodes. After a few iterations and discussion with the deployment team and the optics industry, it was clear that the Coherent MuxPonder (CMP) solution was extremely competitive.

Figure 10 shows a block diagram of the current CMP solution currently being deployed by Comcast. It basically consists of a pair of Ciena 5171 switches configured as muxponder switches where each one of the 40 x 10Gbps ports on one side is mapped directly to the same port on the other side. Each group of 10 x 10 Gbps ports is aggregated into a dedicated 100Gbps BiDi CFP2 optics. This solution is also internally called DAAS Extension solution since it is equivalent to moving the DAAS switch ports further down in the OSP closer to the customers. Figure 11 exemplifies the typical secondary hub location that the solution is intended for to illustrate its physical and environmental challenges.

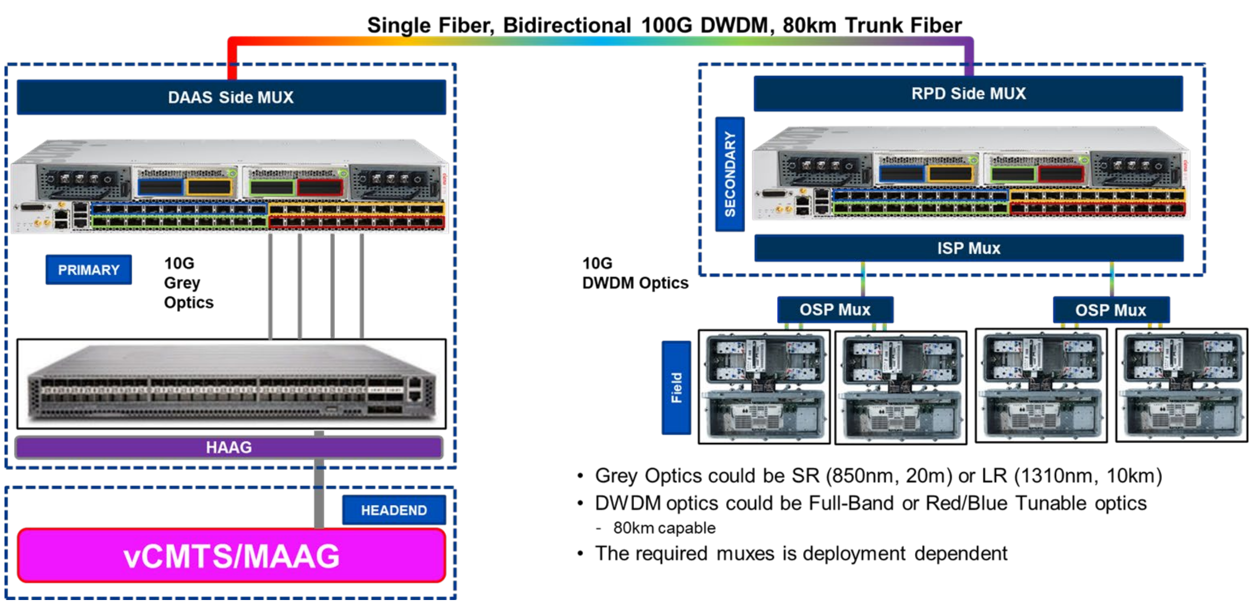


**Figure 10 – DAAS Extension CMP solution**

 

**Figure 11 – Bremerton Primary and Poulsbo Secondary in WA**

This solution is currently deployed in two different regions that started in 2022. The first deployment took place in the West division. Its main objective was to provide an alternative solution for remote areas currently served with very long reach analog links with marginal performance. Since the CMP solution can extend the DAAS reach to more than 80km, not including the additional reach of the DWDM optics (additional 80km) at the secondary hub, making more than 160km links possible, depending on the optical loss of the fiber networks and passives. (It is important to note that the DOCSIS 150km limitation takes place from the demarcation point provided by the RPD.) The cutover results were very promising with average MER performance improvement around 6dB.

The second deployment in the Central division was also very successful since it was part of the Hurricane Ian recovery effort when Comcast was able to quickly reestablish service to the devastated Sanibel and Captiva islands area when only limited fiber was available. This recovery effort is better described in another paper being presented at this Technical Forum. Please check reference [13] for more details of this CMP success story.

