Electronic and Photonic Processing in Advanced Photonic Long-Haul Transmission

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ABSTRACT

The advancement of electronic integrated circuit technology and photonics in the last decade have allowed the design and demonstration of ultra-high bit-rate transmission over advanced optical fiber transmission line employing in-line optical amplification as well as electronic compensation and equalisation of linear and nonlinear distortion effects. The research and development of novel modulation techniques to achieve effective signal bandwidth and energy distribution per bit for extending the transmission reach are also attracting intensive interests. This paper presents: (i) A brief overview of optical fiber communications employing advanced modulation and novel formats, especially the amplitude and phase shift keying (ii) Distortion and dispersion effects due to linear and nonlinear effects and experimental demonstration of electronic and photonic compensation methodologies (iii) Practical demonstration of the transmission of multiple channels at 40 Gb/s over several fiber spans of dispersion managed optical fibers (iv) Demonstration of 40 Gb/s over 10 Gb/s wavelength multiplexed optically amplified long haul transmission for capacity upgrading.

1 INTRODUCTION

The staggering success of optically amplified fiber communications has established this mode of information transmission as the choice for delivering ultra-high capacity communications for metropolitan area networks, regional networks and long haul information transport. The transmission bit rate has matured at 40Gb/s and reaching 160 Gb/s per wavelength channels. The development of various modulation formats has also attracted significant attention for effective transmission of wideband information signals over long reach transmission optical lines [1-4 i ii iii iv]. The multiplexing of several 40 Gb/s over the central or short and long wavebands of the low loss transmittance region of the single mode fibers aggregates to a total capacity of Tb/s.

This success has been based exclusively on photonic signal processing for chromatic and polarization mode dispersion compensation and equalization, the dispersion management technique. In contrast to other modes of transmission, electronic signal processing is absent from fiber communications. The reason for that was due to the fact that: the bit rate of fiber transmission systems was above the capabilities of electronics. However, in recent years continuous progresses in semiconductor technologies have enabled electronic processing for the first time to match the information speed of optical fiber systems. This gives the opportunity to fiber system designers to benefit from electronic signal processing and design systems whose performance will exceed that of systems without electronic processing at lower cost.

Upgrading existing fiber communications backbone infrastructure is also very important in the near future, especially for transmission link in the Internet intensive demand regions. One of the possibilities is selectively increasing the transmission rate 40 Gb/s over the existing 10G return to zero (RZ) format dense multi-wavelength (DWDM) optical communications systems. Due to the properties of the installed fiber, the transmission methods must be highly tolerant to the chromatic-dispersion (CD) and polarization-mode dispersion (PMD) effects. This favors the use of advanced modulation formats (such as variants of phase-shift-keying) rather than ultra-high-rate time division-multiplexed (TDM) schemes, because the effects of CD and second-order PMD are proportional to the square of the bit-rate.

This paper thus presents (i) A brief overview of the advancement of photonic transmission over optically amplified fiber media that would allow the transport of Tb/s (ii) The original physical phenomena of linear and nonlinear distortion effects and their impact on the signal transmission quality (iii) Pre- and post- compensation/equalization techniques in either electronic or photonic domain; and (iv) Demonstration of the long-haul optically amplified and distortion-equalized transmission systems of 40 Gb/s in multiple-wavelength multiplexing or over 10Gb/s dense wavelength-multiplexed (DWDM) media.
2 ADVANCED OPTICALLY-AMPLIFIED AND DISTORTION-EQUALIZED TRANSMISSION SYSTEM

