Proactive Network Maintenance Evolution to the Optical Domain in Coherent Optics

A Technical Paper prepared for SCTE•ISBE by

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Introduction

Proactive network maintenance (PNM) in the HFC environment has taken advantage of the intelligence available in cable network elements such as the CMTS and CM, as well as plant information to determine type, severity, and location of the impairment. As fiber penetrates deeper in cable networks, the portion of transmission that takes places over coaxial cable is reduced and the resulting fiber networks become more elaborate. In these fiber networks, a fiber bundle branches into more paths to reach these deeper points. Next generation optical systems will have to be deployed in this new optical transport environment. This new optical transport environment will have a greater number of short optical segments that will likely be subjected to more handling as numerous optical drops to customers are installed. This requires enhanced troubleshooting tools as well as very granular data from the optical distribution plant in order to extract the valuable information needed to perform PNM troubleshooting.

Luckily, as the cable industry prepares to introduce coherent optics into its access networks, we have a transport mechanism that enables rich intelligence through the numerous processes that take place within the transceivers. These processes, combined with information gathered with other instruments, plant topology, and device configuration knowledge, can lead to detailed information regarding location, nature, severity, and duration of the problem.

Drawing on similarities from the coaxial PNM predecessor, maintaining high-order optical modulation profiles will require more scrutiny and maintenance than traditional analog and digital optical systems. When operating significantly higher data rates and service level agreements (SLA), many of the impairments that are commonplace within the optical domain will need to be maintained to a higher standard. This is especially important when considering some critical business services such as medical and mobile/cellular backhaul. These PNM capabilities will provide continuous reporting about the availability and quality of the optical links to support the SLA agreements of these services. Most importantly, operators can have a full awareness of problems before they impact the services, and provide an opportunity to proactively mitigate them.

1. Optical Network Topology and Network Elements

1.1. Optical Network Topology

When cable fiber networks were initially implemented in the mid 1990s, they used a tree and branch architecture, both in the fiber and the coaxial parts of the network. Figure 1 shows the fiber portion of the distribution network, extending from hub to fiber nodes, in addition to the interconnecting regional or metropolitan fiber networks typically in a ring configuration.

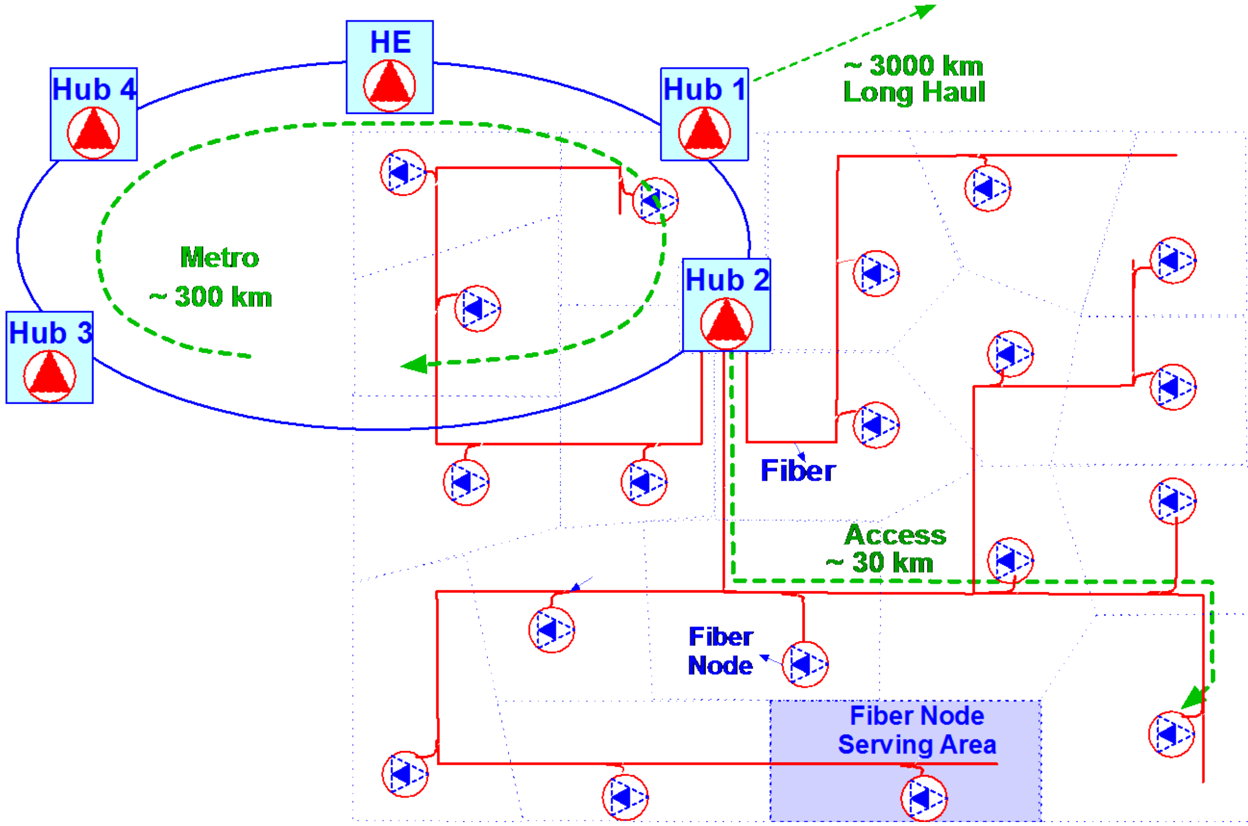

Figure 1 – Regional and Access Networks Connecting to Backbone

1.2. Optical Access Distribution Environment

Prior to embarking in a discussion of cable fiber topology, it is worthwhile to become familiar with the terminology related to how fiber strands are aggregated and carried though cable networks. Fiber strands are grouped in bundles or tubes, and these bundles or tubes are grouped in sheaths. In the case of underground infrastructure, operators deploy conduits through which the sheaths of fiber are blown. The bundles of fiber typically consist of either 12 or 24 fibers. Each fiber and bundle is color-coded to facilitate their management and manipulation (Figure 2).

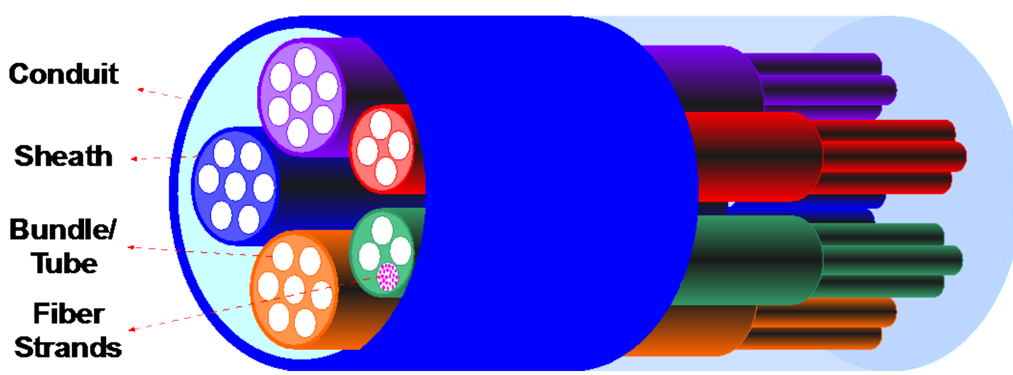

Figure 2 – Schematic Representation of Fiber Sheaths in Conduit

The fiber access networks extend from the hub or headend to the fiber node. These fiber links are typically laid out by running fiber sheaths with fiber bundles that pass different nodes. From a fiber splice point near a fiber node, a fiber jumper cable with fewer fiber strands is trenched or strung to the node. In the initial HFC buildout, six to eight fiber strands were typically dedicated to a node. Most fiber distances from node to hub are less than 40 kilometers, although in a few areas (where hubs may have been consolidated) distances may reach 120 kilometers. Figure 3 shows in greater detail a representation of the fiber access network extending from hub to nodes.

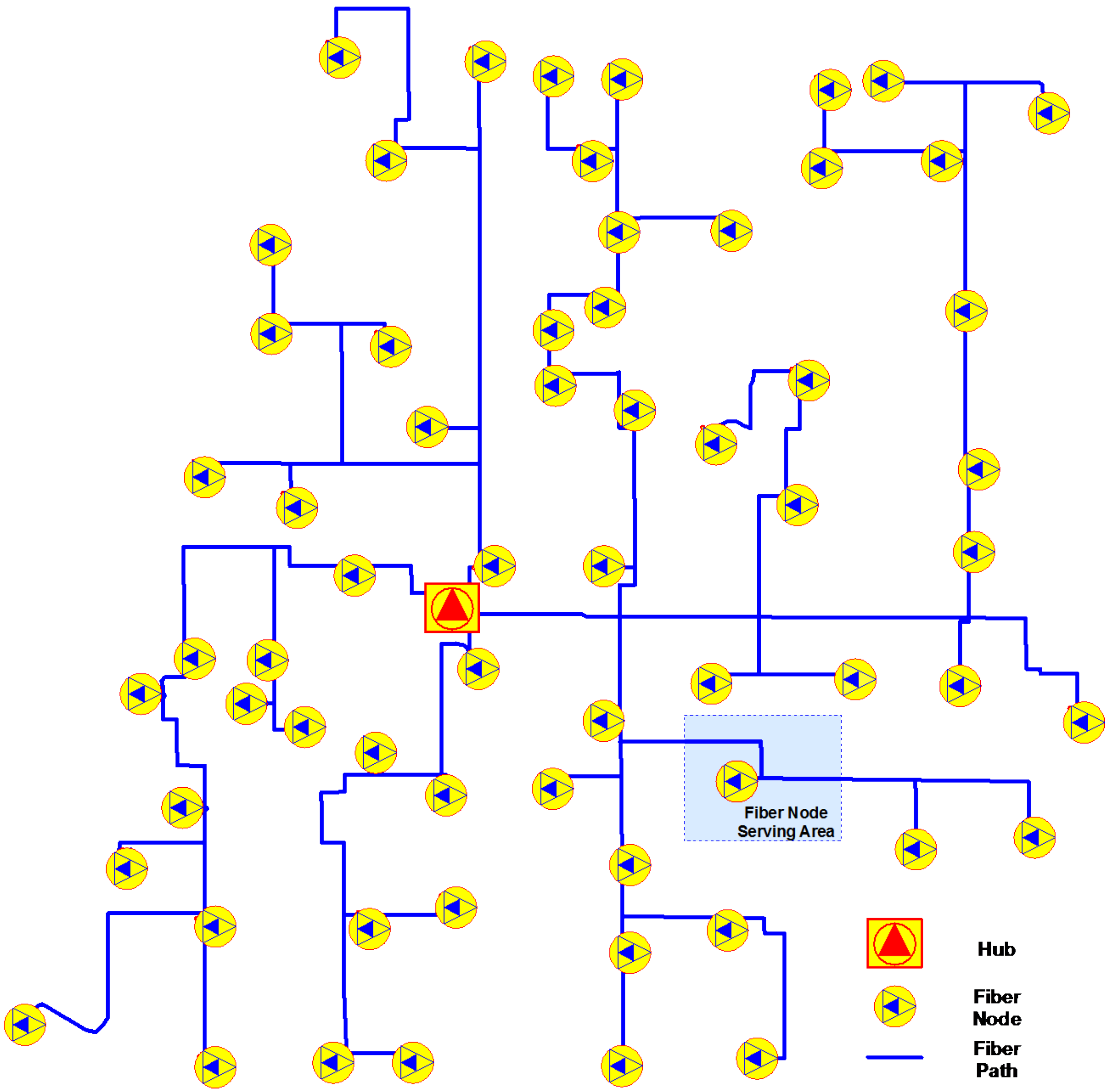

Figure 3 – Cable Access Network Topology Example

The shaded region in Figure 3 represents a traditional fiber node serving area. This fiber node serving area, shown in more detail in Figure 4, extends coaxial cable segments from the fiber node with a few amplifiers in cascade before reaching the subscriber. In addition to the amplifiers that maintain the RF signals at suitable levels, the coaxial cable segment uses taps (green squares in Figure 4), which couple RF energy to the drop cable that connects to the customer premises. It is important to note that while the fiber distribution network exhibits a tree and branch topology, from a connectivity perspective, the optical link between the hub and fiber node is a point-to-point link. It is important to be aware of, and to be able to determine, all the points in the fiber distribution network where the fiber paths bifurcate, as well as any changes in the number of fiber strands within consecutive sheaths of fiber along a transmission path. Transitions from one sheath to another at these points could potentially become problem areas in the future, requiring troubleshooting and maintenance.

