When Wavelengths Collide Chaos Ensues: Engineering Stable and Robust Full Spectrum Multi-Wavelength HFC Networks

SCTE Cable-TEC Expo
Atlanta, GA
November 15-17, 2011

Fernando Villarruel
Business Development Manager
CISCO
villarf@cisco.com

Venk Mutalik
VP of Technology and Strategy
ARRIS
Venk.Mutalik@arrisi.com

Kuang-Yi Wu
Technical Leader
CISCO
kuanwu@cisco.com

Marcel Schemmann
Principal Engineer
ARRIS
Marcel.Schemmann@arrisi.com

ABSTRACT: Recent advances in C-Band multi-wavelength technology have generated substantial interest in it as a deployment strategy of choice the world over. The Cable industry is actively making provisions to be the best provider of end to end IP services. In the case of HFC this means being able to provide an increasing number of optical connections, while at the same time maintaining the investment already made in fiber plant. This means that most, if not all solutions moving forward will have multiple optical signals co-propagating in a single fiber [1,2]. With the need for higher capacity networks comes the need for a wavelength plan, which should be inherently stable, operationally robust and based on open standards. Such a plan must also allow for innovations in device and system designs and be able to accommodate additional services while providing a cost effective base for deployment to the industry. In this paper, we describe the first steps towards evolving a stable and robust wavelength plan for multi-wavelength deployments in the C-Band. This paper discusses the possible and the practical in multi-wavelength systems design and deployment. We begin with an introduction to multi-wavelength systems in general, followed by a discussion of the various optical effects and non-linearities that could affect these systems. The paper continues with a discussion of some common errors in design and deployment and proposes a framework for building a stable robust and open wavelength plan.

INTRODUCTION: There has been much work about this topic in the last decade. Initially much of the work revolved about understanding multiple wavelength mechanisms with the intent of applying to broadcast/narrowcast optical overlay architectures, then the interest turned to implementing multiple wavelengths in the O-Band, near 1310nm, for point to point architectures. Recently there has been a strong interest in the transmission of multiple wavelengths with full RF spectrum in the 1550nm/DWDM/C-Band region. As a result of this interest there have been a number of wavelength plans proposed, and while each plan may work under some conditions, many plans are not unconditionally stable and not robust enough to last the lifetime of deployment. Sometimes, the many deleterious effects of an unstable wavelength plan are felt only long after initial deployment. What makes the problem worse is that changes in wavelength plan post-deployment would require a change in the deployed optical passives at the headend and in the field, which can have a dramatic effect on the lifetime product and maintenance cost of systems. It is ultimately important to deploy the proper wavelength plan initially. There is therefore a need for system providers in our industry to arrive at a common consensus on a methodology to derive stable multi-wavelength plans. This paper is a first step towards outlining a framework for generating such a stable plan moving forward.

LEGACY O-BAND AND C-BAND SOLUTIONS: As mentioned above, the industry has had deployment experience with both O-Band solutions and C-Band solutions. O-Band solutions have been deployed in a Full Spectrum (FS) configuration over the last five years. Operators typically avoid the zero dispersion region to enable this technology and it is common to see O-Band systems in the 1291 nm or the 1331 nm region.

The C-Band solutions that have been deployed over the last decade have been primarily broadcast/narrowcast QAM overlay systems (BC/NC QO). Here, the broadcast signals are transported via a high quality optical transmitter, over a separate fiber, while the narrowcast wavelengths are generated on separate transmitters, multiplexed together and transported over a second fiber to the field hub. At the hub the BC light is split and the NC light is demultiplexed and both these are then combined in a precise ratio and sent to a common receiver. Although the BC and NC signals are in the C-Band, since they are on different wavelengths, the common receiver is able to detect the respective RF signals independently on a single photodiode. This system has served the industry well over the years although it does have a certain complexity in initial installation and in adapting to varying NC load .

Recent technology enhancements have enabled cost effective full spectrum transmitters that do not require separate optical transmission of broadcast and narrowcast signals. In the full spectrum solutions, the entire set of BC and NC signals that make up the full RF spectrum are applied to one transmitter. A number of such transmitters are multiplexed together and sent to the node or hub locations, where they are demultiplexed and the individual wavelengths fed to the individual receivers. Since there is only one wavelength feeding the receiver, the receiver detects this wavelength and sends the full spectrum signal onto the RF plant. Effective multi-wavelength FS solutions enable virtual independent links that share a single fiber. These types of systems are easy to setup and allow for growth to all NC content.

BC/NC QO systems in use today feature low light levels in the NC sections. Therefore, as we show in the following sections, the optical impairments are very modest also. But with a move to FS systems, the light levels are comparable to single wavelength transmission, the loading on the transmitters is also more stringent and therefore the combination of higher light levels and higher performance requirement for each individual transmitter together can make these systems more susceptible to optical impairments.

WAVELENGTH PLANS: A substantial portion of the system stability is dictated by the wavelength plan chosen. Specific device selection and transmitter design, while important, are subordinate to an appropriate wavelength plan. A simple wavelength plan, such as for instance a standard 100 GHz uniformly spaced wavelength plan, might work well for a BC/NC QO system, but might not be an appropriate wavelength plan when dealing with FS transmission.

While there is significant interest today in the deployment of C-Band FS solutions, to date there has been no common alignment in the industry regarding wavelength plan selection. It is an objective of this paper to examine the various facets of desirable wavelength plans and to delineate the possible and the practical in multi-wavelength solutions. This paper will attempt to address some of the following questions:

- Why are there so many multi-wavelength plans?
- What are some of the important system impairments?
- What should the cable operator look for when evaluating wavelength plans?
- Can a cable operator use standard ITU filters, how about using existing ITU filters and EDFAs?
- Can there be one ultimate set that works for all architectures?

We will address the questions above from the perspective of systems engineering, focusing on full spectrum transmission in the 1550 nm range. Along the way we will add some original material where appropriate and describe a set of possible and practical solutions that we believe can address most of the technical and operational hurdles that are typically encountered.

SYSTEM IMPAIRMENTS: The optical spectrum covers large variations in loss and dispersion characteristics. Note that while non-linear mechanisms of multi-wavelength interaction exist throughout the spectrum, they manifest themselves with important variations depending on the positioning of the optical sources, see Figure 1.