Another effort using coherent optics is in the core network transport, where there are many ways of increasing the total fiber capacity. Comcast is already using 100 Gbps optics as their backbone and it is currently evaluating the progression to 400 and even 800Gbps.

From the longer-term point of view, Comcast also started looking at ways of potentially using coherent optics to match our DOCSIS capacity needs. This is explored in the next section while Section 8 discusses the nuances of capacity planning when related to coherent optics.

## 7. DOCSIS Implications

As stated before, capacity is the driving force behind the constant upgrades that operators need to provide to keep up. With Compound Annual Growth Rate (CAGR) between 20 and 25%, it is critical that operators work ahead to provide cost-effective solutions. That is true not only to the access network but, consequently, also to the metro (C-RAN) and backbone networks feeding the access networks. The goal is to avoid bottlenecks that limit the current demands and quality of service.

DOCSIS success and longevity is rooted in delivering the right capacity in a flexible, gradual, and cost-effective way to their customers. There are different ways to add capacity in the access, including increasing the modulation order, number (or width) of channels, or reducing the size of the service group (number of subscribers served by a group of channels). Besides that, DOCSIS is very adaptable, allowing the modulator order to be adjusted depending on the channel signal quality. Features such as PMA provide such flexibility and allow the system to optimize spectral efficiency to the conditions. That is something Fiber-QAM does not support right now.

Capacity planning is an end-to-end exercise. As higher speed new service tiers start to be offered as FDX DOCSIS becomes part of our access options, proper capacity allocation needs to planned not only for the back-haul side, but also on the access network. Since FDX provides dynamic bandwidth allocation for both downstream and upstream, flexible capacity allocation serving FDX nodes/RPDs would be a great synergy. Optical solutions such as XR subcarrier technology [12,13] could provide some flexibility in the optical domain as well. The XR technology, intended for point-to-point and point-to-multipoint application, has been pioneered by Infinera and is now part of the Open XR Forum [14], which is one of the ways to address concerns of a proprietary technology.

Figure 11 shows the XR transmitter output spectrum for 3 conditions, 100Gbps (4 x 25 Gbps subcarriers), 200Gbps (8 x 25 Gbps subcarriers) and 400Gbps (16 x 25 Gbps subcarriers) using 16-QAM subcarriers. In this scenario, all subcarriers are being used to provide the selected bandwidth with each sub-carrier configured as an independent data pipe. This feature could be very useful for point-to-point and point-to-multipoint single-fiber applications. Note that the total power is the same for all the conditions.

The subcarrier utilization could also be set individually as downstream (downlink) and upstream (uplink) for all subcarriers in the same optical ITU channel. That enables different types of applications such as P2P, P2MP, and PON equivalent applications.

