POLMUX-QPSK modulation and coherent detection: the challenge of long-haul 100G transmission

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Abstract *The rise of coherent detection and digital signal processing is drastically changing the design of optical transmission systems. In this paper we review the challenges and opportunities offered by such receivers in the design of long-haul 100G systems.*

Introduction

The recent progress on high-speed digital signal processing enables the use of *digital coherent receivers* in long-haul optical transmission systems [1-3]. A digital coherent receiver basically combines the state-of-the-art in optics and electronics; (1) coherent detection as the theoretically optimum detection principle and (2) a receiver implementation that can equalize for practically any amount of linear transmission impairments. Although this is a new development in the field of optical communications, it mirrors the technical evolution taken years ago in radio and wireline communication. As such, it is likely that digital coherent receivers will rapidly become the undisputed technology of choice in long-haul optical transmission systems.

The rapid shift away from direct-detection receivers and towards digital coherent receivers is fuelled by a number of technology drivers. Among others, digital coherent receivers have spurred the use of higher-order modulation formats (e.g. quadrature phase shift keying [QPSK]), polarization-multiplexing, the compensation of linear transmission impairments such as chromatic and polarization-mode dispersion (PMD) [1-2], the design of Erbium-doped fiber amplifiers without mid-stage access, as well as improvements in optical performance monitoring [4]. Although most of these technologies are not exclusive to digital coherent receivers, it is the combination that generally results in improved optical performance and enables a more cost-effective solution.

In this paper we review some of the possibilities offered by digital coherent receivers and detail how this will enable the next generation of long-haul optical transmission systems. We focus in this discussion on long-haul transmission using 100-Gb/s *polarization-multiplexed quadrature phase shift keying* (POLMUX-QPSK) modulation, which is likely to become the next standard for long-haul optical transmission systems. Note that POLMUX-QPSK modulation is often also referred to as CP-QPSK, PDM-QPSK, 2P-QPSK or DP-QPSK.

Transmitter and receiver architecture

A POLMUX-QPSK transmitter consists of two quadrature (e.g. QPSK) modulators and a polarization beam splitter (PBS) to multiplex the two outputs on orthogonal polarizations. At the receiver side, the received optical signal is split in two tributaries with arbitrarily, but orthogonal, polarizations using a second PBS. Both tributaries are subsequently mixed in a 90^0 hybrid structure with the output of a local oscillator. The outputs of the 90^o hybrids (in-phase and quadrature components of both polarizations) are then detected with 4 photodiodes (either balanced or single-ended) and converted to the digital domain using high-speed analog-to-digital converters (ADCs). A more detailed description of the transmitter and receiver configuration is discussed in [1].

$$\begin{cases} x(\varphi_h, \varphi_v) = [R + r \cdot \cos(\varphi_v)] \cdot \cos(\varphi_h) \\ y(\varphi_h, \varphi_v) = [R + r \cdot \cos(\varphi_v)] \cdot \sin(\varphi_h) \\ z(\varphi_h, \varphi_v) = r \cdot \sin(\varphi_v) \end{cases}$$

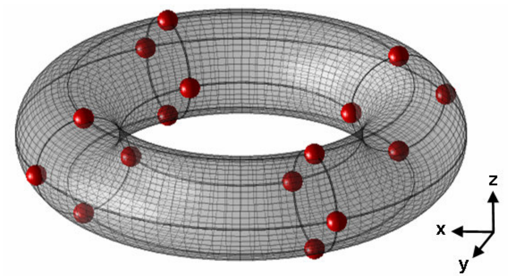

Fig. 1: *POLMUX-QPSK constellation diagram.*

As POLMUX-QPSK modulates 4 bits per symbol, a low symbol rate of ~28 Gbaud is sufficient to obtain a 111-Gb/s line rate. This translates into a 100-Gb/s *net data rate* when a forward-error correction (FEC) overhead of ~7% and an Ethernet overhead of ~4% are subtracted. The lower symbol rate improves the tolerance to linear transmission impairments, which in turn allows for less stringent requirements on the electrical equalization, as well as making it possible to use lower-frequency electrical components. Fig. 1

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shows the constellation diagram of POLMUX-QPSK modulation, represented as a 4-dimensional hypercube. The hypercube is described by the optical phase (in-phase and quadrature) on each of the two polarizations (φ_v and φ_h), where R and r are the outer and inner radius of the torus (with R > r).