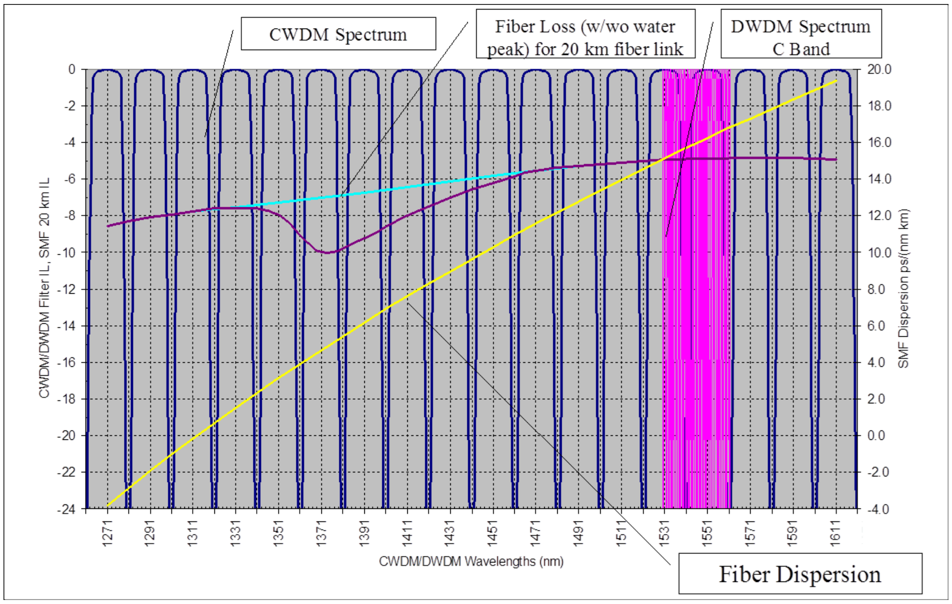


Figure 1. Optical spectrum ITU G.652 including CWDM and DWDM region, dispersion and attenuation map [1].

There are many fiber effects and non-linearities as well as system impairments that must be fully understood and managed simultaneously for stable and robust performance of the optical system [3,4].

- Fiber Non-linear Impairments
  - Multi-wavelength Optical Beat Interference effect called the
    - Four Wave Mixing (FWM)
  - Multi-wavelength Crosstalk effects such as the
    - Cross Phase Modulation (XPM),
    - Stimulated Raman Scattering (SRS),
    - Optical Kerr Effect – Polarization Dependent Loss (OKE-PDL)
  - Single wavelength non-linearities such as
    - Stimulated Brillion Scattering (SBS) and
    - Self Phase Modulation (SPM)
- Link Impairments
  - Optical Passives affect performance due to their
    - Passband Ripple
    - Polarization Dependent Loss
    - Adjacent Channel Isolation
  - EDFA effects related to
    - Gain Flatness and

        - Dynamic Gain Tilt
    - Fiber effects such as
        - Fiber Loss and
        - Fiber Dispersion

Of all these impairments Four Wave Mixing (FWM) is the most debilitating. FWM is an Optical Beat Interference (OBI) effect. When FWM occurs the noise floor at the receiver rises significantly and dramatically depending on the amplitude of the FWM product. Very low beat power levels such as 60 dB lower than the optical carriers can begin to have a measurable impact on system performance. This effect causes intermittent but precipitous drops in CNR, MER and BER performance. Since the effects are intermittent, it can be challenging to evaluate a system and gain a measurement of FWM using standard link evaluation metrics. One could readily miss FWM effects when testing only a small number of optical channels out of a large number of optical channels or when looking at only a few RF channels out of the few optical channels selected. But effects of an unstable deployment could be devastating and the only antidote to an intermittent but precipitous drop in performance is a change of optical wavelength plan that will necessitate a change in headend and field optical passives, proving very onerous and disruptive to the operator.

Optical crosstalk effects such as SRS and XPM manifest themselves as RF crosstalk impairments and must be tackled next. While SRS generally becomes worse as the optical spacing becomes wider and affects the low frequency band, the XPM generally becomes worse with narrower optical spacing and affects the high frequency band.

Minor ripples in the passband of optical multiplexer passives in conjunction with laser chirp give rise to waveform distortions, manifesting as CSO in the RF spectrum. Ripples in the passband are generally managed by low chirp sources or thru electronic compensation. While the imperfections in the passband can be compensated electronically if the passband characteristics are known and are stable, the optical passband does move with temperature. The optical de-multiplexers at the node are in the outside plant where temperature swing is high and unpredictable, and so is the ripple. It is generally very hard to control or compensate for passband imperfections in the optical passives outside of the laboratory environment

EDFA gain profiles can vary across the optical spectrum and gain levels. The former is called the gain flatness while the latter is referred to as dynamic gain tilt. To overcome the noise figure degradation of the EDFA, oftentimes EDFAs in multi-wavelength systems have high input powers and consequently low gain levels. These high levels in and amongst themselves could induce deleterious optical effects such as EDFA induced FWM. Due to all of these effects, specialized multi-wavelength EDFAs are generally designed to satisfy the various requirements listed above.

Finally, fiber dispersion is a known entity. High dispersion around 1550 nm in conjunction with laser chirp and laser linewidth contributes to fiber CSO and dispersion noise. The fiber CSO is tackled with lower linewidth sources or thru electronic dispersion compensation or via Dispersion Compensating Modules (DCM). Other issues such as the Optical-Kerr Effect in the presence of Polarization Dependent

Loss (OKE-PDL), Stimulated Brillouin Scattering (SBS), or Self-phase Modulation (SPM), have a lesser overall impact on the wavelength plan but still must be accommodated by appropriate design targets and component selection.

When all the effects, impairments and non-linearities are analyzed in this order, credible multi-wavelength plan solutions can emerge, and while they will not all be the same, they should have some sufficient similarities. Thus while there can be many wavelength plan propositions, there may be only a few stable and robust ones.

FOUR WAVE MIXING: FWM is the optical analog of CTB in the RF domain and is the beat product of three optical frequencies, f1+f2-f3, or 2f2-f1. FWM is a serious system concern because when signals overlap beat products, noise components are created with RF signatures that strongly affect both signal to noise ratios (CNR) and modulation error ratios (MER).

Figures 2, 3 and 4 show the FWM beat map for four, eight and sixteen, 100 GHz evenly spaced co-polarized channels, respectively, launched into 35 km of fiber at 10 dBm per lambda.

