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Coherent detection associated with digital signal processing for fiber optics communication

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Abstract

Optical transmission systems have seen their performance (system capacity and system reach) drastically improved in the last 15 years by using new technologies such as wide band optical amplification, wavelength division multiplexing (WDM), dispersion management, introduction of 10 Gbit/s channel rate and now 40 Gbit/s, Differential Phase Shift Keying (DPSK) modulation.... In order to further increase system capacity while relaxing the constraints associated with higher channel rate (i.e. 100 Gbit/s), the association of multilevel modulation format with coherent detection and digital signal processing appears as a key enabler. This article describes the actual modulation and detection methods in order to explain how a coherent receiver including digital signal processing works. The efficiency of coherent receiver to compensate for linear distortions induced by fiber optic propagation will also be detailed. The promising association of coherent receiver with multilevel modulation format, especially for 100 Gbit/s channel rate will be described. Eventually, the limitations of optical communication systems relying on coherent detection will be explained. ***To cite this article: G. Charlet, C. R. Physique 9 (2008).***

Résumé

Détection cohérente associée au traitement du signal numérique pour la communication par fibre optique. Les systèmes de transmission optiques ont vu leur performances (capacité de transmission du système et portée) très fortement augmenter au cours des quinze dernières années par l'introduction de nouvelles technologies telles que les amplificateurs optique large bande, le multiplexage en longueur d'onde (WDM), la gestion de dispersion chromatique, les équipements fonctionnant au débit de 10 Gbit/s et maintenant de 40 Gbit/s ainsi que de formats de modulation utilisant la modulation de phase (DPSK).... Afin de continuer à augmenter la capacité du système tout en diminuant les contraintes associées à la propagation de canaux à très haut débit (100 Gbit/s), l'association de formats de modulation multi-niveaux avec des techniques de détection cohérente associées à du traitement du signal numérique apparaît comme très efficace. Les méthodes de modulation et de détection utilisées actuellement seront décrites ainsi que le fonctionnement d'un récepteur cohérent. L'efficacité de la détection cohérente pour compenser les distorsions linéaires introduites par la propagation sera aussi détaillé. Nous verrons également que l'association de la réception cohérente avec des formats multi-niveaux est particulièrement prometteuse au débit de 100 Gbit/s. Finalement, les limitations des systèmes de transmission optique utilisant ces techniques de détection cohérente seront expliquées. ***Pour citer cet article : G. Charlet, C. R. Physique 9 (2008).***

Keywords: Phase shift keying; Optical communication; Polarization multiplexing; Optical modulation; Coherent detection; Digital signal processing

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Mots-clés : Modulation de phase ; Communication optique ; Multiplexage en polarisation ; Modulation optique ; Détection cohérente ; Traitement du signal numérique

1. Introduction

At the beginning of optical communications, binary electrical data were converted into optical data in a simple way: a binary electrical “0” was converted into a low intensity optical signal, whereas a binary electrical “1” was converted into a higher intensity optical signal. In order to cope with the continuously increased bandwidth requirement, two main methods have been used. The first method has been to increase the channel bit rate from 155 Mbit/s to 622 Mbit/s, 2.5 Gbit/s, 10 Gbit/s and now 40 Gbit/s by using the progress of Time Division Multiplexing (TDM) technologies, whereas the second one, to raise the number of wavelengths transmitted over a single fiber from one to several tens or hundreds by using Wavelength Division Multiplexing (WDM) technologies. However, with the increase of data rates (i.e. 40 Gbit/s and 100 Gbit/s), more advanced ways have been required to encode data into optical signal (i.e. more advanced modulation formats) and to detect the optical signal.

The most widely deployed backbone systems are working with wavelengths modulated at a bit rate of 10 Gb/s, with the simplest modulation format, i.e. Non Return to Zero (NRZ). Up to approximately 100 wavelengths can be multiplexed into a single fiber with a channel spacing of 50 GHz. This corresponds to an information spectral density of 0.2 bit/s/Hz. 40 Gb/s equipment has also started to be deployed for one or two years on the network of telecom operators. This was done so as to fulfill the capacity requirement while keeping the same channel spacing (or only doubling it at 100 GHz channel spacing). 100 Gb/s technology is now requested by some telecom operators for the 2010–2012 time frame, but will have to be compliant with the same 50 GHz channel spacing. To answer to these new constraints (higher bit rate and still same channel spacing), new modulation formats and detection methods have been proposed. These new techniques are expected to be implemented soon.

Coherent technology has been investigated at the end of the 1980s [1] in order to combat the attenuation of optical fiber for bit rate ranging from 155 Mbit/s to 2.5 Gbit/s. The introduction of the Erbium Doped Fiber Amplifier (EDFA) at the beginning of the 1990s [2] made the complex coherent technology useless. In 2004 the first paper demonstrating the potential of a coherent receiver associated with digital signal processing has been published [3]. Coherent technology associated with multilevel modulation format and digital signal processing [4] is now seen as a key method to increase the system capacity and the tolerance to fiber impairments.

2. Optical communication limitations

In order to understand the requirements on the modulation format and detection method, current limitations of optical communication systems will be described. The strategies used up to now to compensate or mitigate them in order to push the transmission reach limit will also be explained.

2.1. Linear effects

2.1.1. Fiber attenuation

The most challenging limitation encountered in optical transmission until the 1980s was the attenuation of optical fibers. Thanks to the progress of fiber manufacturing, the attenuation of fibers has gone down to slightly below 0.20 dB/km at 1.55 μm (the wavelength where the attenuation is nearly at its minimum). After 100 km, the loss is 20 dB, i.e. the optical power has been divided by 100.

Optical amplifiers are therefore mandatory when propagating over long distances without the need of electronic regeneration. Optical amplifiers based on the Erbium doped fiber have been developed at the end of the 1980s decade [2], and are now widely deployed within terrestrial and submarine systems. They can provide high gain (> 20 dB), large optical bandwidth (> 4 THz i.e. more than 32 nm around 1550 nm) and low Noise Figure (NF < 6 dB). Several tens of Erbium Doped Fiber Amplifiers (EDFA) can also be cascaded in terrestrial network and more than one hundred in some submarine links.

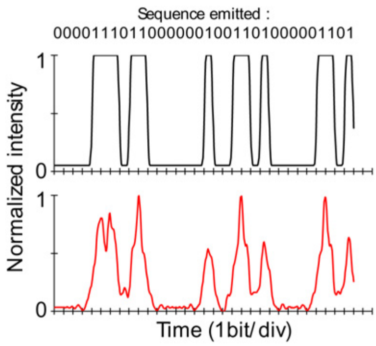

Fig. 1. Impact of chromatic dispersion on pulses integrity.

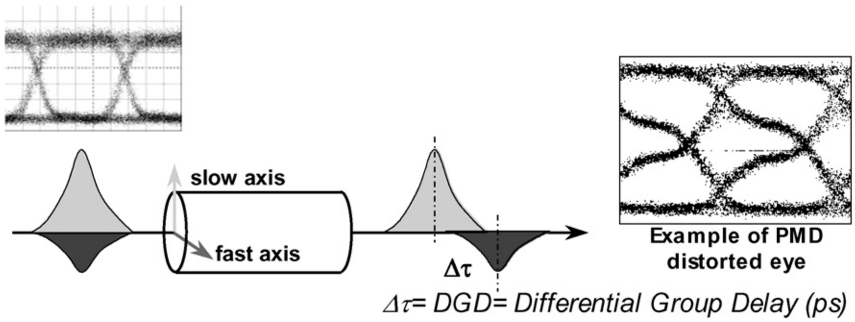

Fig. 2. Impact of DGD on the pulse broadening and on the eye diagram.

2.1.2. Chromatic dispersion

Once periodical amplification is implemented, the impact of fiber chromatic dispersion [5] arises as one of the most limiting impairments. Chromatic dispersion refers to the phenomenon by which the various spectral components of the signal do not travel at the same speed. This corresponds to the wavelength (or frequency) dependence of the fiber refractive index. Owing to this effect, the pulses broaden, leading to bit-to-bit overlaps and the information after detection may be corrupted because of Inter-Symbol Interference. If we consider a conventional 10 Gb/s signal (spectrum width ∼0.15 nm), the maximum transmission distance over SSMF (standard single mode fiber, which has a chromatic dispersion of 17 ps/nm/km), does not exceed 100 km. The impact of chromatic dispersion on a sequence of data is shown in Fig. 1.