The combination of POLMUX-QPSK modulation and coherent detection allows for an OSNR requirement close to the theoretical optimum [5]. At a BER of 1e-3, 111-Gb/s POLMUX-QPSK typically requires an OSNR of ~15.5 dB (with 0.1 nm res. bw.). In comparison, the OSNR requirement of *filter-tolerant* 43-Gb/s DPSK (today's most widely deployed 40G format) is approximately 13.5 dB [6]. The mere 2 dB difference despite the factor of 2.5x increase in data rate underlines the excellent OSNR performance of POLMUX-QPSK combined with coherent detection.

Upgrading existing transmission links to 100G

At first sight the advantage of digital coherent receivers might not be entirely straightforward as the *transmitter and receiver complexity* is generally much higher in comparison to established direct-detection modulation formats, such as 43-Gb/s differential phase shift keying (DPSK) or even 43-Gb/s differential quadrature phase shift keying (DQPSK) [7]. However, when we look at the overall *system complexity,* the advantages of POLMUX-QPSK modulation and digital coherent receivers are much more pronounced.

In order to upgrade existing transmission links to a 111-Gb/s line rate, the modulation format should be able to cope with all of the transmission impairments incurred by the already installed equipment. This includes transmission over high-PMD fiber, installed dispersion compensation modules (e.g. dispersion compensating fiber [DCF] or fiber Bragg gratings [FBGs]) as well as a limited optical bandwidth through cascaded filtering in photonic cross-connects (PXC). For 43-Gb/s DPSK modulation, transmission links with high-PMD fiber or many cascaded PXCs are straight-out challenging, resulting in a reduced transmission reach. DQPSK modulation is a promising alternative at a 43-Gb/s line rate as it is significantly more tolerant to both PMD and narrowband optical filtering [7]. However, at a 111-Gb/s line rate the optical spectrum of DQPSK modulation is too broad to fit within a 50-GHz channel grid, making it incompatible to most field-installed transmission systems [8]. 111-Gb/s POLMUX-QPSK modulation combined with a digital coherent receiver, on the other hand, can compensate for dispersion map deviations, PMD [1], FBG-induced phase ripples [9], as well as being more tolerant to the optical filtering incurred by cascaded PXCs on a 50-GHz channel grid [1]. This will enable transmission links that cannot support 43-Gb/s line rates using direct-detection receivers to *upgrade* to 111-Gb/s line rates using POLMUX-QPSK and digital coherent receivers.

Regretfully, POLMUX-QPSK modulation and coherent detection do not simplify all aspects of transmission link design. In particular the *nonlinear tolerance* of POLMUX-QPSK is significantly reduced compared to DPSK or even DQPSK modulation. At a 43-Gb/s line rate, XPM penalties reduce the nonlinear tolerance of POLMUX-QPSK with 3 - 5 dB compared to 43-Gb/s DPSK (on SSMF and depending on the dispersion management) [10]. This would have a significant impact on the transmission reach, were it not for the fact that the improved OSNR requirement (compared to DPSK) partially offsets the reduced nonlinear tolerance. When scaling to an 111-Gb/s line rate the impact of XPM reduces due to the higher symbol rate, which increase the nonlinear tolerance of POLMUX-QPSK with approx. 3 dB compared to 43-Gb/s POLMUX-QPSK. This helps to partially offset the ~4 dB increase in required OSNR (and therefore lower reach) when scaling from a 43-Gb/s to an 111-Gb/s line rate.