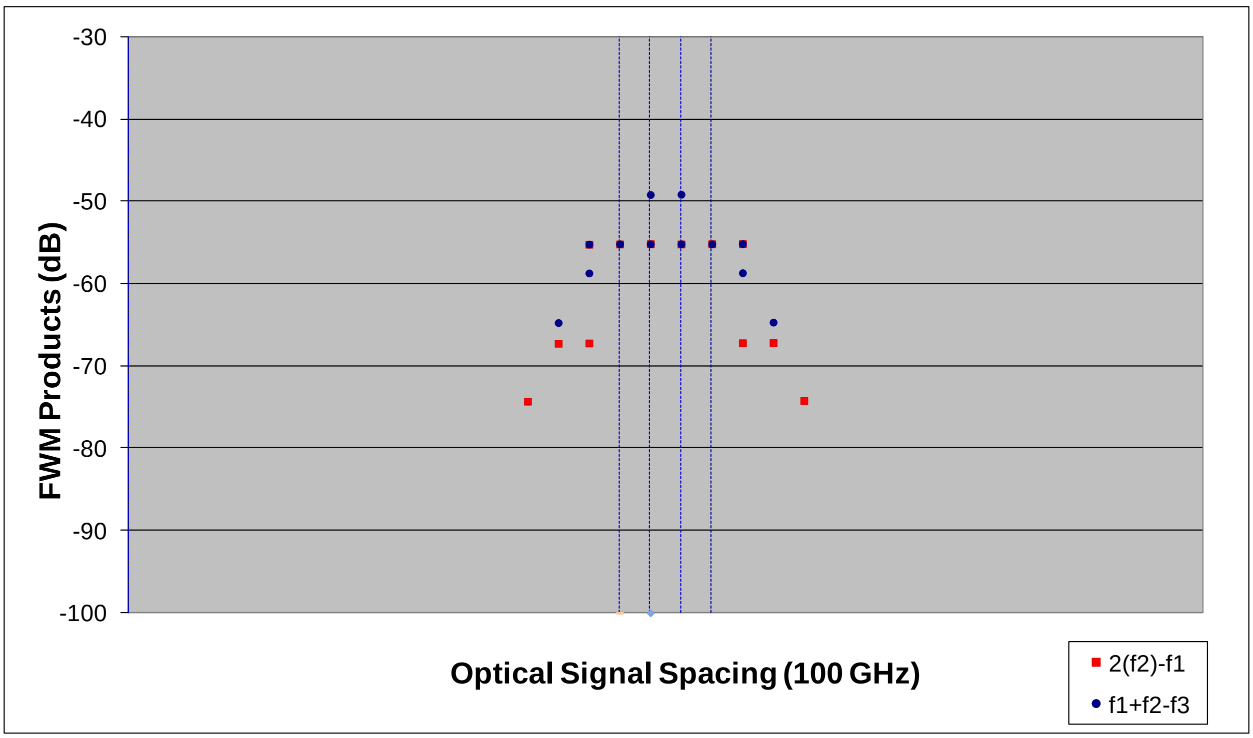


Figure 2. FWM beat map for four, 100 GHz evenly spaced co-polarized channels launched at 10 dBm per wavelength into 35 km of fiber.

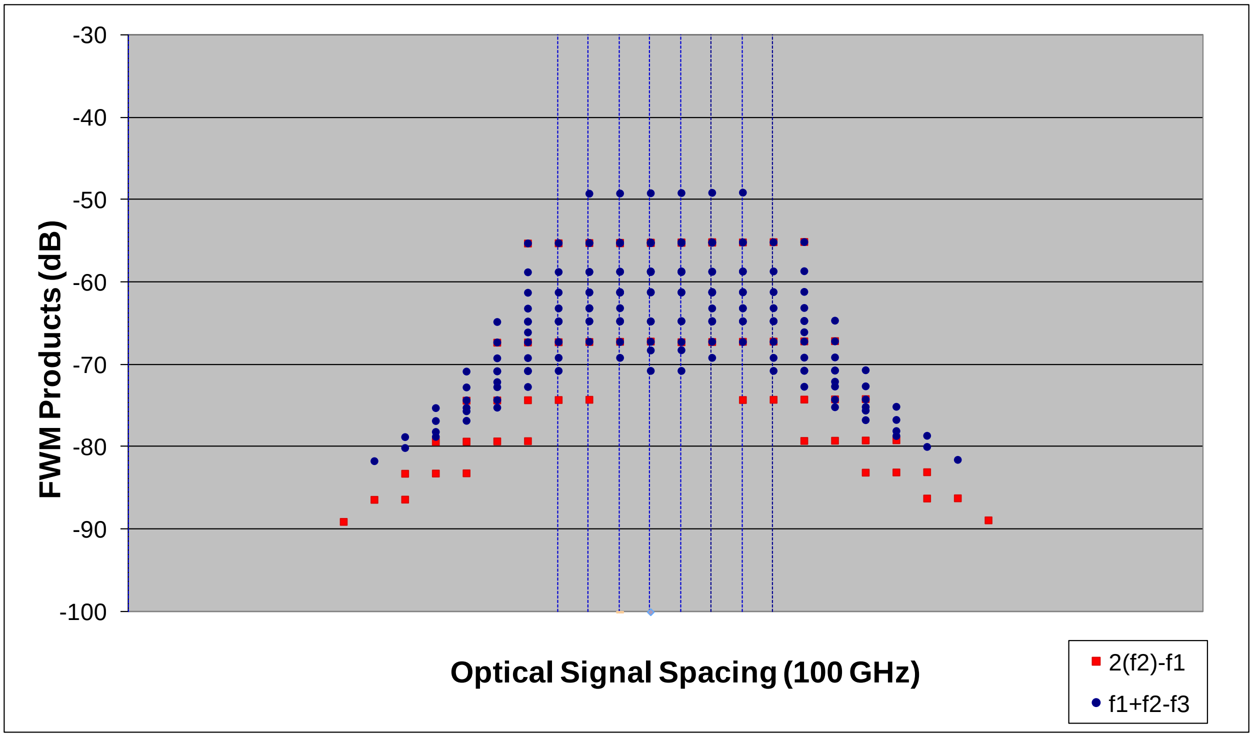


Figure 3. FWM beat map for eight, 100 GHz evenly spaced co-polarized channels launched at 10 dBm per wavelength into 35 km of fber.