The optical transmitter converts an electrical binary sequence into optical power (upper part of Fig. 1). Due to fiber chromatic dispersion, each "1" broadens and "0" and "1" are increasingly difficult to distinguish, as shown in the lower part.

When moving from 10 Gb/s to 40 Gb/s, the constraints due to chromatic dispersion increase by a factor 16 (the impact of chromatic dispersion evolves as the square of the variation of the bit rate i.e. here 4^2) and the transmission reach could be limited to a few kilometers only. This resulting limitation on distance can be overcome by compensating for the chromatic dispersion by concatenating the transmission fiber with another fiber or component exhibiting a dispersion of the opposite sign such as a Dispersion Compensating Module (DCM).

2.1.3. Polarization mode dispersion (PMD)

PMD is another physical phenomenon in the fiber which may degrade high bit-rate transmissions. Due to the imperfections of fiber manufacturing (namely non-perfectly circular fiber core, constraints within the fiber, stress induced birefringence), the light velocity within the fiber can change slightly depending on the polarization of light. This effect is called Polarization Mode Dispersion (PMD) [6]. It may cause pulse broadening, as shown in Fig. 2, by generating a Differential Group Delay (DGD) between the two parts of the pulse: one aligned along the slow axis and the other one along the fast axis. Contrary to chromatic dispersion, polarization mode dispersion changes quickly with time (second to millisecond range) [7]. The PMD value of a fiber is defined as the average value of the DGD over time. The impact of PMD is difficult to apprehend, because most of the time it is small but suddenly may turn the system Bit Error Rate (BER) above acceptable limits during a few minutes per year. The impact of PMD evolves linearly with the symbol duration, i.e. a 40 Gbit/s signal is 4 times less tolerant to PMD than a 10 Gbit/s one. PMD constraints are challenging to surmount at 40 Gb/s and 100 Gb/s especially when current 10 Gb/s systems with a non-negligible amount of PMD have to be upgraded to higher bit rate.

Some techniques have been proposed to mitigate this impairment. Historically, the most performant one resorts on an optical method. The optical PMD compensator uses one or two sections of birefringent elements which are dynamically adjusted per channel to mitigate the impact of the PMD. Nevertheless, the cost associated with such optical PMD compensators is relatively important and explain why large scale deployments have not yet occurred. However, a wider scale deployment of 40 Gb/s solutions (using DPSK [8] and PSBT [9] modulation format) in the coming years could change the situation.

At 10 Gb/s, Maximum Likelihood Sequence Estimation (MLSE) techniques have been implemented in commercial transponder to relax the constraints in term of signal distortion since 2004 [10]. By using such technology, tolerance to PMD can be widely increased [11] at a reasonable cost. However, this technique is not available for 40 Gb/s yet. This is due to the lack of a key component required for such application, namely a high speed Analog to Digital Converter (ADC) operating at 40 Gb/s.

Operators choose sometimes to replace fibers having poor PMD properties by new ones with better specifications (but this may be very costly) or to electrically regenerate the optical signal before the degradations introduced by PMD are too large.

Another possibility is to select a modulation format or a detection method which is more tolerant to PMD impairments. We shall see that the association of multilevel modulation format with coherent detection and digital signal processing can be extremely effective for compensating PMD distortions of high speed signals (40 Gb/s and 100 Gb/s especially).

2.2. *Noise and non-linear effects*

When fiber loss is compensated by optical amplifier gain and chromatic dispersion issues are solved, new problems arise which, contrary to the previous case, cannot be fully compensated. Due to the cascade of optical amplifiers, the Optical Signal to Noise Ratio (OSNR) degrades along the transmission path. When the OSNR becomes too low, it is no longer possible to recover the information. This means that the Bit Error Rate (BER) worsens beyond acceptable limits.

These limits are defined by the correction capabilities of the Forward Error Correction (FEC) code used; a signal having a BER of 10^{-3} can be corrected to a quasi error free stream (BER better than 10^{-13}) thanks to modern FEC. A limited overhead is required to implement the FEC – it is usually around 7% – leading to a bit rate of 43 Gbit/s (instead of 40 Gbit/s). Nevertheless, for simplicity and clarity purposes, 40 Gbit/s will still be used to describe a signal with the 7% FEC overhead, and 100 Gbit/s, to describe signal propagating at a bit rate up to 112 Gbit/s (due to FEC and protocol overhead). The more direct way to improve the OSNR is to increase the signal power at the input of the optical amplifiers. This can be made possible by increasing the signal power at the output of the previous amplifiers.

This leads to new limitations called non-linear effects [5]. The transmission length of optical communication system can be very long (typically several hundreds or thousands of kilometers), and the light is confined within a very small core (characterized by the effective area $A_{\text{eff}} \sim 50$ to 80 μm^2). So a moderate power level P at the input of each span (~ 1 mW, i.e. 0 dBm), leads to a modification of the fiber refractive index with the signal, which can degrade the signal quality through the tight interplay with chromatic dispersion after hundred or thousand of kilometers.

Non-linear effects are often categorized into two sets of effects: those resulting from the propagation of a single channel and those resulting from the interactions between WDM channels. Single-channel non-linear effects manifest mainly through Self Phase Modulation (SPM), whereby each channel alters its own phase. SPM translates into pulse distortions through chromatic dispersion. WDM non-linear effects are often split into Cross Phase Modulation (XPM) whereas the phase (and also polarization) of each channel is modified by the power of the neighboring channels, and Four Wave Mixing (FWM), whereby three channels interact to transfer a fraction of their energy to a fourth one.

Trade-offs on optical power between too much noise and too much non-linear effects have to be found for optimal system performance, i.e. minimal BER. Techniques used to improve tolerance to optical noise or non-linear effects are welcome in order to increase transmission reach.

2.3. Upgrade constraints

Operators have built wide WDM optical networks working at a bit rate of 10 Gb/s between the years 2000 and 2008. Most of them do not intend to built a specific network for 40 Gb/s applications from scratch, but wish to upgrade them smoothly from 10 Gb/s to 40 Gb/s and even to 100 Gb/s. In these networks, light is passed into Dispersion Compensating Fiber (DCF), so as to avoid large accumulation of chromatic dispersion within the link, as well as into optical filters within Reconfigurable Optical Add and Drop Multiplexers (ROADM) which are usually designed for systems working with 50 GHz channel spacing at 10 Gb/s.

This generates some constraints when moving to 40 Gb/s and 100 Gb/s as these high bit rate channels have to be compatible with the 50 GHz slots defined by ROADM. As the spectrum is naturally four times broader at 40 Gb/s than at 10 Gb/s when the same modulation scheme is applied, the simplest modulation format, which is Non Return to Zero (NRZ), cannot be used directly (the spectrum occupancy of the signal is around twice the symbol rate, i.e. 80 GHz at 40 Gb/s). For this reason, new generation of modulation formats have been pushed to handle this specific bandwidth limitation.

The modulation formats proposed at 40 Gbit/s and 100 Gb/s need to be compatible with the co propagation with 10 Gb/s signals which are based on intensity modulation technique. Modulation formats proposed for 40 Gb/s and 100 Gb/s usually resort to phase modulation and possibly to multilevel signal coding and polarization division multiplexing. In Section 4, the non-linear interactions between intensity modulated signals and modulation formats using phase/polarization encoding will be described and some of the limitations will be highlighted.

3. Key advantages of coherent receiver associated with multilevel modulation format and digital signal processing

3.1. Direct detection receiver description

Direct detection receivers are currently used in almost all deployed optical networks today. For bit rate of 10 Gb/s and below, modulation format are intensity modulated and intensity detected through direct detection (except for some submarine links which use phase modulation). The modulation/detection technique is called On Off Keying (OOK) or Intensity Modulated Direct Detected (IMDD). The most commonly used modulation formats are Non Return to Zero (NRZ) and Return to Zero (RZ). In both cases, the information is encoded within the intensity of the light, but with RZ modulation, "ones" are encoded by pulses as depicted in Fig. 3.

In order to detect the optical signal and to convert it back to a digital electrical signal, light is sent onto a photodiode, which is followed by a low pass filter (with a 3 dB bandwidth around 0.7 × bitrate) so as to integrate the signal over a bit duration. A clock recovery circuit is then used to provide the right sampling phase to a decision element. This decision element selects whether the incoming signal is a "1" or a "0" by comparing the electrical level at its input with a reference threshold, as depicted in Fig. 4. The digital electrical signal can then be processed by a FEC decoder and then sent to a cross-connect, either an Ethernet switch or an IP router for further processing.