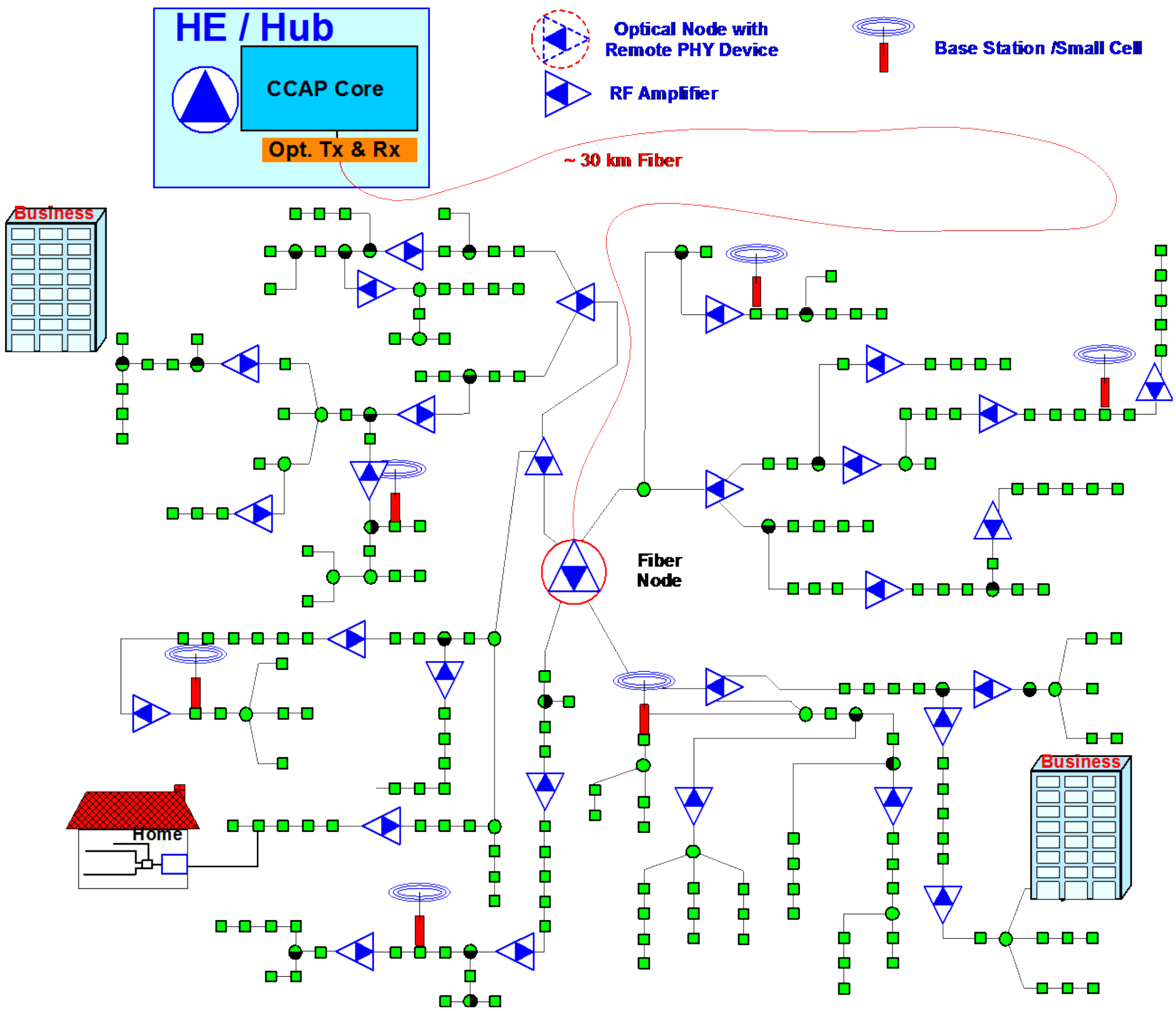

Figure 4 – Traditional HFC Fiber Node Topology

An architecture evolution approach to address the increasing demand in capacity is achieved by segmenting or splitting the fiber node serving area into smaller sections. The evolution of the same legacy node, shown in Figure 4, into an N+0 architecture, a fiber node followed by zero amplifiers, is shown in Figure 5.

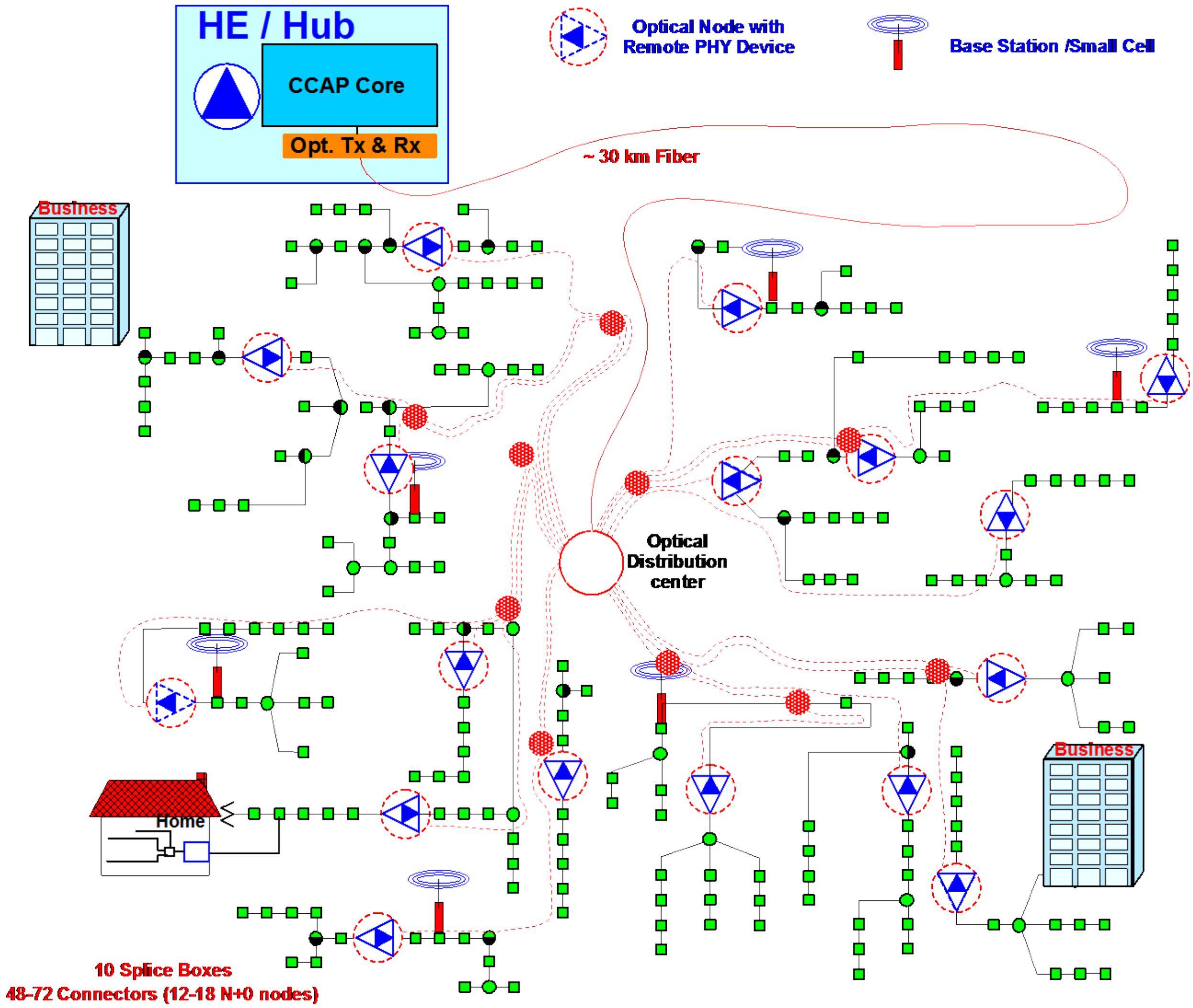

Figure 5 – N+0 Fiber Deep Network Topology

The upgrade of a traditional node into an N+0 architecture typically results in 12 to 18 deeper nodes. The motivation to push fiber deeper is twofold: To better serve residences with increased capacity, and to provide connectivity to businesses, cellular base stations, and wireless access points.

As depicted in Figure 5, the upgraded or "legacy" fiber node no longer serves as a location to transition to RF signals from an optical signal and vice versa, and instead becomes an optical distribution center, or ODC.

Deeper fiber penetration results in a more intricate distribution network that generally terminates within 1,000 feet of residences. The intricacy comes from relatively short fiber sheaths that subdivide into lower count fiber sheaths, and those subdivide again into even lower fiber count sheaths. In fiber-to-the-home (FTTH) or fiber to the end user scenario, it is from these lower fiber count sheaths that fiber drop cables are laid to connect to the endpoints.

While longer, uninterrupted fiber segments connect hub-to-node or hub-to-hub, as fiber reaches closer to homes, the fiber segments are much shorter. There is also an abundance of points where the fiber has been physically manipulated and spliced, therefore there are also many points with a higher likelihood of failure. As fiber penetrates deeper, the fiber topology begins to resemble the original cable topology, from the perspective of splits and segment lengths. That's one reason why it's vital to have granular location information about fiber plant and transceivers. With granular location information, it's easier to determine where problems exist, and their nature, so as to be better prepared in solving them.

A fiber distribution network generally runs a few dedicated fibers from the hub to the "legacy" fiber node, but an evolved network will likely have many more fiber strands from the "legacy" fiber node to deeper points in the network. At this legacy fiber node or optical distribution center (ODC), some optical signal manipulation will likely be conducted. The signal at the legacy node could be translated into the electrical domain by performing detection and retransmission, or it could remain in the optical domain and perform signal routing based on wavelength. Cost considerations and demand for capacity at the endpoints will determine what type of transition takes place at the ODC.

In the access environment, approximately 50% of the fiber is deployed underground and the rest is aerial. Aerial fiber is subject to wind movement, which can cause changes in state of polarization of a coherent signal. Other events that can generate changes in state of polarization (SOP) include lightning and arcing. The capability of adjusting and recovering after a sudden change in SOP is quantified in units of kilo-radians per second. Indications about whether the transceiver is compensating or adjusting for changes in state of polarization can provide insight into environmental conditions.

Link length is an important parameter when assessing coherent link budgets and the need of amplification. In addition to accurately determining the link lengths through topology maps, tools exist within the transceiver that accurately estimate the length of the optical link. Several impairments that need to be compensated for are dependent on the optical link length, and accurate estimation of these impairments can facilitate link length estimation.

In a limited fiber strand environment and with a diversity of services carried over cable networks, coexistence of a variety of optical signal types over the same fiber is necessary. The signal types in cable fiber networks include analog optics, non-coherent digital optics, and coherent digital optics. Analog optical signals are transmitted at very high optical output powers, which can drive fiber into non-linear behavior and impact the transmission of other signals on the same fiber. It is important to have an accurate wavelength map of all the optical carriers that reside within each fiber segment, including transmit optical power, signal path traversed and launched location. Accurate optical carriers' characteristics and wavelength information allow us to estimate the impact of non-linear distortion.

An example of the channel map on a fiber strand within a bundle and a sheath is shown in Figure 6.

Signal Wavelength Map for Fiber34/Sheath ID-45								Bundle/Fiber BR/BL	Length 14,000'
	Signal Type	Frequency Terahertz	Wavelength nm	Sheath Signal Type	Channel Width GHz	Launch Power dBm	Baud Rate/ Bandwidth GHz	Format Modulation	Signal Fiber Segments Association
O-Band									
	Analog US	229.0	1310				1	SCM	Fbr 34/SheathID-45, 1x40MuxID-33, Fbr 23/SheathID-15, Fbr2/JmprID-12
	IM-DD	222.2	1350				10	OOK	Fbr 34/SheathID-45, 1x40MuxID-33, Fbr 17/SheathID-67, Fbr2/JmprID-4
C-Band									
	Coherent	193.1	1553.60	CO_31	100	0	30	DP-QPSK	Fbr 34/SheathID-45, 1x40MuxID-33,Fbr 22/SheathID-15, Fbr2/JmprID-11
	Analog DS	193.2	1552.80	AN_32	100	12	1.2	SCM	Fbr 34/SheathID-45, 1x40MuxID-33, Fbr 23/SheathID-15, Fbr2/JmprID-12
	Coherent	193.3	1551.99	CO_33	100	0	30	DP-QPSK	Fbr 34/SheathID-45, 1x40MuxID-33, Fbr 24/SheathID-15, Fbr2/JmprID-13
	Coherent	193.4	1551.19	CO_34	100	0	30	DP-QPSK	Fbr 34/SheathID-45, 1x40MuxID-33, Fbr 25/SheathID-15, Fbr2/JmprID-14
	Analog DS	193.5	1550.39	AN_35	100	12	1.2	SCM	Fbr 34/SheathID-45, 1x40MuxID-33, Fbr 26/SheathID-15, Fbr 27/SheathID-25, Fbr2/JmprID-21
	Coherent	193.6	1549.59	CO_36	100	0	30	DP-QPSK	Fbr 34/SheathID-45, 1x40MuxID-33, Fbr 27/SheathID-15, Fbr 27/SheathID-25, Fbr2/JmprID-22
	Coherent	193.7	1548.79	CO_37	100	0	30	DP-QPSK	Fbr 34/SheathID-45, 1x40MuxID-33, Fbr 28/SheathID-15, Fbr 27/SheathID-25, Fbr2/JmprID-23
	Coherent	193.8	1547.99	CO_38	100	0	30	DP-QPSK	Fbr 34/SheathID-45, 1x40MuxID-33, Fbr 29/SheathID-15, Fbr 27/SheathID-25, Fbr2/JmprID-24
	Analog DS	193.9	1547.19	AN_39	100	12	1.2	SCM	Fbr 34/SheathID-45, 1x40MuxID-33, Fbr 14/SheathID-67, Fbr2/JmprID-1
	Coherent	194	1546.39	CO_40	100	0	30	DP-QPSK	Fbr 34/SheathID-45, 1x40MuxID-33, Fbr 15/SheathID-67, Fbr2/JmprID-2
	Coherent	194.1	1545.60	CO_41	100	0	30	DP-QPSK	Fbr 34/SheathID-45, 1x40MuxID-33, Fbr 16/SheathID-67, Fbr2/JmprID-3
	IM-DD	194.2	1544.80	IM_42	100	0	10	OOK	Fbr 34/SheathID-45, 1x40MuxID-33, Fbr 17/SheathID-67, Fbr2/JmprID-4
	Coherent	194.3	1544.00	CO_43	100	0	30	DP-QPSK	Fbr 34/SheathID-45, 1x40MuxID-33, Fbr 18/SheathID-67, Fbr2/JmprID-1
	Analog DS	194.4	1543.21	AN_44	100	10	1.2	DP-QPSK	Fbr 34/SheathID-45, 1x40MuxID-33, Fbr 19/SheathID-67, Fbr2/JmprID-2
	Coherent	194.5	1542.42	CO_45	100	0	30	DP-QPSK	Fbr 34/SheathID-45, 1x40MuxID-33, Fbr 20/SheathID-67, Fbr2/JmprID-3
	Coherent	194.6	1541.62	CO_46	100	0	30	DP-QPSK	Fbr 34/SheathID-45, 1x40MuxID-33, Fbr 21/SheathID-67, Fbr2/JmprID-4
	Coherent	194.7	1540.83	CO_47	100	0	30	DP-QPSK	Fbr 34/SheathID-45, 1x40MuxID-33, Fbr 22/SheathID-67, Fbr2/JmprID-5
	Coherent	194.8	1540.04	CO_48	100	0	30	DP-QPSK	Fbr 34/SheathID-45, 1x40MuxID-33, Fbr 23/SheathID-67, Fbr2/JmprID-6

Figure 6 – Fiber Segment Sample Description with Wavelength Map

In order to fully identify the path of an optical signal in an environment that includes detailed topology information and component configuration, the information required is the signal location (i.e., hub), the fiber and sheath identification, and the signal's frequency or wavelength. If the wavelength and the components that the signal traverses are known, as well as how those components have been configured to manipulate or route wavelengths, then the path traversed by the signal can be determined. Figure 7 provides a signal identification example using a name convention that uniquely identifies the signal path, which is also included with other parameters.

