ENABLING 40Gb/s OPTICAL NETWORKS
SYSTEM OVERVIEW OF ISSUES AND SOLUTIONS

Brian Lavallée, P.Eng., M.B.A.
Senior Manager, Nortel Networks, Optical Networks Systems Engineering
e-mail: brianlav@nortelnetworks.com

Abstract

This paper reviews the primary challenges involved with commercializing 40Gb/s-based optical networks based on Dense Wavelength Division Multiplexing. The inherent issues to be overcome when designing 40Gb/s transmitters, receivers, and optical transmission management schemes are also discussed from a systems perspective with proposed solutions to overcoming these significant yet surmountable issues.

Introduction

To meet the seemingly insatiable demand for information-carrying capacity and distance-independent connectivity, further advances to existing optical networking technologies are required. This voracious appetite for increased capacity is what is driving the optical networking industry to innovate upon the experience gained from recently deployed 10Gb/s-based optical networks. The 40Gb/s optical networks of tomorrow will allow the industry to meet consistently growing bandwidth demands while at the same time driving down the cost per managed bit/second. Achieved advantages will be similar to those enjoyed when the industry migrated from 2.5Gb/s to 10Gb/s optical networks just a few years ago. Further maximizing the data-carrying capacity of a wavelength leads to a reduction in optical equipment thereby simplifying system designs and reducing overall network costs. For spectral efficiencies to surge forward in a cost-effective manner, innovative methods of managing the inherent effects of 40Gb/s transmission must be developed and optimized so as to facilitate commercialization and overall market acceptance.

What Makes 40Gb/s Optical Networking Different?

What is it that makes 40Gb/s optical networks so different from 10Gb/s optical networks? The obvious difference is the quadrupled line rate that results in a bit unit interval that is four times narrower. As pulse spacing is reduced by a factor of four, much less pulse spreading and/or distortion will be tolerated by the system. The inverse square relationship between dispersion susceptibility and bitrate dictates that 40Gb/s-based networks are actually 16 times more susceptible to pulse spreading and/or distortion than are 10Gb/s-based networks. Subsequently, the pulse shape and spacing mandates stringent management techniques to allow receivers to correctly distinguish between the optical pulses. The main challenge is to fully understand what causes transmitted optical pulses to distort and then implement effective management solutions. The ultimate goal is to deliver a *pulse* at the network *egress* point that is similar in both *shape* and *timing* to when it was launched into the network *ingress* point. The undesired effects leading to light pulse distortion as well as various proposed management solutions are discussed.

Optical Communication Link

A transmitter, optical waveguide, and receiver as shown in Figure 1 can be used to illustrate a typical optical communication link. Substantial advances in the generation of the required 40Gb/s optical signals at the transmitter, the mitigation of the debilitating effects inherent to the transmission over optical fibers, as well as the ability to properly distinguish between received optical pulses must be achieved. There are numerous methods of meeting these challenges of which only a few will be discussed in this paper. It is the correct combination of available solutions that is the key to making 40Gb/s optical networks a reality.

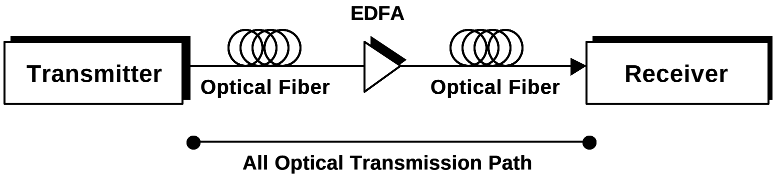

Figure 1: Generalized Optical Communications Link

40Gb/s Optical Transmission: Issues & Enabling Technologies

The design of optical transmitters and receivers are tightly related to the inherent characteristics of the optical fiber itself. Once a firm understanding of the effects incurred during optical transmission is achieved, the design characteristics of the transmitters and receivers can commence. Effects to be surmounted are similar to 10Gb/s transmission but are much more pronounced and thus represent significant advances to the already impressive technologies deployed today. The vast experience and knowledge gained over the past few years with regards to 10Gb/s optical networks will be pivotal in the design and deployment of 40Gb/s optical networks and will further accelerate commercialization.

