Leveraging Deployed Fiber Resources for the Implementation of Efficient Scalable Optical Access Networks

A Technical Paper prepared for SCTE/ISBE by

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Introduction

The great HFC build-out in the 1990's resulted in a significant amount of fiber deployed in the access network. Typically, 6 fibers were dedicated to each fiber node, serving approximately 500 homes. Two fibers were dedicated for downstream and upstream, but since that initial build out, unused fibers have been used in node splits and to support business services. As the industry moves towards deeper fiber penetration, as the demand for fiber connectivity to businesses increases, and connectivity to base stations becomes a strategic imperative both as a potential source of revenue and for mobility play readiness, the efficient use of optical access resources for Gigabit and beyond service delivery becomes critical in terms of meeting traffic demand and lowering cost per bit.

This paper reviews alternative architectures and technologies to optimize optical fiber resources in the access network. Analog versus digital modulation for transport capacity increase is reviewed as well as wavelength division multiplexing (WDM), and higher spectral efficiency optical transport techniques. The digital optical transport approaches discussed here include both direct detection and coherent techniques with multi-level advanced modulation formats.

This analysis highlights the introduction of optical transport technologies within the cable access context of an optical access network with shorter fiber lengths, limited need of amplification, lower optical power budget, and limited fiber strand availability.

A major consideration in the analysis of architectures and technologies is the flexibility and potential level of scalability they provide in future proofing the optical access network. The re-use of fiber already deployed from node to hub minimizes fiber re-trenching expenses, influencing the approaches examined.

Content

1. Optical Access Network Environment

The fiber access networks extend from the hub or headend to the fiber node. These fiber links are typically laid out by running a fiber bundle that passes by different nodes. From a splice point near a fiber node, a fiber cable with fewer fiber strands is trenched or strung to the node. In the initial HFC build-out, 6 to 8 fiber strands were typically dedicated to a node. Most fiber distances from node to hub are less than 25 miles, although in a few areas where hubs may have been consolidated, distances may be as long as 100 miles. leveraging the maximum distances allowed in DOCSIS 3.0 and earlier versions. Figure 1 shows a representation of the fiber access network extending from a hub.

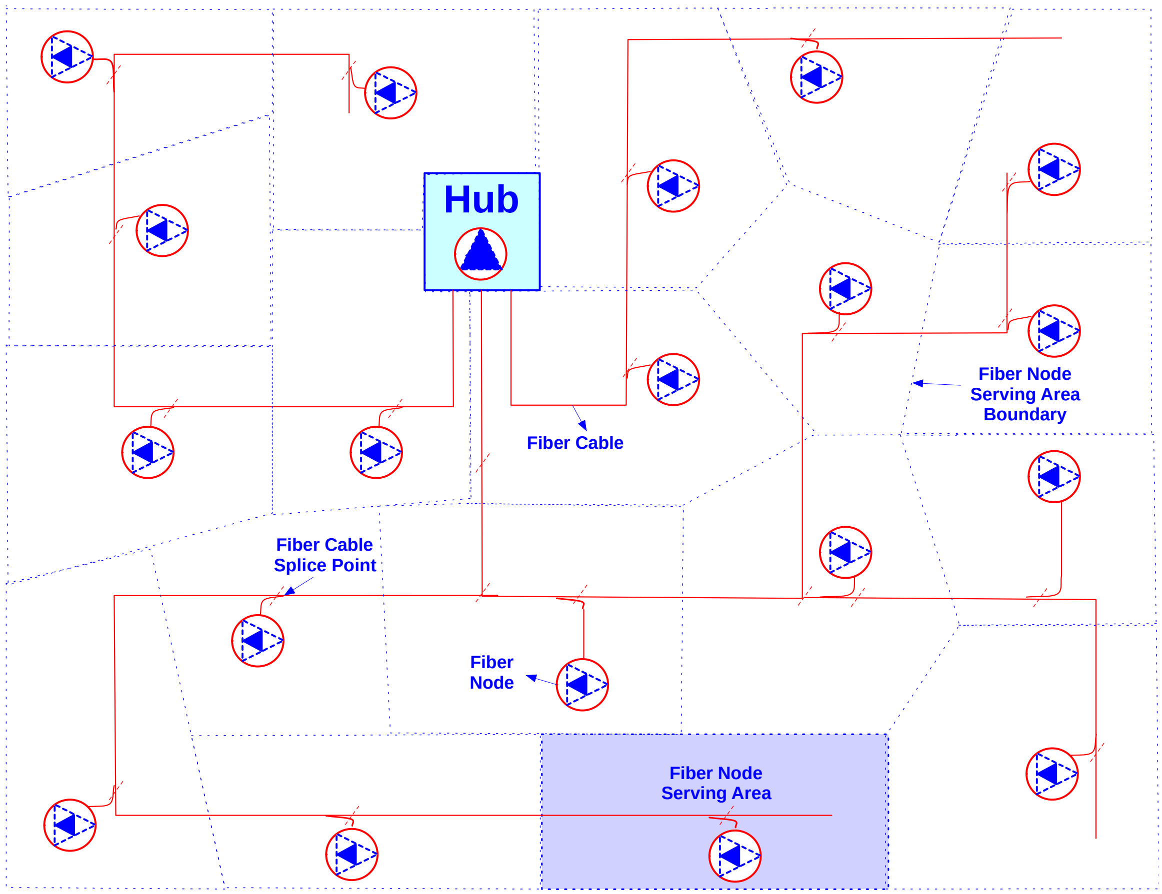

Figure 1 - Hub-to-Node fiber access network topology example

2. Optical Signal Coexistence in the Access Network

It was mentioned earlier that there was limited fiber availability in the access. Often there is no fiber available when there is a need to do node splitting in order to add more capacity to customers. One alternative in these scenarios is to use wavelength division multiplexing technologies.

In order to illustrate how an existing node may evolve under increasing traffic demand, Figure 2 shows an original 500 homes passed serving area that has been split several times and has also incorporated EPON technology to satisfy business customers using direct fiber connectivity to base stations and businesses.

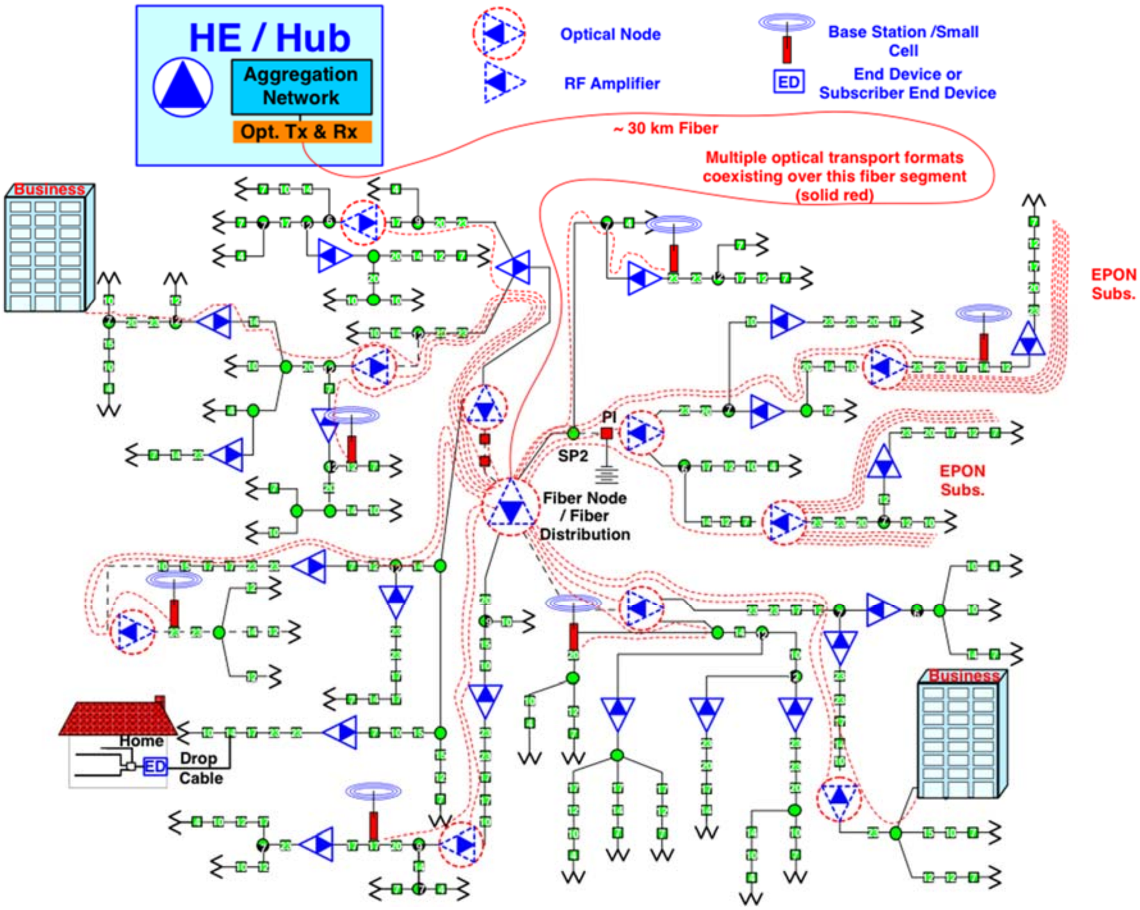

Figure 2 - Original fiber node serving area

Figure 2 illustrates an original fiber node serving area with fiber deeper, fiber to the business and EPON upgrades. Today there are commercial products that multiplex four-wavelengths carrying analog optic signals over a single fiber. The wide spectrum available in the C-band that is typically used provides significant room to place these wavelengths far apart and limit interference. This becomes more challenging, although not impossible, when you have to multiplex 8 wavelengths. Including more wavelengths in the transmission band leads to closer proximity among neighboring wavelengths and less flexibility to find a low distortion portion in the band. The increased power load resulting from additional wavelengths results in increasing fiber non-linear effects, such as four-wave mixing and others.

Retrenching could be an approach to wavelength and fiber shortage. It is however, a very expensive solution that could perhaps be justified for high margin business customers, but would be very challenging for residential and small businesses.

An approach to re-use existing fiber resources by simulating fiber coexistence among simultaneous transmissions of similar and dissimilar modulation formats is quite useful. It enables the assessment of how to best leverage the infrastructure already in the ground. This paper provides guidelines on what metrics to configure and monitor when introducing different transmission types within a single fiber and when full occupancy within a fiber has been reached. This paper discusses coexistence among homogeneous transmission types and heterogeneous transmission types.

3. Optical Components in the Access Network

There are some fundamental components used in the optical access network. The components that have most widely been used in the access, as well as the components that may play a significant role in the access network of the future are described below. These components include laser diodes and external modulators, optical receivers, optical fiber, splitters and wavelength multiplexers and de-multiplexers.

3.1. Laser Diodes

A laser diode is implemented from a semiconductor junction operated in forward bias mode. Electrons in that junction transition from a higher to a lower energy state. In that process, a photon that has an energy equal to the difference in energy states of the electron is emitted. This is spontaneous emission of light which is present in LEDs (Light emitting Diodes). In a laser diode, reflective facets or mirrors are implemented so that the generated photons bounce back and forth, stimulating along the way the emission of more photons. This stimulated emission, or lasing, results in light emission at higher intensity levels and with a high degree of coherence. The mirrors or facets on opposite sides of the active region formed by the junction create an optical cavity. The geometry of that cavity along with the range in energy levels generated by the change of state in the junction will determine one or more dominant resonant wavelengths transmitted by the laser diode.

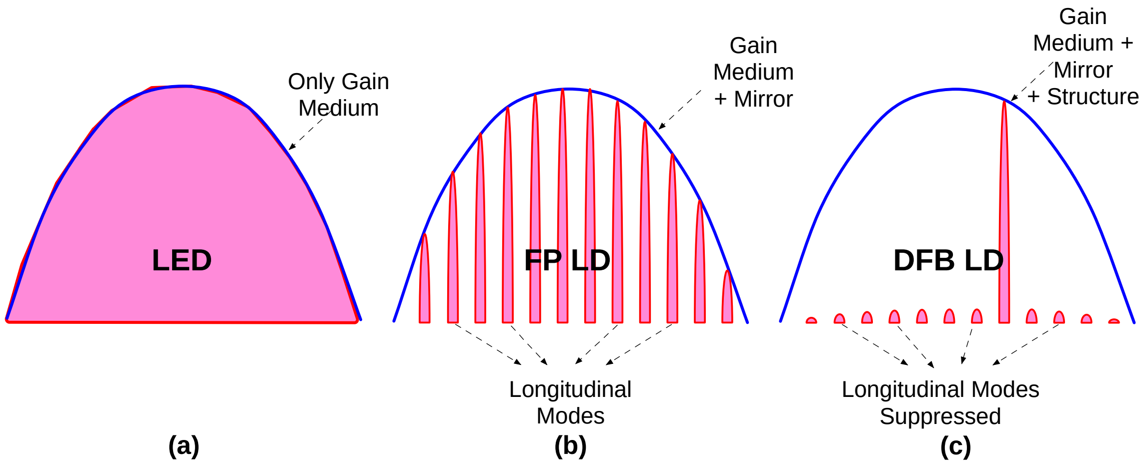

Figure 3 - Light Emission of three Semiconductor Structures

Figure 3 compares light emitting semiconductor structures that highlight light emission versus wavelength of three different diode structures a) LED, b) simple Fabry-Perot stripe laser and c) Distributed Feedback (DFB) laser

The linewidth in wavelength of emitted light is important to higher speeds, higher dynamic range, higher coherence and coexistence among optical carriers on the same fiber. When sharing fiber spectrum with other optical sources (WDM) it is important to have an optical source that can be confined to a narrow spectrum and does not spill over energy to other channels.