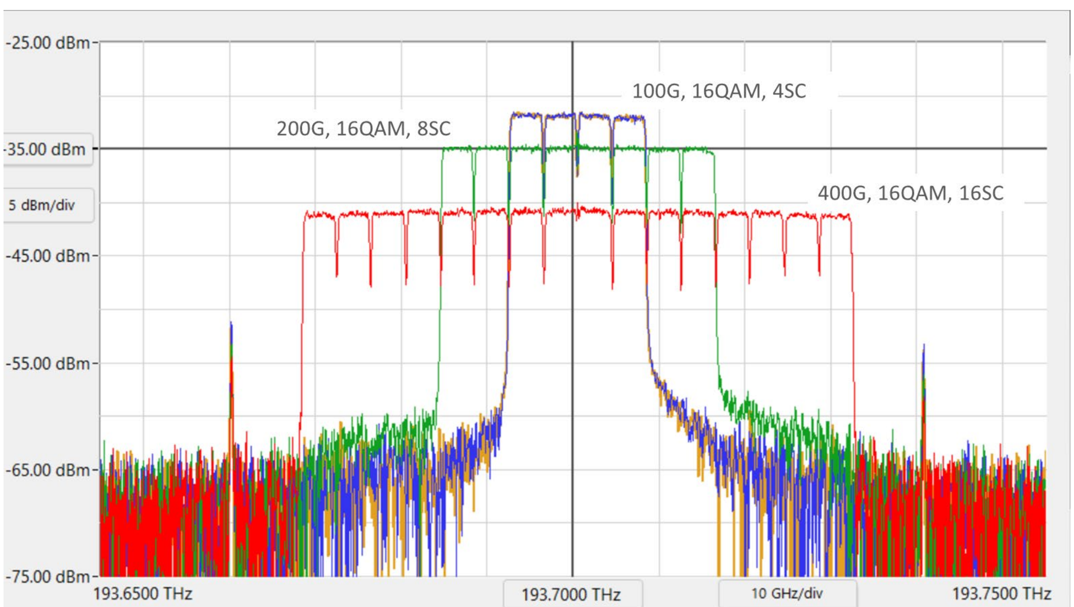


**Figure 12 – XR Transmitter Optical Spectrum for 4, 8 and 16 bidirectional subcarriers**

It is important to note that the functionality and flexibility the subcarrier technology offers could be replaced with less granular bidirectional channel multiplexing instead, since coherent optics devices are tunable. That is similar to the RF-QAM progression, which moved from granular SC-QAM to much larger OFDM blocks. The OFDM blocks are, however, composed of many subcarriers.

 

Such flexibility could be used to better manage the available bandwidth allocation across different end users, including fiber nodes, in a more advanced distributed access architecture (DAA). That may be possible if we can map the control signals currently used in a FDX DOCSIS. That is a departure from the current static capacity management to a more dynamic approach.

The main concern, from the operator's point of view, is that you may be paying extra for something that you may not use. However, the expectation is that using such a device over a wide range of applications may bring economy of scale which eliminates that expectation.

## 8. Capacity Implications

All this work has a simple objective: to make sure we can deliver the necessary bandwidths to our customers. The goal is to have a path to continuously increase the capacity in our core, metro, and access networks as demands require. The transition path must be smooth and cost effective.

Table 4, below, shows the estimated sensitivity and total capacity delivered by fiber for different data rates and modulation orders. The estimated sensitivity assumes a thermal noise limited system that is valid only when the optical power levels are low but provides an indication of the link budget requirements as we increase modulation order and bandwidth. Frequency roll-off and overhead due to FEC is assumed to be 20%. The total capacity assumes an Extended C-band system with 48 x 100GHz spaced DWDM system. Moving to a Super C + L band extension with 60 channels would add 25% capacity to the estimated numbers.

**Table 4 – Total Capacity Estimation per Fiber for Different Modulation Orders**

| Data Rate | Modulation Order | Modulation Rate | # of Pol. | Symbol Rate | SNR @ 1e-3 PreFEC BER | OSNR @ 1e-3 PreFEC BER | Sensitivity (Th. Noise) | Total Capacity |
|---|---|---|---|---|---|---|---|---|
| Gbps/Ch | QAM | bits/S | | Gbd or GHz | dB | dB | dBm | Tbps |
| 100 | QPSK | 2 | 2 | 30 | 10.3 | 14.1 | -31.7 | 4.8 |
| 200 | QPSK | 2 | 2 | 60 | 10.3 | 17.1 | -28.7 | 9.6 |
| 200 | 8-QAM | 3 | 2 | 40 | 14.1 | 19.2 | -26.7 | 9.6 |
| 300 | 8-QAM | 3 | 2 | 60 | 14.1 | 20.9 | -24.9 | 14.4 |
| 400 | 8-QAM | 3 | 2 | 80 | 14.1 | 22.2 | -23.7 | 19.2 |
| 400 | 16-QAM | 4 | 2 | 60 | 17.3 | 24.1 | -21.7 | 19.2 |
| 400 | 32-QAM | 5 | 2 | 48 | 20.3 | 26.1 | -19.7 | 19.2 |
| 400 | 64-QAM | 6 | 2 | 40 | 23.5 | 28.6 | -17.3 | 19.2 |
| 800 | 32-QAM | 5 | 2 | 96 | 20.5 | 29.4 | -16.5 | 38.4 |
| 800 | 64-QAM | 6 | 2 | 80 | 23.5 | 31.6 | -14.3 | 38.4 |

Looking at the sensitivity requirements listed in the table, it is easy to notice the expected linear relationship with the bandwidth. Doubling the bandwidth would increase the sensitivity requirement by 3dB for the same modulation order. The same is not true about increasing the modulation order.