Chromatic Dispersion (CD)

Light pulses representing data have a definite spectral width. The intrinsic properties of the optical fiber dictate that different wavelengths propagate at different speeds thereby resulting in CD (pulse spreading). If left unmanaged, pulse spreading eventually results in inter-symbol interference when adjacent pulses overlap leading to subsequent bit errors. Fortunately, this relationship is near linear in nature, not intensity related, and lends itself to relatively "simple" management techniques in most applications. The traditional accepted method of managing CD was to install inline *fixed* passive dispersion compensation modules (DCM) that were constructed using specifically doped optical fibers that *reversed* the incurred CD. This solution is well understood and is sufficient for the majority of 10Gb/s optical networks. Most CD compensation deployed today is coarse in nature in that all wavelengths are compensated for simultaneously resulting in an *averaging* approach where wavelengths at the spectrum ends receive either too little or too much dispersion compensation. Recently deployed sloped dispersion compensation modules have improved this situation. However, for 40Gb/s transmission even finer compensation is required primarily due to the extreme susceptibility of 40Gb/s networks to dispersion as stated earlier.

Numerous approaches exist for achieving finer compensation from the grouping of bands of wavelengths right down to per wavelength compensation. Using fixed compensation modules to perform very fine compensation requires numerous modules resulting in a solution that is relatively lossy in nature that although workable is not an optimal solution. As a result, *active* dispersion compensation techniques will achieve more elegant solutions [1]. The combination of both active *and* passive sloped dispersion compensation yields an even more optimal solution. Residual dispersion resulting from imperfect slope matching of the fiber plant and dispersion compensation fibers (DCF) can be actively corrected. Increases in network robustness are also achieved by actively correcting for changes in dispersion due to ambient temperature changes and/or physical changes to the fiber plant. Since carriers have typically spaced their network huts 80-120km apart, 40Gb/s networks must respect this physical constraint making the amount of required chromatic dispersion compensation already known. Fixed sloped compensation modules will perform coarse compensation and active compensation will perform the fine-tuning of residual dispersion.

Optical Amplification

Attenuation is the reduction of optical signal strength as it propagates in an optical fiber. Fortunately, the lowest region of attenuation, namely the C-band (1530-1565nm) and L-band (1565-1620nm), is also the gain region of Erbium Doped Fiber Amplifiers (EDFA). It is precisely this beneficial relationship that has enabled the current DWDM optical networking industry. The concept of using the EDFA for optical amplification is not new, however, 40Gb/s optical networks are significantly less tolerant of optical noise and nonlinear effects, both related to the EDFA. Each amplifier adds cumulative noise to the optical link while high power levels achieved by the EDFA lead to nonlinear effects. Thus, EDFAs with much lower noise figures are required for reliable 40Gb/s transmission. Alternative network topologies may also be exploited that yield lower noise figures such as combining distributed Raman amplification (DRA) and EDFAs. DRA has essentially the same effect as lowering the noise figure of the EDFA and/or lowering the span loss of the link itself thereby helping to enable 40Gb/s optical networking.

EDFAs perform sudden amplification of all incoming signals to high power levels, which are then launched into the fiber plant. Unfortunately, it is precisely these high optical intensities that quickly incur debilitating nonlinear effects (NLE) thereby limiting allowable bitrates and distances. However, low power, and hence low noise, EDFAs used in conjunction with DRA enables improved OSNR levels while reducing the optical intensity at any point in the fiber core. This is attainable since Raman amplification is distributed in nature and uses the fiber plant itself to amplify the signals over very long distances. Thus, DRA allows using low-noise low-power EDFAs by amplifying at the receiving end in a backward pumping architecture as shown in Figure 2. Adding multiple Raman pump lasers operating at different frequencies with precisely controlled output powers ensure flatter gain profiles. This is the Raman functional equivalent of required dynamic gain flattening filters that must be integrated into these low power EDFAs to combat amplifier gain tilt and unequal channel power equalization. Since DRA exploits a nonlinear (optical intensity related) effect, DRA is better suited to fibers with smaller cores.