Figure 4 shows the characteristic curve that describes the laser diode optical intensity behavior with current.

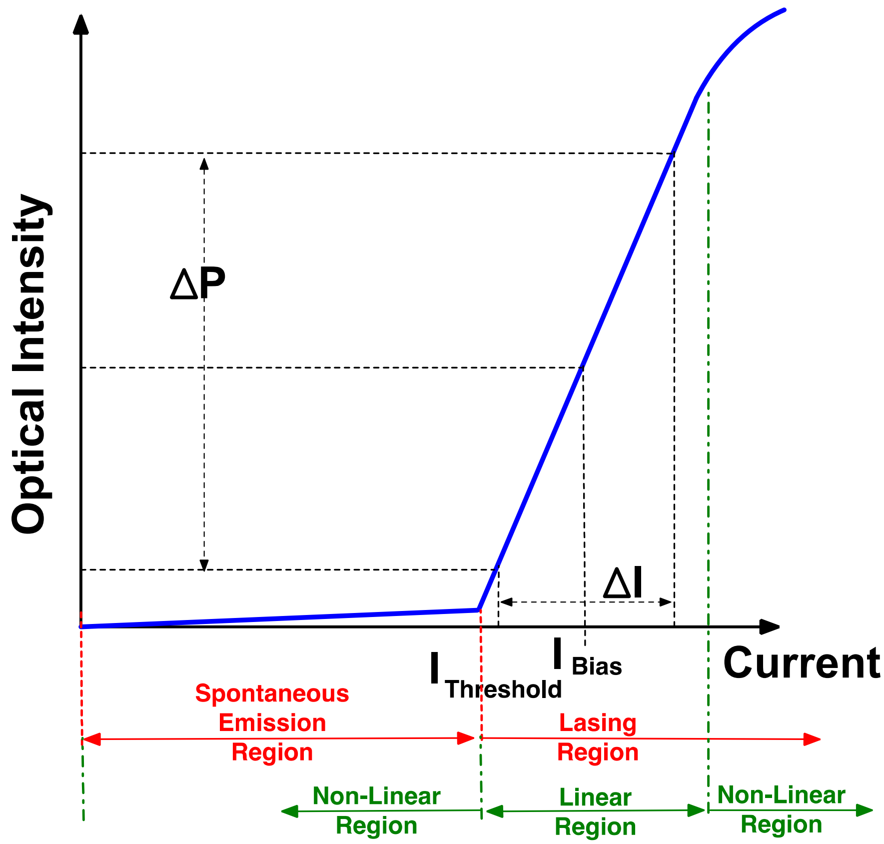

Figure 4 - Laser diode current versus optical intensity behavior

This laser current-optical intensity characteristics change with age and temperature. Maintaining operating characteristics is critical for WDM systems, as changes in average optical intensity can induce a change in wavelength. In a WDM environment the system has to maintain its wavelength at the desired value. To have better wavelength control it is recommended to incorporate thermo-electric-cooling capabilities. Adding minor cost to the optical end devices can go a long way in facilitating wavelength multiplexing and avoiding fiber retrenching costs.

3.2. External Modulators

Two types of external modulation approaches are typically used. One uses electro-absorption effect which controls the degree of attenuation through an optical transmission path. The second one uses an interferometric approach which changes light amplitude by adjusting the relative phase on the two split optical branches, so that after combination they can add destructively (180 degrees out of phase) and no light leaving the modulator, or add constructively (in-phase) with maximum optical intensity out of the modulator. This is called a Mach-Zehnder Interferometer or Mach-Zehnder Modulator (MZM). Figure 5 shows the structure of the MZM.

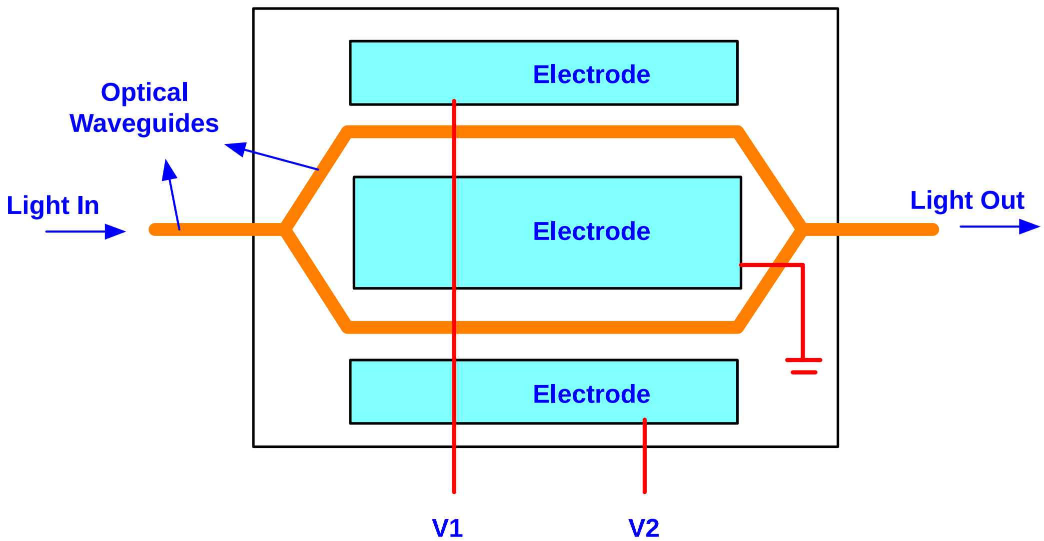

Figure 5 - Mach-Zehnder intensity modulator structure

In coherent systems, rather than modulating only the amplitude of light, both amplitude and phase are modulated. The most popular digital coherent modulator is the nested IQ Mach-Zehnder based modulator shown in Figure 6.

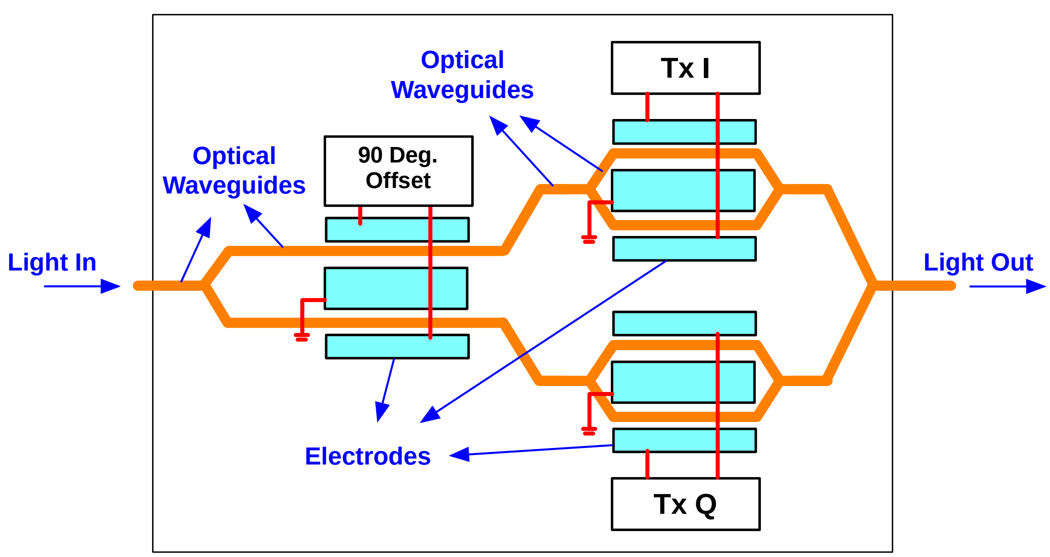

Figure 6 - IQ Modulator structure using two Mach-Zehnder modulators shifted by 90°

In Figure 6, the optical signal is split in two paths, the I (in-phase) and Q (in-quadrature) paths. These paths are phase shifted to be at 90° difference. This allows the generation of information states in a two dimensional constellation.

3.3. Optical Transmission Medium

The optical transmission medium in the access network consists of point-to-point optical links from hub to fiber node for the distribution of residential services through the RF cable spectrum carried over an optical carrier. In cases of fiber shortages, wavelength division multiplexing has been used to reach more nodes. RF over Glass (RFoG) has also been used to directly reach the customer premises via fiber. RFoG architecture from a fiber perspective is point-to-multipoint. The fiber that comes from the hub is physically split one to 32 fibers to reach the customer. In RFoG, the same RF spectrum used for carrying services to a conventional cable modem or set-top box, is used in the home once the RF spectrum has been regenerated. In addition, the access network may also have EPON based services to commercial subscribers. In EPON again the fiber is split into 32 fibers. The type of signal carried in EPON is baseband digital optics which is non-coherent. Typical lengths in the access are less than 40 km (25 miles). In most scenarios optical amplification is not required. The fiber type is the conventional G.652 single-mode fiber.

3.4. Optical Receivers

Optical receivers convert signals from the optical to the electrical domain. Their implementation may differ depending on the particular type of optical transmission system, but in all cases at the heart of the receiver is a reversed bias junction diode that receives photons. The energy of the photon in turn, excites an electron from a lower to a higher state such as the conduction band. This photocurrent generated is proportional to the optical intensity, therefore conveying the information from the optical domain to the electrical domain. This photocurrent is amplified, low-pass filtered, and used to drive analog or digital electronic circuits.

A more elaborate receiver is used in coherent systems. A coherent receiver collects information that exists in two simultaneous orthogonal streams (90° out of phase). These two streams, I and Q streams, are discriminated using a 90° optical hybrid and an optical local oscillator to selectively demodulate the desired stream. The optical detection could be done using single ended detector or a balanced detector which provide greater sensitivity. Figure 7 shows a functional representation of a coherent balanced optical receiver. It is noted that polarization multiplexing/demultiplexing can be used through additional polarization beam splitter/combiner for further doubling the system capacity.

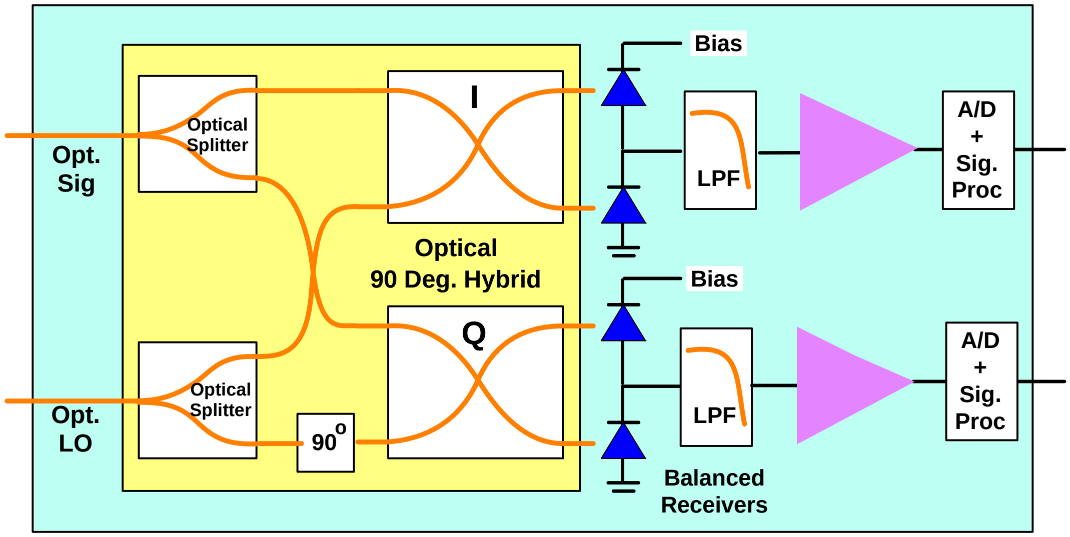

Figure 7 - Coherent balanced optical receiver

4. Transmission Types in Optical Access Network

In the cable access network there are three types of transmission options that are considered today and for potential use in the evolved access network of tomorrow. The most widely used transmission type is analog optics which consists of amplitude modulated light to carry the RF spectrum with analog video and digital channels. The second transmission type is baseband digital optics using direct detection. This is a non-coherent optic used by Gigabit Ethernet and EPON. The third transmission type is coherent optics which is included here as a transmission technology for future use.

4.1. Analog Optics

Cable's downstream RF spectrum consists of multiple digital and analog channels. In the United States these are spaced 6 MHz apart and a cable system spectrum may have about 155 channels in a 1 GHz capable system. From an optical transport perspective these channels are subcarriers. Carrying these channels on an optical carrier is known as subcarrier multiplexing (SCM).

Typically, this information is carried from hub to node by directly modulating the current of a laser to generate a proportional variation in optical intensity.

In a directly modulated diode laser the bias current is selected in the middle of the linear region (Figure 4). This optimizes linear behavior, as the expected current swing caused by the RF modulation covers, by design, the entire linear region.

In cable's multi-carrier environment, there are very high dynamic range requirements. Composite triple beat (CTB) and composite second order (CSO) distortion must be better than - 51 dBc to properly carry this aggregate analog TV and digital QAM channels that encompass the RF cable spectrum.

The main signals carried today over cable are the DOCSIS signals. The new DOCSIS 3.1 specifications with their higher order modulation options put stringent requirements over the optical access links. The upstream and downstream electrical CNR requirements are included in Table 1 below.