2.1 Transmission system overview

*Figure 1*(b) shows a generic optical fiber transmission system employing in-line optical amplifiers and dispersion compensating fiber modules. Multiple carrier-modulated channels are multiplexed and demultiplexed into parallel streams in the photonic domain using an array waveguide grating device which employs the principles of spatial interferometry. They are then optically boosted to an appropriate level for transmission over several optical fiber transmission and compensating spans. For system engineering it is preferred that the long haul systems composes of modular spans which can consist of the transmission fiber plus a mid-span optical regenerator (MOR). This MOR manipulates signal channels in the photonic domain in which the carrier-modulated signals are phase compensated via the dispersion compensating module (DCM) that has a reverse phase delay effects to that of the transmission fibers, hence compensation of the distortion of the phases of the optical waves. The MOR would also consist of two lumped optical amplifiers of either Erbium doped or Raman-pump types. The first one uses to compensate for the transmission loss with a moderate optical power output in order to avoid the nonlinear self-phase modulation effects of the compensating fibers. Due to the small cross section, and hence effective mode spot size, of the silica-based dispersion compensating fibers, its nonlinear power threshold is fairly low, about 0 dBm for a 17 \( \mu m^2 \) effective area. The second optical amplifier is employed at the output of the DCMs to compensate for the optical loss in the compensation fibers and boosting the total average optical power at its output for transmission to the next fiber spans. This complexity of the DCM and optical amplifiers can be overcome by pre-distortion of the electrical driving signals before modulating the external modulator. This is described in the next section.

The mismatching of the dispersion compensation of the multi-span distortion and the non-uniformity of the dispersion characteristics of the fibers lead to residual dispersive effects at the end of the transmission system. Hence dispersion mopping is necessary at this stage for each individual channels before the optical receiver and recovery circuits. Furthermore the polarization dispersion can also be equalized at this point. Nonlinear effects are also expected. However there are no photonic components that would exhibit negative nonlinear coefficients to compensate for this nonlinear impact – this is thus compensated in the electrical domain, normally after the opto-electronic front end amplifier. *Fig. 1*(b)

*Figure 1*(b) shows the Siemens TranXpress Multi-wavelength transport system that could carry 8x 10 Gb/s wavelength channels in the Blue and Red regions of the low loss 1550 nm spectral range over 800 km standard SMF and dispersion compensating modules with lumped optical amplifiers per span as described above. The frequency spacing between wavelength channels is 200 GHz. This allows the injection of more channels with narrower spacing.

![Fig. 1(a)](image-url)
Fig. 1 (a) A generic in-line optically amplified and distortion compensation for long-haul multi-span transmission. Legends: MOR = mid-span optical regenerator, Red – Blue: group wavelength channels of longer or short spectral regions; DCM = dispersion compensation module – fiber-based technique; SSMF = standard single mode fiber. AWG = array waveguide gratings for either channel multiplexing or demultiplexing (b) Monash Siemens TranXpress Wavelength Transport System – bidirectional 8 x 2 x 10 Gb/s – transmission distance 8 x 100 kms dispersion-managed (SSMF + DCMs) optically lumped amplified spans.

2.2 Photonic Transmitters

Naturally due the high speed operation of the modulation, the direct modulation of the driving current of a laser source is not possible as this would broaden the linewidth of the laser, normally the distributed feedback laser of a line width of about 100 kHz under continuous wave operation. The CW lightwaves are then modulated via electro-optic modulators whose structure would follow an interferometric structure of Mach-Zehnder type (MZIM). There are two MZIM types: single drive and dual drive electrode structures in which the traveling-wave electrodes are placed across the optical waveguide branches of an optical interferometric structure as shown in the insert of Figure 2 [5]. The phase modulation of lightwaves propagating through these arms generates destructive or constructive interference at the output, thence amplitude or phase modulation. The DC biasing applied to these electrodes is also critical to the phase difference of the modulated lightwaves. For example a bias difference of pi would set a suppression of the carrier at the output of the modulator as shown in Figure 2(b). The formats of RZ or non-return-to-zero (NRZ) can be generated by using a pulse carver that would periodically switch on and off the lightwaves as indicated in Figure 3. The electrical data sequence can be either amplitude or phase encoded and then applied to the external data modulator. Normally due to the cos² profile of the modulator the bandwidth of the modulator would assume about 70% of the bit rate for RZ format. The amplitude of the electrical signals as compared with the Vp (the voltage at which the phase shift is 180°) of the MZIM would determine the phase difference of the modulated sequence.

