PHASE MODULATION FOR THE TRANSMISSION OF NX40GBIT/S DATA OVER TRANSOCEANIC DISTANCES

Gabriel Charlet, Sébastien Bigo, Jérémie Renaudier, Mathieu Lefrançois

gabriel.charlet@alcatel-lucent.fr

Alcatel-Lucent, Research and Innovation, Route de Nozay, 91460 Marcoussis, France

Abstract: The implementation of 40Gb/s rate in submarine system is very challenging from a technical point of view. Nevertheless, advanced technologies have been proposed and demonstrated in the past 5 years in order to turn it into a reality. Phase modulation of the light is one of the key enabling technologies. We will give an overview of different ways to exploit all the potentialities of phase modulation for improving the system performance and for increasing the system capacity.

1 INTRODUCTION

In terrestrial WDM networks, a few early adopters have already implemented 40Gbit/s technology, but deployments in large volumes is not expected until the next few years. Submarine optical networks are expected to catch up by this time. However, 40Gbit/s technology is more challenging than 10Gbit/s technology and innovative approaches are required. Among them, alternative modulation formats show the greatest promises.

Many research reports concur that Phase Shift Keying (PSK) is much more beneficial to 40Gbit/s transmission than conventional Amplitude Shift Keying. The first feasibility demonstration that 40Gbit/s data can be transmitted over transpacific distances has been obtained with PSK, and the largest capacity ever over a transatlantic distance was also demonstrated with PSK. However, PSK can take several forms, with return-to-zero-like pulse carving, with bit-to-bit polarization interleaving or with multi-level signaling. We will recall the pros and cons on each of these approaches as a function of distance and system capacity based on the results of our multiterabit/s transmission experiments.

Besides, photodiodes are not sensitive to phase and PSK requires novel detection schemes in order to demodulate the optical data, either by differential detection or coherent detection. We will compare the performance of both approaches. We will particularly illustrate the promises held by coherent detection when combined with high digital signal processing, as a remedy against various propagation impairments.

2 40GB/S BINARY PSK SIGNAL

Different modulation formats based on phase modulation have been proposed, but the first kind of transponders produced in large volume will be based on Differential Binary Phase Shift Keying (DBPSK, often called DPSK for simplicity). In order to modulate the optical phase of light, a phase modulator or a Mach-Zehnder based amplitude modulator can be used. Mach-Zehnder modulators offer better performance due to accurate phase shift generation due to its Mach-Zehnder interferometer structure. Photodiodes detect only the intensity of the light (the square of the module of the amplitude) and are not sensitive to the phase shift generated at the transmitter side. A phase to intensity conversion can be done by an optical demodulator which consists of a two-wave interferometer (such as Michelson or Mach Zehnder interferometer) having a one bit delay. The two complementary output of the demodulator are fed to a balanced photodiode which is connected to the clock and data recovery module. The association of DPSK modulation with differential demodulator and balanced detection provides a 3dB Optical Signal to Noise Ratio (OSNR) improvement compared to standard formats [1].

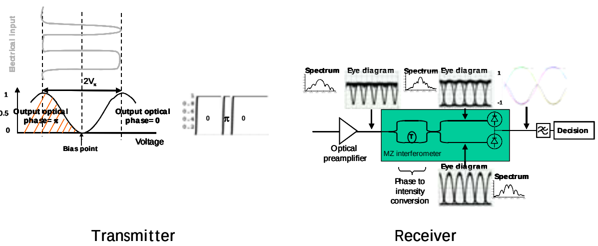

Fig 1 : DPSK transmitter (left) and receiver (right)

Beside the improved OSNR sensitivity, 40Gb/s DPSK is also more tolerant to non linear interactions than 40Gb/s OOK formats. This is mainly due to the phase jumps within the signal which allow to reduce intrachannel non linear effects and particularly intrachannel Four Wave Mixing (iFWM). 40Gb/s DPSK is now almost ready for field deployment.