Careful system design is in particular required when POLMUX-QPSK modulated channels *co-propagate with other modulation formats* on neighboring WDM channels [11]. For example, when 111-Gb/s POLMUX-QPSK co-propagates with 10-Gb/s on-off-keying (OOK) channels (which generate much larger XPM penalties) at 50-GHz channel spacing, the nonlinear tolerance is reduced by approx. 4 dB [12]. Intermixing of 10-Gb/s OOK and POLMUX-QPSK modulation can therefore severely limit transmission over long-haul distances. However, these penalties can be lowered by optimizing the respective channel powers [12] or by spectrally separating the 40G/100G channels from already deployed 10G channels [13].

100G-optimized transmission links

On newly deployed transmission links, which generally use high-quality fibers, not the optical performance but *simplicity* and *flexibility* of the transmission link are the most important advantages that digital coherent receivers can offer. Instead of using a traditional in-line dispersion map (i.e. dispersion managed transmission), it allows for the possibility to realize long-haul transmission without in-line dispersion management (i.e. dispersion un-managed transmission). The complete chromatic dispersion is then compensated for in the electrical domain. Such a dispersion un-managed link offers advantages in transmission latency, sparing of dispersion compensation modules, removes the nonlinear impairments in the DCF, and allows for simpler amplifier structures without mid-stage access. In addition, the optical performance monitoring capabilities that a digital coherent receiver can offer reduce the number of required measurements when

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installing the transmission link and simplify monitoring of transmission performance.

The impact of dispersion un-managed transmission on the nonlinear tolerance is particularly important to understand in order to design the next-generation of 100-Gb/s optimized transmission systems. Fig. 2 shows the simulated nonlinear tolerance of 111-Gb/s POLMUX-QPSK modulation when transmitted over 30 spans of SSMF (30 x 95 km, in total 2850 km). The SSMF (DCF) attenuation coefficient used in the transmission simulations is 0.21 dB/km (0.5 dB/km), the chromatic dispersion coefficient 16.8 ps/nm/km (-170 ps/nm/km), and a nonlinear coefficient of 1.14 $W^{-1}km^{-1}$ (5 $W^{-1}km^{-1}$). The DCF input power is reduced with 7 dB compared to the transmission fiber.

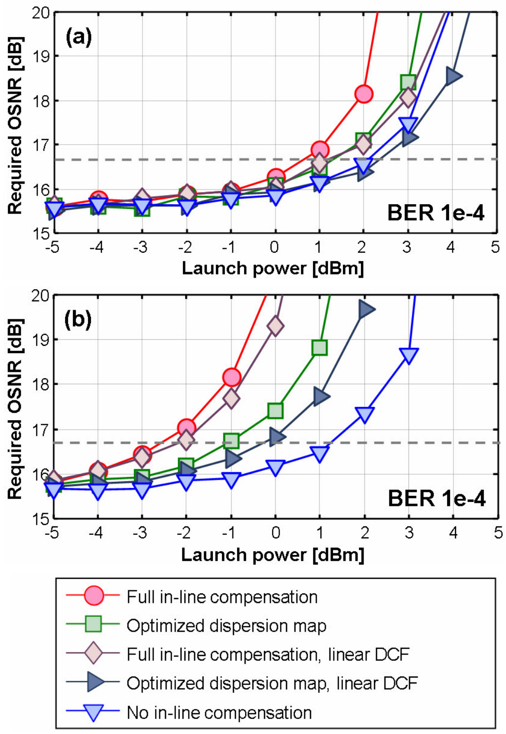

Fig. 2: *Nonlinear tolerance of 111-Gb/s POLMUX-QPSK modulation over 30 spans of SSMF (a) single channel: (b) 9 channels, 50 GHz channel spacing.*