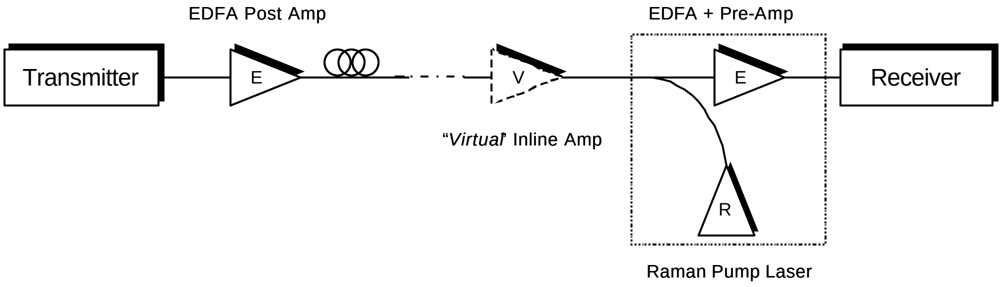

Figure 2: Backward Pumping EDFA+Raman Architecture Block Diagram

It is the nature of *distributed* Raman gain that enables three key benefits. First, it provides a mechanism for gently amplifying signal powers along the length of the fiber plant without physically inserting an amplifier mid-span resulting in lower noise. Second, by implementing backward-pumping DRA, lower power levels are achieved at any point along the fiber span thereby reducing the prevalence of nonlinear effects while achieving maximum gain. By forward pumping, the combined EDFA and Raman laser pump output powers would by very high leading to increased nonlinear effects and little Raman gain due to rapid pump depletion. Overall, DRA used in conjunction with the EDFA leads to lower noise floors and improved OSNR thus enabling new applications with higher bitrates and/or longer distances. Third, distributed Raman amplification may be used to amplify the S-band (1450-1530nm) and open this untapped transmission region where the EDFA is unable to amplify due to their gain characteristics.

Non-Linear Effects (NLE)

NLE experienced in optical fibers are not design or manufacturing defects but are inherent characteristics of electromagnetic energy passing through a dielectric medium that arise from the intensity dependence of the index of refraction of the optical fiber. At sufficiently high optical intensities, nonlinear refraction occurs in the core (Kerr effect), which is the variation of the index of refraction with light intensity. This makes NLE a critical concern in optical networks since long-haul transmission commonly relies on high-power lasers to transmit optical pulses over long spans to overcome attenuation. NLE depend mainly on the fiber type and length and can be placed into two categories. The first includes nonlinear effects that affect the *energy* of an optical pulse and includes:

- Stimulated Brillouin Scattering (SBS)
- Stimulated Raman Scattering (SRS)
- Four-Wave Mixing (FWM)
- Modulation Instability (MI)

Nonlinear effects that affect the *shape* of an optical pulse include:

- Self-Phase Modulation (SPM)
- Cross-Phase Modulation (XPM)

NLE are more prevalent when light intensities surpass their respective nonlinear thresholds, which are dependent upon the fiber type and other related factors. Once the specific thresholds are exceeded in the core, the once linear relationship is subsequently rendered invalid. Thus, the goal is to operate at the maximum power levels possible to combat attenuation without entering in the nonlinear region of operation. Since each NLE has different thresholds, this complicates the overall system design. There are additional techniques available to the system designer to circumvent these unwanted nonlinear effects other than simply ensuring that optical power intensities remain below the specific nonlinear thresholds.

- *Stimulated Brillouin Scattering (SBS):* SBS is a narrowband effect relative to the data channels operating in the terahertz range resulting in shorter wavelengths amplifying longer wavelengths by depleting themselves. With today's wavelength spacing of 50/100GHz, SBS is not yet of critical concern but can be further minimized by introducing chirp (frequency broadening).

- *Stimulated Raman Scattering (SRS):* Fortunately, the Raman gain coefficient is much less than the Brillouin coefficient requiring much higher power to generate SRS effects of the same order of magnitude. The main method of reducing SRS is to reduce the core power intensities using optical fibers with larger effective areas that result in a lower optical intensity on the core. Other methods include channel pre-emphasis and gain-equalization techniques along the link.

- *Four-Wave Mixing (FWM):* FWM is more prevalent when adjacent channels are phase-matched along a length of optical fiber. Introducing slight amounts of sloped chromatic dispersion reduces the pulse interaction time (walk-off effect) to further reduce FWM. Non-Zero Dispersion Shifted Fiber is an effective industry solution that effectively combats FWM. Although using increased asymmetric channel spacing would further reduce FWM, it is counter-intuitive to cost-effective networking since non-standard wavelengths would be required at a reduced spectral efficiency.

- *Modulation Instability (MI):* MI is essentially the overall instability affecting both the pulse shape and intensity due to the interplay between the nonlinear and dispersive effects occurring under positive dispersion. Distributing specific dispersion compensation modules (DCM) strategically along an optical link to achieve a parabolic dispersion profile minimizes MI. The dispersion profile should be zero at the end of the link such that the receiver sees the smallest distortion possible. Product specific link budget rules typically account for MI by incorporating this effect into recommended link budgets and link engineering rules.