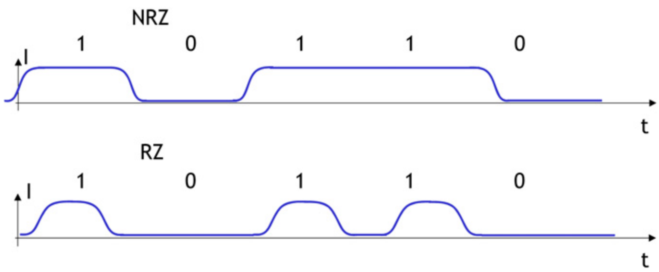

Fig. 3. Temporal intensity waveform of On Off Keying signal, NRZ (top) and RZ (bottom).

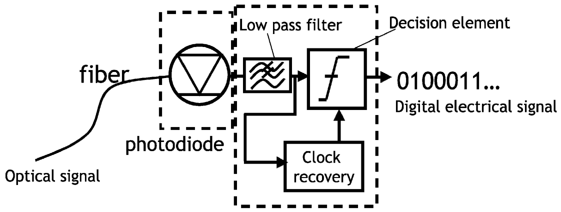

Fig. 4. Schematic of an OOK receiver.

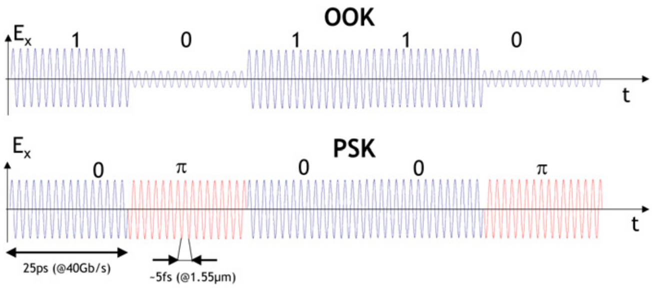

Fig. 5. Electrical field representation of OOK format (top) and PSK format (bottom).

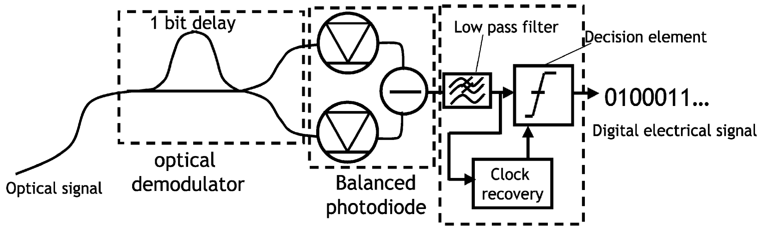

Fig. 6. Schematic of DPSK receiver including optical demodulator.

When bit rate is increased to 40 Gb/s, another modulation technique associated with a different detection technique is often used. The association of Phase Shift Keying (PSK) and differential detection at the receiver side is called Differential Phase Shift Keying (DPSK) or Differential Binary Phase Shift Keying (DBPSK); B indicating that a binary modulation is used. The electrical field representation of the standard OOK modulation, and of the DPSK modulation is schematized in Fig. 5. For the wavelength range used in optical communication systems, i.e. around 1550 nm, the frequency of the electrical field is around 200 THz.

Phase Shift Keying (PSK) has been first proposed more than 20 years ago but a renewed interest has been observed since 2002 [8] when it was demonstrated that extremely good performance transmission was achievable at the bit rate of 40 Gbit/s in WDM configuration. In order to avoid the use of complex coherent receivers, which enables the detection of the phase of the encoded signal, a differential approach has been proposed in conjunction with a balanced receiver. One of the main advantages of Differential Phase Shift Keying (DPSK) is the 3 dB improved tolerance to optical noise, also called OSNR sensitivity, brought by the balanced receiver [12].

As photodiodes are insensitive to the phase of the light, an optical Mach Zehnder interferometer (also called optical demodulator) having a 1 bit delay between the two arms of the interferometer generates interferences between a bit and the previous one. When two consecutive bits have the same phase, constructive interference generates an optical pulse at the output of the constructive port, and destructive interference generates no optical signal on the destructive port. When two consecutive bits have a phase difference of π, destructive interference produces no optical signal at the output of the constructive port, and constructive interference produces an optical pulse on the destructive port. Balanced photodiodes are connected to the two ports of the optical demodulator, and then to the low pass filter followed by a decision element and clock recovery circuit as depicted in Fig. 6.

In Fig. 7 left, the modulated electrical field is represented for three modulation formats, OOK (On Off Keying), BPSK (Binary Phase Shift Keying) and QPSK (Quadrature Phase Shift Keying), as a function of time. The oscillation period of the electrical field is around 5 fs as the carrier frequency is around 200 THz for fiber optics transmission.

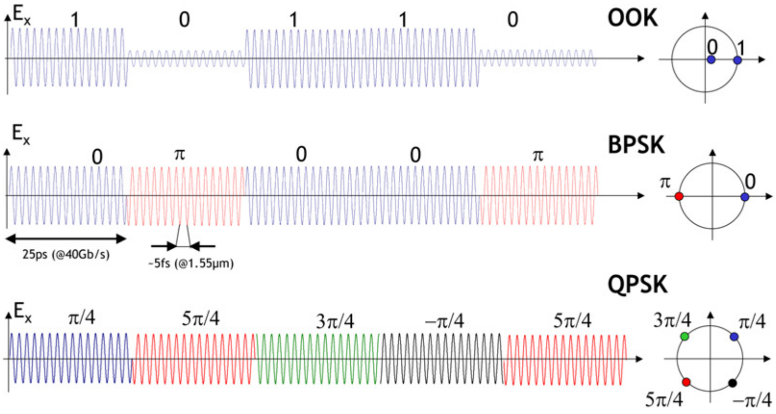

Fig. 7. Electrical field representation and constellation diagram of OOK, BPSK and QPSK signals.

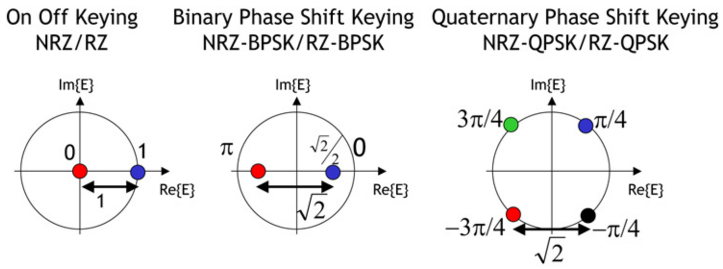

Fig. 8. Constellation diagram and symbol distance for OOK, BPSK and QPSK.

Considering a signal at 10 Gsymbol/s, each symbol contains ∼20 000 oscillations. In Fig. 7, a few oscillations are depicted for practical reasons. For OOK format, the amplitude (thus intensity) of the electrical field is modulated. For BPSK format, the phase of the signal can be changed by π from one symbol to the next one. For QPSK, the signal phase can reach four values, $+\pi/4$, $+3\pi/4$, $-3\pi/4$, $-\pi/4$.

For representing the various states taken by the modulated symbol, a constellation diagram is often used. Plots are indicated on a trigonometric circle representing the module, and phase of the electrical field at the center of each bit (or symbol) in the time domain.

The constellation diagrams of OOK, BPSK and QPSK are depicted in Fig. 7 right. For OOK, the phase is constant for all symbols, but amplitude can reach two levels, thus two points are plotted along the horizontal line of the constellation diagram, one near the center of the circle for low intensity symbol “0”, the other one on the trigonometric circle to represent “1”. For BPSK and QPSK, amplitude is constant, but phase can reach different values. The various possible states which can be reached are thus regularly dispatched on the trigonometric circle. Two dots are plotted on BPSK constellation diagram but 4 for QPSK. This is especially useful to represent modulation formats with higher complexity such as Quaternary Phase Shift Keying (QPSK), where the signal information is encoded within 4 phase levels. One advantage of QPSK is to encode 2 bits per symbol, and thus to reduce the symbol rate for a given bit rate compared to a modulation format based on 2 states such as Binary Phase Shift Keying (BPSK). By doubling the symbol duration, while keeping the same information rate, the spectrum width is divided by a factor of 2, and the tolerance to PMD is also doubled. This may be two key advantages for some optical systems where narrow channel spacing is required and when line PMD is high.