Table 1 - DOCSIS 3.1 CNR requirements for different constellations

Constellation	Upstream dB	Downstream (dB) Up to 1 GHz	Downstream (dB) Up to 1.2 GHz
QPSK	11		
8-QAM	14		
16-QAM	17	15	15
32-QAM	20		
64-QAM	23	21	21
128-QAM	26	24	24
256-QAM	29	2	2
512-QAM	32.5	30.5	30.5
1024-QAM	35.5	34	34
2048-QAM	39	37	37.5
4096-QAM	43	41	41.5
8192-QAM		~45	~45.5
16384-QAM		~49	~49.5

*(Optional downstream modes in red have not yet been specified and are estimated [1]).

Typically, lower cost directly modulated Fabry-Perot lasers don't meet these stringent linearity requirements. The downstream semiconductor lasers that meet these requirements and are suitable for these type of applications are distributed feedback lasers (DFB). One characteristic of DFBs is that its structure limits the generation of other modes (Figure 3 c).

The very high optical powers required to carry the high quality RF signals and meet the high dynamic range requirements can limit the use the fiber resources. Non-linear fiber conditions are present on fiber when optical power levels approach 20 dBm [2] in optical links less than 100 km in length. High end analog lasers are capable to transmit at power levels around 18 dBm. Adding multiple analog optics wavelengths require careful positioning within the wavelength range to limit non-linear effects. Another limiting factor is optical chirp introduced in the direct modulation process, especially when combined with fiber dispersion effect.

In analog or digital directly modulated systems of shorter lengths (<100 km) the dominant source of noise is relative intensity noise or RIN. Figure 7 shows thermal noise and RIN influences for different receive levels. RIN also contributes to the limitation in SNR and dynamic range.

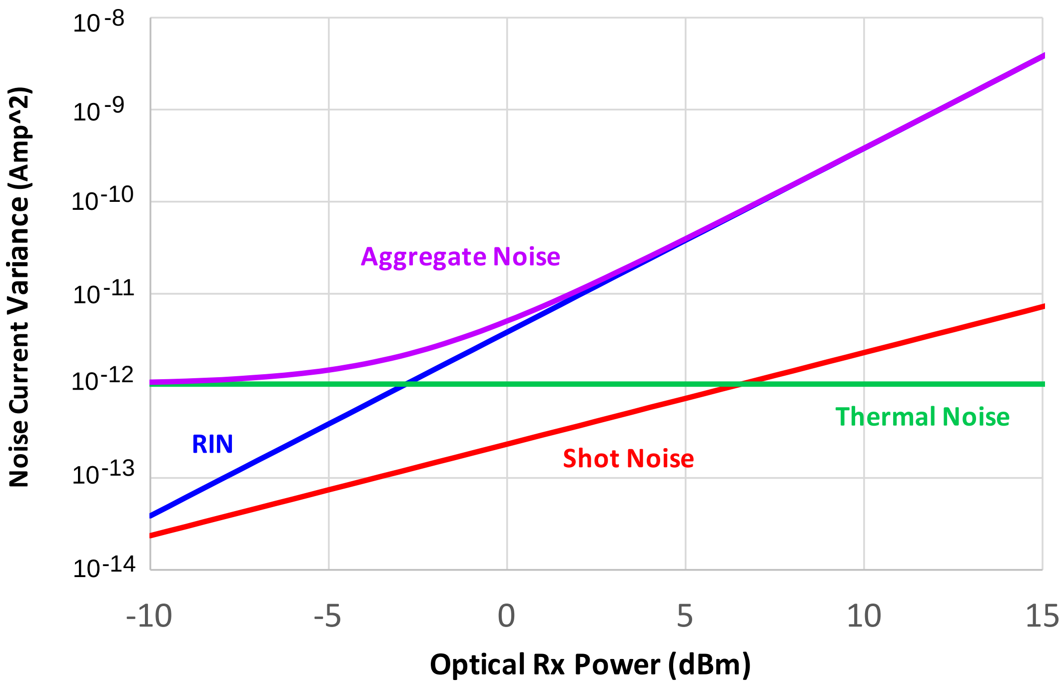

Figure 8 - Types of noise contributions in optical link

4.1.1. Analog optics using external modulator

In some cable access scenarios, particularly in longer hub to node distance cases, external modulation is used. The Mach-Zehnder intensity modulator has a characteristic sinusoidal voltage versus optical intensity behavior, so it requires linearization compensation to leverage the full optical intensity variation that a Mach-Zehnder modulator is capable of.

The subcarrier multiplexing approach, also referred to as analog optics or amplitude modulated optics, has become more challenging to implement as the power requirements have increased due to wider bandwidths and higher order modulations. This optical modulation approach is also used in RF over Glass (RFoG) implementation with the difference that the optical link terminates at the customer premises rather than at the fiber node.

There is on-going transmitter research to achieve high linearity at lower optical power levels.

4.2. Non-Coherent Digital Optical Transport in Cable Access Network

The cable TV industry has used digital optical transport for a variety of use cases. It has used EPON to reach business and residential customers, and it has used Gigabit Ethernet to reach businesses, base stations and to reach remote CMTS and remote PHY nodes. In the upstream, digital non-coherent optics is used for RF spectrum digitization. Different non-coherent digital modulation approaches are discussed next.

4.2.1. Directly modulated optical links using direct detection

Most types of digital optical links are implemented using directly modulated lasers and direct detection receivers. These links are robust for the environment that they intend to cover. The link lengths supported are typically 20 to 40 km. In EPON the topology typically follows a 32 split architecture. By using higher power transmitters 64 split ratios can be achieved.

When requiring higher speeds and lower noise, external intensity modulation can be used. An advantage with digital modulation formats such as NRZ or RZ is that there is no need to worry about linearization as only two states or levels are important. This changes, of course, if multilevel formats are used.

One long term limitation worth mentioning is the frequency response of directly modulated lasers. Assuming that the high frequency influence of all parasitics is eliminated, the directly modulated laser diode still exhibits an intrinsic frequency response limitation that depends, among other things, on the relaxation oscillation frequency. This limitation is typically in the order of 25 GHz and has to be considered as higher speeds are required.

4.2.2. Externally Modulated Optical Links Using Direct Detection

It is worth noting that external modulators don't suffer from the same frequency response limitation as directly modulated lasers. Frequency responses as high as 100 GHz have been achieved with external modulators [5].

One advantage of external modulation is that it decouples the light source from the modulation function. This way the laser selection can be optimized for highest power and the modulator can be optimized for speed without the worry of optical chirp generation.

A drawback with some external modulators is size and cost compared to direct modulation alternatives. As photonic integration continues to evolve this difference is less significant.

4.3. Digital Coherent Optical Transmission

Coherent optics has been used extensively in the long haul and metro environments. The significant bandwidths that can be achieved with coherent optics, as well as the efficient wavelength packing capabilities in fiber, makes it the most bandwidth scalable technology. The receiver complexity of coherent systems is higher than non-coherent systems, but optical integration is making these differences less critical. The cost of coherent optics technology is coming down, and it is worth considering as a potential fiber tenant of cable's access network.

Long haul environments due to the very long lengths and resulting noise and distortion, typically transmit using QPSK. In the access however, due to the benign environment resulting from the shorter links, higher modulation orders become feasible. In addition to the higher order modulations, coherent optics enables the use of polarization multiplexing which doubles the capacity. Coherent optic systems require smaller guard-bands than non-coherent direct detect systems. This results in a more efficient packing of wavelengths for much higher spectral efficiency and interference reduction among adjacent optical carriers. The higher sensitivities that are achieved with coherent optics also result in lower transmit power and higher overall fiber occupancy without incurring into non-linear conditions.

5. Optical Channel Impairments in the Access Environment

The fiber access environment is critical in determining the performance of systems that reside and coexist within the fiber strand. There are different fiber-related impairments impacting performance. Some of these impairments are fiber length dependent, and some are dependent on fiber geometry, material, wavelength, bandwidth and optical power level.

5.1. Dispersion

Dispersion is one of the fiber length dependent impairments. Dispersion occurs when different portions of the signal travel at different speeds. As a consequence there is a spreading of the signal in time. There are different types of dispersion. There is chromatic dispersion, waveguide dispersion, modal dispersion and polarization mode dispersion. Chromatic or material dispersion is caused by the change of refractive index with optical frequency. Waveguide dispersion relates to how well the index of refraction represents an ideal waveguide throughout the fiber length. The differences from an ideal waveguide causes dispersion. Modal dispersion occurs when different propagating modes are present in fiber. In the cable access environment, the predominantly deployed fiber is single mode fiber (SMF-28), so fiber modal dispersion is not present and waveguide dispersion is negligible compared to chromatic dispersion. This paper focuses on material or chromatic dispersion and briefly discusses polarization mode dispersion. Chromatic dispersion is approximated by the formula

$$Dispersion(\lambda) = \frac{S_0}{4} * \left[\lambda - \frac{{\lambda_0}^4}{\lambda^3}\right] ps/(nm * km)$$

Where λ_0 is the zero dispersion wavelength which for SMF-28, is typically 1313nm (1302 nm -1322 nm range) and S_0 is the zero dispersion wavelength factor which typically is 0.086 ps/(nm^2*km) and always less than 0.092 ps/(nm^2*km). The variation of dispersion with wavelength for SMF-28 fiber is shown in Figure 9.

5.2. Attenuation

Attenuation in fiber is dependent on the wavelength or frequency and for the single mode fiber, SMF 28, used in cable access, is 0.22 dB/km for 1550 nm transmission and 0.3 dB/km for 1310 nm transmission. Figure 9 also shows attenuation versus wavelength and the optical transmission windows. The transmission window that is highly coveted is the C-Band (1530 nm–1565 nm) because of the option for amplification in addition to its low loss characteristics. However, in the access network, due to the shorter distances in many use case scenarios, there is no need of amplification. This opens up also the L-Band (1565 nm-1625 nm) which is beyond the gain region of erbium doped fiber amplifiers (EDFAs).

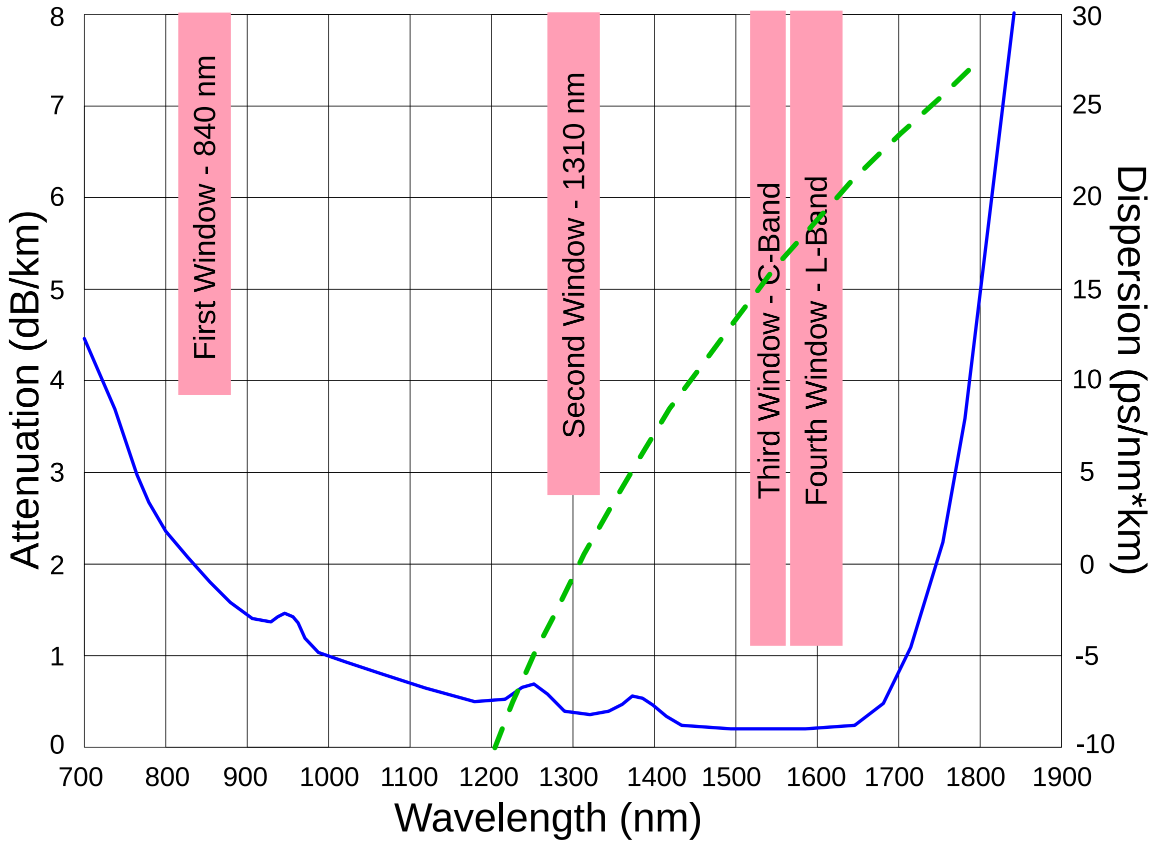

Figure 9 - SMF-28 fiber attenuation (blue trace) and dispersion (green trace) versus wavelength characteristics

In the cable environment, the impact of optical reflections are diminished by using angle faceted connectors. The small angle of an angle faceted or APC connector causes a reflected signal to exit the fiber. Nevertheless, splice imperfections can also generate reflections which impact performance.