- *Self-Phase Modulation (SPM):* At low optical intensities, refractive index perturbations are negligible. Above certain thresholds, these fluctuations are more pronounced causing the fiber refractive index to change more significantly. SPM is further minimized by introducing small controlled amounts of dispersion compensation and/or using fibers with large effective areas. More elegant solutions include precisely manipulating the intensity and spectral profile of the launched optical pulses providing maximum tolerance to nonlinear phase modulation.
- *Cross-Phase Modulation (XPM):* XPM is essentially an extension of SPM in multi-channel DWDM networks. XPM results from a modulated index of refraction from the signal itself as well as adjacent propagating signals. Adding small amounts of chromatic dispersion results in reduced interaction times (walk-off effect) between adjacent pulses to help reduce XPM.

The above recommendations are listed in isolation and are all encompassing since most if not all of the NLE interact with one another to varying degrees. The level of interaction depends on a variety of factors and will ultimately be determined by the target network application. For instance, ultra long haul transmission will exploit SRS and SPM (solitons) and/or increased bitrates such as 40Gb/s.

Polarization Effects of Electromagnetic (Light) Waves

Single-mode fiber is a misnomer since optical light pulses in “single-mode” fibers actually propagate in *two* polarization modes. Ideally, these two modes (states) travel at precisely the same speed, although practically speaking, the two modes actually travel at slightly different speeds due to birefringence in the optical fiber. Birefringence occurs when propagating light experiences a different index of refraction for the different polarization states resulting in the effect known as polarization mode dispersion (PMD) which is quantified by its differential group delay (DGD). The causes of PMD result from the following.

- Ellipticity, or non-circularity, of the fiber optic core.
- Intrinsic characteristics and properties of the optical fiber itself.
- Non-homogenous material properties of the fiber optic core.
- Applied installation methods that subject the optical fiber to undue physical stress.
- Changing environmental conditions such as temperature, vibration, etc…

Unfortunately, PMD varies statistically over time. For instance, ambient temperature changes will induce changes in the refractive index of the optical fiber core over time. Regardless of its actual cause, PMD ultimately leads to pulse distortion and bit errors if not properly managed and typically leads to reduced system link budgets. Since pulse distortion management is critical in 40Gb/s-based transmission, the statistically slow-changing nature of PMD would suggest dynamic PMD compensation (PMDc) for reliable optical transmission on older (pre-1994) fiber links exhibiting significant amounts of PMD. Already installed fiber plants can exhibit PMD values in the range of tens of picoseconds. Fortunately, since PMD actually varies relatively “slowly” over time, it makes for a more manageable issue and is thus a potential candidate for active mitigation techniques using PMD compensators (PMDc).

Figure 3 illustrates a possible PMDc architecture whose primary goal is to cancel the incurred PMD from transmission or at least minimize its effects. Signals at the *Optical Input* are fed into a *Polarization Controller* to reorient the polarization states of the incoming modes. The reoriented polarization states are fed into *Polarization Maintaining Fiber (PMF)* exhibiting high birefringence resulting in a *fast* and *slow* axis of propagation. By intelligently controlling the polarization states, the PMDc minimizes the resulting differential group delay (DGD), which is measured using a *PMD Analyzer*. These measured values are then fed to the *Polarization Control Intelligence* and are used to control the orientation of the

Polarization Controller. This type of active device would be quite effective in improving the existing system safety margins and/or allowing links with significant PMD (pre-1994) to carry 40Gb/s line rates.

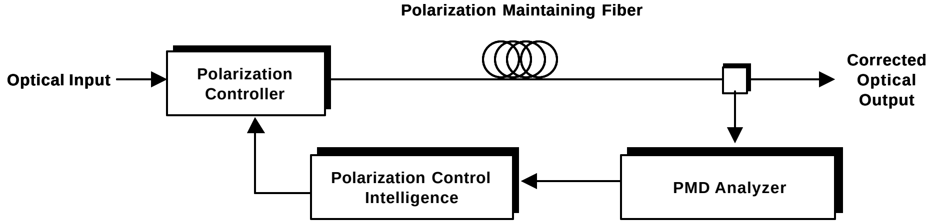

Figure 3: Polarization Mode Dispersion Compensator Architecture

Although 40Gb/s transmission is not recommended on pre-1994 fiber plants, PMDc could potentially enable some of these older fiber plants to support 40Gb/s line rates with certain restrictions. However, given that PMD bit errors are typically *bursty* in nature, there are other available methods, such as strong forward error correction, that can correct PMD related errors to a certain extent as well. This will effectively achieve similar end results as a PMDc from a system level point of view since both methods effectively reduce the overall system bit-error rate. Proper design practices that seek to eliminate PMD should also be investigated. Allowing for PMD and then performing correction leads to more complicated system designs with the possible added complexity of 2nd order PMD mitigation requirements as well.