The distance between two symbols can be easily compared for various modulation formats when constellation diagrams are used. In Fig. 8, OOK, BPSK and QPSK modulation formats are represented assuming a constant energy per bit for each. For OOK format, one bit can either have an amplitude of “1” or of “0” and the distance between the two possible states is 1 (the average power is 1/2, as half of the bits have an intensity of 1 while the other bits have an intensity close to 0). For BPSK, the amplitude of each bit is either $\sqrt{2}/2$ or $-\sqrt{2}/2$ to obtain the same average power of 1/2 as the OOK signal (the intensity of each symbol is 1/2 as signal intensity is equal to the square of the signal amplitude). The distance between the two symbols is thus $\sqrt{2}$ larger than for OOK, and explains the 3 dB improved

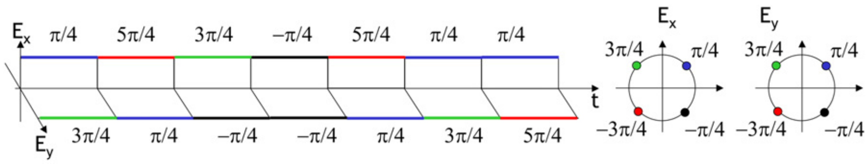

Fig. 9. Electrical field representation and constellation diagram of PDM QPSK signal.

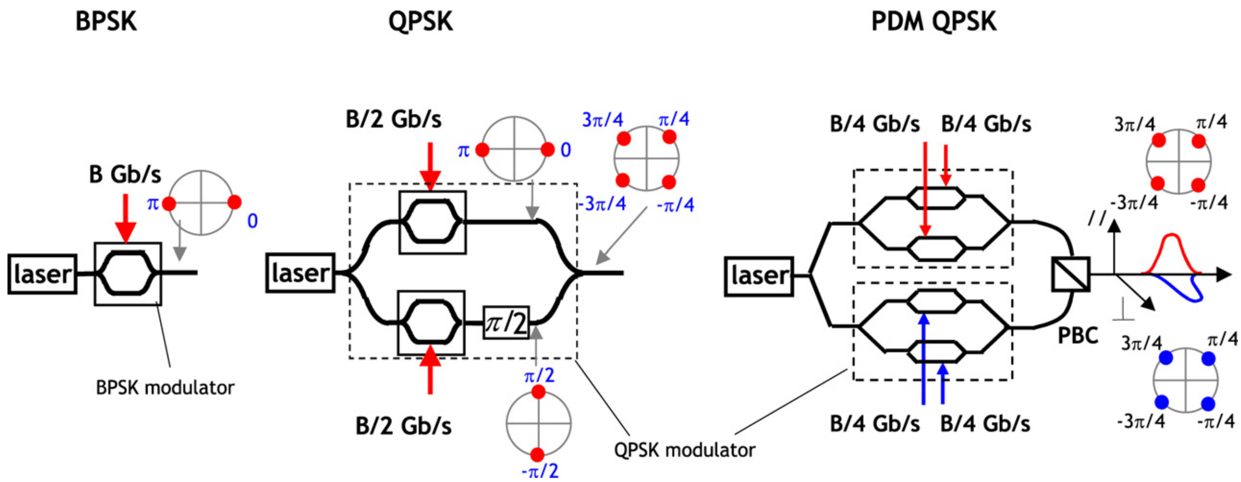

Fig. 10. Description of BPSK, QPSK and PDM QPSK transmitters.

OSNR sensitivity obtained with BPSK [13]. With the QPSK modulation format, two bits are encoded within each symbol. The average power per bit is 1/2, hence the average power per symbol is 1. On the constellation diagram, this translates into symbols located on the circle of radius 1. The distance between each symbol is equal to $\sqrt{2}$, the same as for BPSK. This indicates that the tolerance to noise can be as good for QPSK as for BPSK when an optimum detection method is used [13].

Another parameter used to encode data onto an optical signal is the polarization of the light. The electrical field describing the optical signal can be modulated along two orthogonal axis (x and y in Fig. 9) compared to the propagation axis "t". Encoding different data along each of the polarization, i.e. using Polarization Division Multiplexing (PDM), is now seen as a promising method to double the number of bits transmitted per symbol (especially when it is associated with a coherent receiver).

The higher the number of bits encoded within each symbol, the higher the complexity of the transmitter, as shown in Fig. 10. BPSK modulation scheme is depicted in the left part of the figure. The laser is directly followed by a Mach Zehnder modulator driven at the bit rate, to generate an optical signal with 2 phase levels, either 0 or π.

A QPSK transmitter is depicted in the centre part of Fig. 10. The QPSK modulator includes 2 BPSK modulators within a nested Mach Zehnder structure. Each BPSK modulator generates again an optical signal with 2 phase levels $0, \pi$. The phase of the signal passed through the lower modulator, is shifted by $\pi/2$ compared to the one of the upper modulator. The interference produced at the output of the nested Mach Zehnder produces 4 phase levels, each separated by $\pi/2$. Each of the two binary electrical signals, which drive the QPSK modulator, works at the symbol rate, i.e. at half the information bit rate ($B/2$).

The PDM QPSK transmitter is shown in the right part of the figure. The light coming from the laser is first split in two, sent into 2 QPSK modulators driven by binary electrical signals at a quarter of bit rate ($B/4$) and combined through a Polarization Beam Combiner (PBC) along two orthogonal polarizations.

3.2. Coherent receiver description

Contrary to the direct receiver described in the previous part a coherent receiver, schematized in Fig. 11, uses a local oscillator at the receiver side, i.e. a cw laser, oscillating almost at the same frequency as the signal frequency. In

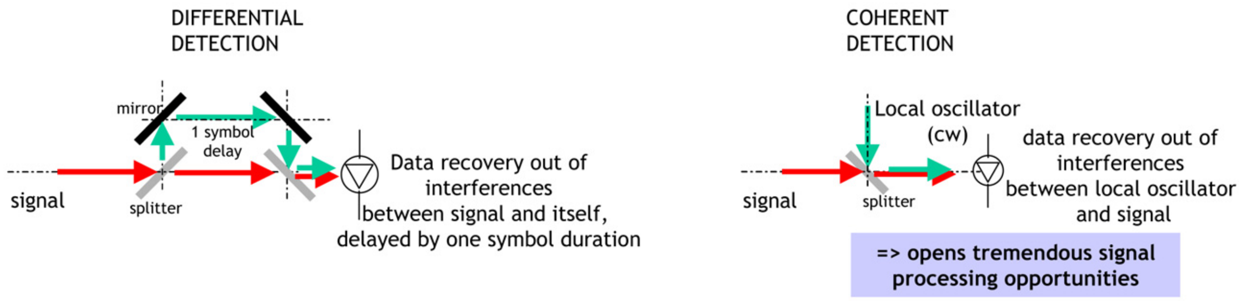

Fig. 11. Basic differences between differential detection and coherent detection.

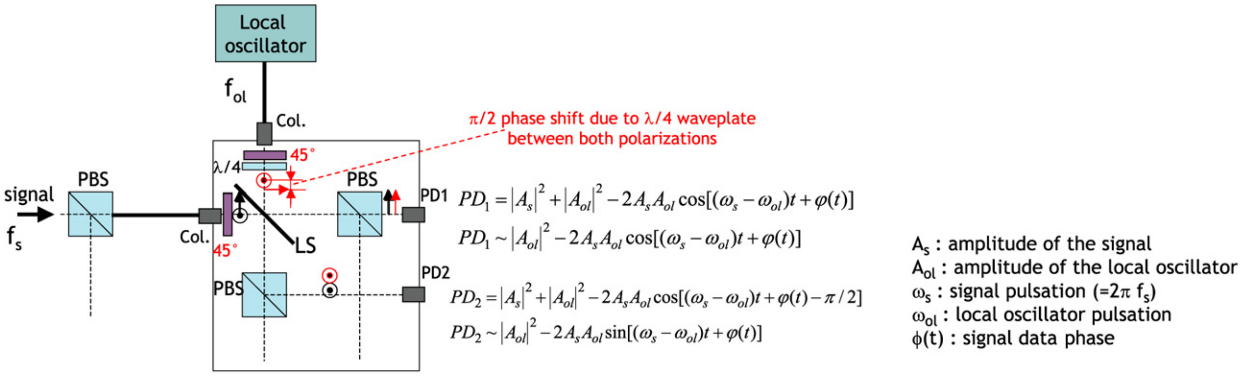

Fig. 12. Coherent mixer description.

the case of differential detection, the reference signal is the previous symbol. This previous symbol has the drawback of being degraded by optical noise accumulated along the transmission path. In the case of coherent receiver, a pure reference signal is provided by the local oscillator.