5.3. Polarization Mode Dispersion

Polarization mode dispersion (PMD) occurs when two orthogonal polarizations travel at different speeds which causes pulse spreading. This is caused by random imperfections such as circular asymmetry. The unit in polarization mode dispersion is in ps/$\sqrt{km}$. PMD in single mode fiber ranges from 0.1ps/$\sqrt{km}$ to 1 ps/$\sqrt{km}$. SMF-28 has PMD < 0.1 ps/$\sqrt{km}$ although after cabling the specification calls for < 0.5 ps/$\sqrt{km}$. A PMD requirement for non-coherent 10 Gbps NRZ of < 4ps is typically used. A 40 km link would have at most 0.5*$\sqrt{40}$ = 3.16 ps which would not require compensation. However for 40 Gbps the PMD requirement is < 1 ps/$\sqrt{km}$ and a 40 km link would require compensation. Coherent detection provides a higher tolerance to PMD than non-coherent so, in principle, higher symbol rates can be achieved with minimal or no PMD compensation for the link distances of the access network. PMD is not an issue in analog optical links as the modulation bandwidth is about 1 GHz.

5.4. Nonlinear Effects

Nonlinear effects in fiber are due to intensity dependence of the refractive index fiber medium, and due to inelastic-scattering present at very high optical intensity levels. There are also nonlinear effects that could be related to optical amplification systems, but in this access scenario evaluation with typically short distances (<60 km), amplification systems are not considered. This paper focuses on the refractive index dependence on optical power. These refractive index effects are described as self-phase modulation (SPM), cross-phase modulation (CPM) and four-wave mixing (FWM).

5.4.1. *Self-phase modulation*

A time varying signal intensity generates a varying refractive index in a medium with an intensity dependent refractive index such as fiber. The higher intensity portions of an optical signal, encounter a higher refractive index compared to the lower intensity portions of the signal as it travels through the fiber. This effect of variation in index of refraction generates chirping and dispersion. In SPM, the power level and length of interaction are key in the amount of self-phase modulation.

5.4.2. *Cross-phase modulation*

It is in principle the same effect we have with self-phase modulation but in this case, it is the effect that the intensity varying index of refraction has on other optical carriers that are propagating at the same time as the original signal. As the number of channels increases the amount of CPM also increases. In a WDM system, CPM converts power fluctuations in a particular channel to phase fluctuations in the other co-propagating channels. CPM is higher with high power levels and greater interaction lengths (longer fiber links).

5.4.3. *Four-wave mixing*

Four-wave mixing (FWM) is a third order nonlinear effect of susceptibility. In FWM, if you have three fields propagating at frequencies ω_1, ω_2 and ω_3, a fourth frequency ω_4 is generated such that $\omega_4 = \omega_1 \pm \omega_2 \pm \omega_3$. FWM is independent of modulation bandwidth and is dependent on channel spacing and fiber dispersion. Since dispersion varies with wavelength, the signal waves and the generated waves have different group velocities. This destroys phase matching of waves and lowers the efficiency of power transfer to newly generated frequencies. Therefore, dispersion shifted fibers have a more severe FWM effect than regular single mode fiber. The higher the group velocity mismatch and wider the channel spacing, the lower the four-wave mixing effect.

6. Signal to Noise Ratio and Probability of Symbol Errors

Different types of optical transmission formats have different SNR requirements. The types of optical transmission format are analog or amplitude modulated signals, digital non-coherent direct detected signals, and digital coherent signals.

The analog optical signals are subcarrier multiplexed analog video and digital channels on an optical carrier. The digital non-coherent signals include NRZ (non-return to zero) signal and PAM-4 (4 level - pulse amplitude modulated) signals. The coherent optical signals include QPSK, 16QAM, and 64QAM signals.

In the case of analog signals, it is important to determine the impact that the dominant source of noise has on the optical SNR. The main source of noise in shorter high optical power access links is relative intensity noise.

Relative intensity noise or RIN at the transmitter which on a directly modulated laser is given by:

$$\sigma_I^2 = RIN(I_p^2)\Delta f$$

where I_P is the average current, *RIN* is the average relative intensity noise spectral density and Δf is the receiver bandwidth.

Shot noise and thermal noise are introduced at the receiver. Shot noise (σ_s^2) is given by:

$$\sigma_s^2 = 2q(I_p + I_d)\Delta f$$

where I_P is the average photocurrent determined by the incident optical power P_{in} and the receiver responsivity $\mathcal{R}$ ($I_p = \mathcal{R}_d P_{in}$), I_d is the dark current, q is the electron charge and Δf is the detector bandwidth.

Thermal noise (σ_T^2) is given by:

$$\sigma_T^2 = (4k_B T/R_L)F_N \Delta f$$

where k_B is Boltzmann constant, T is temperature in Kelvin, R_L is the load resistance, N_F is the noise figure and Δf is the receiver bandwidth.

From these noise contributors we have that the OSNR becomes:

$$OSNR = \frac{I_p^2}{\sigma^2} = \frac{\mathcal{R}_d^2 P_{in}^2}{2q(\mathcal{R}_d P_{in} + I_d)\Delta f + \left(\frac{4k_B T}{R_L}\right) F_N \Delta f + RIN(\mathcal{R}_d^2 P_{in}^2)\Delta f}$$

As you see the resulting optical SNR is dependent on multiple factors. The OSNR versus incident optical power is shown in Figure 10. Typical parameters in the cable environment are; R_L = 75 ohms, T = 297K, $\mathcal{R}$ = 0.6 A/W, Δf = 1.2 GHz and RIN = -150 dB/Hz.

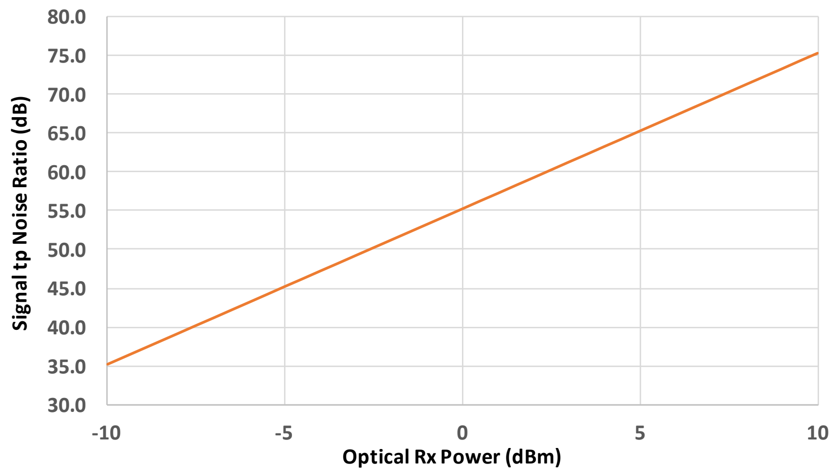

Figure 10 - Signal to Noise ratio variation with optical power receive assuming negligible nonlinearity

This curve in Figure 10 does not include the impact of nonlinearities. Nonlinear behavior in the analog optical link is better observed using the Noise Power Ratio (NPR) characteristics of the optical links. This nonlinear behavior is primarily driven by the nonlinear behavior of the lasers when driven at high power levels. In the NPR curves shown we observe that beyond certain power level there is a decrease in the noise power ratio. At high values NPR approximates SNR and is a good indicator of the link SNR.

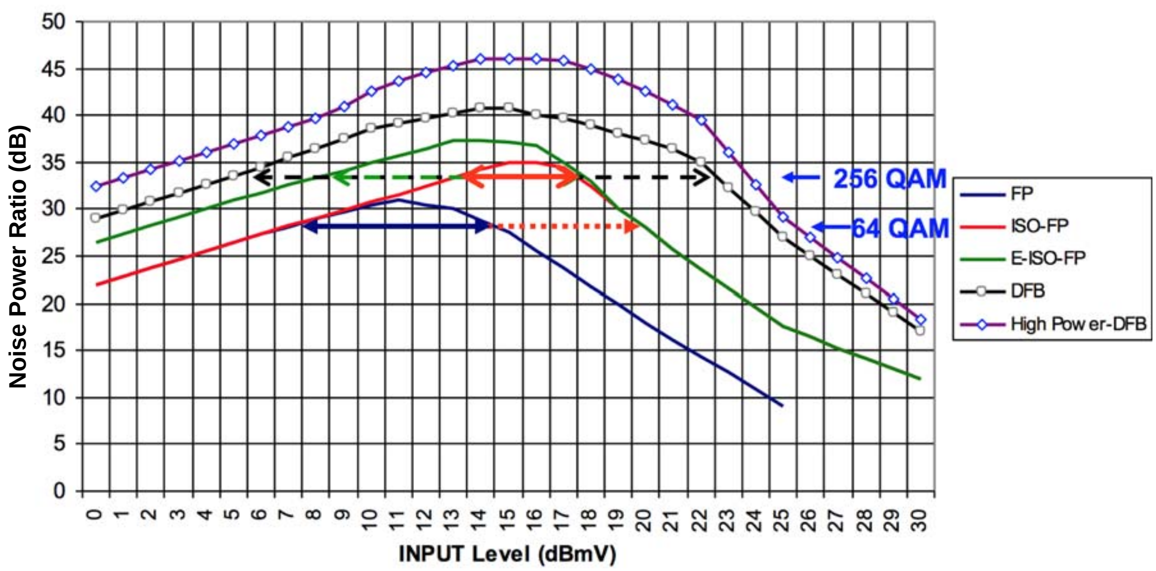

Figure 11 - Noise power ratio measured on optical links with different laser types

In Figure 11 horizontal dashed lines indicate operating regions for 64 QAM and 256QAM (DOCSIS 3.0/2.0 RS encoding are assumed).

While the previous SNR relations along with Noise Power Ratio (NPR) characterization provide an indication on the SNR that can be achieved with analog optical links. In order to better estimate the requirements of digital coherent and non-coherent links the constellations in digital optical links are examined.

The most basic and most popular non-coherent modulation type is NRZ (Non-return to zero) or 2 level On-Off Keying (Figure 12 a). This modulation option relies on transition from a state of high optical intensity (On or 1) to a state of low optical intensity (Off or 0). This modulation can take place using direct laser modulation or using external modulation.

A second non-coherent modulation option is “non-coherent PAM 4” or 4 level On-Off Keying (Figure 12 b). In this modulation type the value of the optical signal can take one of 4 levels. Since this is a non-coherent type the value takes only positive values or zero.

The next two modulation types are coherent modulations that have two and 4 information states. These are BPSK which in this example takes values of -1 and 1 and the next modulation is coherent PAM-4 that takes values of -3, -1, 1 and 3 (Figure 12 c and d). In these modulation types shown, the spacing between constellation points are adjusted so that the amplitude obtained from the square root of the average power is the same for all constellations. This is done so that different type of constellations can be visually compared, at least from a first order perspective. A smaller spacing between constellation points would result in a higher signal to noise ratio requirement. From all these modulation types PAM-4 would require a much higher SNR than the other modulations.

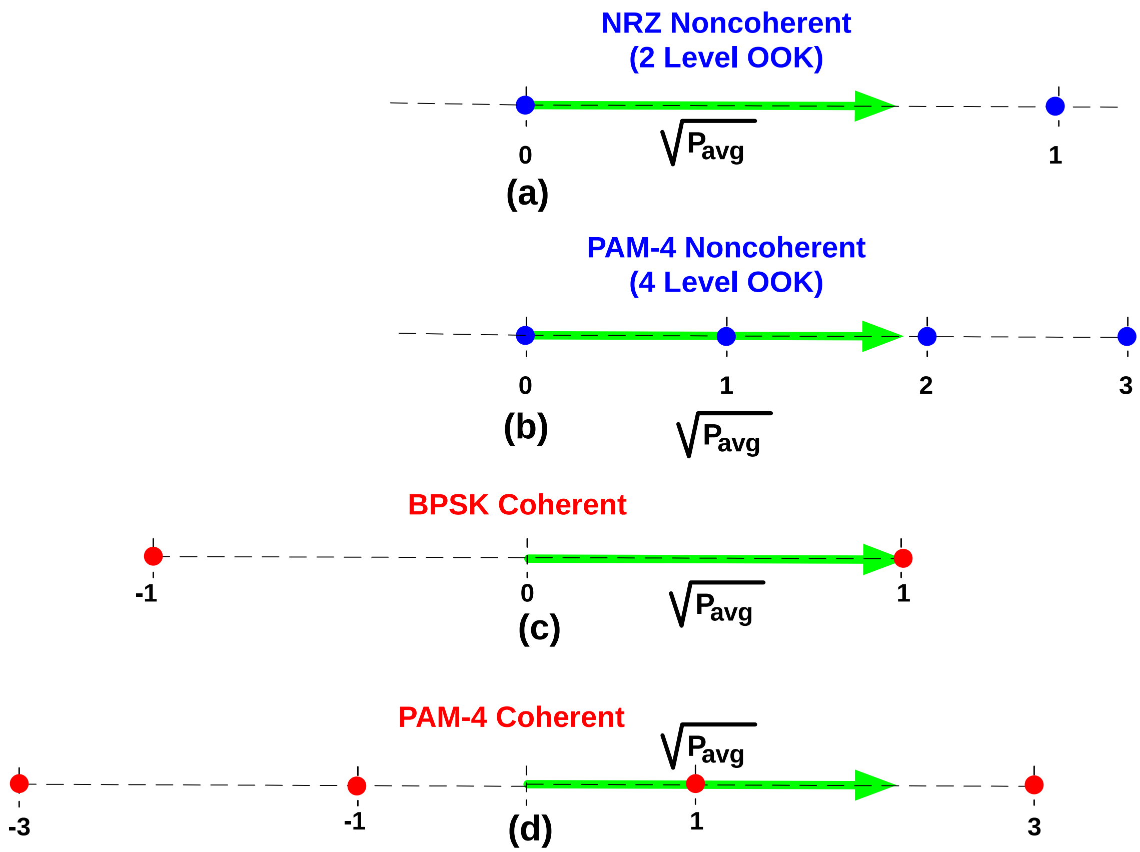

Figure 12 - Constellations of NRZ (2 level OOK), non-coherent PAM4 (4 level OOK), BPSK (coherent) and coherent PAM4 signals.