40Gb/s Transmitter Challenges & Enabling Technologies

As discussed, transmission issues arise when light propagates within the optical fiber dielectric medium. The goal is to generate optical signals that are highly tolerant to these negative effects. The transmitter design is therefore highly dependent upon the fiber plant as well as the inline active (e.g. amplifiers) and passive (e.g. dispersion compensation fiber) components mandating the generation of optical pulses of the correct bitrate and pulse shape for the specific application requirements. No directly modulated solutions available today achieve such requirements nor will there be in the near future. This means that innovative solutions implementing external modulators will be required for 40Gb/s transmitters.

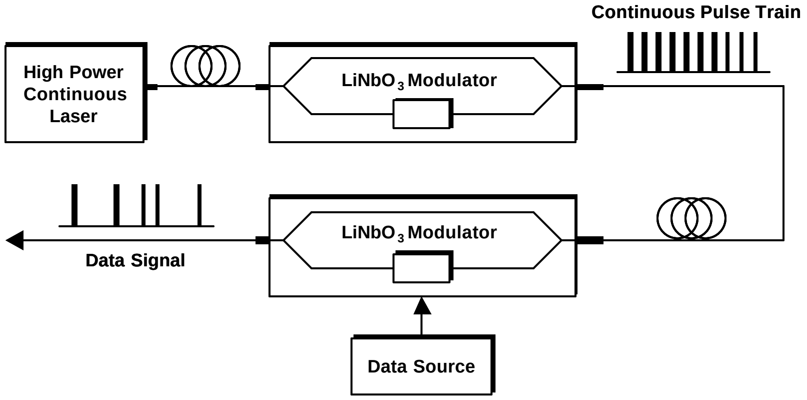

Figure 4: Serially Modulated Transmitter Device Architecture

Present DWDM transmitters are constructed using external modulators constructed of $LiNbO_3$ materials in a Mach-Zender configuration that converts continuous laser output into a modulated output stream of optical pulses. Thus, innovating upon this well-understood and reliable technology is an excellent place to start. Since dispersion is a major factor that must be dealt with, it is likely that systems designers will initially lean towards $LiNbO_3$ modulators that today provide superior extinction ratios when compared to present electro-absorption based modulators. Figure 4 shows a possible architecture for a 40Gb/s transmitter that uses two serially connected modulators. The first one generates a steady stream of 40Gb/s pulses while the second one encodes data in the required Return-to-Zero (RZ) format. These modulators will probably be initially implemented using mature $LiNbO_3$ technology, however, modulators will soon be constructed using EA technologies that are likely based on materials such as InP (Indium Phosphide).

Another method to construct 40Gb/s transmitters is using OTDM (Optical Time Division Multiplexing) techniques as shown in Figure 5 [2]. A steady stream of high-frequency pulses operating at 10Gb/s is fed into a modulated array and then split into four. Each of these resulting pulse streams is modulated by the data and then delayed by ¼ the time period relative to its neighboring pulse stream. They are then multiplexed to form an RZ 40Gb/s data pulse stream. This method uses parallel processing of four lower speed 10Gb/s streams instead of one high-speed serial 40Gb/s stream, which is subsequently easier to design and manufacture. OTDM solutions are also based on RZ coding, which is highly tolerant to transmission impairments experienced while propagating along the optical fiber [3]. Due to the parallel nature of this design, OTDM is also very well suited for FEC interleaving which greatly enhances the *burst* error correction capabilities that are discussed later in the paper.

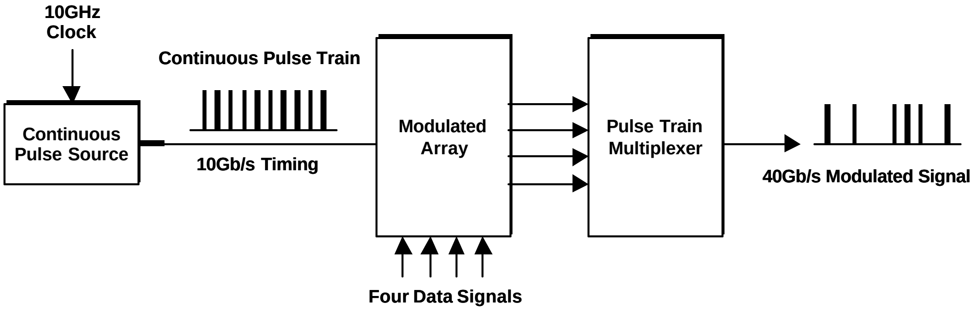

Figure 5: OTDM Transmitter Device Architecture

OTDM-based devices take advantage of the rapid advances achieved in the optical domain that have outpaced the relatively slower advances achieved in the electronic domain in terms of operating speeds. Four slower 10Gb/s data streams in the electronic domain are actually multiplexed in the optical domain. The reverse process is then carried out at the receiver. It should be noted that this method would actually use more components thereby increasing the size and complexity of the design. The choice of transmitter designs, regardless of the ones chosen, must be made with the specific target application in mind so as to simultaneously achieve the desired technological and business goals.