A key component used within a coherent receiver is a “coherent mixer”, which produces interference between a local oscillator and the incoming signal. In order to generate in phase, and in quadrature components of the product signal × local oscillator, the local oscillator is separated in 2 parts, having a 90° phase shift. The local oscillator has a frequency f_{ol} while the carrier frequency of the signal is f_s, slightly different from f_{ol} by a typical few hundred Megahertz.

A schematic architecture of the coherent mixer based on free space optical technology is described in Fig. 12. Collimators (Col.) are used to send light from fiber optics to this free space device. The polarization of the signal and of the local oscillator are both at 45° of the figure plan. A $\lambda/4$ waveplate is used to generate the 90° phase shift between the horizontal and the vertical components of the electrical field. A Wavesplitter plate is then used to combine the local oscillator and the signal together. Its reflexion ratio is set at 50%. Two polarization Beam Splitters (PBS) are then inserted in order to generate a total of 4 signals which are then sent to photodiodes, for optical-to-electrical conversion. Only 2 photodiodes can be used if the power of the local oscillator is much larger than the one of the signal as shown in equations of Fig. 12 as the term $|A_s|^2$ becomes negligible compare to the product $A_s A_{ol}$. Photodiode 1 (PD1) gives access to the cosine of the phase information ϕ(t) while simultaneously the sine of the phase information is available on photodiode 2 once the difference of pulsation $(\omega_s - \omega_{ol})$ between local oscillator and signal is recovered as described in equations of Fig. 12. The difference of pulsation $(\omega_s - \omega_{ol})$ between the two lasers can be cancelled out by digital signal processing if its own variation is slow enough compared to the symbol rate. Signal phase $\phi(t)$ can then be reconstructed and data encoded at the transmitter side can be recovered.

In order to recover the full electrical field of the signal, polarization diversity scheme is used as shown in Fig. 13. The signal is first split in two by a Polarization Beam Splitter (PBS) which sends each one of the incoming polarization, into two coherent mixers. The four optical interference signals are then sampled, and digitalized by Analog to Digital Converters (ADC). In order to respect the Shannon–Nyquist criteria, the sampling rate of the ADCs has to be at least

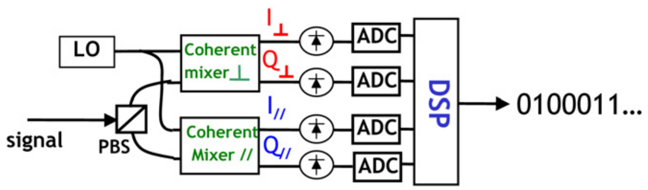

Fig. 13. Schematic of coherent receiver.

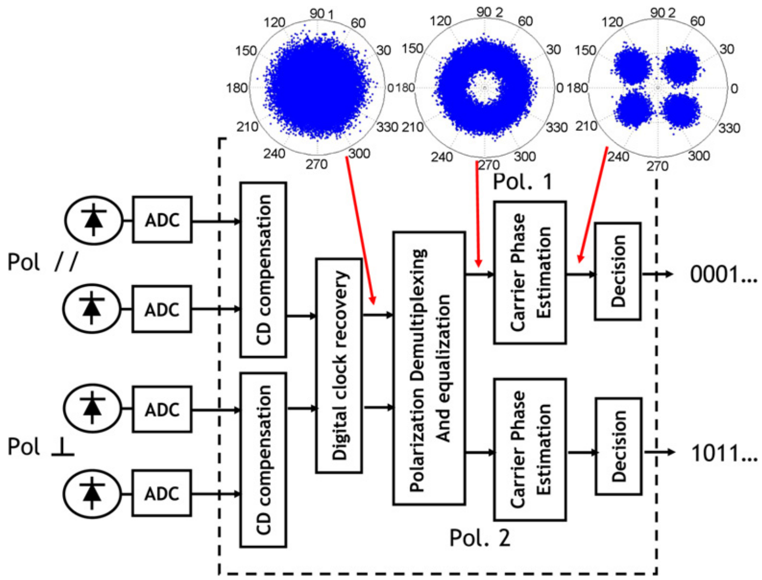

Fig. 14. Schematic of Digital Signal Processing done in a coherent receiver.

twice as large as the largest frequency of the signal. In practice, the ADC 3-dB bandwidth is roughly 0.5 to 0.8 times the symbol rate and ADC sampling rate is twice the symbol rate. The two electrical fields are then reconstructed by digital signal processing and symbols are then identified by a simple threshold method.

The digital signal processing is done in several steps as described in Fig. 14. First, chromatic dispersion (CD) can be compensated, either by using Finite Impulse Response (FIR) filters, or by using Fast Fourier Transform (FFT) method as described in [14]. These filters may be very long (150 taps or more depending on the amount of chromatic dispersion to be compensated for) but are static and do not required fast adaptive algorithms.

A digital clock recovery is then required for the other parts of the processing.

A key part of the DSP is to demultiplex the two initial signals sent along two orthogonal polarizations, and to equalize simultaneously the two signals. This can be done by using Constant Modulus Algorithm (CMA) as proposed in [15]. The filters used within this part, have to adapt themselves continuously to the incoming signal, to follow polarization fluctuation and PMD variations.

The last main part of the digital signal processor is the Carrier Phase Estimation (CPE) process. This process is required to recover and cancel the frequency offset ($\omega_s - \omega_{ol}$) between the local oscillator and the carrier frequency of the signal as described in [15].

The "Polarization Demultiplexing and Equalization" block is described in Fig. 15. The block is composed of 4 FIR filters h_{xx}, h_{xy}, h_{yx}, h_{yy} arranged in a butterfly configuration. Longer FIR filters (here 9 tap filters are represented) can compensate for larger distortions induced by propagation. As all QPSK symbol have the same, the CMA (Constant Modulus Algorithm) tends to force the output signal to converge around a circle as depicted in Fig. 15. As the local oscillator frequency is not equal to the carrier frequency of the signal, the constellation diagram expected (4 dots located at $+\pi/4$, $+3\pi/4$, $-3\pi/4$ and $-\pi/4$) part may "turn" at the frequency difference between the local oscillator and the signal. Thus, the constellation diagram at the output of the CMA block looks like a thick circle. This frequency/phase offset will be recovered by the following block in the DSP. It has to be noted that the two input signals of the block,

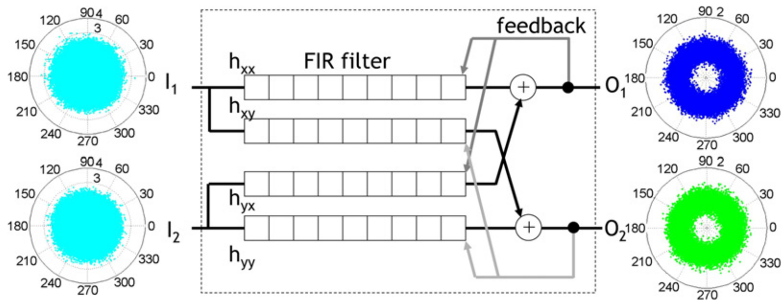

Fig. 15. Schematic description of polarization demultiplexer and equalizer.

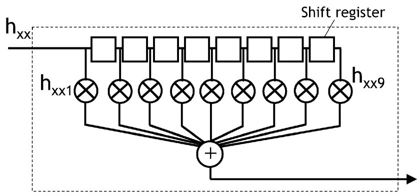

Fig. 16. Schematic description of FIR filter h_{xx}.

I_1 and I_2, contain a mix of the two signals generated at the transmitter side along the two polarization of the light. At the output of the DSP block, the two generated signals are polarization demultiplexed and equalized to undo most of linear distortions occurred within the transmission line.

In Fig. 16, FIR filter h_{xx} schematic is shown. The 9 tap FIR filter is composed of 8 shift registers to give access to the sampled signal at 9 different consecutive instants (with the sampling frequency being usually twice the symbol rate). Each of the complex signal values is multiplied by a complex number h_{xx1} to h_{xx9}. If no equalization is required, all the multiplier coefficients are set to 0 except the center multiplier coefficient h_{xx5} which is set to 1. The values of the multiplier coefficients are updated by the CMA algorithm, as described in [15].

Description of methods to recover frequency/phase offset between signal and local oscillator may be found in [15,16] and will not be presented here.

3.3. Efficiency of coherent detection to combat noise and to mitigate linear impairments

3.3.1. Tolerance to optical noise advantage brought by coherent receiver

One of the main motivations to use DPSK, instead of the more conventional OOK modulation method, in optical communication is the 3 dB improvement in OSNR sensitivity obtained.