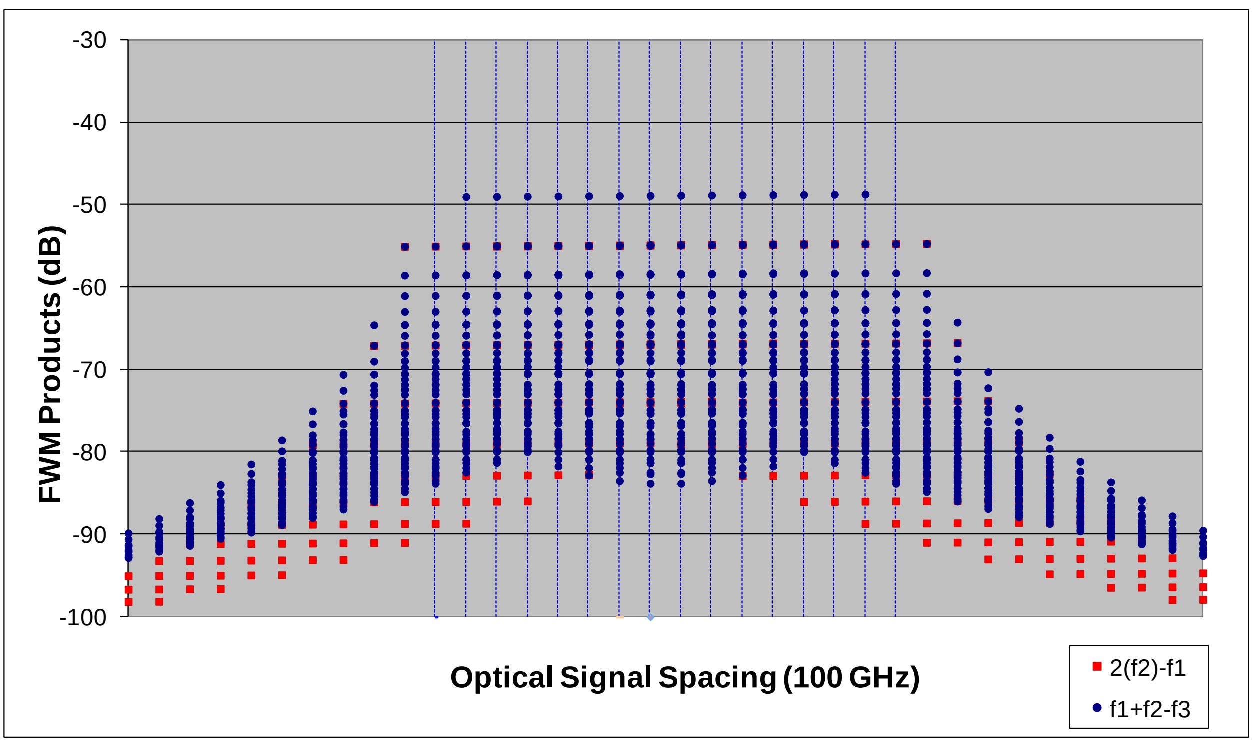


Figure 4. FWM beat map for sixteen, 100 GHz evenly spaced co-polarized channels launched at 10 dBm per wavelength into 35 km of fiber.

While it is commonly understood that FWM decreases with increasing dispersion, as can be seen from the figures 2, 3 and 4 above there is substantial FWM even in the 1550 nm region [5]. The number of FWM beats increases exponentially with the number of optical wavelengths and as a rule-of-thumb, there is a doubling of relevant beats for each additional wavelength and an order of magnitude increase in beats for each doubling of wavelengths. This means that the extent of FWM penalties becomes progressively more damaging with more wavelengths. In the absolute worst case, the polarization alignment of all wavelengths would lead to an addition of all the beats under the channels, ultimately having a destructive effect to the expected end of line performance of the optical link, as can be seen from Figure 5 below.

The practical counter-argument to worst case beat addition is that it is statistically unlikely that all signals are co-polarized, at the same time, particularly for higher wavelength counts. This argument however neglects the fact that the peak amplitude FWM beats are led by only one or two nearest neighbors, and it only takes the polarization alignment of one or two optical signals to incur FWM penalties that are damaging to a system, as can be seen from Figure 5 below.

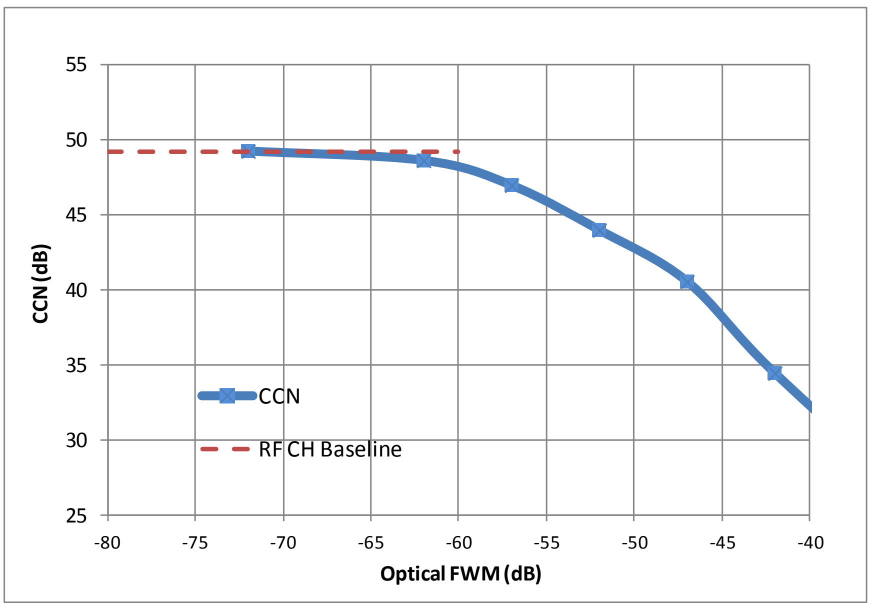


Figure 5. CCN penalty due to FWM on a RF channel. Note the RF channel maximal performance in this case is denoted by the dashed line.

Figure 5 shows the measured CCN penalty due to varying amplitudes of FWM products for a set of broad linewidth laser sources. The dashed line represents the baseline CCN of the tested channel. Figure 5 is an example the very real and direct sensitivity RF signals experience due to the optical effect of FWM. Similar results for differing optical source technologies with varying channel loads exist and must be understood by the system vendor in order to develop a clear multi-wavelength map. If both expected FWM amplitudes and performance target do not align, it should lead to a critical investigation of the given wavelength plan.

Because RF signals are very sensitive to FWM the best way to manage FWM is to avoid it altogether. Designing such wavelength plans is a computationally intense process in regards to optimum wavelength selection and placement. Avoiding FWM is the approach that has been done historically in FS systems that carry somewhere between 4 and 6 optical signals. However, as the need for more signals arises, it is much harder to avoid FWM, either initially or in particular when accounting for wavelength drift. Since the FWM is a third order phenomena, with each movement in the wavelength due to temperature, or over time due to ageing, the beats move three times as fast. It is these constant minor movements of carriers and consequently the beats that result in the beats intersecting with the carrier wavelengths leading to the intermittent but precipitous drops in performance. Tests done with both narrow and broad linewidth sources all show substantial impacts of FWM. Ultimately, a stable robust wavelength plan is the best guarantee of adequate system performance over the life of the product line.

The heart of the problem with FWM is that beats not only need to be accounted for at initial set up, but continue not causing degradation thru temperature cycles and lifetime of the system. In addition to the examples above FWM penalties vary depending on wavelength spacing, launch power, link distance, and modulation signatures from the given optical signals. This dynamic nature of FWM is what makes it by far the most dangerous phenomena of multi-wavelength systems, and its danger is highlighted by the fact that in the optical domain, multi-wavelength systems are very active as there is much movement among wavelengths over temperature and age respectively.