In Figure 12 dimensions normalized to square root of average power $\sqrt{P_{avg}}$ are indicated with green arrow.

A non-coherent PAM-4 or 4 level OOK with the same average power is superimposed for comparison purposes with a 16 QAM-constellation and shown in Figure 13. This figure assumes equal average power P_{avg} ($\sqrt{P_{avg}}$ which is indicated with green arrow).

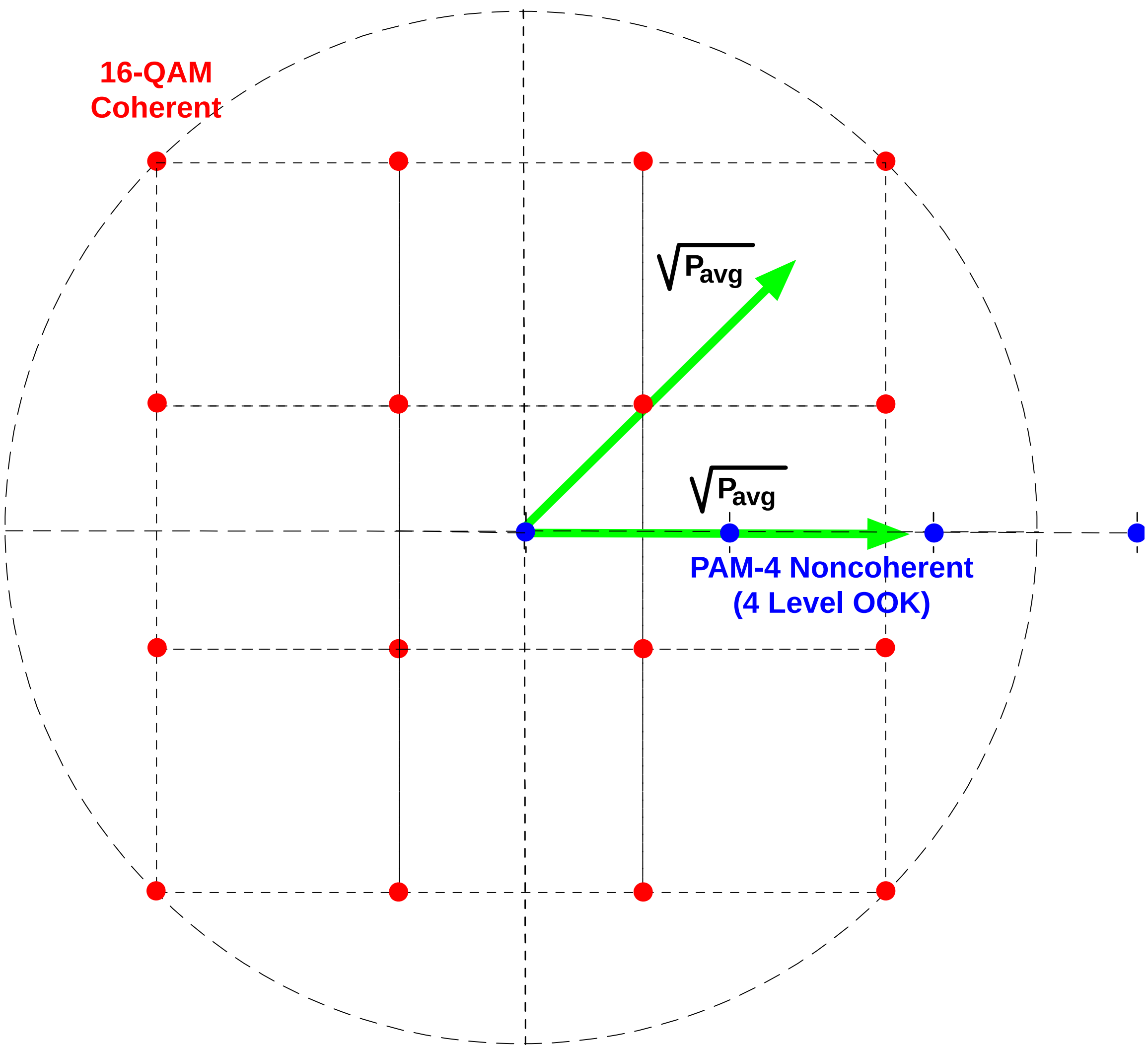

Figure 13 - Constellations of 16-QAM and non-coherent PAM4 (4 level OOK) signals

The symbol error rate as a function of SNR per symbol for an NRZ or 2 level OOK signal can be calculated using the following equation,

$$SER_{NRZ} = \frac{1}{2} erfc\left(\frac{1}{2\sqrt{2}}\sqrt{E_S/N_0}\right)$$

It is worth noting that in a non-coherent optical domain environment we don't have the luxury of using negative symbol values (-3, -1, +1, +3). Negative symbol values can only be implemented using coherent systems. In a non-coherent direct-detect PAM4 (4 level OOK) approach the levels would be only positive (0,1,2,3). This impact the analysis and the separation between symbols that you can achieve for a given maximum power level. The symbol error rate as a function of SNR per symbol for a non-coherent PAM4 or 4 level OOK signal is given by:

$$SER_{DD-PAM4} = \frac{1}{2} erfc\left(\frac{1}{6}\sqrt{\frac{E_S/N_0}{log_2 M}}\right)$$

where M is equal to the number of levels and equal to 4 for a DD-PAM-4 scenario.

The symbol error rate (SER) of QAM signals is given by equation below [4].

$$SER_{M-QAM} = 1 - \left(1 - \left(2 \cdot \left(1 - \frac{1}{\sqrt{M}}\right)\right) \cdot \frac{1}{2} erfc\left(\frac{1}{\sqrt{2}}\sqrt{\frac{3 \cdot E_S/N_0}{(M-1)}}\right)\right)^2$$

where M is the number of points in the QAM constellation. M=4 for QPSK, M=16 for 16-QAM and M=64 for 64 QAM.

Figure 12 and Figure 13 provide a visual first order comparison of the modulation formats. In a more detail comparison, Figure 14 shows the error probability versus SNR for the different digital signals that may coexist in a cable access environment.

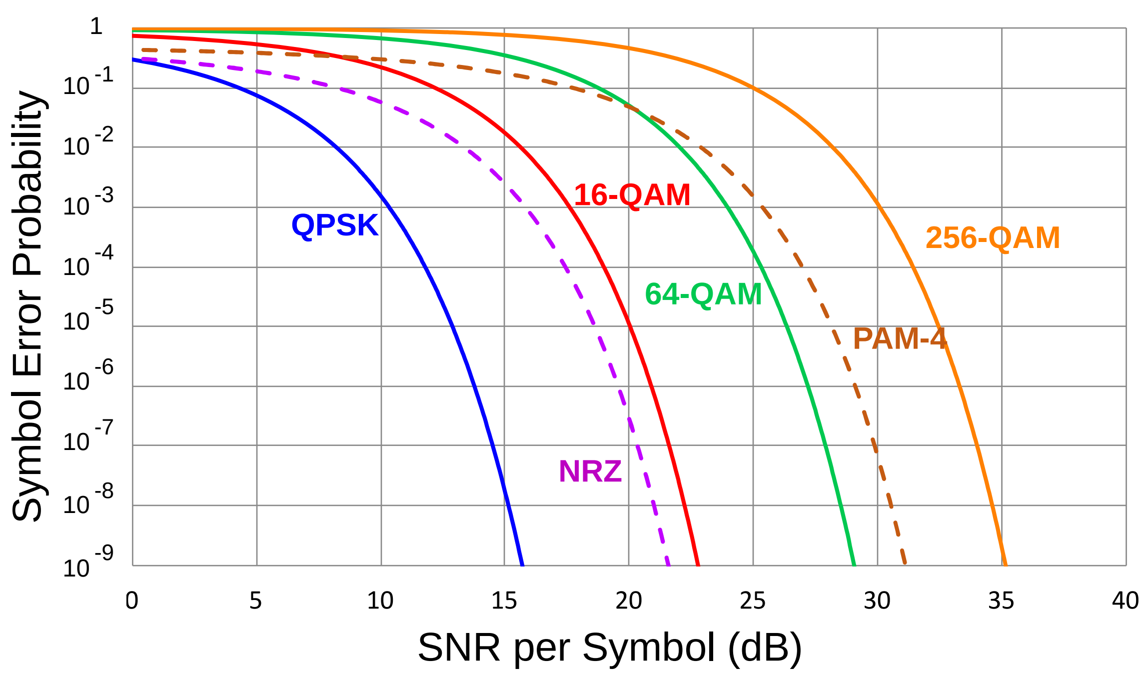

Figure 14 - Symbol error rate in direct detect and coherent modulation formats

The analysis above is strictly theoretical. An actual assessment should include the impact of the channel condition. This includes the sources of noise and distortion in the optical transmitter, the fiber transport medium and the receiver. In addition, there is an implementation penalty. This penalty will depend on the compensation needed in the bandwidth and level resolution that the modulation requires. For example, as implementation factors are considered, it is much more challenging to transmit at 64 GBaud using 64 GHz components than at 16 GBaud using 16 GHz components. A subtle advantage for coherent links, in addition to the theoretical SNR advantage in Figure 14, is the fact that at the receiver there is a higher power laser diode local oscillator that can be leverage to result in coherent gain.

7. Multi-Wavelength Analog Optics Coexistence

It was described earlier that cable access environment in general, has limited spare fibers from hub to node. However, the ever increasing bandwidth demand leads to demand for smaller deeper nodes. In order to avoid retrenching, multiplexing multiple analog optical carriers on the same fiber is a worthy approach.

One challenge to confront is that the CNR requirements on the analog optical link have been increasing with the introduction of higher order modulations of DOCSIS 3.1. A solution for achieving higher CNR is to increase optical power. However, when increasing optical power, the likelihood of introducing nonlinear effects also increases. Simulations on MATLAB and on the VPI platform have been conducted to assess coexistence among multiple analog carriers. In this analysis, 9 equally spaced wavelengths under different configurations are examined. The RF signal driving a directly modulated laser consists of 20 contiguous NTSC channels starting at around 230 MHz. The analog optical carrier that was used when measured as a single optical channel in the fiber had a CNR of 58 dB. The reason why only 20 channels were used is to clearly distinguish second and third harmonics as well as intermodulation.

In addition to power levels, channel spacing and the amount of filtering used to de-multiplex and detect the desired wavelength are changed. In all cases the wavelengths used center around 1550 nm and the fiber type and length used was 40 km of SMF-28.

Figure 15 and Figure 16 compare scenarios with 50 GHz channel spacing, 10 dBm optical power per channel but with different order in the optical de-multiplexing filter. It is clearly shown by comparing the RF spectra that when using a simpler (1st order) de-multiplexing filter, significant crosstalk is introduced. By observing carefully at the NTSC carrier portion of the RF spectrum, a degradation within the RF band containing the NTSC channels is also observed. The CNR within this NTSC RF spectrum portion ranges from 38 dB to 46 dB. The second harmonic distortion was also at the same level or worse that the in-band distortion levels.

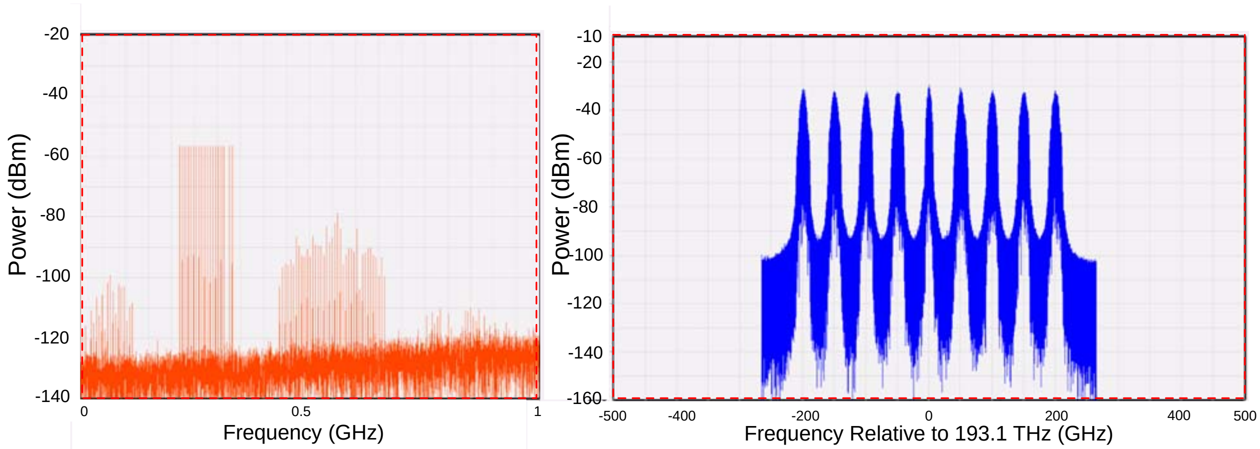

Figure 15 - 9 Analog optics channels transmitting each an optical power of 10 dBm over 40 km of SMF-28 fiber (3rd order filter used)

Channel separation is 50 GHz, a modulation index of 0.15 and a 37.5 GHz 3rd order Gaussian optical de-multiplexing filter in Figure 15.