In order to further reduce interactions between adjacent bits, polarization modulation can also be added on top of phase modulation. A polarization modulator driven at 20GHz inserted after the (RZ)-DPSK transmitter can switch the polarization of every other bit and thus minimize non linear degradations. At the receiver side, a two-bit delay interferometer is used to compare the relative phase of bits having the same polarization. The evolutions required on the transponder are shown in the left part of Fig 2.

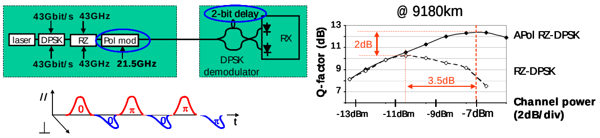

Fig 2 : left : evolution of transponder to evolve from RZ-DPSK to APol RZ-DPSK and impact on waveform. Right : Performance improvement brought by APol RZ-DPSK in a transpacific configuration

Alternate Polarization (APol) RZ-DPSK has been used to increase the system performance evaluated within a recirculating loop emulating a 9,180km long submarine system. By increasing the non linear threshold by more than 3dB, a system margin improvement of 2dB was observed, compared to RZ-DPSK as depicted in the right part of Fig 2.

Nevertheless, APol RZ-DPSK has one major drawback which is the lower tolerance to Polarization Mode Dispersion (PMD) compared to single-polarization modulation scheme, described in Figure 3. As APol RZ-DPSK is expected to be suitable for Ultra Long submarine links due to its superior tolerance to non linearity, a reduced tolerance to PMD is very damageable as, for a given fiber type, the PMD link value grows as the square root of the distance. PMD mitigation or extremely low PMD fibers for submarine cable seem the only two ways to push APol RZ-DPSK from the lab demos to the field.

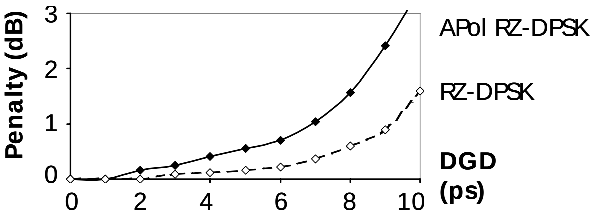

Fig 3 : tolerance to DGD of RZ-DPSK and APol RZ-DPSK

3 40GB/S OVER NZDSF SUBMARINE LINK

Almost all installed submarine systems are based on Non Zero Dispersion Shifted Fiber (NZDSF) having a slightly negative dispersion (around –3 to –2ps/nm/km at 1550nm). The negative dispersion accumulated by the signal during the propagation through this NZDSF-is compensated by Standard Single Mode Fiber (SSMF) having a dispersion around 17ps/nm/km. But the dispersion slopes of both fibers are positive and thus cumulate themselves all along the line. After several thousand kilometers of fiber, the cumulated dispersion can change by more than 400ps/nm from one wavelength to the next, located just 100GHz apart. 10Gb/s systems use per channel compensation to partially mitigate this effect. Nevertheless, the variation of dispersion across the channel bandwidth (around 100GHz for one 40Gb/s DPSK or RZ-DPSK channel) shown in Fig 4 left has a dramatic impact on the signal quality as depicted in Fig 4 right.

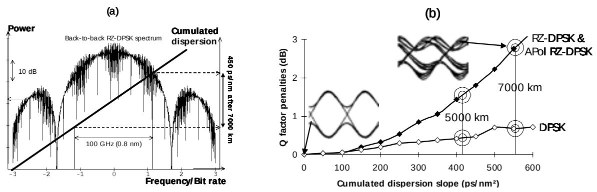

Fig 4 : left : Cumulated dispersion variation inside the RZ-DPSK spectrum. right : Q factor penalties consecutive to the impact of the cumulated dispersion slope inside a channel for both DPSK and RZ-DPSK formats. Insets : RZ-DPSK eye diagrams in back-to-back and after a dispersion slope degradation over 7000 km

The wider the modulation format spectrum, the higher the penalties. Thus RZ-DPSK is more impaired than DPSK and the transmission distance become limited to a few thousand kilometers only [3]. But intrachannel dispersion slope compensation can be applied to cancel this impairment and to allow 40Gb/s transmission over longer distance [4].