THE ACCELERATED FWM TEST: While the figures [2, 3, 4] above suggest that FWM is readily visible and could be easily detected in conventional RF testing, it should be noted that the optical FWM beats cause deleterious effects when the beats line up under the carrier. Oftentimes, this alignment is not observable at the moment of test since the testing is done only on a sample number of wavelengths and a sample number of RF channels for a limited period of time. However, when some beats and carriers align, as they will intermittently, the optical beat and the optical carrier essentially heterodyne at the photo-detector and the weak beat is amplified by the optical carrier. This causes a substantial increase in the noise floor of the carrier and impacts CNR and MER. A review of the operational stability and robustness of the system can be done with a more comprehensive test. We next describe an Accelerated Four wave Mixing Test (AFT) that enables the system operators to do just that.

In Figure 6, we present an example of a 10 wavelength broad linewidth system with optical wavelengths from ITU Channel 21 thru ITU Ch 30, where the wavelength under test is ITU Ch 27. All the transmitters are set up according to their RF specifications and in this case have 30 Analog channels as their load. Once the system has been so constructed, each of the transmitter wavelengths is moved in a manner so as to enable as complete a set of interactions as possible between the many wavelengths. As the wavelengths move around in the optical domain, ITU Ch 27 is kept stable and unmoving. This result is then reflected in the Max Hold screen capture of the optical spectrum analyzer, shown in Figure 7. As the wavelengths move the beats that are generated move around also and intersect with the carriers.

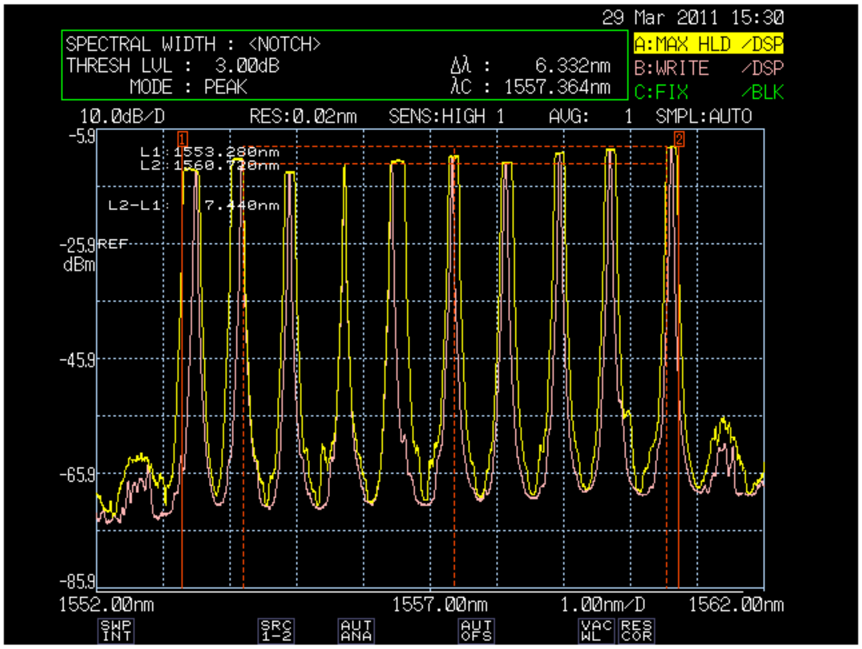
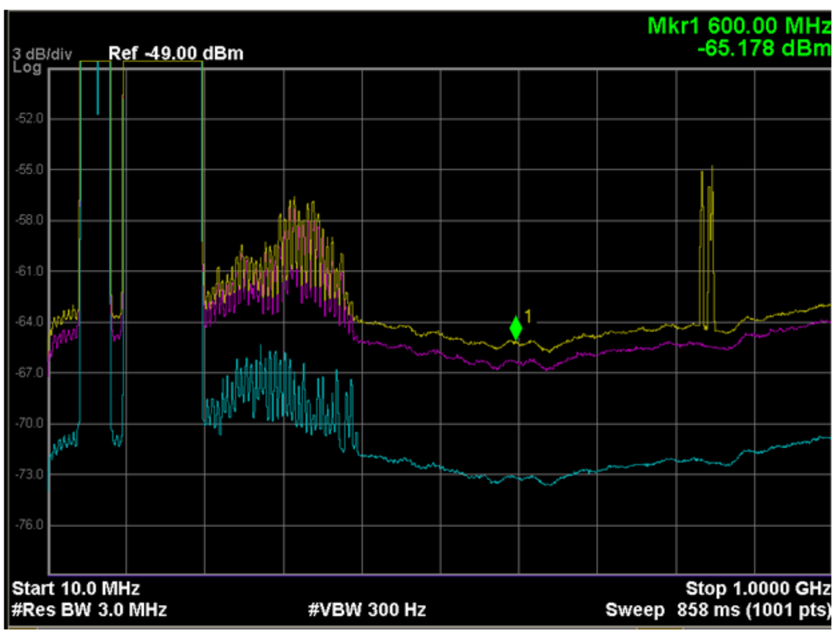


Figure 6. Max Hold OSA screen capture of wavelength movements in the Accelerated Four Wave Mixing Test. Wavelengths ITU 21 thru 30, link 35 km, launch power 10 dBm per lambda. ITU Channel 27 under test

The transmitter wavelength under test - ITU Ch 27 in this case - is tested by itself before the AFT begins and its trace is held in the RF spectrum analyzer.



Blue Trace : Transmitter under measurement with no 4WM
Pink Trace : Instantaneous trace of the transmitter under test with 4WM
Yellow Trace : Maximum Hold trace of the transmitter under test with 4WM

Figure 7. RF Spectrum Analyzer screen capture of the effects of FWM in the Accelerated Four Wave Mixing Test. Wavelengths ITU 21 thru 30, link 35 km, launch power 10 dBm per lambda. ITU Channel 27 under test

As the test proceeds, movement of wavelengths of the carriers cause movements in the beat wavelengths and will therefore cause them to intersect the carriers. The RF output of the system is then displayed on the RF spectrum analyzer and a maximum trace is then instituted, as seen in Figure 7. The more stable and robust wavelength plans have lower variation between these traces. The results show that there is a significant hit to the CNR of the signal under test. In this example there is an 8 dB reduction in CNR due to FWM. Similar tests may be done on all the other wavelengths and a comprehensive view of the system ascertained.

Several years' worth of potential laser wavelength variation may thus be simulated in a few hours and the resultant data provides an objective measure of the system stability. It is imperative then that system operators demand designs accounting not only for FWM but also design rules that protect the system from FWM over its operating lifetime.