Figure 4 shows the optical spectra of various advanced amplitude and phase modulation and NRZ or RZ formats at a base rate of 40 Gb/s. Indeed it requires only one MZIM dual drive to generate all possible amplitude and phase modulation. As described above for RZ and CSRZ it would require an additional pulse carver to generate RZ format pulse sequences. It is noted that whenever there requires the phase modulation of the optical carrier, this operation must be implemented in the photonic domain. Otherwise the signals must be converted back to the electronic domain so that signal processing can be performed. Therefore for any phase or phase difference modulation of optical channels, the encoding is done in the electronic domain, they are then used to manipulate the phase of the lightwaves via the traveling wave electrodes and thence the electro-optic effects in solid state, polymer or semiconductor integrated waveguides.

It is critical that the optical power contained in the carrier can be minimized and that the bandwidth of the modulated signals can be optimized to minimize the total transmission distortion effect. To this end the CS RZ format may offer better transmission performance.
Figure 2: 40 Gb/s external modulation for generation of advanced modulation formats. 10 Gb/s bit-pattern-generator and divider can be now combined using 40 Gb/s bit-error rate test set. An encoder for generation of phase or amplitude shift-keying modulation formats.

Figure 3: Phase generated optical signals using different biasing regions of the optical modulators. Note: only half data rate clock frequency is required for driving the pulse carver if it is biased at the minimum transmission point. The driving voltage is sinusoidal and hence wide bandwidth not required.
2.3 Optical fibers

The transmission and dispersion fibers would be of types standard ITU G. 652, ITU G655 non-zero dispersion shifted fibers (NDSF), or matched dispersion and dispersion slope fibers such as Corning Vascade types etc. The standard optical fibers are usually found in installed system, usually laid in late 1980’s and 1990’s. The dispersion factor ranging from 3 ps/nm/km to 16.8 ps/nm/km for these fibers is specified. Due to the transmission loss of about 0.2 dB/km in the C-band of silica fibers and the sensitivity of lumped optical amplifiers lead to the span length of 80 km to 120 km. This span length can be extended to 160 km if Raman distributed amplification is used. The optical fibers would act as an optical low pass filter with its transfer function is purely a phase modulation component as a function of the square of the frequency difference of the optical passband and the carrier frequency. This frequency dependent phase variation term would be critical for the phase or phase difference modulation formats. These phase distortion can be equalized by using dispersion compensating fibers whose dispersion factors and slopes can be matched to those of the transmission fibers.

2.4 Optical Receivers

Optical receiver would normally consist of a high speed photodetector followed by electronic amplifier and then main amplifier, clock recovery and sampling circuits for the case of amplitude shift keying modulation. Balanced receiver with a dual photodetector pair connected back to back acting as a push pull current generator would also be used for phase shift keying system. If differential phase modulation is employed then it is necessary that a delay interferometer in integrated optic form should be used to compare the phases of the carrier contained in the two consecutive bits. It is possible to construct the delay difference for data sequence operating in the 40 Gb/s or even 160 Gb/s. The delay can be tunable by using thermal effect. Typical eye diagrams detected using balanced receivers are shown in Figure 7.

3 40GB/S TRANSMISSION AND 40G OVER 10G DWDM TRANSMISSION SYSTEMS

Due to the economics of the high speed optical networks, it may require upgrading of existing installed 10 Gb/s with only a few certain wavelength channels to 40 Gb/s. We thus investigate the possibility and engineering of transmission of 40 Gb/s channels over 10Gb/s dense wavelength multiplexed optically amplified transmission system.