What material should be used to construct these devices? InP and its derivatives show great promise in achieving significant benefits that are even more pronounced given the unique requirements of 40Gb/s-based transmission. InP, like the better-known GaAs (Gallium Arsenide), is a compound containing one group III metallic element and one group V non-metallic element from the Periodic Table. These binary compounds have an inherently high mobility of electrons and holes, which is the main reason why GaAs is already used in very high-speed devices. The atomic structure of group III-V based compounds also makes them excellent candidates for constructing integrated devices incorporating both the laser and modulator on a single substrate since one of the key advantages of InP devices is their small size. Unlike $LiNbO_3$ modulators, InP modulators are polarization-insensitive making them better suited for OTDM-based transmitters. Rapid advances in hetero-junction bipolar transistors may allow for the complete integration of the laser, modulator, and required drive circuitry into a single InP-based device. This would increase device performance and lower manufacturing costs.

Forward Error Correction (FEC)

There are two mindsets driving the reliable transmission of data over a given fiber optic link. The first mindset is to ensure that there are extremely little to no incurred bit errors during transmission regardless of the debilitating effects present. This mandates extremely precise optical management techniques that quickly become cost and technology prohibitive especially at 40Gb/s line rates. The second mindset is to allow and accept a certain amount of received bit errors during transmission and then dynamically detect and correct them in real-time at the receiving end. This latter method leads to a much more cost-effective solution as compared to purely optical solutions given the recent significant advancements in FEC and ASIC design. The strictly *mathematical* process of FEC essentially encodes the data to allow FEC enabled receivers to dynamically detect and correct a given number of received bit errors. The actual error correcting capability of the FEC is determined by the coding scheme chosen and the method chosen to transport the generated FEC codes. More coding data generated leads to improved error-correcting ability but also requires more codes to be transported alongside the data signal itself. This essentially increases the effective line rate results in what is referred to as a line rate “tax”.

There are two methods of FEC that are available; namely, in-band (IB) FEC and out-of-band (OOB) FEC. IB FEC maps the generated FEC codes into the undefined SONET/SDH overhead bytes for transport from the network *ingress* point (transmitter) to the network *egress* point (receiver). Since SONET/SDH only has a limited number of undefined overhead bytes, the ultimate FEC error-correcting capability is therefore limited and is insufficient for 40Gb/s applications. It is however quite sufficient for most 10Gb/s-based optical networks being deployed today due to their decreased susceptibility to transmission issues when compared to 40Gb/s transmission. As an added advantage, IB FEC can be made to interoperate with certain non-FEC enabled systems as well. There does exist certain proprietary applications that use these undefined bytes and must accounted for from an interoperability perspective.