STIMULATED RAMAN SCATTERING: A system design must account for crosstalk between wavelengths due to Stimulated Raman Scattering (SRS), where both proximity to each other and positioning in the spectrum make a difference. In Figure 8 we compare modeled results of the Raman crosstalk between a pair of co-polarized 100 GHz spaced (ITU 30, 31) and 3000 GHz spaced (ITU 30, 60) wavelengths launched at 10 dBm per lambda into 35 km of fiber.

As wavelengths get closer together, the Raman crosstalk penalty is nearly flat over the RF spectrum, whereas when wavelengths are farther separated, the penalty increases for lower frequencies. For systems where broadcast will be present and will take up the low frequencies in the RF spectrum the spacing of a wavelength plan can increase, because broadcast channels are much more robust to crosstalk penalties than are narrowcast channels. The RF signature of the SRS impact creates a decision point for the operator regarding the extent of BC bandwidth that is currently in use and that will be carried in the future. Full spectrum narrowcast applications will require a more complete understanding of SRS induced crosstalk and must be designed in into the wavelength plan.

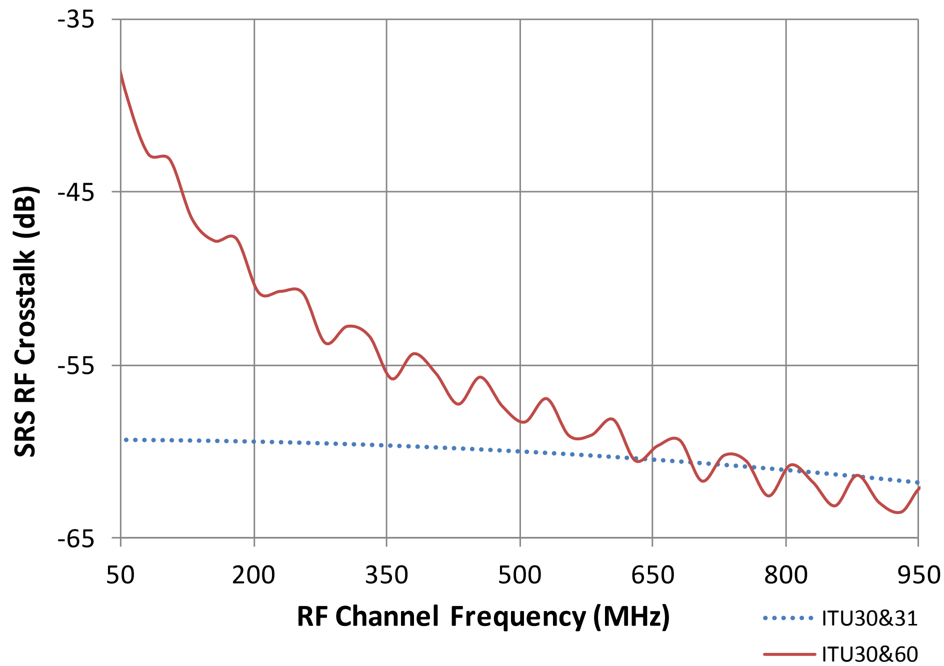


Figure 8. Raman crosstalk comparison. Co-polarized optical signals, ITU 32 and 30, ITU 30 and 60, link 35 km, launch power 10 dBm per lambda.

Incidentally, the Raman gain has an effective separation window of about 150 nm. Outside this window, such as between the C-Band and the O-Band, the SRS has no effect. But within the SRS window it peaks at about 90 nm [6]. Solutions within the DWDM band will not explore spacing greater than 100 nm so SRS must be managed within the system.

CROSS PHASE MODULATION: A system design must also account for crosstalk from fiber Cross-Phase Modulation (XPM). In the RF domain XPM has quite nearly the opposite effect as that of SRS, although the amplitude of the crosstalk is in general lower than SRS. The dynamic is such that the crosstalk gets worse the closer the channels are to each other, and the RF signature tends to increase from low to high frequencies. XPM is generated from the refractive index dependence on optical intensity as signals propagate through fiber. Figure 9 below shows the plot of a 100 GHz spaced, and a 400 GHz spaced pair of wavelengths, co-polarized with a launch power of 10 dBm per wavelength into 35 km of fiber. Clearly, the 100 GHz scenario is more challenging for narrowcast channels that reside at high frequencies. Just as SRS sets the stage for the maximum spread of wavelengths, XPM sets the stage for the minimum spacing between wavelengths. This is why, for instance a minimally 200 GHz spaced channel plan is preferred to a 100 GHz spaced plan, and it is also the reason why channel plans would have a hard time migrating to 50 GHz spacing, as in high speed digital deployments, even if the cost targets were attainable.

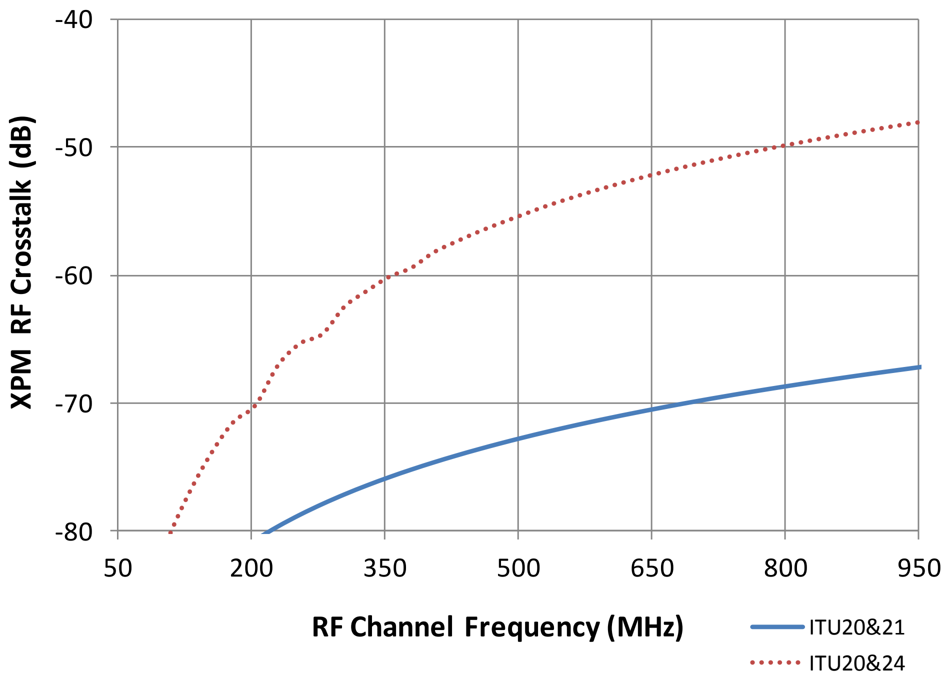


Figure 9. Cross Phase Modulation crosstalk comparison. Co-polarized optical signals, ITU 20 and 21, ITU 20 and 24, link 35 km, launch power 10 dBm per lambda.