Signal ID	Fiber34/SheathID45_193.3_HubA
Launched fiber	Fiber34/SheathID45
Frequency/Wavelength	F_193.3 Terahertz /W_1551.99 nm
Signal Type CO/IM-DD/Analog	CO
Baud rate/ bandwidth	30 GHz
Launched power	0 dBm
Modulation /Bit rate	DP-QPSK
Signal path traversed	Fbr 34/SheathsID-45, 1x40MuxID-33, Fbr 24/SheathID-15, Fbr2/JmprID-13

Figure 7 – Optical Signal Descriptors

1.3. Optical Network Elements

Along the optical connection paths and at the end points, there exists a number of optical network elements that aid in the transmission from hub to an optical transmission end point. Figure 8 depicts the most prevalent components in the optical access network.

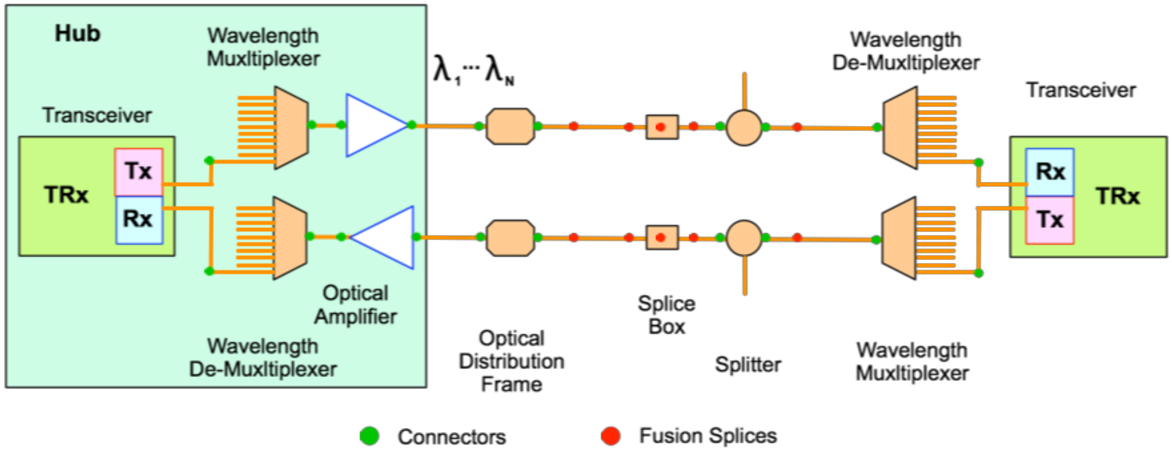

Figure 8 – Optical Network Elements along Hub and Endpoint Transmission Path

Depending of the type of optical transmission system, the transmitters and receivers may not be integrated in a transceiver as shown in Figure 8, but would be separate from each other, as is typically the case for analog optics.

Figure 8 does not include less frequently used components designed to facilitate monitoring or redundancy in the optical network. These include ROADMs, optical switches, wavelength switches, optical filters, attenuators, fiber drops, etc. In addition to the optical transport devices, the optical terminal devices are key elements of the optical distribution networks. Like their coaxial CM and CMTS equivalents, significant information can be extracted from these optical terminal devices regarding the health and characteristics of the optical network. Some key components of this optical distribution network are described next.

1.3.1. Optical Sources

The types of optical components used depend on the signal type in the optical link. The dominant optical links in cable access are the analog optical links. These are intensity-modulated links where the RF signal modulates the intensity of light to convey information through the RF modulated optical carrier. A second type of link used is a non-coherent digital optics link. They are also known as intensity modulation direct detection links (IM-DD), which are used in Gigabit Ethernet and GPON or EPON links. The third type of link is the coherent optical link. These are also digital optical links, but rely on a local oscillator as a reference at the receiver, and are able to distinguish phase and polarization information of the optical receive signal.

An analog optical link and an IM-DD link consist typically of a directly-modulated laser as the source, and a photodetector as the direct detection receiver. In longer links, the analog optics links may also be implemented using external modulation.

The coherent link transceivers are typically implemented using a complex external modulator called an IQ modulator. The key ingredient in a coherent link is the local oscillator laser at the receiver. At the receiver's photodetector, the incoming signal and the local oscillator signal beat together, generating a signal proportional to their product. This distinguishes the amplitude and phase information of incoming signals.

In analog optics, the linearity of the link is very important. When directly modulating the laser diode, the laser diode is operated at specific current and intensity levels such that it can take full advantage of its linear region. For maximum signal to noise ratio (SNR), the amplitude swing of the modulating signal is as large as possible without exceeding the linear range.

The laser diode biasing could become misaligned as the laser ages, or with temperature shifts that are not compensated. This sub-optimal biasing of the laser diode introduces non-linear distortion and degrades the signal. Sometimes the signal modulating the lasers exceeds the normal amplitude swing. Impulse and burst noise can cause these unwanted laser current amplitude swings, which also introduce distortion. This is called laser clipping and is typically seen in upstream transmissions. Interleaving incorporated in transmission systems is designed to overcome this type of impairments.

In order to achieve the high signal to noise ratio that is required to support DOCSIS 3.1 higher order modulations (16384-QAM and 4096-QAM), a very high optical transmit power is typically required. This high optical power level could drive fiber into nonlinear behavior and introduce distortion, particularly when multiple optical carriers are used.

Most of these problems are associated with an increase in codeword errors and a decrease in SNR and MER. Some of these distortion metrics can be assessed through optical and electrical spectrum analysis that show the generation of non-linear components. Laser clipping, for example, is detected when energy is generated above the maximum upstream frequency.

Diode lasers are resonant cavities that, depending on their design, can generate one or multiple modes of light. A simpler laser cavity like the Fabry-Perot laser has multiple resonant modes across the gain spectral region of the laser. Distributed feedback lasers significantly inhibit the generation of multiple modes through a periodic internal structure that is tuned to a specific resonant frequency. Other structures, like external cavity lasers, are more restrictive in the energy they generate. In later sections, the performance degradation attributable to the laser emission characteristics is discussed. Figure 9 provides a schematic representation of laser structures used in cable.

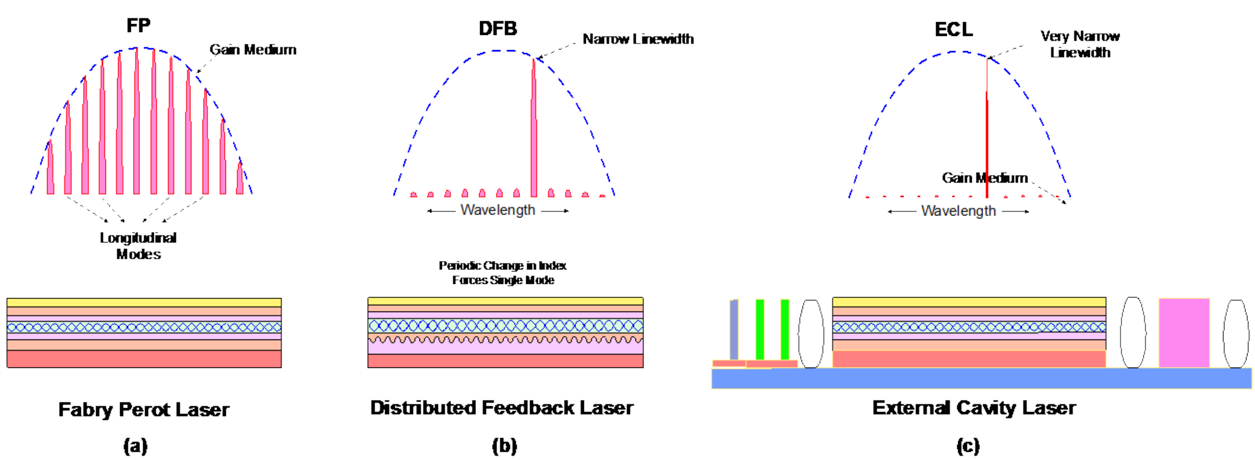

Figure 9 – Laser structures, a-Fabry Perot (FP), b-Distributed Feedback (DFB), and c-External Cavity (ECL)

The high dynamic range required in cable's multichannel environments prompted the use of Distributed Feedback (DFB) lasers in analog optics. DFB lasers are also used in non-coherent digital optics implementations, although they don't demand as high a dynamic range as do analog optics. Early in cable, the upstream signal path required only the transmission of a few channels, at low modulation orders. That allowed the use of the simpler Fabry-Perot (FP) laser, although in many instances FPs suffered from laser clipping, and as a result, the industry migrated away from them.

In certain cable upstream implementations, the RF spectrum was digitized and transmitted on IM-DD links, to overcome the distance limitations in analog links.

As part of the management information of the optical link types -- in addition to specifying whether the signals are analog, IM-DD or coherent -- it is worthwhile to go to a deeper description level and indicate in analog optics if the signals are externally modulated and in IM-DD if the signal is digitized RF.

Intensity Modulation Direct Detection (IM-DD)

Non-coherent digital optical links or intensity modulated direct detect (IM-DD) links typically use On-Off-Keying (OOK), that turns light intensity On and Off to encode information. In this type of modulation, linearity considerations are not critical. The receive sensitivity of the link and the transmit power level have to be such that after all the system losses, the signal to noise ratio is still appropriate for OOK transmission. Non-coherent transmission typically operates at lower power levels than analog optics, so fiber non-linearity is not an issue. In the future, non-coherent digital optical transmission could include multi-level signal transport using, for example, pulse amplitude modulation (PAM). PAM modulation, such as four level PAM-4, is sensitive to component linearity.

Coherent Links

External modulation is typically used in coherent links. The spectral purity of the laser signal enables the encoding and detection of both amplitude and phase information of the optical carrier. This spectral purity is quantified by measuring the laser linewidth. This is the 3 dB spectral width occupied by the unmodulated optical carrier. In coherent optical links the polarization can also be discriminated. All this allows for the encoding of information on an optical carrier in three dimensions; amplitude, phase, and polarization.

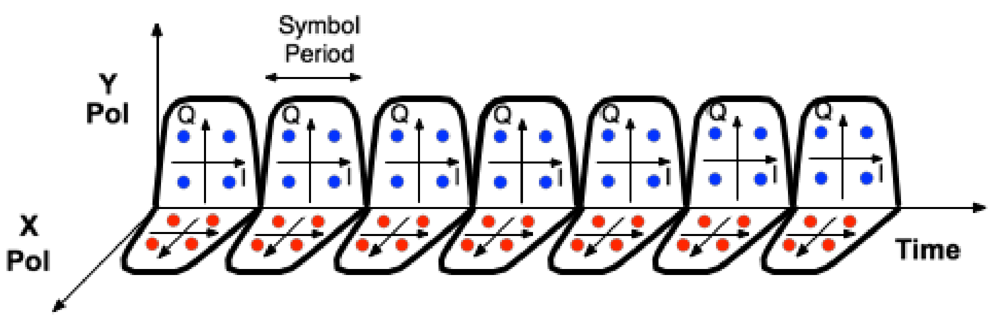

Figure 10 – Coherent Transmission using Amplitude, Phase, and Polarization

The modulator to encode information in these three dimensions onto light is the IQ modulator, shown in Figure 11.

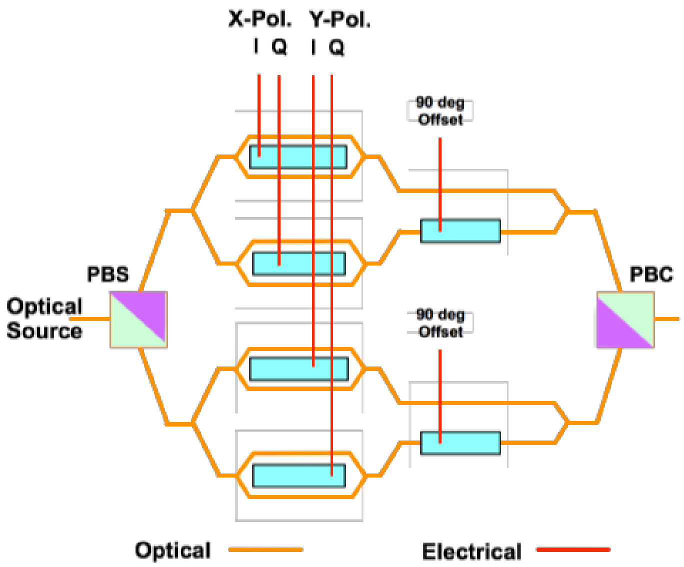

Figure 11 – Dual Polarization IQ Modulator

2. Optical Signals, Transmission Environment and Impairments

2.1. Point-to-Point (PTP) and Point-to-Multipoint (PTM)Transmission Environment

In each fiber strand there can be a multitude of optical signals that operating on different wavelengths share a portion or the whole optical path with other signals. Understanding the characteristics of this fiber access environment and its signals is critical in determining the performance of the optical links that reside and coexist within the fiber strand. There are different fiber-related impairments that can impact performance. Some of these impairments are fiber-length dependent, and some are dependent on fiber geometry, material, wavelength, bandwidth, and optical power level. In cable, even though the fiber cable paths follow a tree and branch topology, the actual fiber connectivity is point-to-point and no optical splitting or coupling takes place. There are, however, passive optical networks in residential green field scenarios, where RFoG technology is deployed, and PON networks predominantly deployed in business access. In both cases, these P-to-MP fiber networks are implemented using a 32- or a 64-way split.

2.2. Fiber Characteristics and Impairments

2.2.1. Attenuation

Attenuation in fiber is dependent on the wavelength or frequency. For the particular type of single-mode fiber typically used in cable access, the attenuation is 0.22 dB/km for 1550 nm transmission and 0.3 dB/km for 1310 nm transmission.

2.2.2. Chromatic Dispersion

Dispersion is one impairment associated with fiber length. Dispersion occurs when different portions of the signal travel at different speeds. As a consequence, there is a spreading of the signal over time. There are different types of dispersion: Chromatic, waveguide, modal, 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 cause 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), so fiber modal dispersion is not present and waveguide dispersion is negligible compared to chromatic dispersion.

2.2.3. 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 glass imperfections, such as circular asymmetry. PMD is compensated in the DSP of coherent receivers. Since PMD is distance-dependent, compensation for it provides another indicator for link distance estimation. Non-coherent receivers typically have no PMD compensation mechanisms and have to deal with PMD as part of their error correction techniques. This limits performance and link distance. PMD is not an issue in analog optical links, as the modulation bandwidth is about 1 GHz.