In terms of migration path, this table offers a few options. The first one is the default approach of adding more channels as necessary. Once all the wavelengths are taken, we can start the process of upgrading the modulation order if the switch and the pluggable modules support that. Upgrades up to 400Gbps should be easily adjusted by properly setting margins during the design or by adding amplification. Pluggable optical amplifiers are readily available and could be easily operationalized as other devices. That would support a smooth 800Gbps upgrade as well.

## 9. Conclusions

As we show in this paper, the QAM challenges we are facing right now with coherent optics are similar to what RF-QAM followed over the many years it has been around and we believe we can learn a lot from that experience.

We have covered a few aspects that remind us of such parallels. Minimizing plant reflections, offering bandwidth granularity with optical subcarriers like SC-QAM, and concern with the pass-band of optical passives are a few of the many technical aspects that we need to further define and standardize across the industry.

However, there are many other technical aspects that we did not cover here that need more attention. The first is optical non-linearities and its impact on the system performance as we move to higher modulation orders. That is connected to other Comcast efforts related to Hollow Core Fiber (HFC) that we reported at last year's SCTE technical forum [15]. The hollow core approach reduces not only latency due to lack of glass and light interaction, but also has many linearity advantages that makes this type of fiber very attractive for many applications, including access networks.

A second aspect is making sure we don't degrade performance as we start to aggregate a large number of channels and subchannels to provide the capacities we need. That may lead to some opportunities to be better defined and a possible cost reduction in the optics that we are currently using. We believe that will be something similar to the Downstream RF Interface Specification (DRFI) [16] exercise that enabled the development of very dense Edge-QAM devices used in the industry.

The third aspect is to consider proactive network maintenance aspects of the coherent optical network by defining the key performance indicators (KPIs) to proactively address issues impacting service experience. We expect that many of the RF QAM KPIs would be used for that purpose.

In conclusion, coherent optics is maturing and ready to be used in operator links across the world. Let's use the lessons learned from RF-QAM to make Fiber-QAM another successful optics technology.

# Abbreviations

| | |
|---|---|
| ADC | Analog to Digital Converter |
| BER | Bit Error Ratio |
| BiDi | Bi-Directional |
| CAGR | Compound Annual Growth Rate |
| CD | Chromatic Dispersion |
| CFP2 | C Form-factor Pluggable type 2 |
| ComCMP | Coherent MuxPonder |
| DAA | Distributed Access Architecture |
| DAAS | DAA Switch |
| DCO | Digital Coherent Optics |
| DGD | Differential Group Delay |
| DOCSIS | Data Over Cable Service Interface Specification |
| DRFI | Downstream RF Interface |
| DSP | Digital Signal Processing |
| DWDM | Dense Wavelength Division Multiplex |
| Gbps | Giga bits per second |
| FDX | Full Duplex (DOCSIS) |
| FEC | Forward Error Correction |
| FWM | Four Wave Mixing |
| GMSK | Gaussian Minimum-Shift Keying |
| Hz | Hertz |
| LDPC | Low Density Parity Check |
| MER | Modulation Error Ratio |
| NCG | Net Coding Gain |
| OFDM | Orthogonal Frequency-Division Multiplexing |
| OFDMA | OFDM Access |
| OFC | Optical Fiber Conference |
| OSFP | Octal SFP |
| OSP | Outside Plant |
| ORL | Optical Return Loss |
| OSNR | Optical SNR |
| P2P | Point-to-Point |
| P2MP | Point-to-MultiPoint |
| PM | Polarization Maintaining |
| PMA | Profile Management Application |
| PMD | Polarization Mode Dispersion |
| PON | Passive Optical Network |
| QAM | Quadrature Amplitude Modulation |
| QSFP | Quad Small Form-factor Pluggable |
| QPSK | Quadrature Phase Shift Keying |
| QSFP-DD | QSFP – Double Density |
| RF | Radio Frequency |
| SC | Subcarrier |
| SCTE | Society of Cable Telecommunications Engineers |
| SFP | Small Form-factor Pluggable |
| SNR | Signal to Noise Ratio |

| | |
|---|---|
| SPM | Self-Phase Modulation |
| WDM | Wavelength Division Multiplex |
| XPM | Cross Phase Modulation |

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