The optically amplified fiber transmission set up is shown in Figure 5(a). A tunable laser source is coupled with the SHF-5003 optical transmitter to modulate lightwave channels. Various formats such as RZ, Carrier suppressed RZ, NRZ, RZ-DPSK, RZ-DQPSK can be generated. Array waveguide gratings with ITU- standard wavelength grids are inserted at the transmitter and receiver sites. Optical amplifiers as pre-amplification-sub-systems and booster are employed at the front and post end, respectively of DCM to compensate for transmission and compensating fiber losses and boosting the power of optical channels so as to keep the transmission system uniform over the spans of the transmission link. Differential or intensity receivers are used at the receiving end before inserted to the error analyzer. The average optical power is measured via coupling 1:10 coupler at the input of the receiver. Thus all optical receiver sensitivity must be increased accordingly. The transmitter consists of two cascaded interferometric optical modulators. One serves as the pulse carver and the other for data switching. A CSRZ format can thus be created by biasing the pulse carver at its minimum transmission point. If it is biased at maximum transmission the generated data sequence would operate at a carrier-max state. DPSK and DQPSK formats can also generated by integrating an electrical pre-coder and then amplified to an appropriate level so as to swing the data pulses.
over the biasing state with a phase difference of 0 and $\pi$. An optical attenuator is used to adjust the optical power entering the receiver to evaluate the receiver sensitivity. Several types of optical filters are inserted such as NEL AWG mux/demux filter with a 0.45 nm 3 dB bandwidth (BW) and 100 GHz spacing (ii) Piri AWG mux/demux filter 0.5 nm (3dB bandwidth) - 200 GHz spacing (iii) FBG of 0.55 nm passband (iv) AWG 8 Channel Demux – 0.35 nm passband (v) JDS tunable filter of 1.3 nm passband (vi) Santec 0.5 nm BW – wideband roll off which are inserted into the transmission system wherever appropriate.

![Diagram](image1.png)

Figure 5 Demonstration of optical transmission system set-up for 40 Gb/s advanced modulation format – total fiber length 320 km and an effective 328 km dispersion compensation (a) schematic diagram (b) optically amplified and dispersion compensated fiber transmission line (left) – transmitter and receiver plus bit pattern generator and error analyzer (right).

Initially the impacts of the optical filtering characteristics of the mux are evaluated with back to back transmission set up. The sampling clock is set directly from the auxiliary clock output of the $2^{31}-1$ pattern generator. Although two AWGs can be used as muxes and demuxes we use only one AWG at either the transmitter or receiver sites. The other filter can be substituted by a thin-film multilayer optical filter. Two optical filters acting as mux and demux at the transmitting and receiving ends are then used to evaluate their impacts on 40 Gb/s channels. We observe insignificant degradation of the BER as shown in Figure 8. Note that the sensitivity must be read 10 dB down from the scale given in these figures due to the coupling 1:10 ratio.

Typical eye diagrams detected of the differential phase shift keying formats are shown in Figure 7. Decision threshold can be set at an optimum level to achieve the best bit-error rate that can be measured by an error analyzer SHF 44EA. The transmission distance is set so that the dispersion tolerance of the transmission formats can be characterized. Thus the back to back and up to 4 km transmission through various lengths of SSMF can be achieved. The bit-error-rate (BER) is plotted against the receiver sensitivity are obtained for various modulation formats ASK and DPSK and DQPSK with RZ, NRZ or CSRZ are shown in Figure 8. The sensitivities do not change significantly under the influence of the 0.5 nm optical filter on 40 Gb/s channels operating under different modulation formats. The filtered spectra of ASK and DPSK modulation formats as shown in Fig. 4 (b). The Gaussian-like or cos’ profile of the pulses generated at the output of both optical modulators and the parabolic passband properties of the AWG can tolerate wider signal spectra. We do not observe any degradation of the BER versus the sensitivity for the cases of wideband optical filters (1.2 nm) and 0.5 nm optical filtering of the multiplexer.
Figure 6 Optical passbands of AWG filters (a) top left corner: signal spectrum of a channel (b) right top: Optical passbands of the multiplexed output of the AWG – note the parabolic passband characteristics and the “black” curve of the output spectra of a wavelength channel (c) Signal spectrum and its output of the AWG (d) same as (c) but different wavelength region.