2.2.4. Nonlinear Effects

Nonlinear effects in fiber are attributable to intensity dependence of the refractive index fiber medium, and due to inelastic-scattering present at very high optical intensity levels.

These non-linear effects include self-phase modulation (SPM), cross-phase modulation (XPM) and four-wave mixing (FWM). The dominant non-linear effect in fiber is four-wave mixing. In four-wave mixing, if three fields are 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 instead dependent on frequency spacing and fiber dispersion. This effect is critical when multiple high power optical analog carriers are present on the same fiber. Maintaining a detailed fiber wavelength occupancy map --, including optical carrier types such as analog, IM-DD or coherent, optical carrier bandwidth, center frequency, modulation and optical power -- is important to estimate aggregate optical power and potential impacts to any carriers.

2.3. Optical Connectors and Splices

Optical connector and splices are incorporated through cable's fiber network to enable connectivity to the desired endpoints. Connectors are used at endpoint or at mid-point where reconfiguration is not expected. In cable analog optics, the stringent requirements to avoid optical reflection prompted the use of angle-polished or angle-faceted connectors. These connectors have a mating surface that is not perpendicular to the axis of the fiber, but is instead at an angle, so that any reflection leaves the core and vanishes. Other potential sources for reflections are suboptimal fusion splices. Even though these may rarely occur because of the large number of splices in the network, it is possible to find a few bad splices. Connector problems or splice problems can be detected using an Optical Time Domain Reflectometer (OTDR). Alternatively leveraging the coherent transceiver DSP capabilities, optical reflections, and other distortions can be detected, measured, compensated, and located in a similar fashion that equalization coefficient analysis is used to determine reflections in cable's coaxial environment. In the field, fiber patch panels and splices are housed in enclosures or splice boxes in cabinets or pedestals. Again, detailed records of the fiber-to-fiber mapping are important to troubleshoot and to follow the fiber connectivity paths throughout the cable network. These records should point to the wavelength occupancy map described above.

Many times there are sheaths with dissimilar fiber counts entering a splice box or cabinet. As an example, you may have a 312-fiber sheath, a 216-fiber sheath and a 48-fiber sheath in a splice box. This mismatch in number of fiber strands ($312-216-48 \neq 0$) leaves fiber strands available for future use. Good accounting and management of these available fibers and reclaimed fibers through the effective use of wavelength multiplexing provides the operators with significant long term fiber resources.

2.4. Optical Amplifiers

In cable, a majority of optical links are short enough to not require optical amplification. Nonetheless, a number of scenarios can exist, where optical amplification is necessary. In particular, as cable is moving to a WDM environment, in order to make more efficient use of fiber's wavelength spectrum, the additional loss of multiplexing, demultiplexing and other wavelength manipulation functions may require the introduction of optical amplifiers.

Some optical equipment incorporates an optical amplifier, but in other cases optical amplification is needed to overcome loss in the fiber path and to compensate for splitting, coupling losses, losses in wavelength multiplexing and other losses. An optical amplifier located immediately following the transmitter is called booster amplifier; one located in the optical distribution network is called an in-line amplifier; and one located just before the receiver is called pre-amplifier.

The most common optical amplifier used in optical transport networks is the Erbium-doped fiber amplifier (EDFA), while the semiconductor optical amplifier (SOA) and the Raman amplifiers are less common.

The EDFA functions by using two optical signals. One is the optical carrier to be amplified, typically carrying information, and the second one, which operates at a different wavelength, is used to excite the Erbium atoms to a high-energy state. When these excited atoms return to a lower energy state, they release photons at the same wavelength, phase and direction as the information-carrying signal, therefore amplifying the signal. The optical signal used to excite the atoms is called the pump signal.

The gain in Erbium-doped fiber (EDF) is not flat, so in many cases amplifiers include an optical filter that equalizes the signal by flattening the frequency response. Not all the photons generated are stimulated by the signal to be amplified -- some photons are spontaneously emitted and they contribute to noise. This noise associated with the optical amplification process is called Amplified Spontaneous Emission noise or ASE. Depending on the implementation, the noise figure may range from 4 dB to 7 dB.

EDFAs operate mostly in the C-band (1525 nm -1565 nm) but they can also be designed to operate in the L-band (1570nm-1610nm). Erbium can be excited using 980 nm and 1490 nm pump wavelengths. In low noise applications, 980 nm pump wavelengths are used. Non-linearities are also present in EDFAs, mostly in the form of gain saturation. The EDFA's capabilities, configuration, wavelength occupancy and aggregate power within the fiber have to be taken into account for proper operation. A basic design of an Erbium-doped fiber amplifier is shown in Figure 12.

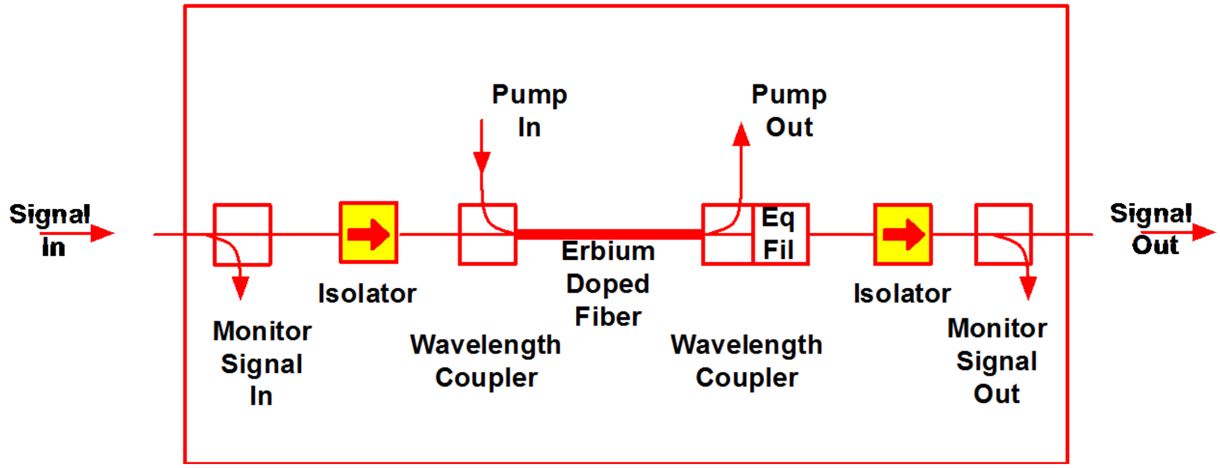

Figure 12 – Components of Typical Erbium-doped Fiber Amplifier

Raman optical amplifiers use stimulated Raman scattering, where light is scattered from a lower wavelength to a higher wavelength. Raman optical amplifiers are not practical by themselves, because they need extremely high optical pump powers (~30 dBm). They can, however, be used with EDFAs to implement ultralow noise amplification. An advantage is that the amplified wavelength is related to the pump wavelength, which provides more flexibility to amplify in different optical bands where other amplification methods may not be practical.

Semiconductor optical amplifiers (SOAs) work in a similar fashion as EDFAs except that, instead of an optical pump that brings the atoms into an excited state, it uses an electrical pump. With it, the electrons are brought to an excited state through the biasing of a semiconductor junction. These excited electrons release photons that are stimulated by the optical signal carrying information. SOAs have a similar structure as a laser diode except that SOAs do not have reflecting facets at both sides of the cavity. SOAs typically have medium gain (<20 dB) and low saturated optical power (<10 dBm). Since SOAs share a similar structure and operation as semiconductor lasers, SOAs are typically incorporated within transmitters or receivers.

2.5. Multiplexers and Demultiplexers

In the topology discussion of Section 1.1, we see that cable uses fiber that penetrates very deep, although there are not many fiber strands available at the endpoints. This prompts the industry to use fiber's wavelength spectrum very efficiently, so that a single fiber can carry a multitude of optical signals. This is accomplished by multiplexing optical carriers on the same fiber. In cable we deal with a diversity of signals. Analog optical signals, non-coherent, or intensity modulated-direct detect (IM-DD) signals and coherent signals -- must all coexist within the same fiber. A separate paper [1] assessing the coexistence of different optical signals in cable is also presented. A key component in the multi-optical carrier future is the wavelength multiplexer and demultiplexer.

A wavelength multiplexer filters specific wavelengths and routes and aggregates them to specific output ports. A wavelength demultiplexer distributes different wavelengths into different ports. Wavelength multiplexers and demultiplexers are bidirectional. Depending on how a device is configured and driven, it may function as a multiplexer, as a demultiplexer, or both.

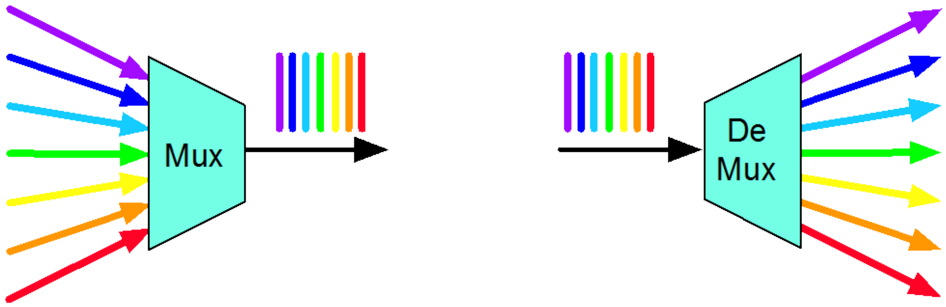

Figure 13 – Optical Wavelength Multiplexer and Demultiplexer

2.6. Optical Splitters and Couplers

In basic point-to-point optical links there is no need to split the optical signal. Where optical splitting becomes advantageous is when networks are point-to-multipoint. Cable systems tend to leverage PTM networks, PON networks, and RFoG networks. In the cases of PTM and PON, these P-to-MP fiber networks are implemented using a 32- or a 64-way split. In the case of RFoG, the signal that is typically shared among the 32 subscribers is the same RF signal over an optical carrier that an optical node would receive. Some of these 32-way split optical networks may be combined at the hub in order to have a suitable DOCSIS® and video serving group size.

Digital E-PON and G-PON networks are also used by operators, where fiber is again split in 32- or 64-ways, to provide connectivity to business or residential subscribers.

2.7. Isolators and Circulators

Isolators leverage polarization to allow only one direction of transmission, while circulators leverage polarization to force a signal to traverse the three-port circulator, following input-to-output rules where the signal's direction in the circulator depends on the direction of entry.

2.8. Optical Fiber Switches and Wavelength Switches

While optical switches are used today primarily for redundancy applications and automatic configuration, a greater need is expected for conducting wavelength manipulation in the access environment. As mentioned before, the condition of deep but sparse fiber penetration prompts the industry to look into very efficient usage of their wavelength spectrum. The way networks are evolving in cable is happening coincidentally with the advent of distributed access architectures (DAA). In the evolved fiber distribution network, there is a transition -- with dissimilar fiber counts coming into the legacy node or optical distribution center, and going out of the node, to deeper points in the network. In order to retain the flexibility in that portion of the network, wavelength manipulation may be needed. This could be static manipulation, through wavelength multiplexers or demultiplexers, or it could be flexible and agile, through wavelength switches. This wavelength manipulation functionality is used today in fiber backbones through reconfigurable optical add-drop multiplexers (ROADMs). In the access plant, conventional ROADMs provide much more functionality and capacity than what would be required at the node -- but in future and simplified implementations, with a subset of the functionality, they could play a role in the industry's access networks.

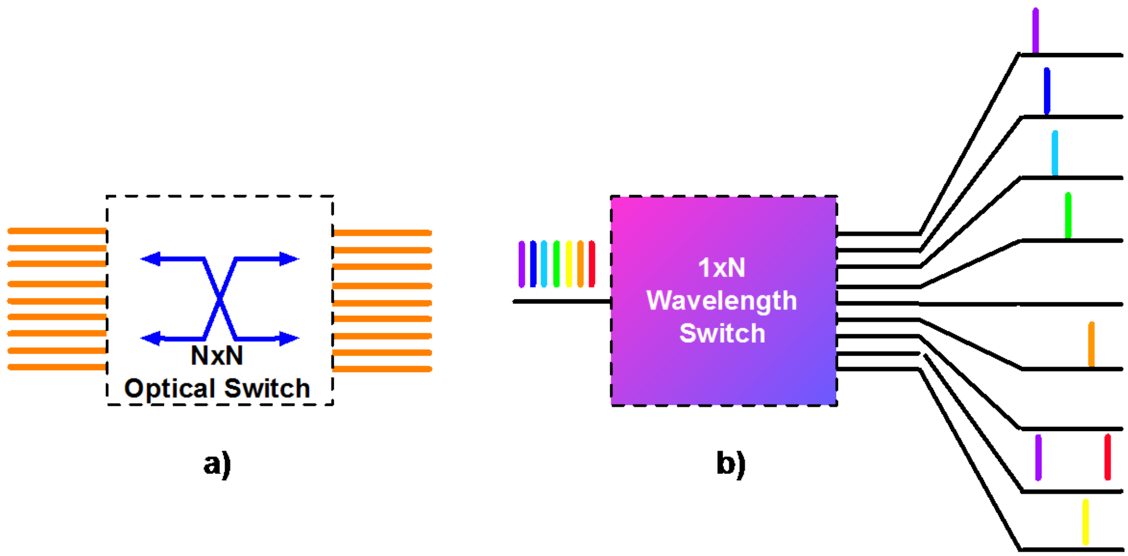

Figure 14 – NXN Optical Switch and a 1xN Wavelength Switch

2.9. Coherent Receiver

2.9.1. Digital Coherent Receiver Types

In a coherent receiver, a local oscillator (LO) is used to down-convert the electrical field of the incoming optical signal to a baseband intermediate frequency (f_{IF}). This coherent detection maps an entire optical field into the digital domain, therefore allowing the detection of the signal's amplitude, phase, and state of polarization. Depending on the intermediate frequency, defined as $f_{IF} = f_s - f_{LO}$, coherent receivers fall into three classes: Homodyne, intradyne and heterodyne, as illustrated in Figure 15, where $Bandwidth_s$ is the optical signal bandwidth.

Intradyne receivers are the de facto choice for contemporary 100G coherent systems. In an intradyne receiver, the f_{IF} is chosen to fall within the signal band by roughly aligning the f_{LO} with f_s. Intradyne detection allows the detection of both the in-phase and quadrature component of the received signal. For that reason, the intradyne receiver is also referred to as a "phase-diversity receiver." Digital phase locking algorithms are needed to recover the modulation signal from its sampled I and Q components; this requires high-speed analog-to-digital conversion and DSPs.