RIPPLE IN OPTICAL PASSIVES PASSBAND: The passband of optical multiplexers exhibit ripples within the passband. While not ordinarily noticeable, they are nonetheless visible when the passband is scanned in precise terms with a tunable laser. Ripple can be considered the noise of a filter passband, it is a byproduct of the deposition characteristics of a filter chip at the wafer level. It has been well documented and tested that the intersection of a broad linewidth signal on a tilted passband creates CSO [7]. This concept applied to filters means that the slope of a filter in the range of the line width of the incident source can be critical to proper system operation. That is, the slope of a filter when zooming into the filter passband a few GHz at a time is what contributes CSO noise to the system. It turns out that even a very small ripple creates CSO that is detrimental to analog transmission, and thus the reason why multi-wavelength transmission with analog loading has required special provisions in specifications for passives in order to operate with minimal impairments.

Even with the more modest requirements for QAM transmission, the ripple can also contribute a strong noise component and in certain cases can be the dominant noise component. Further complicating matters is that the slope can vary greatly from filter to filter and is also temperature dependent.

As an example Figure 10 shows a measured typical pass band insertion loss and ripple of a 100 GHz DWDM filter. Figure 11 shows the CSO penalty for the filter region that would be typically utilized during the lifetime of the passive presented in Figure 10.

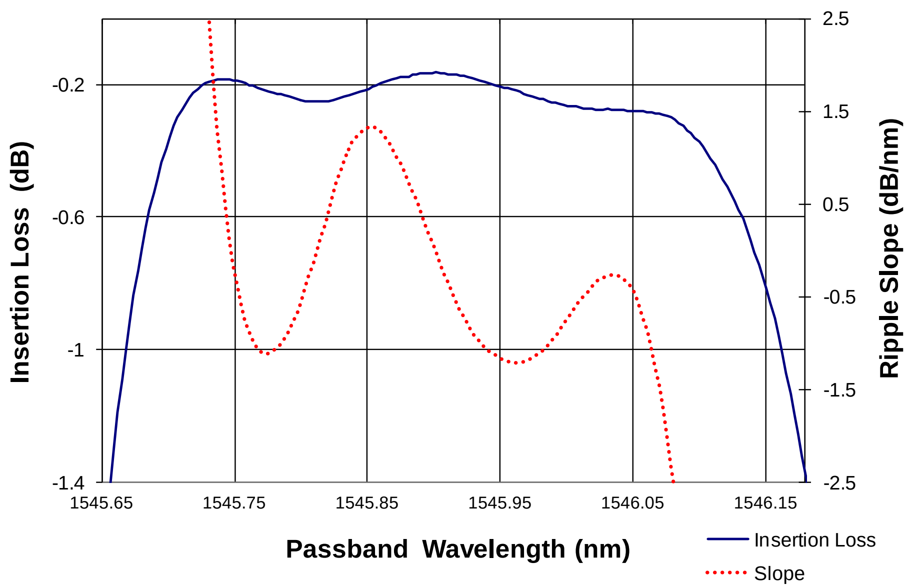


Figure 10. Measured pass-band insertion loss and ripple of a typical 100 GHz DWDM filter.

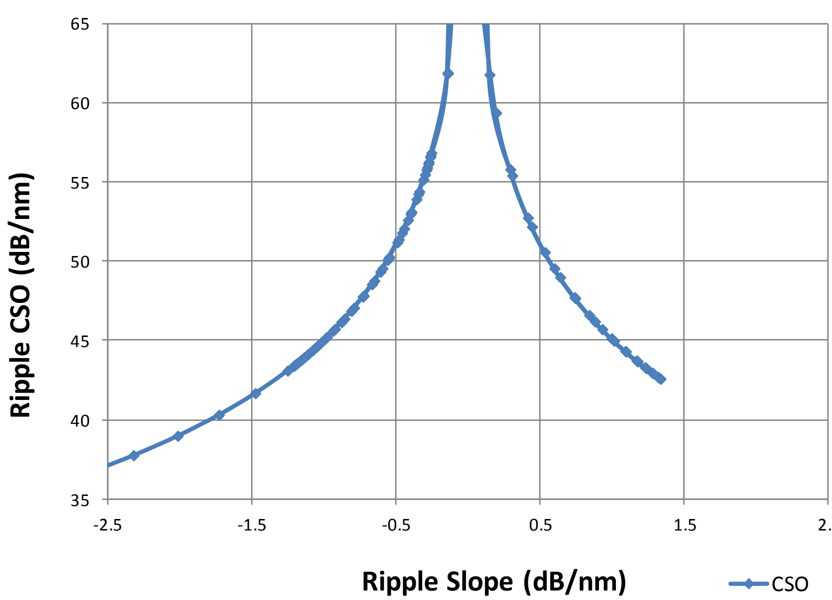


Figure 11. CSO penalty calculated at channel 4 of a 153 channel load, transmitted on a typical broad line width optical source, through the passband presented in Figure [7].

To put the CSO results of Figure 10 and 11 in the context of system performance for an all QAM load we note that we can directly apply the CSO value to the CIN and thereby approximate the impact to the equalized MER directly [8]. Thus, the MER contribution of the filter in Figure 8 and 9 could be as bad as 37 dB. Thus if the individual optical link was designed for 38 dB MER, then the inclusion of this particular filter could leave the system near 34.5 dB MER, for a penalty of 3.5 dB over the individual optical link performance. In essence, and particularly over their lifetime, filters can have a detrimental impact on system performance even for all QAM transmission, not to mention the fact that systems need a minimum of 2 filters (multiplexer and demultiplexer), thus the worst case a link could suffer two large CSO penalties simultaneously leaving the channel completely unusable.

It is important to note that there are various ways to avert the filter CSO penalty. However, one thing is certain, it must be accounted for when a system is designed. To design a system without mitigating the extent of this damage can prove detrimental. This is an area where system vendors can bring value with particular solutions and must be asked to do so.

MULTI-WAVELENGTH EDFA DESIGN: EDFA gain profiles vary across the optical spectrum and across gain levels. The former is called the gain flatness while the latter is referred to as dynamic gain tilt. Typically, an effective multi-wavelength amplifier will have a passband flatness within +/- 0.5 to +/- 1.0 dB, and exhibit a dynamic gain tilt of less than 1.0dB/dB change in gain around a nominal gain value. These specifications will allow for a predictable receiver input across the occupied optical spectrum.

Generally, in order to overcome the noise figure degradation of the EDFA, oftentimes EDFAs in multi-wavelength systems have high input powers and consequently low gain levels. These levels in and of themselves could induce deleterious optical effects such as EDFA induced FWM. Due to all of these effects, specialized multi-wavelength EDFAs are generally used to satisfy the various requirements listed above. Some EDFAs may be designed with mid stage access to allow for gain flattening filters or for DCMs. However, all these features do complicate design and add to the overall cost of the project.