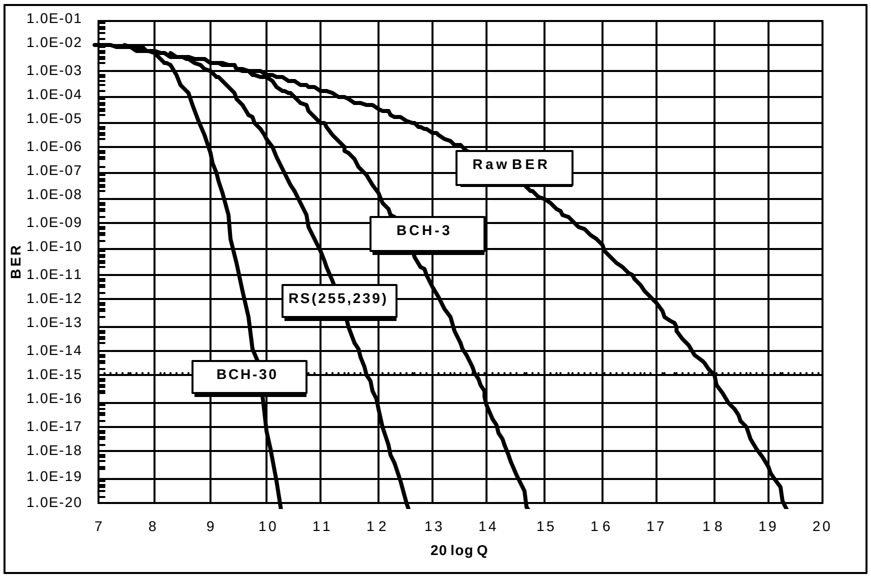

Figure 6: Comparison Between FEC Coding Schemes and Achieved Coding Gains

OOB FEC increases the line rate by adding the generated FEC codes to the original transmitted data without using the SONET/SDH overhead itself. Although the line rate is indeed increased to a certain extent, significant coding gains can be achieved. For example, existing ultra long-haul 10Gb/s-based optical equipment is capable of correcting a BER of 10^{-3} to below 10^{-20} using strong OOB FEC schemes. This significant increase in error detection and correction enables longer spans and/or higher bitrates. The 40Gb/s networks of tomorrow will exploit OOB FEC rather than IB FEC due to its significantly improved error correcting capability and subsequent achievable coding gains. The decision now is to decide which coding scheme will be implemented given the trade-off between coding gain and increased line rates. Figure 6 illustrates achievable coding gains for different FEC coding schemes. As shown, FEC coding based on BCH-30 achieves similar performance in terms of BER for much smaller OSNR values.

Due to the direct relationship between OSNR and bit-error rate (BER), a lower BER leads to a higher OSNR and vice versa. Thus, using FEC schemes to correct the raw (actual) BER will subsequently result in an improved effective system OSNR by *extrapolation*. Thus, FEC *mathematically* overcomes such incurred transmission impairments as attenuation, dispersion, and noise that cause bit errors in order to maintain reliable cost-effective link performance even at 40Gb/s line rates. Since FEC is a mathematical and not purely optical technique, it is cost-effectively embedded into discrete ASIC devices.

Further extending the error correcting capability of FEC coding is achieved using a technique called *interleaving* that matches the error-correcting capabilities of the FEC coding to the error characteristics of the transmission environment itself. Interleaving enhances the random-error correcting abilities of the FEC codes making them more efficient in handling burst error environments such as PMD impaired fiber links. Interleaving rearranges the encoded bits over separate block lengths. The interleaver span length is determined by the amount of error protection desired and is based on burst error lengths encountered during transmission. Receiver decoding must be matched to the coding employed at the transmitters for proper error detection and correction to take place. The ultimate goal of interleaving is to distribute long bursts of bit errors that will appear to the decoder as independent random bit errors or shorter more manageable burst errors. Interleaving performance is typically dictated by proprietary schemes.

Pulse Shape Formats

System designers have numerous available coding formats at their disposal. They fall into two main categories; namely, RZ (Return to Zero) and NRZ (Non-Return to Zero) as illustrated in Figure 7. The traditional method of representing digital information utilizes the simpler NRZ coding format.

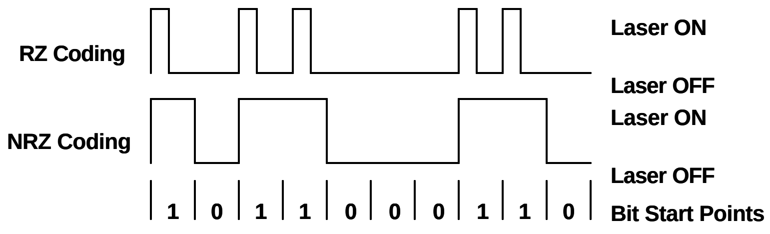

Figure 7: Comparison of NRZ versus RZ Coding

In the NRZ optical domain, a *zero* bit is represented by the *absence* of an optical pulse of light while a *one* bit is represented by the *presence* of an optical pulse of light. Although simpler to implement, this coding format does have certain drawbacks. A sequence of optical bits will contain a relatively high average power level as compared to RZ coding making them more conducive to nonlinear effects, which are more pronounced at higher optical power levels. Since bit transitions do not return to zero after each pulse interval, they are inherently more susceptible to transmission impairments. Without scrambling techniques, it would be possible to obtain no changes in power levels for a long sequence of ones or zeros leading to clock recovery issues. Overall, these issues make NRZ non-optimal for 40Gb/s transmission.

RZ is a more optimal coding solution for 40Gb/s transmission especially in longer reach applications. In the optical network domain, a *zero* bit is represented by the *absence* of an optical pulse of light while a one bit is represented by the *presence* of an optical pulse of light during the first half of the bit and absence of light during the second half. It is the RZ coding format that enables certain key benefits applicable to 40Gb/s transmission. When a data stream contains long sequences of ones and zeroes, transitions are still present enabling easier clock recovery. RZ pulse formats are also inherently more immune to NLE and PMD so detrimental to 40Gb/s transmission. The primary challenge related to RZ coding is the higher required bandwidth due to the increased number of bit transitions when compared to NRZ coding thus requiring faster transmitters and receivers. However, recent advancements in transmitter and receiver technologies make RZ technically and economically feasible.