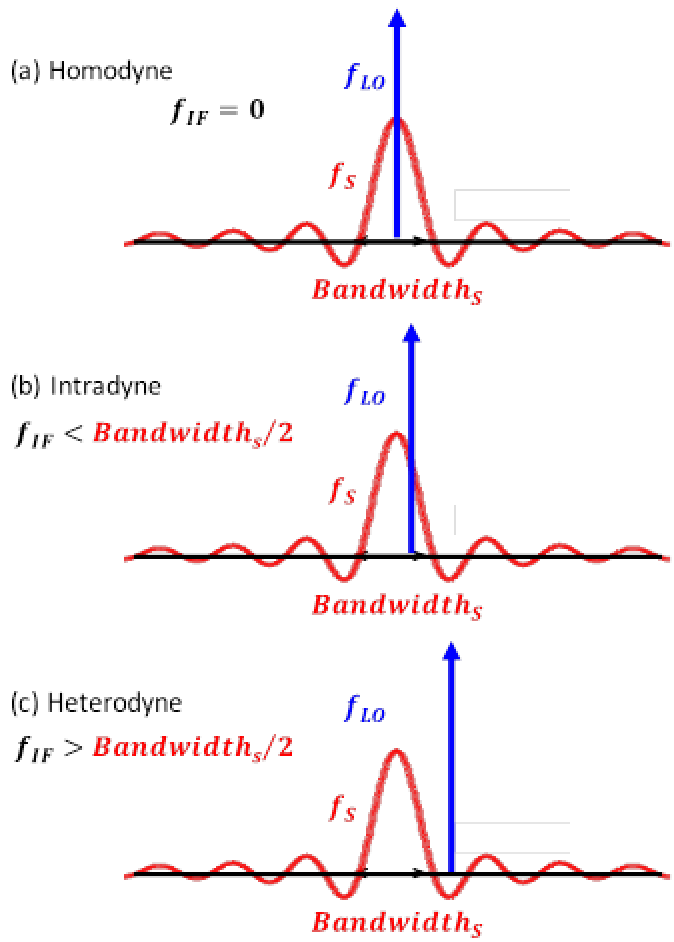

Figure 15 – Three Coherent Detection Schemes: (a) Homodyne, (b) Intradyne, and (c) Heterodyne

2.9.2. Coherent Receiver Architecture

In a coherent receiver, the modulated optical signal and a continuous wave LO beat together in the photo detector, generating a component proportional to the product of their electric fields which can be processed electrically. To detect both IQ components of the signal light, a 90° optical hybrid is utilized to provide a 90° phase shift between its direct-pass and cross-coupling outputs, which is used to discriminate between real and imaginary components of the optical signal. This is done for both polarizations. Balanced detection is usually introduced into the coherent receiver as a means to suppress the DC component and maximize the signal photocurrent.

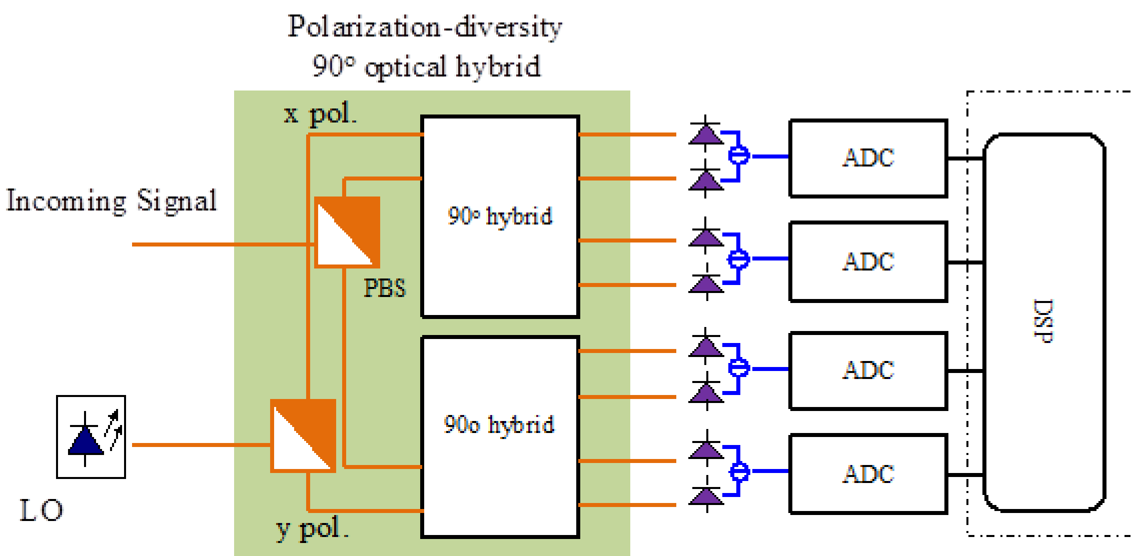

Figure 16 – Phase and Polarization Diversity in Coherent Receiver Architecture

The schematic diagram of a polarization multiplexed coherent receiver is shown in Figure 16. Both the incoming PM signal and LO are split into two orthogonal polarizations using a polarization beam splitter (PBS), after which the copolarized signal and the local oscillator are mixed in two 90° optical hybrids to produce an in-phase and quadrature component for each polarization. The four signals are then digitized by four analog-to-digital converters (ADC), after which DSP can be performed for signal demodulation.

2.10. Impairments Impacting Coherent Systems

There are impairments that impact the signal while it is in the optical domain, and there are impairments that are generated and impact the signal while it is in the electrical domain. Most of the electrical domain problems are related to the implementation of the system's transmitter and the receiver of the system, while many of the optical domain impairments are dependent on the fiber and related optical components along the optical connectivity path. Since the electrical impairments provide insight about the design but not about the plant, this paper places emphasis in the assessment and compensation of the optical impairments. Electrical and optical impairments are shown in Table 1 and in Table 2.

Table 1 – Electrical Impairments

Electrical frequency response
Impedance mismatches
Polarization imbalance and skew
In-phase and Quadrature (IQ) imbalance and skew
Transimpedance amplifier (TIA) and noise

Table 2 – Optical Impairments in Coherent Link

Linear distortion	Chromatic dispersion
	Polarization mode dispersion
	Optical reflections/multipath
	Group delay distortion
	Optical back reflections
	Filter narrowing effect
	Optical components frequency response
Non-linear distortion	Fiber non-linearities (i.e. four-wave mixing)
	Optical amplifier non-linearities
	Modulator non-linearities
Loss	Attenuation
	Insertion loss
	Polarization dependent loss
	Thermal noise
Noise	Shot noise
	Relative intensity noise
	Amplified spontaneous emission noise
	Optical back scattering

3. Optical Link Metrics and Link Characterization Tools

3.1. Optical Link Metrics

Different optical signal types have some common, as well as some unique, metrics that help to assess the quality and health of an optical link. Since many impairments do not change with wavelength, coherent links can be used to measure the health of IM-DD and analog optical links. The optical path may not be common from end to end between an analog, a non-coherent and a coherent optical signal, so when troubleshooting non-coherent and analog links, multiple coherent links may be needed to evaluate the entire non-coherent signal path. A list of useful optical link metrics is included in Table 3.

Table 3 – Optical Link Metrics

Optical Link Budget
Optical Signal to Noise Ratio (OSNR)/ Error Vector Magnitude (EVM)
Bit Errors/Symbol Errors
Pre-FEC BER
Post-FEC BER /Codeword Errors
State of Polarization Variation
Noise Figure
Linear Distortion - Reflections
Linear Distortion - Chromatic and Polarization Mode Dispersion
Link Length
Return Loss
Insertion Loss
Gain Compression (Including non-linear distortion)

3.2. Optical Link Characterization Tools

A diverse set of instruments exists that can be used in the analysis and troubleshooting of optical networks. Some popular instruments include:

Optical Power Meter

Optical Spectrum Analyzer (OSA)

Optical Time Domain Reflectometer (OTDR)

Optical Modulation Analyzer (OMA)

Optical Vector Analyzer (OVA)

The optical power meter consists of a calibrated photodetector, which, by knowing the responsivity of the photodiode versus wavelength, can accurately estimate the optical power level. Because the responsivity doesn't change drastically with frequency, it is sufficient to know the band of the optical signal in order to have a good estimate of the power level. The optical spectrum analyzer, on the other hand provides a detailed behavior of power versus wavelength or frequency (Figure 17).

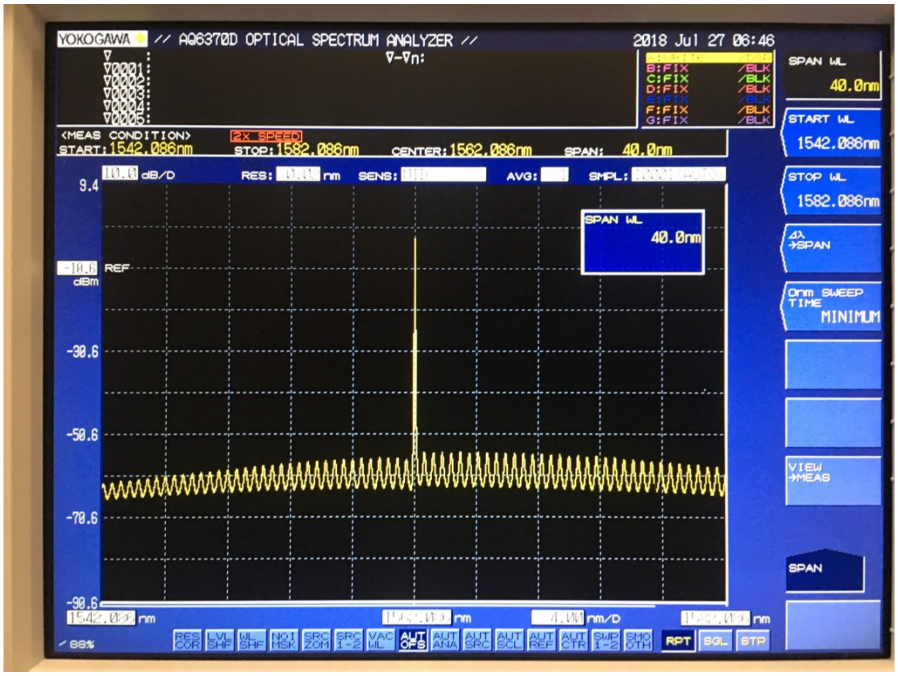

Figure 17 – Optical Spectrum Analysis

In a similar fashion as the electrical time domain reflectometer, the optical time domain reflectometer (OTDR), operates by sending a narrow pulse, and in the same channel, detects the reflected pulse energy. This allows for the identification of optical transmission discontinuities as well as loss assessments along the optical transmission path (Figure 18).

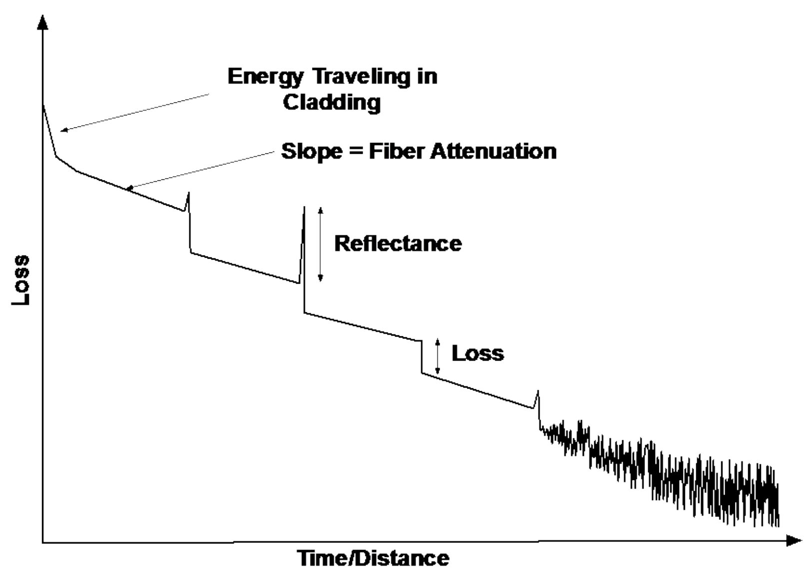

Figure 18 – Optical Time Domain Reflectometer (OTDR) Analysis

The optical modulation analyzer (OMA) is a very powerful tool that is typically used more in the laboratory than in the field, but it is worth describing because of the informational richness it provides about link performance. An OMA enables measurement of the constellation quality of each polarization, as well as error vector magnitude (EVM) (which is equivalent to modulation error ratio [MER].) Constellation analysis can also provide IQ and polarization amplitude imbalance and skew. OMAs can independently characterize each information lane (XI, XQ, YI, YQ) by measuring the eye diagrams, in addition to providing BER and channel frequency response. The distortion compensation that the OMA applies to correct the channel provides great insights into channel characteristics (Figure 19).