<table>
<thead>
<tr>
<th>Transmission distance w/o dispersion compensation</th>
<th>RZ DPSK</th>
<th>Carrier suppressed DPSK</th>
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<tbody>
<tr>
<td>Back to back</td>
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<td><img src="image2" alt="Carrier suppressed DPSK" /></td>
</tr>
<tr>
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<td><img src="image4" alt="Carrier suppressed DPSK" /></td>
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<td><img src="image6" alt="Carrier suppressed DPSK" /></td>
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<tr>
<td>3 km SSMF</td>
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</tr>
<tr>
<td>4 km SSMF</td>
<td><img src="image9" alt="RZ DPSK" /></td>
<td><img src="image10" alt="Carrier suppressed DPSK" /></td>
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Figure 7 Detected eye diagrams of differential phase modulation with formats RZ and carrier suppressed RZ.
Figure 8  (A) BER versus received optical power (at the power meter – 1:10 coupler before Rx). Note: “blue” (a) CSRZ-DPSK; “red” (b) RZ DPSK; “green” (e) NRZ ASK; “yellow” (c) CSRZ-ASK; “c” (d) RZ-ASK. (B) BER versus received optical power (at the power meter – 1:10 coupler before Rx). Legends: (a) “blue x” CSRZ-DPSK (one NELAWG); (f) “red - cross” – RZ DPSK (one NELAWG); (d) “green” NRZ ASK (one NELAWG); (b) “yellow” – CSRZ-ASK (one NELAWG); (c) “c” RZ-ASK (one NELAWG); only one optical filter NEL AWG is used; (f) “Red o” CSRZ DPSK two AWGs; (b) “blue o” RZ-DPSK with two AWGs.

Figure 9  Transmission system: 328 km SSMF + DCM320 (320 km effective compensating length) compensating fibers. (a) CS-RZ DPSK modulation format (red curve) (b) RZ-DPSK modulation format.

The transmission is then conducted with a total transmission length of the standard single mode fiber (SSMF) of 320 km and an effective dispersion compensating length of 328 km of SSMF. That means that an effective 8 km SSMF mismatch of dispersion in the 1550 nm spectral window. The BER versus the receiver sensitivity for RZ-DPSK and CS-RZ DPSK formats is obtained as shown in Figure 9 (a) and (b) respectively. The optical filters used as muxes have a typical passband of 1.2 nm and 0.5 nm. No degradation of the receiver sensitivity is observed for different passband filters. A 4 dB improvement on the receiver sensitivity is observed for CS-RZ DPSK over that of RZ-DPSK due to an enhancement in the total energy contained in the pulse sequence with a suppression of the carrier of the CS-RZ DPSK.
4 IMPACTS OF ADJACENT 10G ON 40G CHANNELS AND VICE VERSA

The 320km transmission is also conducted to assess the performance of 10G NRZ ASK and a CS-RZ DPSK 40G channel. The transmission of adjacent and non-adjacent channels is demonstrated and evaluated with a 100GHz AWG mux and a 1.2nm tunable filter at the input of the Rx. Insignificant power penalty is observed when adjacent 40G channel is co-transmitted. The set up of the transmission system with 320km SSMF and dispersion compensating module with 2 100GHz AWG’s used as muxes and Rx filter to measure the impact of adjacent CS-RZ DPSK 40G channel on 10G NRZ-ASK performance. No significant sensitivity degradation of 10 G channels is noted when 40G channel, adjacent or non-adjacent, is co-transmitted as evaluated in Figure 10.