Differential detection may also be used to detect QPSK modulation format. In this case, the OSNR tolerance is degraded by 1 to 1.5 dB compared to BPSK scheme at the same bit rate.

When coherent detection is used, the OSNR sensitivity approaches very near to the fundamental limit predicted by digital communications theory, and thus cannot be further improved. With BPSK modulation format, the advantage over differential detection is around 1 dB (as the reference signal comes from a pure local oscillator instead of the noisy previous bit). The same OSNR sensitivity is obtained with BPSK and QPSK modulation scheme when coherent detection is used, contrary to differential detection. The advantage of QPSK combined with coherent detection over the differential detection scheme is therefore around 2.5 dB [13].

Moreover, coherent detection can easily handle a Polarization Division Multiplexed format, without any impairment, by implementing the polarization demultiplexing in the digital domain. Hence PDM QPSK has the same sensitivity as QPSK and BPSK (at the same bit rate), all being at the fundamental limit of digital communication. OSNR sensitivity measurements of coherent PDM QPSK, DPSK and RZ-DQPSK are presented in Fig. 17

All measurements are 1 or 2 dB away from the theoretical expectations due to implementation penalties. Nevertheless, when comparing OSNR sensitivity at Q^2-factor of 12.5 dB (corresponding to a BER of 1×10^{-5}), coherent

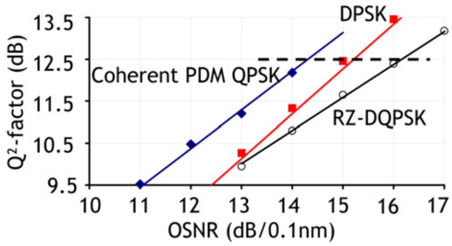

Fig. 17. Measurement of OSNR sensitivity of coherent PDM QPSK, DPSK and RZ-DQPSK at 40 Gb/s.

Table 1
Relation between BER and Q^2-factor.

BER	Q^2-factor
1×10^{-9}	15.6
1×10^{-6}	13.6
1×10^{-5}	12.6
1×10^{-4}	11.4
1×10^{-3}	9.9
4×10^{-3}	8.6

PDM QPSK is 1 dB better than DPSK which is also 1 dB better than RZ-DQPSK (RZ over modulation allowing to slightly improved the experimental OSNR sensitivity of DQPSK).

For practical reasons, the system performance measured is usually not expressed in BER but as a Q^2-factor. A direct relation ship relying BER to Q^2-factor in dB is presented in Table 1.

3.3.2. Compensation of linear impairments by coherent receiver

Several impairments are associated with fiber optic propagation. These impairments may be split mainly in two categories: linear impairments and non-linear impairments. Linear impairments correspond to distortions of the electrical field amplitude which can be modeled by a linear filter. Some impairments, such as chromatic dispersion and polarization mode dispersion, can be represented by an all pass filter (i.e. no loss of signal). The inverse filter can thus be calculated, within the coherent receiver, to undo the deformations introduced by propagation. This is a main motivation for the introduction of coherent detection in optical communication.

3.3.2.1. Chromatic dispersion compensation Chromatic dispersion has been managed for WDM system working at 10 Gb/s and 40 Gb/s by using mainly optical methods such as Dispersion Compensation Fibers (DCF), Fiber Bragg Gratings (FBG), or etalon-based structures.

At 10 Gb/s, most of the installed systems rely on DCF, inserted within the interstage of dual-stage amplifiers along the line. The optical module is thus shared between all the WDM channels.

At 40 Gb/s the same strategy is usually used, but due to some dispersion uncertainties and dispersion mismatch between DCF and line fiber within the WDM band, tunable dispersion compensation systems are usually inserted in each receiver to finely adjust the residual dispersion before intensity detection with a photo-receiver.

A coherent receiver detects the amplitude and the phase of the optical field. Thus coherent detection offers the possibility to compensate for chromatic dispersion by digital signal processing by digitally applying the right reverse filter. Therefore, tunable optical compensators can be removed and DCFs in the line are also no longer required. A demonstration of 40 Gb/s transmission over link without dispersion compensating fiber have been made over several thousand kilometers [15] by using coherent detection and digital signal processing.

Chromatic dispersion compensation is usually performed first as the operation in the digital signal processor can be done before polarization demultiplexing and digital clock recovery, as indicated in Fig. 14 by using either a FIR filter or an FFT-based method.

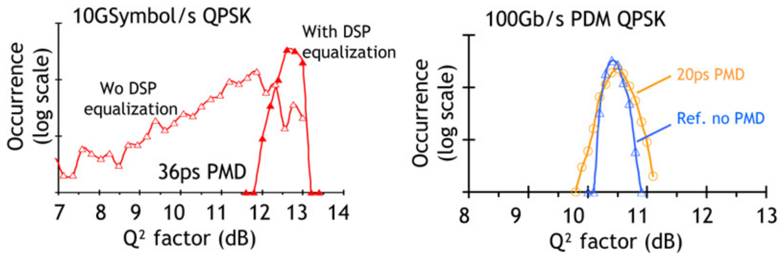

Fig. 18. Improvement brought by DSP equalization in a high PMD case with 10 Gsymbol/s QPSK (left), Impact of PMD on Q-factor distribution of a 100 Gb/s PDM QPSK signal when processed by a coherent receiver (right).

3.3.2.2. Polarization mode dispersion compensation Polarization Mode Dispersion is another major linear limitation. Recent fibers have very low PMD, around 0.05 ps/sqrt(km). Nevertheless, fiber deployed before 1995 may suffer from very large PMD value, sometimes higher than 1 ps/sqrt(km).

Typical 10 Gb/s systems are limited by PMD when the total PMD in the link reaches 10 to 16 ps.

At 40 Gb/s the PMD constraints are 4 times larger, and the maximum PMD tolerated is around 2.5 to 4 ps. This is a major problem for 40 Gb/s deployment. The solution first proposed for 10 Gb/s systems (i.e. Optical PMD Compensator), which was not adopted due to cost reasons, is now recommended again. Optical Polarization Mode Dispersion Compensators (OPMDC) are able to mitigate (but not to compensate!) PMD impact. As the OPMDC does not work for all the WDM channels simultaneously, one OPMDC has to be included within each receiver. Hence this solution is costly but allows one to manage PMD impact up to ∼ 8 ps at 40 Gb/s.

At higher bit rate, the PMD problem is even more severe and no "good" (i.e. low cost and capable to mitigate large values of PMD) solutions have been proposed until interest in coherent detection arose.

Digital Signal Processing associated with coherent receiver has been shown to be able to compensate for a very large amount of PMD. In Fig. 18 left, the impact of equalization provided by digital signal processing through CMA is depicted. A 10 Gsymbol/s QPSK signal was passed through a 400 km long transmission line with a PMD value as high as of 36 ps, and signal was recorded at the receiver side. White triangles represent the Q^2-factor distribution when no equalization processing was done, and dark triangles depict the performance when equalization was switched on. Thanks to the equalization, Q^2-factor stayed above 11.5 dB, while it can be reduced below 7 dB without equalization. In Fig. 18, the impact of PMD on a 100 Gb/s PDM QPSK signal is shown for low PMD values (1 ps) and high PMD values (20 ps) [17]. Typically 10 Gb/s standard systems can tolerate nearly 12 to 16 ps PMD. Here, by using coherent detection and digital signal processing, a higher amount of PMD may be tolerated for a 100 Gb/s signal (which could be expected to be 10 times less tolerant than a 10 Gb/s one). We observe that the Q-factor distribution is only slightly distorted and that the performance degradation is low (less than 0.5 dB when the lower tail of the distribution is observed).

3.4. Association of coherent detection with advanced multilevel modulation format

Due to the limited bandwidth of current optical amplifiers, increasing the capacity transported within a fiber optic based system required to raise the information spectral density (i.e. the number of bit/s transmitted in a unit spectral band).

Increasing the number of bits transported per symbol is very effective to contain spectral occupancy while increasing bit rate. Modulation formats with 2 bits per symbol, have been proposed such as QPSK (Quaternary Phase Shift Keying [18]) and 4 levels On Off Keying modulation (this modulation format did not meet large interest due to its poor tolerance to optical noise). Recently, a modulation format transmitting 4 bits per symbol has attracted a lot of interest. By combining polarization multiplexing and 4 phase levels, Polarization Division Multiplexing Quadrature Phase Shift Keying (PDM QPSK) [15] is seen as extremely promising for high capacity 100 Gb/s transmission [19,20].