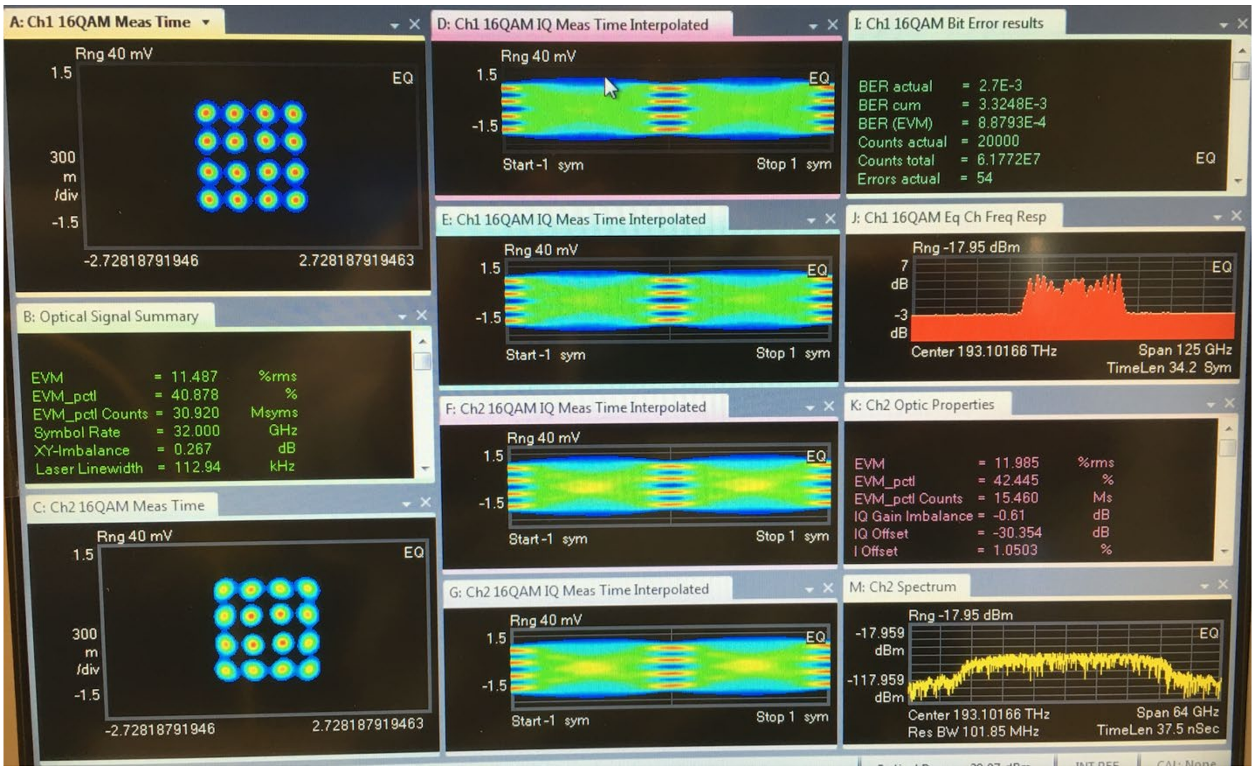

Figure 19 – Optical Modulation Analyzer (OMA) Metrics

The least common instrument is the optical vector analyzer (OVA), which provides equivalent measurements as an electrical vector network analyzer -- insertion loss, return loss as well as system transfer functions.

Some of these instruments are quite complex and expensive. However, in coherent optical networks, there is an opportunity to leverage information generated by the coherent optical transceiver while compensating the different impairments and conditions in the optical link. These parameters can provide useful distortion, reflection, and loss information.

4. Coherent Optical Transceiver Intelligence

Coherent Optics System – The optical coherent transmission system undergoes a variety of processes before it sends its signal to the optical transmission medium.

4.1. Coherent transmission system

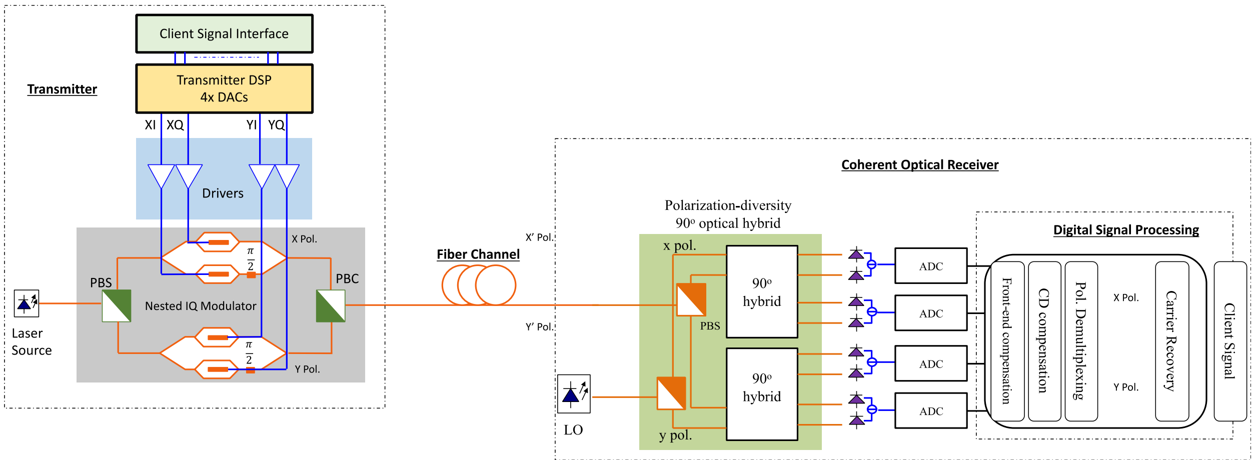

Figure 20 – Coherent System with a Transmitter, a Transmission Fiber, and a Coherent Optical Receiver with Digital Signal Processing Flow Blocks

As an example, Figure 20 presents a coherent optical system with a transmitter, a transmission fiber, and a coherent receiver [2] [3] . In the transmitter there is an optical nested IQ modulator with dual Mach-Zehnder modulators (MZM) for QPSK or higher modulation QAM formats. It can be composed of a phase modulator and two MZMs, and is commercially available in an integrated form. The incoming light is equally split into two arms: The in-phase (I) and the quadrature (Q) arm. In both paths, a field modulation is performed by operating the MZMs in a push-pull mode, at the minimum transmission point. Moreover, a relative phase shift of $\pi/2$ is adjusted in one arm, for instance by an additional phase modulator. This way, any constellation point can be reached in the complex IQ-plane after recombining the light of both branches. One of the most important parameters of the coherent QAM signal modulation in the transmitter is the modulation loss, which depends on the following factors:

- Insertion loss and bias points of modulator
- Driver swing and driver rise/fall times
- Modulation format
- Linearity of modulator
- Spectral shaping and pre-compensation

Operational optimization is needed to maximize the output power of the modulation while balancing linearity.

For generating dual-polarization modulation formats, typically two triple MZMs are used in parallel, each modulating an orthogonal polarization. The two unmodulated carriers come from the same laser and are split into orthogonal linear polarizations with a polarization beam splitter (PBS), then the two independent polarization modulated signals are multiplexed together with a polarization beam combiner (PBC).

The PM signal demodulation at the receiver was described is Section 2.9.2. As a result of the demodulation process four electrical signals or data lanes corresponding to the in-phase and quadrature components of the X and Y polarizations are generated. These four signals are then digitized by four ADCs after which DSP can be performed for signal demodulation.

Coherent optical transceivers now utilize DSP, with the transmitter being responsible for modulation, pulse shaping, and pre-equalization, and the receiver responsible for equalization, synchronization, and demodulation. At the transmitter, the DSP, in conjunction with the DACs and FEC, convert the incoming data bits into a set of analog signals. In correspondence with the operation of the transmitter, the major advantage of receiver-side DSP stems from its ability to arbitrarily manipulate the electrical field, after the ADC enables the sampling of the signal into the digital domain.

First, the four digitized signals after an ADC are passed through the block to compensate for front-end imperfections. The imperfections may include a timing skew between the four channels, attributable to the differences in both the optical and electrical path lengths within a coherent receiver. Other types of front-end imperfections can manifest in the difference between the four channels' output powers, due to different responses of PINs and TIAs in the receiver, and quadrature imbalance because the optical hybrid may not exactly introduce a perfect 90-degree phase shift.

Second, the major channel transmission impairments -- in particular, CD and PMD -- are compensated through digital filters. The static equalization for CD estimation and compensation is performed first, because of its independence of SOP and modulation format, plus, the impact on the subsequent blocks before the CD estimation is needed to achieve accurate compensation. Then the clock recovery can be processed to track the timing information of incoming samples. Note that it is possible to perform joint processing between the blocks of clock recovery and polarization demultiplexing for achieving the symbol synchronization. A fast-adaptive equalization is carried out jointly for two polarizations through a butterfly structure. Then the frequency offset between the source laser and the LO is estimated and removed to prevent constellation rotation at the intradyne frequency.

Finally, the carrier phase noise is estimated and removed from the modulated signal, which is followed by symbol estimation and hard- or soft-decision FEC for channel decoding. Note that for a particular digital coherent receiver, the ordering of DSP flow may differ slightly because of different design choices. Besides the feed-forward process, it is possible to perform joint processing and feedback among different process blocks, such as clock recovery and butterfly structured polarization demultiplexing.

On top of these typical demodulation processes, the huge amounts of parameters can be estimated and monitored using coherent DSP. In that case, the DSP would be dedicated to recycle data from the coherent demodulation process, so as to turn the coherent transponder into a multi-purpose measuring instrument for network management purposes.

4.2. Coherent Optical Performance Monitoring

Various optical performance monitoring (OPM) techniques using coherent detection have been proposed in scientific literature to monitor one or multiple parameters independently or jointly [4] [5]. Highly desirable features of a coherent optical system include higher robustness, reconfigurability, and flexibility. To enable robust and flexible operation, the coherent optical system should be able to:

(1) measure its physical state and the quality of the propagating data signals;

(2) automatically diagnose and repair the failures;

(3) take actions before data loss and failure occur; and

(4) allocate resources, including signal wavelength/power, tunable compensation, channel coding, and channel bandwidth.

Figure 21 shows the typical list of monitoring parameters for signal quality supervision at the optical layer.

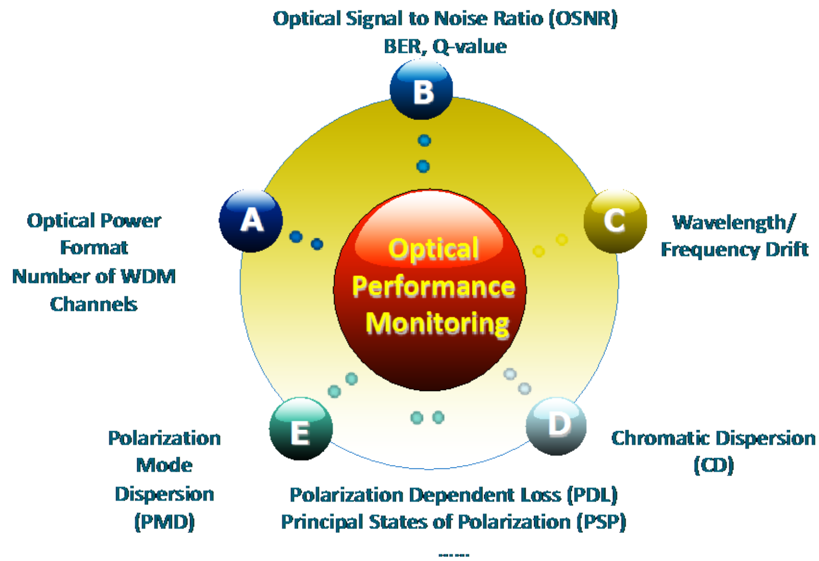

Figure 21 – Typical Parameters at Optical Layer

Monitoring at the digital and optical layers is an important element of PNM. It has shown competitive advantages in that it simplifies system design, optimizes system performance, shortens system installation, and lowers operations costs. Proactive network maintenance relies on advanced trend analysis of characteristic performance parameters that are observed at regular intervals over a long period of time. Repair is initiated as soon as negative trend is visible, and normally long before the client layer is affected. A lot of parameters shown in Figure 21, such as power, OSNR/BER/Q-value, and polarization tracking speed, can be used for proactive maintenance purposes.

It is worth mentioning that the equalizers that are used to compensate PMD and CD also provide great insight into channel distortion and the potential causes for such impairment. Amplitude ripple generated by reflections, filter narrowing, and DGD due to multiple cascading of wavelength multiplexers are a few examples of the information obtained.

If one follows conventional practices for monitoring and managing coherent optical systems, one could rely on external devices such as optical spectrum analyzers and RF instrumentation. However, in the access environment where the number of coherent links could easily be two orders of magnitude to what is found in the backbone, a more scalable management strategy could be implemented. In coherent optical links, the baseband representation of the optical field (amplitude and phase) in the electrical domain, and its digitization, leads to effective post-detection processing techniques in digital domain as introduced in above section. These digital equalizer structures embedded in coherent transceivers can not only compensate for all deterministic linear channel impairments, but can also enable a comprehensive optical PNM. That matters because it provides information about the fiber linear parameters in a simple, cost- and power-effective way. Expensive external devices are not required to evaluate optical properties or to tap the optical signal, which eventually reduces the effective received optical power. In addition, DSP-based OPM techniques are adaptable to varying data rates and modulation formats, and are capable of realizing and jointly monitoring different parameters. Therefore, coherent systems provide a better way to support fault forecasting, detection, diagnosis, and localization. Additionally, they provide a resilience mechanism in addition to basic monitoring capabilities of optical signal power level and wavelength for both traditional analog and intensity modulated access networks.

4.3. Basic Operation Principle

There are a number of technical papers that demonstrated the CD, DGD, and OSNR monitoring techniques by analyzing a bank of finite-impulse response (FIR) filters arranged in a butterfly structure in the digital domain [5], which is shown in Figure 22 below.

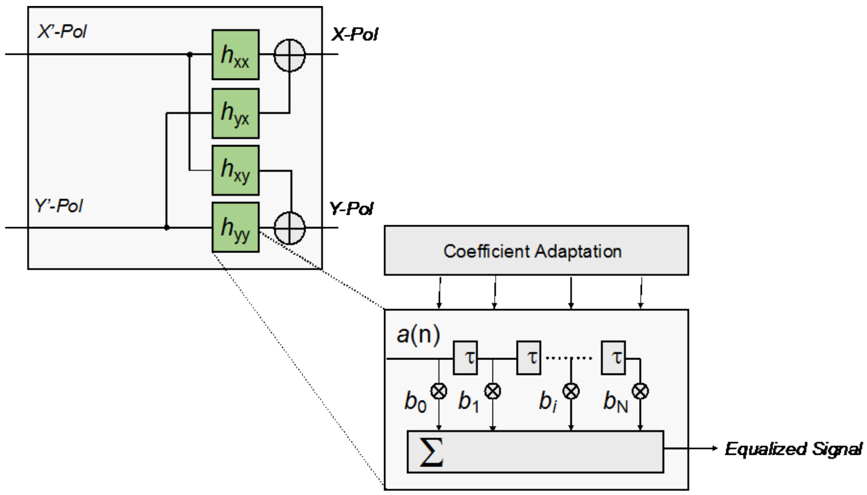

Figure 22 – Butterfly-structured Equalizer for Coherent Optical System

In such an equalizer, once the tap-setting algorithm for blind adaptation has converged, the filter's transfer function $H^{-1}(f)$ can be assumed as the inverse response of the fiber link $H(f)$. This equalizer consists of four complex-valued FIR filters arranged in this butterfly structure, which can be described with a single Jones matrix:

$$H^{-1}(f) = \begin{pmatrix} h_{xx}^{-1}(f) & h_{xy}^{-1}(f) \\ h_{yx}^{-1}(f) & h_{yy}^{-1}(f) \end{pmatrix}$$

On the other hand, the fiber channel is modeled by a concatenation of the following basic elements (the linear rotation of polarization is not included here):

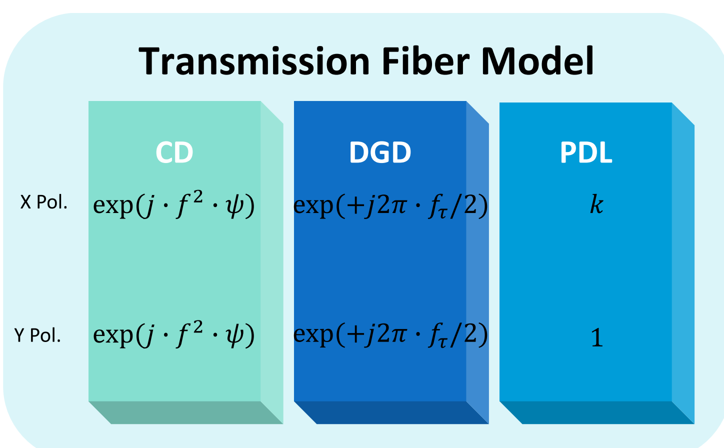

Figure 23 – Simplified Fiber Model including Major Transmission Elements

Among them,

- CD: in frequency domain, CD can be described with $e^{j\psi f^2}$, where $\psi = 2*\pi^2\beta_2 z$ and β_2 is the propagation constant of fiber and z is the fiber length.
- DGD: only the first-order DGD is considered here, in frequency domain, $e^{+\frac{j2\pi\tau f}{2}}$ and $e^{-\frac{j2\pi\tau f}{2}}$ are for two polarizations, where τ is the group delay.
- PDL: causes attenuation of $k(0 < k \leq 1)$ to the X-polarized optical field. The Y-polarized tributary remains unperturbed.