FIBER DISPERSION: Finally, fiber dispersion is a known entity. The high dispersion around 1550 nm in conjunction with laser chirp and laser line width contributes to fiber CSO and dispersion noise. The fiber CSO is tackled with lower line width sources or thru electronic dispersion compensation or via DCMs. There are however practical limitations in each case that must be overcome. If electronic compensation of the link is attempted, then the system would need to know the fiber link length to be compensated. The compensation is only accurate over a small range, say within +/-5 km of the target link. This means that in redundant systems where the primary and secondary links are different, the transmitters should have handles to accommodate differing link lengths. In the case of DCMs, while there are gratings based DCMs and DCFs, it is critical to place them in such a way so as not to encounter distortions from the DCMs themselves and also such that they are not adding to the noise in the system.

ALL-DIGITAL NETWORKS and OPTICAL NON-LINEARITIES: One note that must be mentioned is that while all of the fiber non-linearities can be quite difficult to handle simultaneously, there does exist one cure to all non-linear ills. The lower the launch power per wavelength, the less detriment that comes from all fiber impairment components. The cable industry is at a crossroads, with major MSOs having embarked on the goal of commissioning all digital networks. More directly, the reduction or elimination of analog channels and the move to all-digital networks enables lower launch levels per wavelength or greater link budget. This could lead to lower cost networks, more wavelengths, longer links or all of the above.

PRACTICAL and COST EFFECTIVE DESIGNS: The distinction between the possible and the practical for multi-wavelength solutions can be impacted by business case hurdles. There are several clear, straightforward technical solutions that are often not mentioned because they do not make sense from a financial perspective. For example there is the controlling of polarization per lambda at the launch of a link. This is technically possible, but the cost to keep the alignment of polarization intact from the laser source to link fiber input would increase the cost of actives and passives by more than 3X, so it is not a realistic solution. We have also talked about the importance of accounting for FWM through the lifetime of a system. This too has a straight forward solution. The addition of wavelength lockers, as is done in high speed digital transmission, can make this problem easier to handle. Wavelength lockers however add a considerable expense to transmitters and do not make an appealing business case at this time. For dealing with FWM, there is also the possibility of using non-ITU centered passives. While this is a technically feasible solution without a large cost adder, unless it is truly necessary it always makes more sense to lean on an ITU standard that is larger than just the HFC industry to leverage existing cost benefits. There are other examples of technically feasible approaches as well, but they are not readily implemented because they do not fit within the cost constraints of the HFC market.

CHARECTERISTICS OF A STABLE WAVELENGTH PLAN: What are the characteristics of the ideal wavelength plan? How would cable operators know an ideal wavelength plan if they see one?

- It all begins with a thorough analysis of FWM. Since the impact of deploying an unstable plan is so great, customers should evaluate the stability and robustness of the wavelength plan. Good plans would generally not have contiguous uniformly spaced blocks of wavelengths. Such a placement, especially over 100 GHz is an immediate cause for alarm due to excessive FWM. Ideal plans will have non-uniformly spaced wavelengths to minimize FWM
- Since conventional tests of figures of merit do not reveal latent FWM instabilities, customers must inquire about the theory and testing to conclusively establish the stability of the system. An ideal wavelength plan would be supported by extensive theoretical analysis and test data
- Wavelength plans must accommodate XPM. Robust plans would not feature a large number of wavelengths within 100 GHz of each other. If the wavelengths are spaced too close together, the accumulation of XPM will have negative impact on system performance. Higher XPM limits the upper end of the frequency band and could impose drastic limitations in reach and capacity
- Ideally, the wavelengths would use the entire C-Band to spread out to accommodate FWM and XPM. This affects SRS but is a good tradeoff in the sense that beyond approximately 200 MHz, any of these plans will still be able to accommodate unique content
- Optical passives are an important complement to the wavelength plan. Ideally for full analog transmission, the standard ITU optical passives must either have low linewidth sources or, if using broad linewidth sources, the optical passives must be centered on the ITU grid with flat

passband and high adjacent channel isolation. For all digital transmission, the optical passives impacts are somewhat reduced

- Fiber dispersion must be adequately compensated with either low linewidth sources or with appropriate electronic or DCM compensation. If it is with electronic compensation the fiber length parameter should be easily identifiable and be set for each link
- State of the art wavelength plans allow for up to 16 wavelengths that can co-propagate over relatively long links in a FS system configuration

CONCLUSIONS: As the Cable industry makes relentless strides towards providing more services demanding higher bandwidth, full-spectrum C-Band multi-wavelength architectures enable elegant straightforward solutions. We have summarized the most important concepts guiding full spectrum C-Band multi-wavelength architecture design and have provided a framework for building operationally stable and robust networks. However, it will take collaboration within the whole industry to realize the full benefits of multi-wavelength full spectrum systems. System vendors must fully understand all the technical, practical and cost parameters involved over the lifetime of equipment and present these concepts transparently. System operators on the other hand must ask all the pertinent questions and be willing to put these answers in the context of necessary changes for network deployments moving forward. This paper is a first attempt at realizing this dynamic.

REFERENCES:

1. Shamim Akhtar, Venk Mutalik et. al., *"Gigabit Ethernet and Analog QAM: Traffic Compatibility in HFC Networks: A Case for Physical Layer Convergence",* SCTE Conference on Emerging Technologies 2006
2. Timothy Brophy, Fernando Villarruel, Kuang-Yi Wu,*"The delicate balance, Choosing Robust Alternatives for Multi-Wavelength Systems",* Scientific-Atlanta, Inc. White Paper, 2007.
3. Andrew Chraplyvy, *"Limitations on Lightwave Communications Imposed by Optical-Fiber Nonlinearities",* Journal of Lightwave Technology, Vol. 8 No. 10. Oct
4. David Large, James Farmer, *"Broadband Cable Access Networks",* Morgan Kauffman MA,, Elsevier, 2009
5. Govind P. Agrawal, *"Fiber-Optic Communication Systems",* 3rd Edition, Wiley-Interscience, NY, 2002
6. R.H. Stolen, *"Nonlinearity in Fiber Transmission",* Proc. IEEE, Vol 68, p. 1232, 1980.
7. C.Y. Kuo, E. E. Bergnam, *"Erbium-Doped Fiber Amplifier Second-Order Distortion in Analog Links and Electronic Compensation",* IEEE Photonic Lett., Vol 3, No. 9, September 1991
8. Sherryl L. Woodward, Mary R. Phillips, *"Optimizing Subcarrier-Multiplexed WDM Transmission Links",* Journal of Lightwave Technology, Vol. 22, No. 3, March 2004