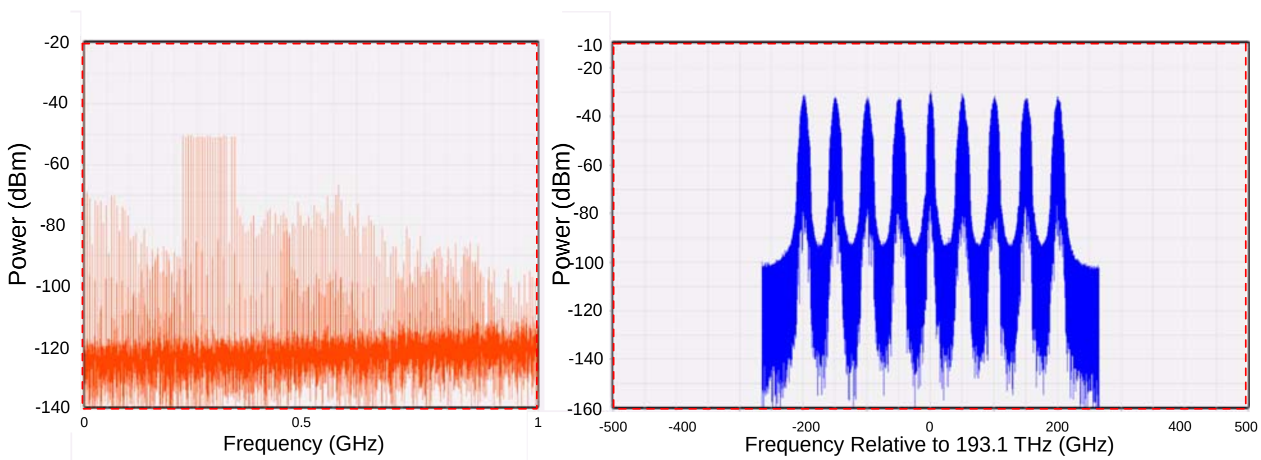

Figure 16 - 9 Analog optics channels transmitting each an optical power of 10 dBm over 40 km of SMF-28 fiber (1st order filter used)

Channel separation is 50 GHz, a modulation index of 0.15 and a 37.5 GHz 1st order Gaussian optical de-multiplexing filter in Figure 16.

Figure 17 and Figure 18 examine the same behavior but instead of having the channel spacing at 50 GHz the channels spacing evaluated is 100 GHz. The observation is quite similar. The lower order (1st order) filter does not prevent the impact of crosstalk among channels at the receiver. The 10 dBm power level is conservative for the type of CNR demanded by DOCSIS 3.1.

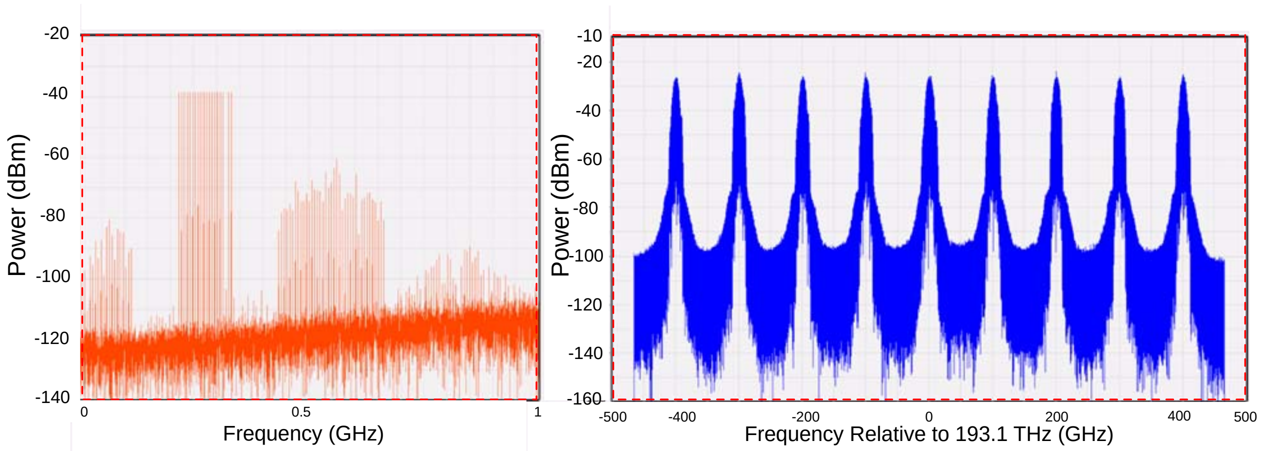

Figure 17 - 9 Analog optics channels transmitting an optical power of 16 dBm over 40 km of SMF-28 fiber (3rd order filter used)

In Figure 17 channel separation is 100 GHz, a modulation index of 0.15 and a 75 GHz 3rd order Gaussian optical de-multiplexing filter.

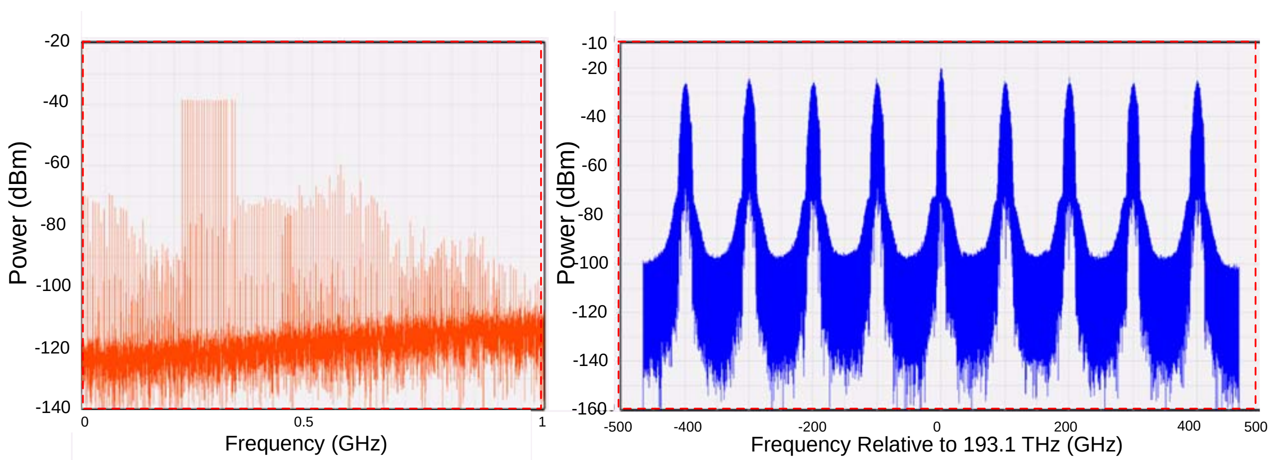

Figure 18 - 9 Analog optics channels transmitting each an optical power of 16 dBm over 40 km of SMF-28 fiber (1st order filter used)

Channel separation is 100 GHz, a modulation index of 0.15 and a 75 GHz 1st order Gaussian optical de-multiplexing filter in Figure 18.

The last analog simulations have 9 analog carriers, 200 GHz apart and at a power level of 10 dBm per channel. The amount of distortion is significant. It can be deduced from these simulations that not just filtering but a higher order (3rd order) filtering is needed to recover the signal. It can be concluded from these simulations, that even a 200 GHz channel separation does not avoid the need for filtering.

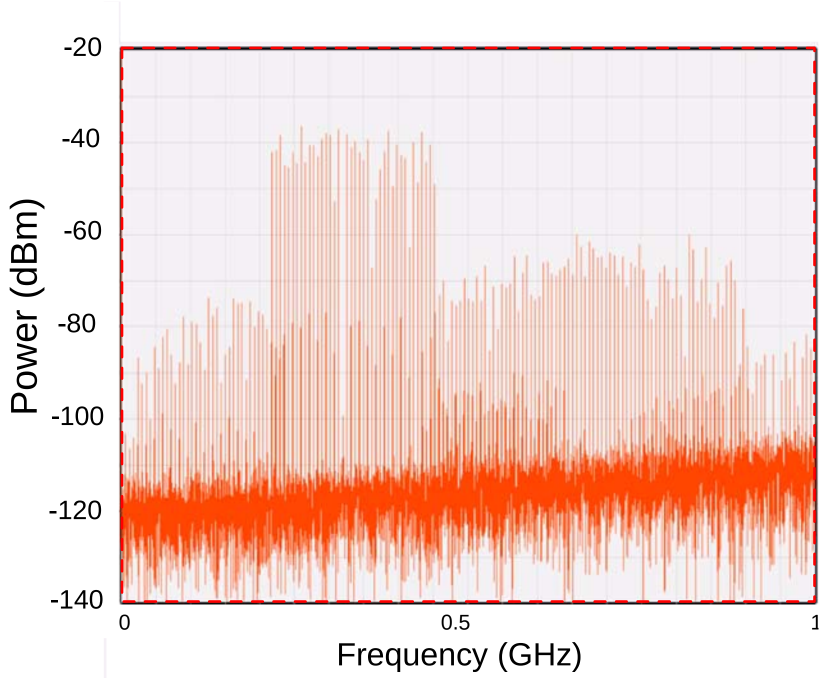

Figure 19 - 9 Analog optics channels transmitting each an optical power of 10 dBm over 40 km of SMF-28 fiber.

Channel separation is 200 GHz, modulation index of 0.15 and no optical filters in Figure 19.

The level of performance achieved with 9 equally spaced channels from 50 to 200 GHz spacing even after introducing optical filtering and adjusting for power levels produced a CNR of 38 dB. Adding the noise figure of the coaxial environment this may drop to 34 dB or lower. Based on Table 1 this would allow in the cleanest portion of the RF spectrum a modulation order of 1024QAM. In order to achieve the higher modulation orders enabled by DOCSIS 3.1, different analog optical transmitter types and approaches should be explored such as linearized externally modulated systems and/or uneven spacing of the optical carriers.

8. Multi-Wavelength Non-Coherent Digital Optics Coexistence

Another optical transmission type used in cable is non-coherent direct detection. This is used in EPON, Gigabit Ethernet and others. The direct detect modulation format most widely used is the 2 level On-Off Keying NRZ modulation (Figure 12 a). A simulation of 9 equally spaced optical NRZ carriers was conducted changing a variety of parameters but in all simulations a fiber length of 40 km SMF-28 representing the cable access network was used Figure 20 and Figure 21 show the 9 carriers at a spacing of 50 GHz carrying a signal of 25 GBaud (1bit/symbol => 25 Gbps) with a 37.5 GHz de-multiplexing filter.

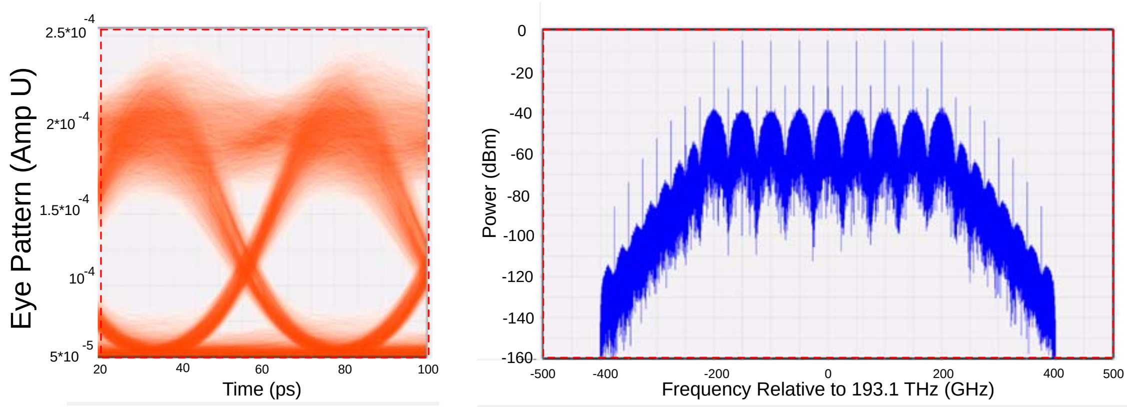

Figure 20 - 9x25 Gbps OOK-NRZ WDM channels with dispersion compensation

Each channel is transmitting at 0 dBm over 40km of SMF-28 fiber with dispersion compensation. The channel spacing was 50 GHz and used a 4th order Gaussian optical de-multiplexing filter (1.5*25G) with a 25 GBaud symbol rate.