4 40GB/S DIFFERENTIAL QUADRATURE PHASE SHIFT KEYING

In order to increase the information spectral density, modulation formats with larger number of phase states have been proposed. 2 bits are encoded within each symbol when a 4 phase levels format is used as it is the case with Differential Quadrature Phase Shift Keying (DQPSK). As the symbol rate is reduced by a factor two at 20Gsymbols/s, the spectrum width is reduced by a factor two also. A scheme of DQPSK transmitter and receiver is plotted in Fig 5. It appears clearly that the complexity is higher than for DPSK transmitter.

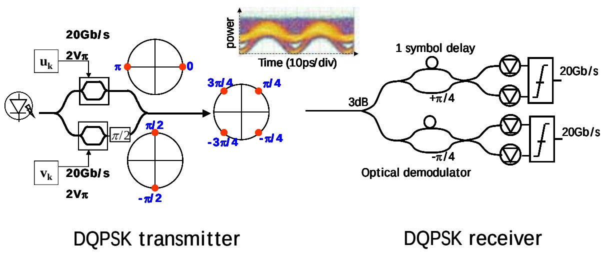

Fig 5 : DQPSK transmitter and receiver

40Gb/s DQPSK have been packed on a 50GHz ITU grid to transmit 150 WDM channel over more than 4,000km [0]. The higher system capacity is obtained here at the expense of the transmission distance which is severely reduced with respect to lower-capacity systems based on DPSK or APol-RZ-DPSK formats.

5 PMD IMPAIRMENTS AND MITIGATION TECHNIQUES

Chromatic dispersion and Polarization Mode Dispersion (PMD) are two main impairments for high speed transmission. Contrary to chromatic dispersion which can be easily compensated by Dispersion Compensating Fiber and/or Tunable Optical Dispersion Compensator, PMD is much more difficult to mitigate.

Several solutions have been proposed to combat the detrimental PMD effect. One solution is to use a modulation format having a reduced symbol rate. 40Gb/s DQPSK resorts of 20Gsymbol/s instead of 40Gsymbol/s for almost all other formats proposed for submarine applications. This reduced symbol rate translates directly into a increased tolerance to PMD by a factor of 2.

A second interesting solution is to use distributed high speed polarization scrambling in conjunction with Forward Error Correction (FEC) code [0]. Thanks to the high speed polarization scrambling, the polarization state of the signal stays during a very short time only on high Differential Group Delay (DGD) values of the link. If the time duration is shorter than the Burst Error Correction Capability (BECC) of the FEC, the burst of error generated during this time can be corrected by the FEC. This method has been proved to be extremely efficient even when the link has a high PMD. It will require the installation of several high speed polarization scramblers undersea and thus this solution is possible only for greenfield deployment.

Another solution is to apply Electronic Dispersion Equalizer (EDE) at the receiver side. This solution can be very cost effective and can be applied on almost all modulation formats to increase theirs PMD tolerance. Nevertheless, the improvement brought by this solution is limited to approximately +50% [0]. This can be sufficient for most of submarine links already deployed which are based on NZDSF of excellent quality and even more for next-generation systems where the fiber PMD is even lower due to recent fiber manufacturing progress.

Performance of signal processing done by EDE is limited as the phase information of the signal is lost after the photodiode which does not detect the electrical field but the square of the electrical field module (ie the intensity). Much more efficient signal processing can be done if amplitude and phase information is preserved at the detection as it is the case in optical coherent receivers.