Polarization Division Multiplexing, which was used in 2001 and 2002 in "record laboratory experiments" in order to increase system capacity by a factor of two, has been then almost completely abandoned due to practical difficulties of implementation, due to the poor cost efficiency of this solution and due to impairments caused either by linear effect such as depolarization induced by PMD [21], by non-linear effect such as depolarization induced by cross

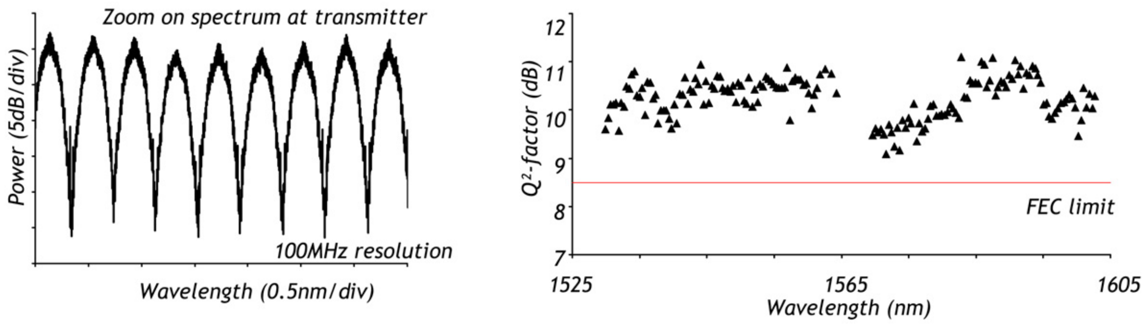

Fig. 19. Optical spectrum and performance recorded after 2550 km.

phase modulation [22] and by the necessity of a high performance polarization tracking component at the receiver side.

The association of coherent detection, abandoned in the first years of the 1990s, and polarization division multiplexing, abandoned ten years later, are coming back together when associated to powerful signal processing for bit rate of 40 Gb/s and 100 Gb/s.

Using this technique channel at 100 Gb/s can be packed on the 50 GHz channel grid. A very high information spectral density of 2 bit/s/Hz can thus be transmitted over long distance, as shown in [19,20]. Fig. 19 shows a zoom on the spectrum of nine 100 Gb/s channels spaced by 50 GHz (left) and the Q-factor measured after 2550 km for all 164 channels transmitted (right). We can first observe that channel overlap is very low as dips between two adjacent channels are as high as 30 dB. The Q-factor monitored for all channels is also better than the FEC limit by more than 1 dB for all channels. This is of course not sufficient for a real commercial system deployment, but it indicates that 100 Gb/s WDM transmission over long distance ($>$ 1000 km) will be feasible in the near future.

4. Coherent based WDM system limitations

The association of coherent detection with powerful digital signal processing is a key method to increase the information spectral density up to 2 bit/s/Hz [19,20], while containing linear distortions induced by optical fiber propagation (chromatic dispersion and PMD). Nevertheless, a good tolerance to non-linear effects is required to allow transmission over long distances, a key feature for cost effective optical network.

As a coherent based transponder can compensate for an almost unlimited amount of chromatic dispersion, transmission systems without in line compensation are investigated as well as more standard system using dispersion compensation. The cohabitation of several bit rates and modulation formats within the system will also be presented. We will especially investigate the impact of 10 Gb/s intensity modulated channels on coherent based system resorting on polarization and phase modulation.

4.1. Impact of non-linear effects in dispersion managed link using coherent detection

Some of the properties associated with the modulation format can be very easily extended from one bit rate to another one. However, it is not the case for non-linear interactions. At 40 Gb/s, a coherent solution is now commercially available based on PDM QPSK modulation format [23]. We will see that this solution can be strongly impacted by WDM non-linear effects.

To evaluate the tolerance of this solution against non-linear effects, we sent a WDM comb of 40 Gb/s PDM QPSK signal into a transmission test bed of 16 spans of 100 km long standard single mode fiber (SSMF) [24]. The BER was measured and converted into Q-factor for various channel powers sent into the fiber, first in a single channel configuration and then in a WDM configuration, as shown in Fig. 20. In the single channel case, the performance continues to improve up to 0 dBm per span, and then starts to degrade slowly. When WDM channels are light on, the optimum performance is obtained for -3 dBm per span, and then degrades sharply highlighting the high sensitivity of this modulation format to WDM non-linear effects. This can be understood because information is encoded within phase and polarization, two dimensions which are directly impacted by Kerr non-linear effects.

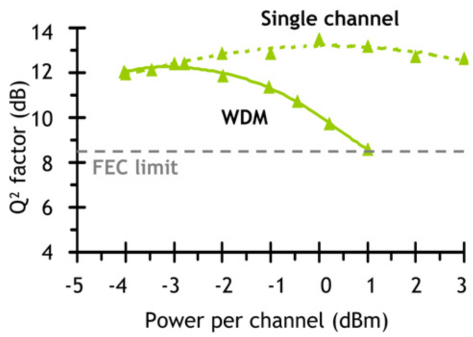

Fig. 20. Impact of WDM non-linear effect on coherent PDM QPSK at 40 Gb/s.

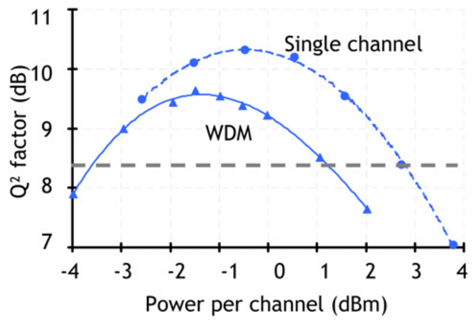

Fig. 21. Impact of WDM non-linear effect on coherent PDM QPSK at 100 Gb/s.

The same experiment has been reproduced at 100 Gb/s in order to evaluate the relative impact of single channel non-linear effects and of WDM non-linear effects [27]. The results are depicted in Fig. 21. It can be noted that the non-linear tolerance is slightly reduced in single channel configuration as compared to the 40 Gb/s situation. However, the WDM non-linear tolerance is improved (maximum Q^2-factor obtained for a channel power of -1 dBm at 100 Gb/s instead of -3 dBm at 40 Gb/s). This can be explained by the reduction of the symbol duration by a factor 2.5 when moving from 40 Gb/s to 100 Gb/s. Chromatic dispersion makes symbols on adjacent wavelengths to travel at different speed within the optical fiber, thus reducing the detrimental non-linear interactions in between. As the channel bit rate is increased by 2.5 when comparing 40 Gb/s and 100 Gb/s, the required OSNR (in noise limited condition, i.e. without any other propagation impairments) to obtain an identical BER is $\sim$4 dB (i.e. a factor 2.5) higher. This explains that the overall Q^2-factor performance is slightly worse at 100 Gb/s as compared to 40 Gb/s.

4.2. Impact of 10 Gb/s intensity modulated channel on a coherent transponder

The upgrade of an existing WDM network based on 10 Gb/s OOK channels to 40 Gb/s is of great interest for most telecom operators, which expect to smoothly upgrade their network infrastructure. Thus, we investigated at the Q^2-factor of the 40 Gb/s PDM QPSK channel when surrounded by 10 Gb/s OOK channels at various channel power [24], to see if system composed of $N \times 10$ Gbit/s channels can be easily upgraded to 40 Gb/s using phase/polarization modulated signals and coherent detection. Despite an optimization in the digital signal processing (especially on the carrier phase estimation averaging), 40 Gb/s PDM QPSK channel is heavily impacted by the 10 Gb/s NRZ channel as shown in Fig. 22. When all channels are modulated with PDM-QPSK format, Q^2-factors around 12 dB are measured for channel power in between -4 and -1 dBm. However, the performance is much worse when adjacent channels are modulated at 10 Gb/s. As 10 Gb/s channels are intensity modulated, they transfer by cross-phase modulation (XPM), their intensity profile to the phase of the PDM QPSK channel, thus degrading its signal quality which is encoded within the optical phase.

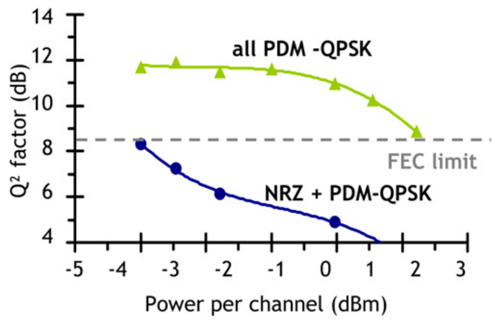

Fig. 22. Impact of 10 Gb/s intensity modulated channels on 40 Gb/s coherent PDM QPSK channel.