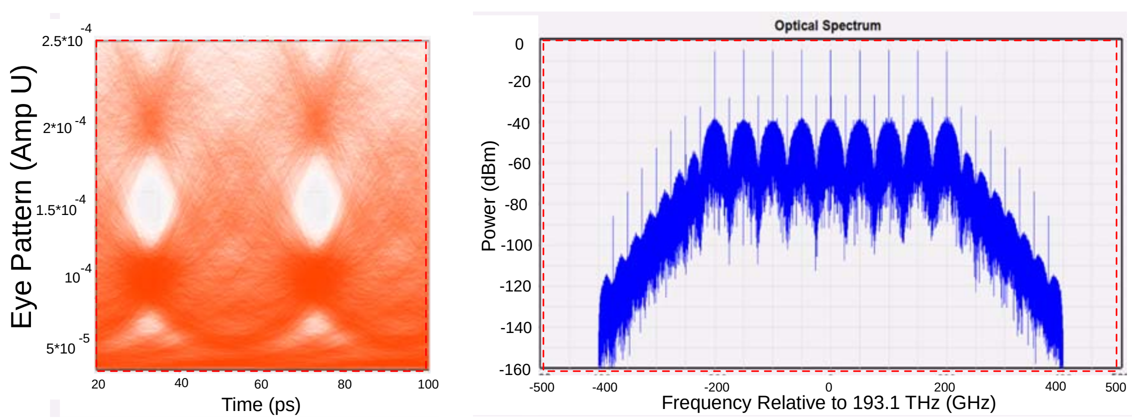

Figure 21 - 9x25 Gbps OOK-NRZ WDM channels without dispersion compensation

Each channel is transmitting at 0 dBm over 40km of SMF-28 fiber without dispersion compensation. The channel spacing was 50 GHz and used a 4th order Gaussian optical de-multiplexing filter (1.5*25G). with a 25 GBaud symbol rate.

The difference lies in that on Figure 20, dispersion compensation was used and Figure 21 shows performance of the center channel when no compensation was used. This clearly highlights the need for dispersion compensation. Next, scenarios with a channel spacing of 100 GHz are examined and shown in Figure 22 and Figure 23. Again there is a significant difference between operation with dispersion compensation and without dispersion compensation. What is worth noting is that Figure 23 shows a much cleaner eye pattern than Figure 20 where the only difference is the channel spacing. This highlights the fact that in spite of the high quality optical de-multiplexing filter (4th Order Gaussian) there is still benefit from further separation of the optical channels.

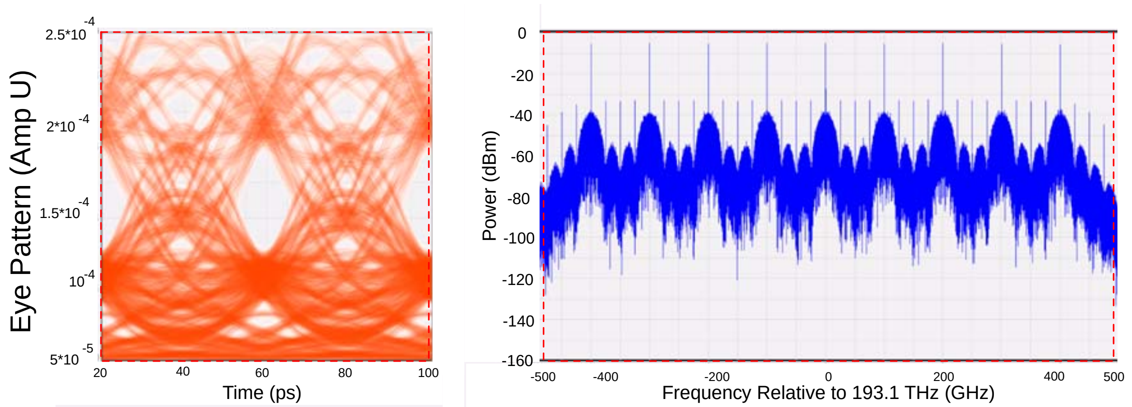

Figure 22 - 9x25 Gbps OOK-NRZ WDM channels without dispersion compensation

Each channel is transmitting at 0 dBm over 40km of SMF-28 fiber without dispersion compensation. The channel spacing was 75 GHz and used a 4th order Gaussian optical de-multiplexing filter (1.5*25G). with a 25 GBaud symbol rate.

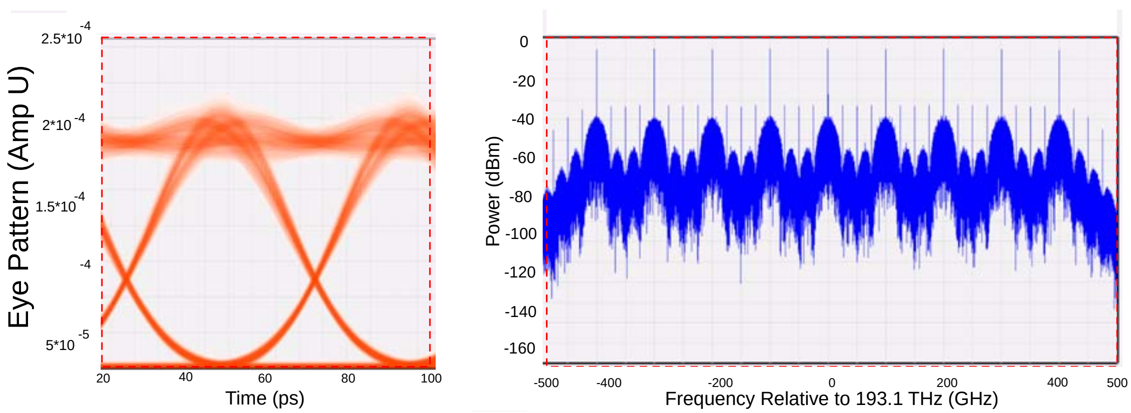

Figure 23 - 9x25 Gbps OOK-NRZ WDM channels with dispersion compensation

Each channel is transmitting at 0 dBm over 40km of SMF-28 fiber with dispersion compensation. The channel spacing was 100 GHz and used a 4th order Gaussian optical de-multiplexing filter (1.5*25G). with a 25 GBaud symbol rate.

The key characteristic for wavelength multiplexing of non-coherent transmissions are the generated side-lobes and the potential crosstalk that these side-lobes impose on adjacent carriers as the simulations have shown.

The above simulations assumed 25 Gbps NRZ transmission. This would ideally require a laser diode with a 25 GHz frequency response which would be pushing the limit of maximum frequency response that directly modulated lasers can achieve. Alternatively, to achieve this rate a laser with a frequency response of 20 GHz or lower could be used along with a pre-distortion or electrical compensation circuitry. A third option would be to have the laser diode followed by an external modulator that would not suffer that frequency limitation.

If higher peak rates per wavelength are not required, multiple 10 Gbps NRZ modulated optical carriers could be used instead. A 10 Gbps optical carrier would be able to fit in a 25 GHz channel. Assuming that the entire 5000 GHz in the C-Band is available, this would facilitate transmission of 200 optical carriers for a total of 2 Terabit/per second capacity. The 25 Gbps NRZ modulated optical carrier would be able to occupy a 50 GHz as long as dispersion compensation, filtering and wavelength control techniques are used. In the C-Band, that results in 100 optical carriers for a total of 2.5 Terabit/per second capacity.

If higher peak rates per wavelength are required using non-coherent techniques multilevel modulation format could be used. As shown in Figure 14 the SNR required with non-coherent PAM 4 (4 levels, 2 bits/symbol) is quite high. In different access network scenarios this SNR is still within reach although increasing power levels and/or increasing channel spacing may be required. For the most part non-coherent digital transport transmits at much lower power levels than analog optics, and nonlinear behavior caused by non-coherent transmission types is not expected.

9. Multi-Wavelength Coherent Digital Optics Coexistence

The third optical transmission type analyzed for use in the cable access network is coherent transmission. Coherent optical links have been used extensively in long haul networks and are being introduced in the metro environment. The highest speeds over fiber on a single wavelength or over multiple wavelengths have been achieved using coherent technologies. The coherent optical components shown in Figure 6 and Figure 7 show higher complexity than components used in non-coherent applications. However as higher speeds are required, and advances in integration continue, the cost per bit of a coherent optical links will become lower than alternative options. The key question is which use case scenarios will demand these high bandwidths and when. Like in previous transmission types, 9 evenly spaced coherent links are analyzed. In all simulations, a 40 km SMF-28 fiber was used carrying a 16-QAM signal with a 32 GBaud symbol rate. Figure 24 and Figure 25 show the 9 channels with a channel spacing of 75 GHz using a raised cosine filter with roll-off factor equal 0.25. In Figure 24, the optical power per channel is 0 dBm and -10 dBm in Figure 25.

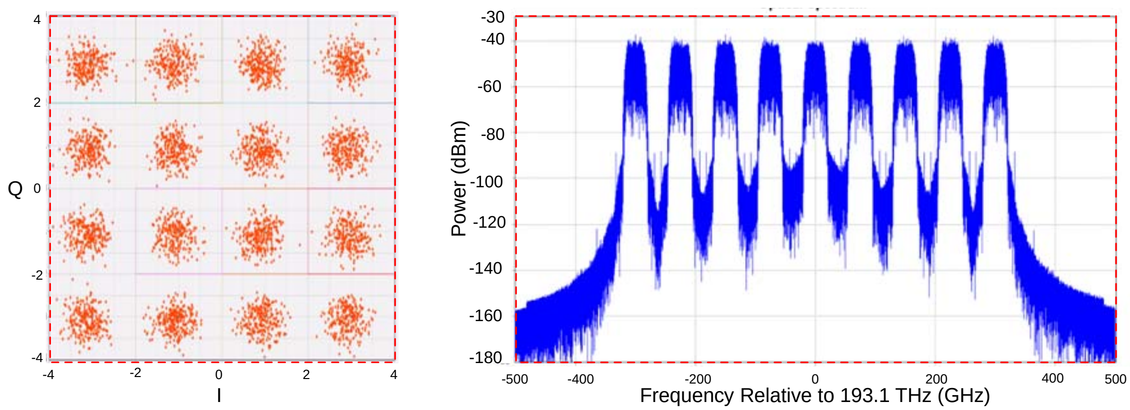

Figure 24 - 9x256 Gbps 16-QAM WDM coherent carriers with 0 dBm optical power

Each channel is transmitting at 0 dBm over 40km of SMF-28 fiber with dispersion compensation. The channel spacing was 75 GHz and used a raised cosine roll-off factor of 0.25 and a 32 GBaud symbol rate.

The constellation for the 0 dBm scenario is cleaner than the -10 dBm scenario, but keep in mind that at this point no error correction has been applied. In both cases off-the-shelve error correction could be introduced to generate error free performance.

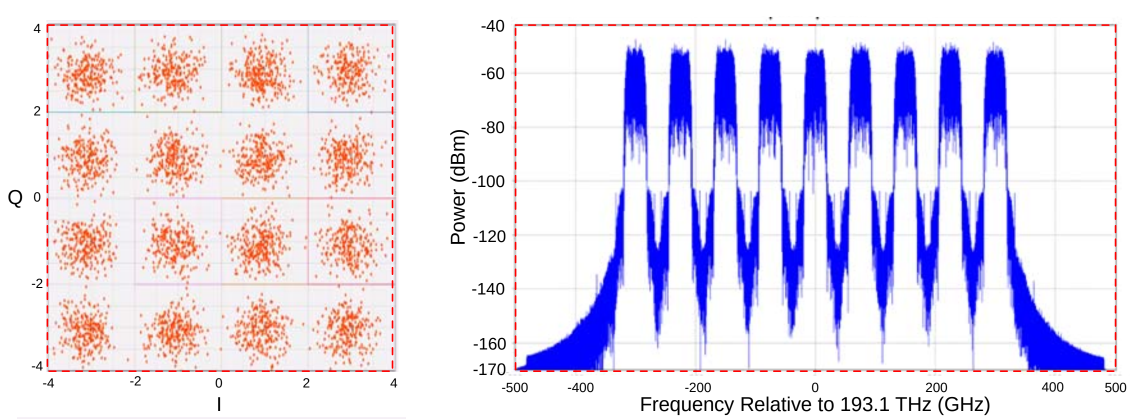

Figure 25 - 9x256 Gbps 16-QAM WDM with -10 dBm optical power

Each channel is transmitting at -10 dBm over 40km of SMF-28 fiber with dispersion compensation. The channel spacing was 75 GHz and used a raised cosine roll-off factor of 0.25 and a 32 GBaud symbol rate.

Figure 26 and Figure 27 show 9 optical carriers with a channel spacing of 50 GHz. The difference between Figure 26 and Figure 27 is that in Figure 26 the roll-off factor is 0.25 while in Figure 27 the roll-off factor is 0.5. Both constellations are clean enough for error free correction with off-the-shelf FEC.

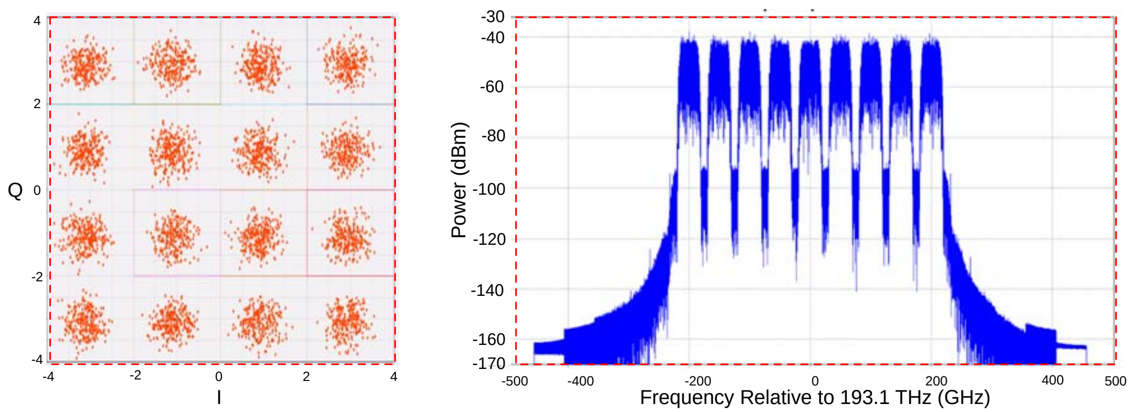

Figure 26 - 9x256 Gbps 16-QAM WDM with roll-off factor of 0.25

Each channel is transmitting at 0 dBm over 40km of SMF-28 fiber with dispersion compensation. The channel spacing was 50 GHz and used a raised cosine roll-off factor of 0.25. and a 32 GBaud symbol rate.