Now, the butterfly matrix can be expressed with the cascade of fiber channel elements:

$$H^{-1}(f) = D^{-1}(f) * E^{-1} * U^{-1}(f)$$

Where $D^{-1}(f)$relates to CD, $U^{-1}(f)$ is the inverse DGD matrix, and $E^{-1}$is PDL vector. The phase and amplitude response of $H^{-1}(f)$ can be used to estimate the amount of DGD, CD, and PDL. For example, to estimate CD,

$$\begin{aligned}
&\arg(h_{xx}^{-1}(f)h_{yy}^{-1}(f) - h_{xy}^{-1}(f)h_{yx}^{-1}(f)) \\
&= \arg(D(f)^2) \\
&= \arg((e^{-j\psi f^2})^2) \\
&= -2\psi f^2
\end{aligned}$$

We know that $\psi = 2*\pi^2\beta_2 z$, therefore the distance and chromatic dispersion value can be estimated from the tap value in this equalizer. An example of the given versus the estimated CD is given in Figure 24 [6]. As the estimation error is relatively small with respect to the absolute values, the deviation of the estimation is only visible with large magnification (see inset).

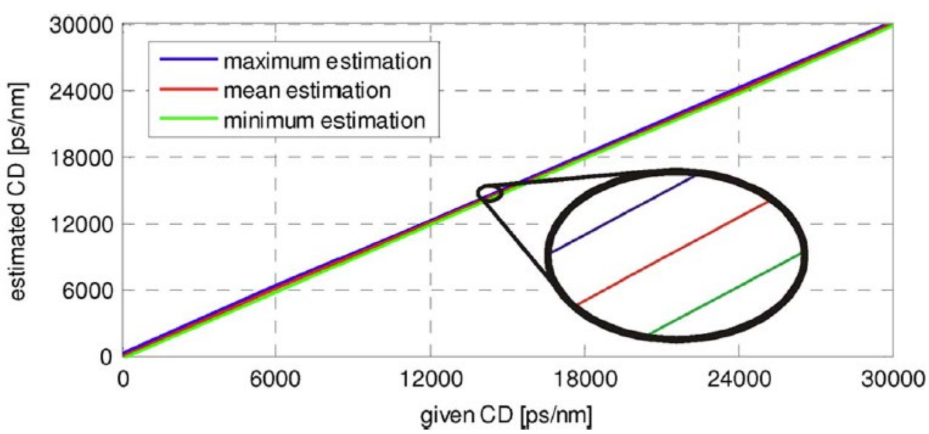

Figure 24 – Given versus Estimated CD Example

For PMD, the monitoring system needs to ensure it will not exceed values beyond which the adaptive filter can compensate. While the monitoring of SOP speed is of paramount importance in proactive failure detection, "slow" SOP monitoring would provide useful information on possible outages -- such as those that appear as a function of aging equipment. The idea is to monitor SOP fluctuations, over time, to evaluate the amplitude of this variation and assess the risk of outage, in the case of a fast SOP variation. Additionally, other impairments such as laser frequency offset and carrier phase are estimated and compensated in a digital coherent receiver. Other techniques such as artificial neural network (ANN) are also proposed for the monitoring of CD, PMD, and especially OSNR, using proper training sets.

4.4. Comparison Between Direct Detection and Coherent Detection

Unlike wireless networks, where all the necessary networking issues (such as link setup, optimization, and testing) are performed automatically, such tasks are currently handled manually in optical cable access networks -- a reality requiring substantial manual intervention. This is because the existing optical access networks are not yet capable of acquiring real-time information about the physical state of the network or the health of the signals propagating through the network. A number of OPM techniques have been proposed involving the time domain, frequency domain, or polarization domain for traditional direct detection systems, but the only digital technique is BER monitoring. When the migration from direct detection systems to digital coherent systems happens, many commonly used OPM techniques proposed for direct detection systems, such as interpolation-based out-of-band OSNR monitoring or polarization-nulling based in-band OSNR become practical.

Monitoring techniques are no longer suitable for coherent detection with very tight channel spacing and polarization multiplexing. Therefore, we have to take another look at the coherent system. Different from direction detection optical system, CD, PMD, PDL, and PSP are linear transmission effects that can be accurately estimated and fully compensated by linear digital filters at the optical coherent receiver. These fiber transmission parameters can be essentially monitored simply by reading the filter taps, as presented in the previous section and which come with almost no additional cost. In contrast to direct detection, the acquisition of channel parameters in general are inherent and integral in the coherent receiver. Table 4 compares the roles of various OPM functionalities in direct-detection to coherent systems.

Table 4: Comparison of OPM Functions in Non-coherent and Coherent Systems

<table>
<tr><th></th><th>CD</th><th>PMD</th><th>PDL</th><th>PSP</th><th>Frequency Offset</th><th>OSNR</th><th>Power</th></tr>
<tr><td rowspan="2">Direct Detection</td><td colspan="7">Additional Function Block Required</td></tr>
<tr><td colspan="7">Analog performance deteccion in time domain (synchronous/asynchronous sampling);
frequency domain (optical/RF domain);
polarization domain (polarization nulling)</td></tr>
<tr><td>Coherent Detection</td><td colspan="5">Inherent in DSP process for estimation and compensation</td><td colspan="2">Embedded DSP</td></tr>
</table>

Through the inherent optical performance monitoring from coherent optical technology, operators can now understand exactly how much margin is currently present in the network, as well as the optimal capacity they can deploy. Combined with software-defined optics or networking analytics, applications such as predictive link failure now become possible, allowing operators to reconfigure their resource allocations.

4.5. Flexible resource allocation

In conventional direct detection-based optical access networks, channels, once initially provisioned, are seldom reconfigured until they are retired at the end of life cycle. The data rate, modulation format, capacity, and reach of a given provisioned channel is static and dependent on the specific transceiver interface being used, as well the network environment. This static feature forces operators to maintain considerable safety margins, in order to provide a reasonable level of reliability. This results in an unintended waste of precious network resources. DOCSIS 3.1 specification-based analog optical channels introduced features to leverage the OFDM-based PHY layer, including variable bit loading and the option to define multiple modulation profiles on downstream and upstream channels. DOCSIS 3.1 OFDM (and OFDMA) profiles provide a wide range of modulation choices that can be used to fine-tune the CMTS's (and CM's) transmissions, to get the best performance from the current network conditions.

Now, the development of coherent optical technology will enable a similar operational style as DOCSIS technology, through the design of adaptive coherent transceivers, which are built to support a number of possible operational configurations, selectable by software. Such software-defined transceiver configurations can create specific modulation formats to support sets of data rates, corresponding tolerances to system impairments, and sets of electronic digital signal processing schemes chosen to function best in a given network environment. They can increase the network capacity and the spectral/energy efficiency, while providing a future-proof and flexible solution for an increasingly heterogeneous cable access network, from fixed to variable symbol rate and bit rate per channel. As an example, Figure 25 shows different modulation formats for different application scenarios, such as at 50 GHz or 100 GHz optical spacing, with or without optical amplification and DWDM Mux and DeMux. In other words, differing configurations can trade off the optical link margin with the data rate/capacity and power efficiency when coherent optics are introduced into cable access networks.

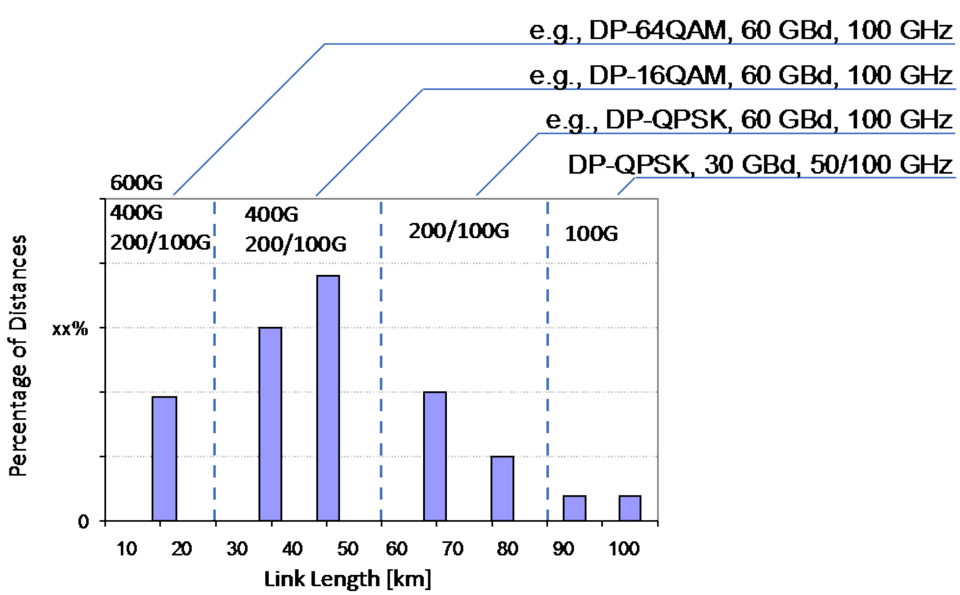

Figure 25 – Adaptive Coherent Transceiver to Support Different Scenarios

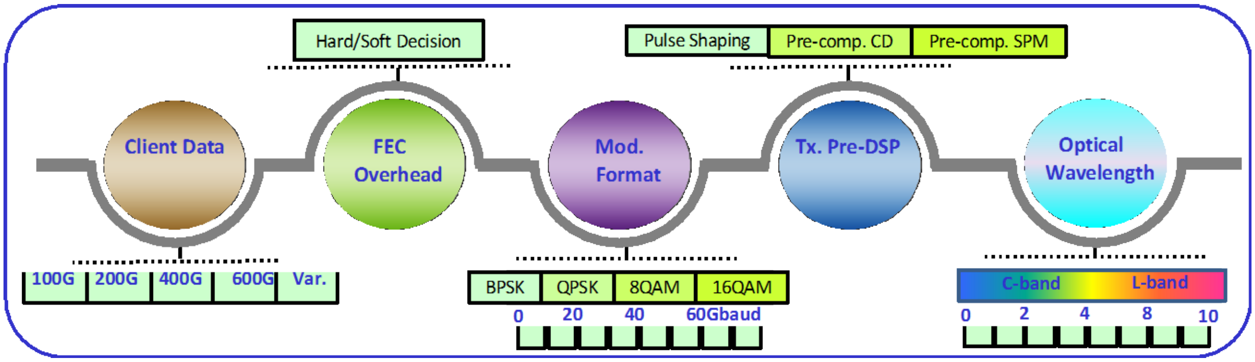

Figure 26 – Approaches for Flexible Data Rates and Software-defined Optics

Approaches exist for implementing flexible data rates with software-defined transceivers, which could operate at a constant symbol rate or could change between two or more symbol rates. Figure 26 illustrates the SDO concept. On the transmitter side, SDO may support variable client services. It can have different overhead coding schemas (hard decision or soft decision FEC) and configurable modulation formats. On the corresponding, transmitter-side DSP, they can support different numbers of optical wavelengths. At the receiver side, a universal DSP is needed for supporting different modulation formats and FEC coding schemes at different baud rates. In terms of ASIC design and implementation, optimization is required between performance and power consumption. The current implementations in the optical industry have demonstrated partial programmable capabilities in terms of modulation format (BPSK/QPSK/8QAM/16QAM), symbol rate, and FEC overhead adaptation.

5. Operational Strategy

An important aspect of PNM in coherent optical networks is that it can reduce the total cost of ownership (TCO) for operators. While it may be attractive to rely on existing PNM cost models, there are some differences that require a fresh look. One considerable difference in cost models is that with coherent optical networks, no benchmarks yet exist to baseline maintenance costs. This paper proposes that PNM capabilities will be available at the time of conception, so there will be no reduction in costs over time -- rather, it will be a matter of cost avoidance and operational efficiency. Similar to traditional coaxial PNM, the same problems exist that can make it difficult to demonstrate a favorable cost picture for PNM. This is because it involves making a claim about something that hasn’t actually happened yet or possibly never will. Fortunately, having a history of PNM cost modeling in traditional HFC coaxial networks allows us to extrapolate certain cost avoidance. The model can be adjusted for construction, repair and maintenance of optical components, instead of active and passive coaxial components.

To begin understanding PNM cost avoidance, several stages of the network lifecycle will be considered. The lifecycle begins with finance, design and construction, which also includes the cost of materials. Next is activation and provisioning, which includes customer turn-up. Finally, and as important, is the ongoing support and maintenance of the network, including outage repair and customer disruption times.

Beginning with construction, there is essentially no additional expense to accommodate PNM features. Because PNM exists as an embedded capability, it is made up mostly of software components, which may require additional memory and processing. However, the size of these components is very small in the context of modern computing, so any additional cost to materials or construction can be considered negligible.