6 COHERENT DETECTION AND DIGITAL SIGNAL PROCESSING

Coherent detection has been widely studied at the end of the 1980s in order to increase the transmission distance of optical systems. The beating between a weak signal and a powerful local oscillator was a way to amplify the signal which has became extremely low by fiber losses. But the complexity of local oscillator frequency/phase locking was very high and the apparition of optical amplifiers makes coherent detection unnecessary. Very recently, the advance of Digital Signal Processing (DSP) put a renewed interest on coherent detection. The advantage of coherent detection is no more its power sensitivity but its capability to detect advanced modulation formats and to compensate “linear” distortions. The phase/frequency constraints on the local oscillator have also been removed by digital signal processing capability. Nevertheless, up to now only off line processing of signals acquired and stored on high speed oscilloscopes have shown promising results. Some real time demonstrations have been published, but at a very low bit rate (less than 2Gb/s) and with poor performances. Advanced of Analog to Digital Converter (ADC) and of DSP is expected in the following years to make possible real time implementation of high performance. A typical implementation of polarization diversity coherent receiver is depicted in Fig 6. A polarization beam splitter (PBS) separate the two polarization of the signal, both of them are mixed with the local oscillator into a so-called coherent mixer or 90° hybrid. The cosine part of the beating term between local oscillator and signal is sent into a first photoreceiver whereas the sine part is sent on a second photoreceiver. ADCs are then used to sample the signal at twice the symbol rate for optimum performance. The digitalized signals are then processed by DSP. Compensation of chromatic dispersion has already been demonstrated (by using off-line signal processing) by several teams at 10Gb/s, 20Gb/s, 40Gb/s and even 80Gb/s.

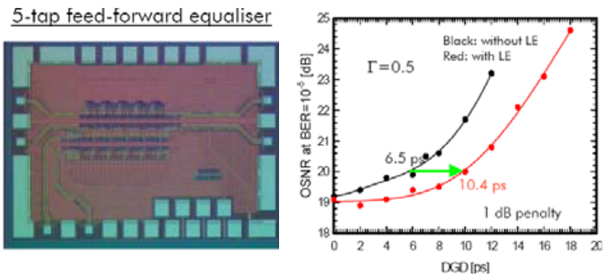

Fig 6: picture of EDE chip and experimental assessment of EDE efficiency to enhance PMD tolerance of modulation formats at 40Gb/s

WDM transmission of 40Gb/s QPSK with coherent detection has been demonstrated over more than 3,000km by using off-line processing [0]. Non linear effect mitigation has also been demonstrated by using the intensity information of each symbol to add a correction on the phase information (where data is encoded). By using Polarization Multiplexing and adaptive filters within the Digital Signal Processor to handle both polarizations [0], it is possible to double the capacity transmitted within the same optical bandwidth.

PMD compensation has also been demonstrated on Polarization Multiplexed QPSK signal. When a 5 tap adaptive filter is used, the OSNR sensitivity of 40Gb/s polarization multiplexed QPSK signal has been measured without any DGD, with 13ps DGD and with 19ps DGD for random input polarization states. Very similar performances have been found as shown in Fig 7. This result highlights the tolerance of 40Gb/s Polarization Multiplexed QPSK associated with coherent detection and digital signal processing to PMD.

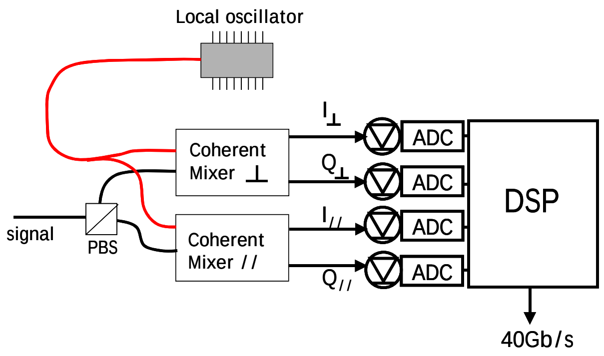

Fig 7 : scheme of coherent detection (can be applied to polarization multiplexed format).

A large information spectral density improvement could be obtained by using the potential of coherent detection for building future ultra high capacity submarine cables in the next 5-10 years.