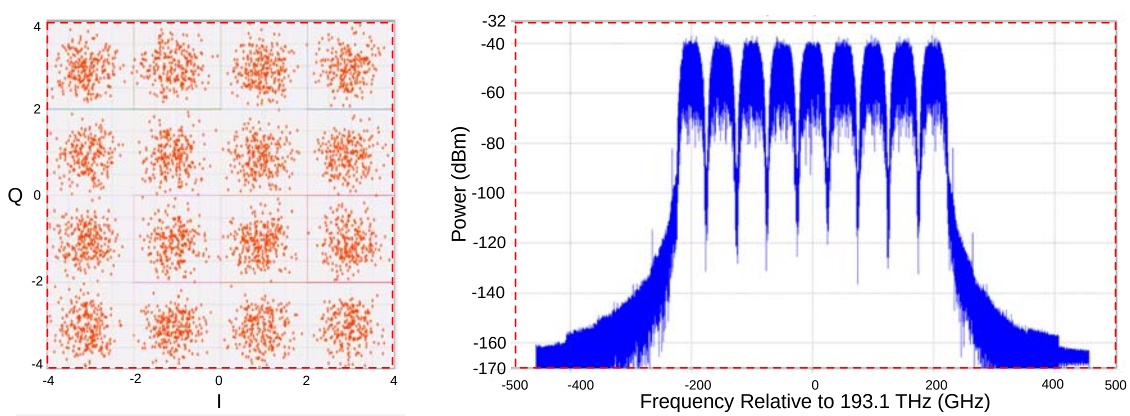

Figure 27 - 9x256 Gbps 16-QAM WDM with roll-off factor of 0.5

Each channel is transmitting at 0 dBm over 40km of SMF-28 fiber with dispersion compensation. The channel spacing was 50 GHz and used a raised cosine roll-off factor of 0.5. and a 32 GBaud symbol rate.

For the same bit rate due to the higher efficiency of coherent technologies with respect to non-coherent approaches, the coherent symbol period is larger than non-coherent symbol period and more robust to dispersion than non-coherent. Nevertheless, in 40 km there is only limited dispersion compensation required compared to long haul systems which represent a significant reduction in complexity compared to long haul. Coherent technologies also enable polarization multiplexing which doubles capacity. If polarization multiplexing is assumed in each of the 9 carriers, the total bandwidth carried becomes 9 chx32 Gbaud x4 bits/symbolx2 pol = 2.3 Tbps which is the capacity calculated earlier for 100 25 Gbps non-coherent carriers occupying the entire C-Band.

10. Multi-wavelength analog optics, non-coherent and coherent digital optics coexistence

The previous analysis highlights the importance of assessing the impact of the different types of optical carriers on the same optical fiber strand. CableLabs is incorporating this previous analysis in a tool that not only would analyze the impact of similar transmission types but also of heterogeneous transmission format. Figure 28 shows the GUI of this tool which intends to help operators manage and configure their optical transport resources.

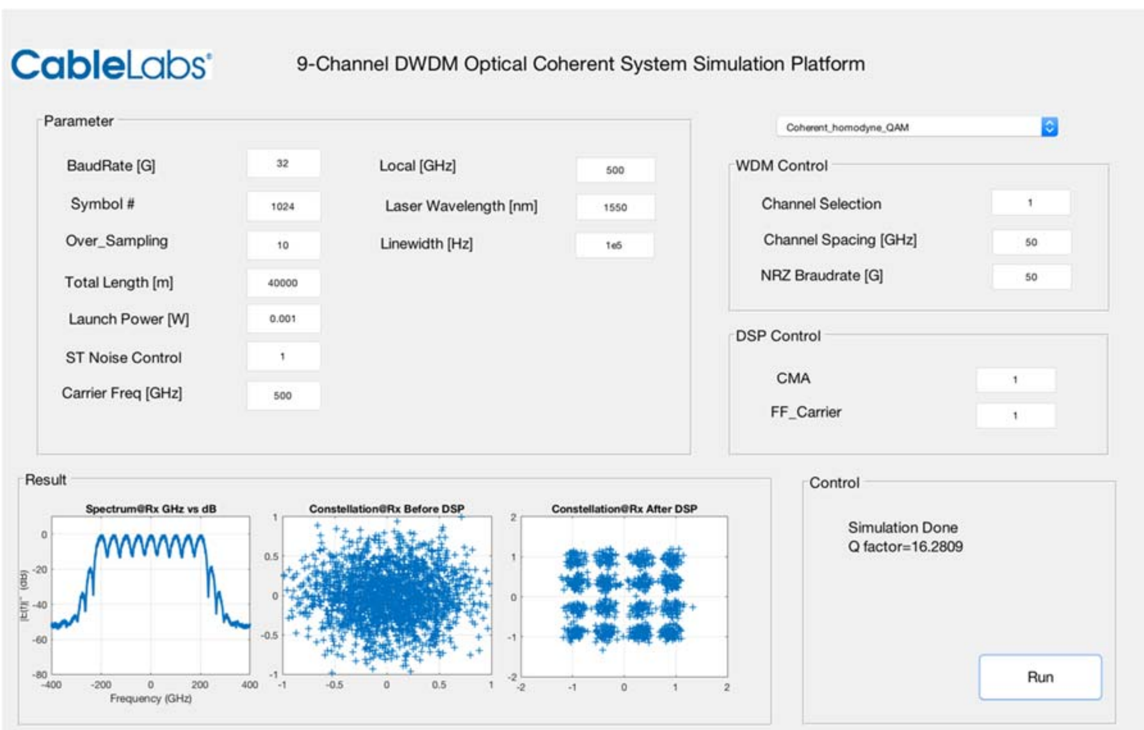

Figure 28 - CableLabs simulation tool to assess performance and coexistence

The findings obtained from the previous analysis indicate that the analog optical carriers are the ones with higher impact on the noise environment across the spectrum available in a fiber strand.

In the access environment, digital non-coherent and coherent optical carriers transmit at much lower power levels , do not cause fiber nonlinearities and spill over energy to other channels. As long as they are properly filtered and their wavelength stability is controlled, digital carriers are good neighbors within the optical fiber spectrum. In particular, coherent techniques have the highest sensitivity which enable transmission at the lowest power levels, and populate fiber with largest number of optical carriers and in the most efficient manner.

The strategy proposed to optimize fiber utilization in the access using different transmission format types is to first introduce the analog channels, optimizing their spacing to minimize interference to adjacent channels in particular, and fiber spectrum in general. This assumes that there is flexibility in selecting the wavelengths of the optical carriers. The analog channels would determine the noise floor across the band. Based on signal to noise ratio requirements for the different transmission formats and associated power levels required, the rest of the fiber spectrum would be populated. The more robust transmission formats like NRZ or QPSK coherent would occupy regions with elevated noise floor, such as channels adjacent to analog channels or channels impacted by FWM. Finally, the other channels would be introduced so that minimum optical transmit power and maximum SNR margin is achieved. Figure 29 shows an illustration of how the different optical carrier types could be distributed across the fiber spectrum

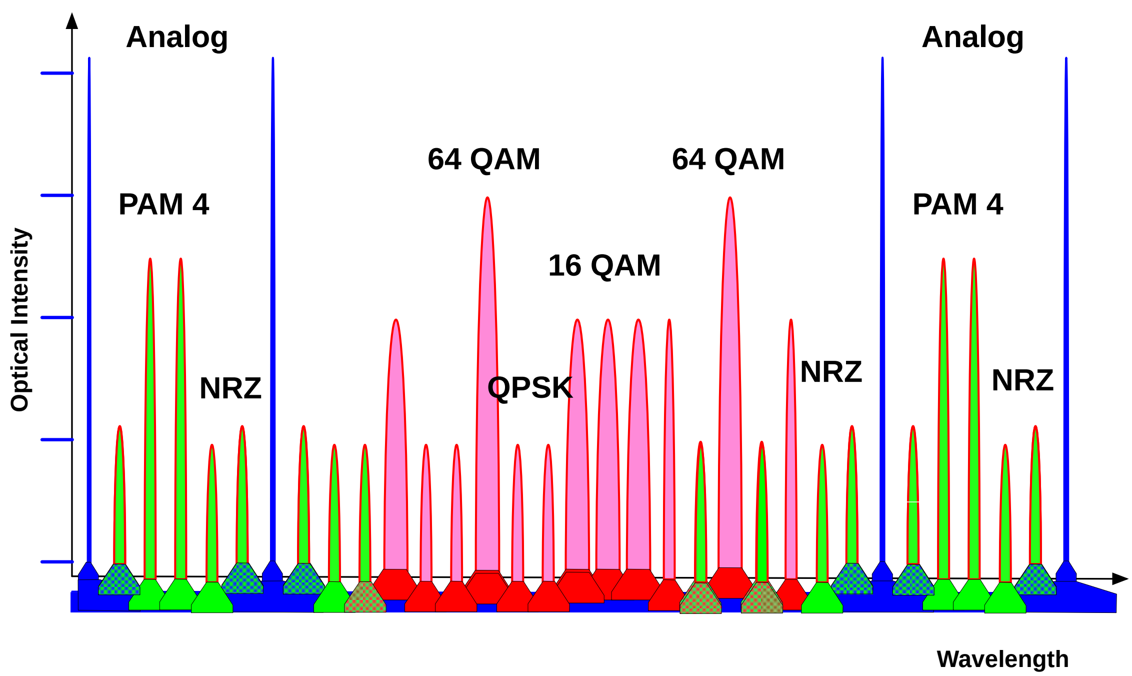

Figure 29 - Optical fiber spectrum with simultaneous transmission of a diversity of optical modulation formats.

Conclusion

This paper analyzed the different optical transmission formats that are and could be used in the access network. Through intelligent placement of the optical carriers within the fiber spectrum and careful transmission parameter configuration of the different optical links, effective sharing of the fiber resources is not only feasible but highly desirable. Limited fiber availability is at a premium and fiber retrenching may only make sense for few very high margin business services.

The metrics to control include, optical power level, wavelength position and stability and type of optical transmission format. The three transmission formats analyzed here include analog optics, non-coherent digital optics and coherent digital optics.

The analog optical links require the highest optical power levels and are the ones that introduce higher levels of nonlinear distortion and noise across the optical fiber spectrum. In this shared fiber spectrum environment, analog optical links would always have to use optical de-multiplexing filters. This analysis also shows that if multiple analog optical carriers are to be used in the same fiber, the degradation in performance would not allow to fully utilize the capabilities of next generation HSD protocols like DOCSIS 3.1. In a DWDM environment, directly modulated optical links would limit transmission to 1024 QAM at best. The alternatives to enable full DOCSIS 3.1 capabilities would be to introduce a different transmitter technology such as externally modulated transmitters, or to introduce remote CMTS or remote PHY architectures. These architectures use Gigabit Ethernet connectivity and would increase the number of non-coherent links in the access network.

Digital optical transmission was simulated and analyzed in detail. The non-coherent NRZ links were the least complex, but were not as efficient and as scalable as coherent solutions. The coherent links showed much higher performance, higher efficiency and significant scalability and future proofing. Coherent optics technology is also the technology with the highest sensitivity, the technology requiring lowest transmit power, and the best neighbor to implement wavelength multiplexing using heterogeneous modulations formats.

Just like in the RF domain where tight coexistence of RF carriers in the 1 GHz RF spectrum was achieved, in the optical domain operators have to develop know-how and best practices. Significant performance monitoring needs to be added. Optical links need to include optical filters, temperature and power control circuitry to maintain the wavelengths at the desired values. The alternative to this approach is fiber retrenching which is costly, cannot be cost justified except for the highest margin business use cases, and if at all possible must be avoided.

As the spectrum of analog optics in the optical fiber is reclaimed, higher capacity digital optics can be introduced. The ultimate goal is to re-use the same fiber infrastructure to connect to deeper fiber nodes, business customers, base stations and wireless access points, and eventually directly to residential customers.

Abbreviations

A/D	analog to digital converter
CNR	carrier to noise ratio
CPM	cross-phase modulation
CSO	composite second order (distortion)
CTB	composite triple beat
dB	decibel
dBm	dB milliwatt
DFB	distributed feedback (laser)
EPON	ethernet passive optical network
FEC	forward error correction
FP	Fabry-Perot (laser)
FWM	four-wave-mixing
Gbps	gigabit per second
GHz	gigahertz
HFC	hybrid fiber-coax
HSD	high speed data
I	in-phase
km	kilometer
LD	laser diode
LED	light emitting diode
LO	local oscillator
LPF	low pass filter
MHz	megahertz
MZM	Mach-Zehnder modulator
nm	nanometer
NPR	noise power ratio
NRZ	non-return zero
OOK	on-off keying
PAM	pulse amplitude modulation
PHY	physical layer
PMD	polarization mode dispersion
Q	in-quadrature
QAM	quadrature amplitude modulation
QPSK	quadrature phase shift keying
RF	radio frequency
RFoG	RF over glass
RIN	relative intensity noise
RS	Reed-Solomon (FEC)
RZ	return to zero
SER	symbol error rate
SNR	signal to noise ratio
SPM	self-phase modulation

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