There are also different types of RZ coding formats available. There exists simple RZ as explained above, chirped RZ (CRZ), and soliton based RZ coding. RZ coding is better than NRZ coding from a technical point of view regardless of the specific RZ coding actually chosen. However, the actual selection will be based on economics, time to market, and the intended network application. In certain shorter reach applications, NRZ will prove sufficient and more cost-effective, while in other applications, such as ultra long haul, CRZ and/or soliton based systems will be much better suited. Thus, both RZ and NRZ are effectively suitable for 40Gb/s transmission depending upon the target application and cost points.

Receiver Challenges & Enabling Technologies

The main challenge related to receivers is to construct a device that is highly sensitive to small amounts of light and simultaneously able to operate at very high bitrates. Unfortunately, the laws of physics dictate that as the bitrate increases the sensitivity decreases. These opposing issues are further exacerbated by the distortion of the received optical pulses as they propagate through optical fibers. Increased receiver functionality such as embedded FEC increases the design challenge even further. However, OTDM techniques discussed earlier allow four parallel receiver circuits to process received data at slower and manageable 10Gb/s bitrates. Parasitic noise in the receiver circuitry only serves to degrade the overall performance. One method to reduce parasitic noise is to shorten interconnections by increased device integration. Again, InP may initially be used for the high-speed electrical portion of the receive circuit due to its very high mobility of electrons and holes. Further integration of the electrical and optical sections will greatly increase performance while reducing costs. Other compounds can and will be used as well.

Fortunately, the design methodologies related to the receiver preamplifier and baseband amplifier have changed significantly due to the emergence of the EDFA. Consequently, the minimum detectable optical power is now primarily determined by the EDFA noise rather than the preamplifier noise thereby relaxing the receiver noise and gain requirements leading to slightly less complex designs. However, high-speed regeneration functionality via the decision and clock-recovery circuits is still required so as to minimize timing jitter caused by cascaded EDFAs [4]. RZ coding further exacerbates the performance requirements of the receiver due to increased bandwidth requirements. Innovative techniques such as OTDM coupled with the inherent capabilities of newer materials like InP, will enable 40Gb/s receiver designers to overcome these significant issues. Different applications will result in many other adopted technologies.

Conclusion

Optical networks based on 40Gb/s line rates mandate extremely narrow pulse spacing when compared to the 10Gb/s networks of today. Managing incurred dispersion and distortion of transmitted optical pulses is vital to the implementation of this bleeding-edge technology of tomorrow. The primary challenges that lie ahead were discussed with some proposed solutions that cannot be looked at in isolation since most, if not all, are highly interdependent. This intimate relationship between the transmitter, receiver, and optical line makes the challenge a significant one. For instance, lowering power levels to minimize detrimental nonlinear effects will prevent the use of distributed Raman amplification, which depends on SRS non-linearities. Removing all chromatic dispersion from the optical fiber prevents soliton transmission, which relies on the interplay between self-phase modulation and chromatic dispersion [5]. Therein lies the primary and very significant challenge to the optical networking industry. It is the judicious and ingenious mix of these often opposing goals and issues that must be studied from a system level if 40Gb/s networks are to become a reality. The wealth of knowledge acquired in the recent deployment of 10Gb/s networks will be of primordial importance to equipment vendors and service providers alike. Deploying future 40Gb/s optical networks will be just as important as the design of the equipment itself. Like any technical challenge that has ever faced mankind, all is eventually achievable given the proper amounts of time, ingenuity, experience, and of course financial resources. It is the inherent benefits of 40Gb/s optical networks itself that will ultimately ensure its own commercialization in the very near future.

References

[1] B.J. Eggleton, "Dynamic Dispersion Compensation Devices for High Speed Transmission Systems", OFC 2001
[2] H. Volterra., "Modulation Advances Drive Next-Generation DWDM Systems", Lightwave, Jan. 2000
[3] B. Bakhshi et al., "Comparison of CRZ, RZ, and NRZ Modulation Formats in a 64x12.3Gb/s WDM Transmission Experiment over 9000km", OFC 2001
[4] E. Sano, "High-Speed Lightwave Communication ICs Based on III-V Compound Semiconductors", IEEE Communications Magazine, Jan. 2001
[5] Agrawal, Govind, Non-Linear Fiber Optics, Academic Press, 2nd Edition, 1995