Conversely, the construction phase of the optical network can benefit from PNM in several valuable ways. The most significant factor in construction costs is labor, which can improve from automation of the post-construction quality control and certification checks. As we've learned in traditional coaxial PNM, many of the network faults began as small construction defects, which eventually deteriorated over time, such as corrosion and resultant micro-reflections. A similar paradigm exists in optical networks, in certain types of connectors, interfaces and fusion splice defects. While it's true that optical components do not corrode, connectors and optical interfaces can still get dirty over time. Likewise, a low-quality splice may deteriorate because of environmental influences, such as wind, water, stretching or enclosure contraction and expansion. These types of problems will be identified and located almost immediately, using the proposed PNM techniques. In addition to automated quality control checks, the amount of labor spent doing post-construction certification will be improved. This time savings could be realized as improved efficiency to allow for more splicing and reduced construction rework.

Most of the automation and quality control benefits will be realized during the network and customer activation stage. This is the point where multiple receivers will be activated, and will start providing valuable PNM information about the quality and condition of the optical links. Similar to contemporary DOCSIS operational support systems (OSS), the optical receivers will be providing remote telemetry data that is vital to assess the conditions of the optical signal.

Ongoing support and maintenance will benefit from the continuous reporting about network conditions at the receiver locations.

These models can be used to approximate the cost of common proactive repairs, which require rework of fusion splices and mechanical connector cleaning. Given the cost fusion splice repairs seen in Figure 27, the following model can be used to approximate the cost avoidance of proactively repairing splices.

Benchmarking Fusion Splice Time

The cross-tabs below, indicates the expected **Middle Position** of an achievable average.

Splice Protection Closures				
1 x fibre tech per joint	**Cable size**	**Preparation**	**Splice and Coil**	**Total**
	4-fibre	20-min	15-min	35-min
	8-fibre	20-min	25-min	45-min
	12-fibre	25-min	35-min	1-hr
	24-fibre	35-min	55-min	1-hr 30-min
	48-fibre	40-min	1-hr 30-min	2-hr 10-min
2 x fibre techs or a fibre tech and assistant per joint	**Cable size**	**Preparation**	**Splice and Coil**	**Total**
	72-fibre	1-hr 30-min	4-hr	5-hr 40-min
	96-fibre	2-hr 30-min	6-hr	8-hr 40-min
	144-fibre	4-hr	8-hr	12-hr

Unpopulated Patch Panels				
1 x fibre tech per panel	**Cable size**	**Preparation**	**Splice and Coil**	**Total**
	4-fibre	30-min	20-min	50-min
	8-fibre	35-min	30-min	1-hr 5-min
	12-fibre	40-min	40-min	1-hr 20-min
	24-fibre	45-min	60-min	1-hr 45-min
	48-fibre	50-min	2-hr 20-min	3-hr 15-min
2 x fibre techs or a fibre tech and assistant per panel	**Cable size**	**Preparation**	**Splice and Coil**	**Total**
	72-fibre	2-hr 30-min	6-hr	8-hr 30-min
	96-fibre	3-hr 30-min	7-hr	10-hr 30-min
	144-fibre	5-hr	9-hr	14-hr

Figure 27 – Average Time to Fusion Splice

Operational Support Systems (OSS)

Cable operators will always need systems to help them support their networks. This remains true in the case of coherent systems. A lack of remote diagnostics and reporting can be a costly mistake when deploying field-based network technology, resulting in significant costs and inefficiency associated with manual labor. One handy example of this condition is found in the case of traditional hybrid fiber-coaxial (HFC) optical nodes. For the vast majority of fiber nodes deployed in cable networks, a technician is usually required out in the field to take measurements and adjustments when needed. Of course, there are examples of fiber nodes which have been instrumented for OSS and remote management, but these are the exception and not the rule. Understandably, it was cost and power prohibitive to embed this type of remote monitoring several decades ago -- but that certainly is not the case today.

Engaging a standards body to construct management information bases (MIBs) is useful to achieve ubiquitous and consistent implementation. A good example of this can be found in CableLabs® and the PNM capabilities that are available in the DOCSIS standards, starting with version 2.0. Because of the well-understood benefits of proactivity, it's now standard practice to conceive these capabilities early in the design phase of the product. Furthermore, when the product eventually becomes deployed in the field, refinements to the specification or implementation may be needed. Considering the many facets of unanticipated conditions out in the operating environment, a mechanism for refactoring requirements is almost always necessary.

Another important consideration for OSS is the timely delivery of information from the network sensors to the management systems. The most common network management protocols provide on-demand telemetry to satisfy immediate diagnostic and reporting needs. There is also usually an event-based reporting capability, to facilitate the time-sensitive, 24x7 monitoring of transient network events, like ingress, in traditional radio frequency (RF) networks. Many of these venerable protocols, such as Simple Network Management Protocol (SNMP), have been around for decades and tend to have their own scale and maintenance problems as a result. Fortunately, there are vastly improved protocols that work in a web-scale cadence, which address the shortcomings found in many Network Management Systems (NMS) and OSS systems. These protocols typically employ web sockets, streaming, and lightweight data models such as JavaScript Object Notation (JSON) that dramatically improve network agility, scalability, and maintainability.

Additionally, a mechanism is required to configure PNM functions such as event thresholds, northbound messaging URIs and OSS registration information.

The following Figure 28 illustrates the software stack, including PNM instrumentation, within the coherent optical receiver.

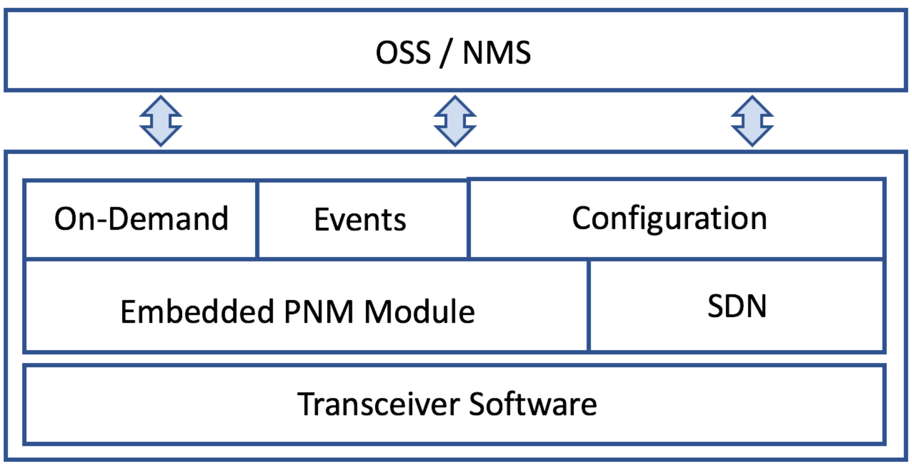

Figure 28 – Example of PNM Software Stack

Wavelength Detection and Inventory Management

Perhaps one of the most intriguing challenges and opportunities presented by coherent optical networking is the significantly increased density of available wavelengths. The intrinsic value of any network is its ability to transport payload on behalf of customers, measured in bits-per-Hertz. By increasing the bandwidth available to customers, the value of the network increases proportionately. However, the challenge is that contemporary optical networks lack the agility required to automatically detect and allocate wavelength spectrum utilization. This creates significant manual overhead and predictable failures to maintain consistent, timely records of the network.

By adding PNM enabled coherent optical receivers, operators will benefit from automated wavelength detection and mapping. Even when beginning with sparsely distributed receivers, operators will begin to populate their wavelength inventory over time due to the strategic location of these receivers. In fact, it's conceivable that operators may discover lost or forgotten available spectrum due to the aforementioned failures created by manual process. This addresses the long-term cost of operation by dramatically reducing the cost and speed associated with its manual counterpart. It also provides added assurance to operators that they will be able to maximize the revenue potential of their costly investment.

Automated Service Activation with Software Defined Networking

As previously noted in Figure 28, the embedded PNM and Software Defined Networking (SDN) modules enable the remote monitoring and configuration required to automate the activation of wavelength services. This is especially attractive to operators interested in providing self-service provisioning directly to customers, thus avoiding additional time and expense associated to manual touch points within the system.

There are many popular open source SDN platforms that would be suitable to pair with coherent optical PNM, such as Open Network Operating System (ONOS) and OpenDaylight. This would enable wavelength programmability by the operator’s NMS and drive further long-term cost reduction in the support and maintenance of the optical network. Likewise, it would increase the operator’s ability to compete by removing days or weeks from the time it takes to activate new services that drive revenue growth. In many cases, new wavelengths could be allocated, activated and delivered to customers instantaneously, without a single human touch.

Access Network Resource Optimization

A fully instrumented monitoring and configuration mechanism also provides for highly elastic resource optimization -- such as for capacity management, redundant path routing and Quality of Service (QoS). A robust network optimizer will be capable of executing multiple optimizations for bandwidth, latency, cost and availability to satisfy the different use-cases previously mentioned.

This is particularly interesting when evaluating the relative value of these network resources to customers. With the new availability of additional capacity, traditional constraints may become a thing of the past. For example, when capacity becomes congested, adding additional fiber capacity may not be a practical option. However, additional wavelengths may now be allocated and provisioned in anticipation of peak congestion to deliver temporary relief of surge traffic. A good example of this might be to accommodate for a major sporting event or holiday. Then, when the anticipated surge traffic has abated, the NMS may tear down and release the resources back to the capacity pool. In this case, the surge traffic was accommodated in a seamless manner to the customers.

Similarly, operators may now offer new, high-value products to their customers that support improved performance and SLAs. As proposed in the elastic capacity example above, higher-order SLAs may now be offered due to the additional capacity and wavelength agility. By creating redundant access network paths, customers could enjoy higher, more reliable service performance by avoiding latency caused by adjacent, shared or impaired wavelength resources.

Co-Existence and Network Reliability

Last but not least, it is also important to consider the extended operational value of introducing coherent optical PNM to operators existing optical networks. Given that coherent signals co-exist well with legacy signals, the operator may quickly achieve improved network reliability by adding just a single coherent signal.

By sparsely distributing coherent receivers, this allows operators to realize the benefits of PNM across their pre-existing optical network. Wavelength detection, splice mapping, fault detection, increased performance, SLAs, QoS, capacity management and redundant access paths all become instantly available to the operator.

With this new visibility, old problems and new opportunities will become illuminated within the already sunk costs of the pre-existing optical networks.

Conclusion

This paper has reviewed the use of coherent optics links for the management, troubleshooting and assessment of health metrics. Health metrics not only of the coherent signal and the fiber paths it is transported in, but also indirectly of the health of all the other non-coherent optical signals, such as IM-DD and analog optical signals that share the same fiber segments with the coherent signal. Coherent links provide a rich set of metrics that provide insight on distortion, noise, link length, polarization state, loss and reflections.

Coherent links have higher sensitivity and higher robustness than IM-DD and analog optical link types. They can sense impairments as soon as the fiber path is affected and provide feedback when non-coherent links may have already ceased to operate. Coherent transceivers become effective health probes of fiber access networks.

Once these rich metrics are correlated with fiber topology, analytics can be leveraged to determine the type of impairment, severity and location. This allows the operator to assess impact and prioritize repairs.

Coherent transceiver capabilities enable the implementation of network embedded instrumentation. Embedded instrumentation will provide cable operators significant CAPEX reduction and ubiquitous coverage through already deployed probes. Traditional long haul and metro transceiver don't provide all the metrics that have been mentioned here because their environment does not require them. It is up to the optical transceiver manufacturers to meet the cable industry's need for certain parameters in the chip so that operators and management systems can analyze and extract the required functionality.

Flexibility and adaptability that can be achieved through SDO enables optimization of performance. The flexibility to remotely configure the optical network along with accurate record keeping helps manage resources better and avoid leaving them stranded.

As cable provides optical connectivity services, in order to maximize existing infrastructure, it has to migrate from fiber services to wavelength services. Cable service providers with few fiber strands available have to be mindful how to use this precious resource. Effective wavelength management rather than fiber management results in a much longer lifespan of cable infrastructure.

Abbreviations

ADC	analog to digital converter
ANN	artificial neural network
ASE	amplified spontaneous emission
ASIC	application-specific integrated circuit
BER	bit error rate
bps	bits per second
BPSK	binary phase shift keying
CAPEX	capital expense
CD	chromatic dispersion
CM	cable modem
CMTS	cable modem termination system
DAA	distributed access architecture
dB	decibels
dBm	decibels milliwatt
DEMUX	wavelength demultiplexer
DFB	distributed feedback laser
DGD	differential group delay
DOCSIS	data over cable system interface specification
DP-QPSK	dual polarization-quadrature phase shift keying
DP-QAM	dual polarization-quadrature amplitude modulation
DSP	digital signal processing
ECL	external cavity laser
EDF	erbium-doped fiber
EDFA	erbium-doped fiber amplifier
EPON	ethernet passive optical network
EVM	error vector magnitude
FEC	forward error correction
FP	Fabry-Perot laser
FWM	four wave mixing
GHz	giga-hertz
GPON	gigabit passive optical network
HFC	hybrid fiber-coax
IF	Intermediate frequency
IQ	in-phase and quadrature
JSON	javascript object notation
LO	local oscillator
MER	modulation error ratio
MIB	management information base
MUX	multiplexer
MZM	Mach-Zehnder modulator
NMS	network management system
ODC	optical distribution center

OMA	optical modulation analyzer
ONOS	open network operating system
OOK	on-off keying
OSA	optical spectrum analyzer
OSS	operations support systems
OTDR	optical time domain reflectometer
OVA	optical vector analyzer
N+0	node plus zero amplifiers
PBC	polarization beam combiner
PBS	polarization beam splitter
PDL	polarization dependent loss
PIN	p-type, intrinsic and n-type layer diode
PM	polarization multiplexing
PMD	polarization mode dispersion
PNM	proactive network maintenance
PON	passive optical networks
PSP	principal state of polarization
QAM	quadrature amplitude modulation
QoS	quality of service
RF	radio frequency
RFoG	radio frequency over glass
Rx	receiver
S	signal
SCM	sub-carrier multiplexing
SDN	software defined networking
SDO	software defined optics
SLA	service level agreement
SNMP	simple network management protocol
SOA	semiconductor optical amplifier
SOP	state of polarization
TCO	total cost of ownership
TIA	trans-impedance amplifier
TRx	transceiver
Tx	transmitter
XI	in-phase x-polarization component
X POL	x-polarization
XQ	quadrature x-polarization component
YI	in-phase y-polarization component
Y POL	y-polarization
YQ	quadrature y-polarization component
WDM	wavelength division multiplexing

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