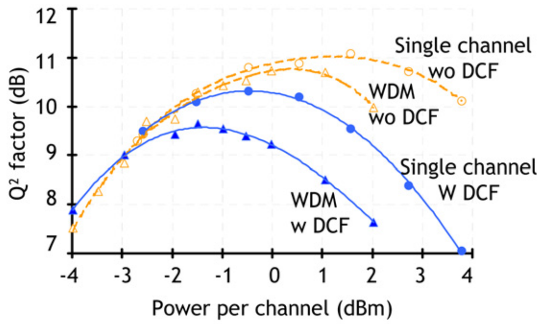

Fig. 23. Performance of 100 Gb/s channels in various configuration.

4.3. Performance of coherent transponder in case of dispersion compensation free system

Transmission without Dispersion Compensating Module (DCM) is possible thanks to the use of a coherent receiver which allows almost unlimited chromatic dispersion compensation. Another proposed solution to remove DCM have been proposed in 2005 [25], at 10 Gbit/s, using electronic pre-distortion and direct detection. But this solution has the main drawback of being severely impacted by non-linear effects [26], and thus to have a limited transmission reach compared to standard solution based on 10 Gbit/s NRZ and DCM in line.

For 100 Gbit/s transmission, removing DCM is interesting mainly if it is not done at the expense of the transmission reach.

A performance comparison of 100 Gb/s transmission between a configuration with, and another one without DCM, is shown in Fig. 23. We observe here that the suppression of DCM is beneficial to system performance, with a single channel or with a full WDM multiplex. This is attributed to a different propagation regime which is experienced with extremely large pulse spreading, and also to the suppression of optical non-linearities within the DCF. In WDM configuration without DCF in line, the maximum Q^2-factor measured is higher than the one obtained in single channel with DCF (10.7 dB instead of 10.3 dB), and the best performance is recorded for a slightly higher channel power (0.5 dBm instead of −0.5 dBm). When no DCF are included with the line, the Q^2-factor degradation observed when moving from a single channel to a WDM configuration is also lower compared to the case with DCF in line (reduction of ∼0.3 dB versus ∼0.8 dB). The impact of cross non-linear effects seems thus reduced without in line DCF.

4.4. Practical realization challenges of a coherent receiver

The realization of a commercial coherent receiver is extremely challenging. Currently, most experimental tests have been made using an high speed oscilloscope to digitize the signals at the output of the coherent mixer (i.e. to act as the ADCs). The signals recorded by the scope are then processed by software on a computer. However, only a few million symbols can be stored (limited by the memory of the scope), and the processing of a few µs of data can take more than one minute on a computer.

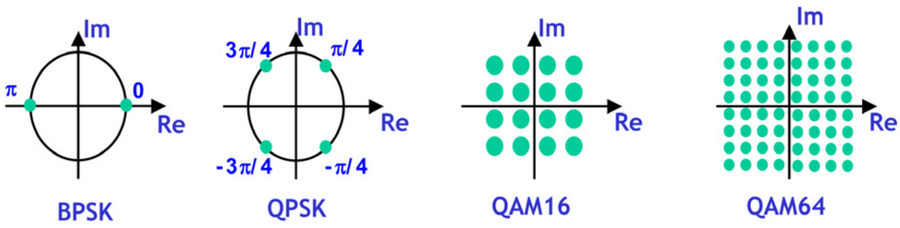

Fig. 24. Constellation diagram of BPSK, QPSK, QAM16 and QAM64.

In a commercial coherent receiver [23], the 4 ADCs and the DSP are included in a single chip. At 40 Gb/s, the chip is realized by using 90 nm CMOS technology and the power consumption is more than 20 W.

An equivalent circuit suitable for 100 Gb/s is extremely challenging to realize. The ADC is probably one of the most critical points. It can be realized either by using SiGe Bipolar technology [28] or in CMOS technology by using the more advanced processes. Bipolar technology should be able to offer a higher performance (at least a higher analog bandwidth of the ADC), but might require higher power consumption. A CMOS process has the advantage of the possible integration of ADC and DSP on the same chip and of a lower power consumption.

4.5. Highly multilevel modulation format associated with coherent detection

In radio communication, highly multilevel modulation formats such as Quadrature Amplitude Modulation (QAM) are commonly used to increase the bit rate while containing the spectrum occupancy. Such method is particularly interesting when the spectral resource is rare and costly as in the radio domain. The modulation format name is QAMxx, xx indicating the number of state of the constellation. When QAM16 is used, 4 bits are transmitted by one symbol. With QAM64, each symbol carries 6 bits. The constellation diagram of BPSK, QPSK, QAM16 and QAM64 are depicted in Fig. 24.

In order to increase even more the information spectral density of optical communication system, it has been proposed to go from QPSK modulation to higher level modulation [29]. But this technique faces two main fundamental limitations.

First, the tolerance to noise (at a given bit rate) is degraded compared to QPSK modulation format [13]. The higher the number of state the signal can take, the poorer the tolerance to noise (QAM64 is less tolerant than QAM16 which is less tolerant than QPSK, but QPSK has the same tolerance to noise as BPSK).

Secondly, the tolerance to non-linear effects is also expected to be very limited when the number of possible states increases, as the phase difference between different symbols is reduced (non-linear effects change the phase of each symbol, depending on the intensity of the channel, but also on the intensity of WDM channels).

The generation of QAM signal is also more challenging as it requires Digital to Analog Converters (DAC) compared to QPSK modulation which resort on a more standard 2 levels electronics at the transmitter side.

Another limitation comes from the very stringent requirement on laser linewidth for transmitter signal and for local oscillator [30].

As a consequence, optical communication systems using QAM have been limited to short distances of a few hundred of kilometers only [29]. Furthermore, compatibility with a dense WDM environment and with 10 Gbit/s adjacent channels has not yet been successfully demonstrated.

4.6. Use of Orthogonal Frequency Division Multiplexing (OFDM) in optical communications

Multiple path interference is one of the main limitations that wireless transmission has to face. This limitation can be overcome either by using digital equalization (as done mostly in GSM network for example, but this processing becomes extremely complex for a QAM signal) or by using extremely long symbol duration as in the case of OFDM. Instead of using one carrier, multiple carriers are generated (up to several thousands) to increase the symbol length (proportional to the number of carriers), each of them can be modulated by QPSK or a QAM format. Fast Fourier Transform (FFT) processing is done at the transmitter side to generate the OFDM signal. Inverse FFT (iFFT) processing at the receiver side allows one to recover the emitted symbols/bits.

OFDM techniques has thus been widely implemented in modern radio communication such as WiMax, Digital TV and WiFi.

OFDM has also been demonstrated recently for optical communication in association with a coherent receiver [31,32] for bit rate up to 100 Gbit/s [33].

One main drawback of this solution compared to PDM QPSK modulation is the need of complex DACs at the transmitter side. The tolerance to non-linear effects seems also relatively low and highly dependent on the dispersion map [34]. The maximum transmission reach demonstrated up to now at 100 Gbit/s (1000 km) [33] is significantly reduced compared to PDM QPSK (more than 2000 km) [19,20]. In fiber optic based systems, large pulse spreading are generated by chromatic dispersion mainly, but this distortion is deterministic and can be easily modeled and compensated by using efficient FFT based method. This could make OFDM less attractive for optical communication than it is for radio communication.

5. Conclusion

Coherent detection gives access to new parameters (amplitude, phase, polarization) compared to standard direct-detection. Hence it opens new opportunities for WDM transmission systems, especially when associated with Digital Signal Processing and multilevel modulation formats.

A commercial solution based on coherent detection is currently available at 40 Gb/s. At this specific bit rate, its advantages, extremely high tolerance to PMD, narrow optical spectrum, excellent tolerance to optical noise, have to be highly weighted with its associated drawbacks (a poor tolerance to non-linear effect, especially when 10 Gbit/s channels co-propagate in the same fiber which limits the maximum transmission reach).

In the coming years, 100 Gb/s transponders resorting on similar technologies should be available. At 100 Gb/s, the advantages seem clearly superior to the drawbacks. This solution appears currently as the most effective way to generate and detect this very high speed modulation rate and it is being considered in standardization bodies. Nevertheless, the realization of an industrial 100 Gb/s coherent receiver and especially of the ADCs and of the DSP is extremely challenging from a technological point of view.

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