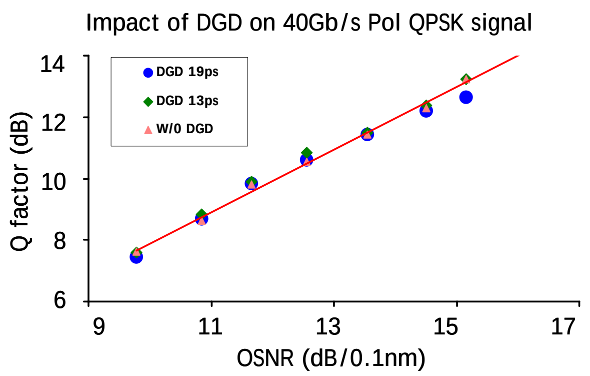

Fig 8 : Impact of DGD on OSNR sensitivity measurement of 40Gb/s Pol Mux QPSK signal

7 CONCLUSION

The first deployments at 40Gb/s in submarine systems are expected in the next years. The need for higher capacity, the development of cost-effective 40Gb/s solutions in terrestrial optical routes and the introduction of 40Gb/s ports on routers could be three of the main drivers for its deployment. It is expected that 40Gb/s systems will be deployed in terrestrial networks before being deployed over undersea links and thus modulation formats designed for Ultra Long Haul terrestrial applications such as 40Gb/s DPSK will likely be used first in submarine networks of moderate reach.

At longer term, APol RZ-DPSK and DQPSK could be interesting solutions, the first one for Ultra Long Haul transmission whereas the second one could be restricted to ultra high capacity – medium reach system.

Coherent detection could be an enabling technology for future systems with extremely high capacity but its ability to allow Ultra Long distances has still to be demonstrated.

8 REFERENCES

[1] A. H. Gnauck et al., « 2.5 Tb/s (64x42.7 Gb/s) Transmission over 40x100 km NZDSF using RZ-DPSK format and all-Raman amplified spans », OFC'02, FC2-1, Anaheim, California, March 17-22.

[2] G. Charlet, R. Dischler, A. Klekamp, P. Tran, H. Mardoyan, L. Pierre, W. Idler, S. Bigo, “WDM Bit-to-Bit Alternate-Polarisation RZ-DPSK transmission at 40x42.7Gbit/s over transpacific distance with large Q-factor margin”, in proc. European Conference on Optical Communications (ECOC’04), paper Th4.4.5., Stockholm, 5-9 Sept. 2004

[3] L. Becouarn, G. Vareille, S. Dupont, P. Plantady, J.-F. Marcerou, A. Klekamp, R. Dischler, W. Idler, G. Charlet, « 42x42.7Gb/s RZ-DPSK transmission over a 4820km long NZDSF deployed line using C-Band only EDFAs », OFC'04, PDP37, Los Angeles, California, March 22-27

[4] J.-X. Cai, C. R. Davidson, M. Nissov, H. Li, W. Anderson, Y. Cai, L. Liu, A. N. Pilipetskii, D. G. Foursa, W. W. Patterson, P. C. Corbett, A. J. Lucero, and Neal S. Bergano, « Transmission of 40Gb/s WDM signals over 6,250km of conventional NZ-DSF with >4dB FEC Margin », 0, PDP26, ,

[5] G. Charlet et al., « 151x43Gb/s transmission over 4,080km based on Return-to-Zero Differential Quadrature Phase-Shift Keying », ECOC’ 05, Th 4.1.3, Glasgow, Scotland, Sept. 25-29

[6] A. Klekamp, B. Junginger and H. Büelow "Experimental PMD mitigation for 43Gb/s DPSK by distributed polariastion scrambling over 4 spans SMF fiber", ECOC'06, Th4.3.6, Cannes, France

[7] B. Franz, D. Rösener, R. Dischler, F. Buchali, B. Junginger, T. F. Meister, K. Aufinger,"43Gbit/s SiGe based electronic equalizer for PMD and chromatic dispersion mitigation", ECOC'05, We 1.3.1, Glasgow, Scotland, Sept. 25-29

[8] G. Charlet, N. Maaref, J. Renaudier, H. Mardoyan, P. Tran and S. Bigo, « Transmission of 40Gb/s QPSK with coherent detection over Ultra Long distance improved by nonlinearity mitigation", ECOC'06, Th4.3.4, Cannes, France

[9] S. J. Savory, A.D. Stewart, S. Wood, G. Gaviolo, M.G. Taylor, R.I. Killey, P. Bayvel "Digital Equalization of 40Gb/s per wavelength transmission over 2480km of standard fiber without optical dispersion compensation", ECOC'06, Th2.5.5, Cannes, France