![Figure 10 320 km transmission 40 G impact on 10G channel: BER versus receiver sensitivity (dBm)- effects of 40 G (CS_RZ DPSK) with 10G (NRZ-ASK) channel simultaneously transmitted for NRZ ASK and CS-RZ DPSK formats – blue dots for 1.2 nm thin film filter and dots for 0.5 nm AWG filter (demux with 100 GHz spacing)](image)

5 ELECTRONIC COMPENSATION AND EQUALIZATION

5.1 Equalization of polarization mode dispersion

As described above the progresses of photonic signal processing for long haul transmission is quite significant. Signal distortion can be compensated in the linear region by using dispersion compensating techniques via the negative dispersion fibers. Other dispersion effects such as polarization dispersion effects can also be evaluated and compensated with optical delay lines and a control feedback in the electronic domain as shown in Figure 11. The polarization of the modulated input electromagnetic lightwaves are rotated according to the electronic detection of the fundamental frequency of the signals which is tapped and detected from the optical signals. The optical delay line, a high birefringence optical fiber, has a very large difference of the polarized mode propagation constants, hence equalization of the delay difference of the two modes of the linearly polarized modes of the transmission SSMF.
5.2 Electronic pre-distortion for dispersion compensation

The complexity of the design of optically amplified long haul fiber transmission with two optical amplifiers in association with the dispersion compensating module can be eliminated if novel compensating technique can be implemented in the electronic domain rather than the photonic. Continuous progress in semiconductor technologies has enabled electronic processing for the first time to match the information speed of optical fiber systems. This gives the opportunity to fiber system designers to benefit from electronic signal processing and design systems whose performance would exceed that of systems without electronic processing at lower cost. The demonstration of such electronic pre-distortion for compensation [6 vi] is shown in Figure 12 in which the amplitude of electrical signals is distorted before modulating the phase of the lightwaves. This phase distortion (ps/nm) would be equivalent to the dispersion of the lightwaves after propagating over a transmission distance. Recent demonstration indicated that over 5000 km of SSMF can be compensated for 10 Gb/s RZ-DPSK channel is possible [7 vii]. This would significantly simplify the transmission system, especially the elimination of at least one lumped optical amplifier and hence associated amplified simulated emission noises. Furthermore if Corning Vascade fibers of positive and negative fibers of approximate identical effective area are used then the transmission distance would be extended much longer than 10,000 kms for 10 Gb/s (more than 1000 km for 40 Gb/s) and it is limited only by the total ASE noises of cascaded optical amplifiers.

Figure 12 Electronic pre-distortion for compensation of fiber dispersion (extracted from Ref [6] vi)
6 Conclusion Remarks

The optical transmission of advanced modulation format channels is presented with photonic and electronic processing techniques. We have also demonstrated that the transmission of 40 Gb/s channels over an optical fiber communication system whose optical characteristics are similar to those of standard 10 Gb/s DWDM channels. The filtering properties of the multiplexers and demultiplexers do not affect significantly the transmission performance in terms of BER and receiver sensitivity. We have also measured the transmission quality of both 40 Gb/s and 10 Gb/s channels and observe no degradation of either channels by the others. Indeed the use of optical filters can also be incorporated with the frequency discrimination technique for phase detection of DPSK channels [6 iv]. In this case a narrow band optical filter will reduce the amplified noises and hence simplify the receiver structure.

We have also reported some recent advanced technique of electronic signal processing for pre-distortion of the electrical signals prior to the modulation of the phases of the lightwaves propagating through an external modulator. This is possible to compensate for extremely long distance transmission without resorting to the use of dispersion compensating fibers, hence significant simplification of the transmission system structure.

Transmission of 40 Gb/s channels will be demonstrated over the commercial 10 Gb/s DWDM Siemens TranXpress System including a PMD emulation so as to prove the effectiveness of advanced modulation formats over practical system. Once this is proven the demonstration of the transmission will be implemented over the installed long-haul transmission system, for example the Sydney-Melbourne optically amplified fiber terrestrial link. The impact of the self-phase modulation nonlinear effects would also be investigated.

Furthermore efficient binary and M-ary modulation techniques such as minimum shift keying (MSK) and continuous phase frequency shift keying (CPFSK) are under our investigations and their transmission performance over long haul transmission will be reported in the future.

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