The single-channel nonlinear tolerance is shown in Fig. 2a. For a 1 dB OSNR penalty, the difference in nonlinear tolerance between the optimized dispersion map (-200 ps/nm pre-compensation, full in-line compensation) and dispersion un-managed transmission is approximately 0.8 dB. However, when neglecting the nonlinearity of the DCF the nonlinear tolerance of dispersion managed transmission increases with ~1 dB and becomes comparable to dispersion un-managed transmission. This could potentially be realized using FBG-based dispersion compensation modules instead of DCF [9]. The small difference in nonlinear tolerance can be understood by noting that intra-channel four-wave-mixing is the dominant nonlinear impairment for POLMUX-QPSK modulation at a 28-Gbaud symbol rate. For a dispersion managed transmission link it is then important to realize link symmetry (i.e. a cancelling out of the intra-channel four-wave-mixing), which can be achieved through an optimization of the pre-compensation [14]. For dispersion un-managed transmission, on the other hand, the intra-channel four-wave-mixing is minimized through the fast pulse spreading (in high dispersion fiber) which partially averages out the nonlinear contributions.

Fig. 3 shows the simulated BER after 30 spans as a function of the in-line dispersion compensation. At near full in-line compensation, large nonlinear penalties arise unless the combination of in-line compensation and pre-compensation is optimized (i.e. link symmetry is achieved). When the in-line compensation is further decreased, the fast pulse spreading and walk-off between WDM channel improves performance and reduces the dependency on the optimization of the pre-compensation.

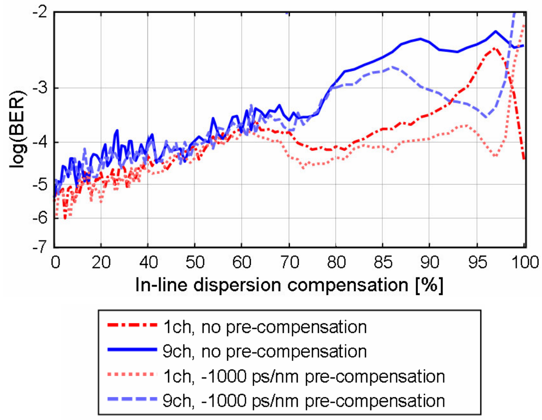

Fig. 3: *Transmission performance as a function of the inline dispersion compensation.*

Dispersion un-managed transmission looks much more attractive when considering WDM transmission (Fig. 2b, 9 channels, 50 GHz grid). The difference in nonlinear tolerance compared to the optimized dispersion map (-1000 ps/nm pre-compensation, -60 ps/nm in-line under-compensation) is now approx. 2.4 dB. This indicates that for SSMF the stronger walk-off between neighbouring WDM channels in dispersion un-managed transmission significantly improves the inter-channel nonlinear tolerance. However, dispersion un-managed transmission does not necessarily improve the nonlinear tolerance for all fiber types. Fig. 4 shows the measured BER after transmission over 20 spans of LEAF (20 x 81 km, in total 1620 km) with 11 co-propagating 111-Gb/s POLMUX-QPSK channels on a 50-GHz grid [15]. The results indicate that for LEAF there is no necessarily a significant difference in nonlinear tolerance between an optimized dispersion map and dispersion un-managed transmission. This is partially the result of the lower dispersion coefficient of LEAF, which allows for a lower in-line compensation (e.g., 70% - 80%) in case of the dispersion managed transmission.

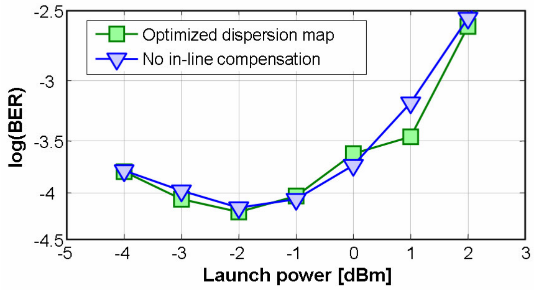

Fig. 4: Measured BER after 1620 km (20 x 81 km) of LEAF.

The optimum fiber type for 100G

In addition to a more flexible dispersion management, the use of coherent detection and digital signal processing allows as well for more *flexibility in fiber design*, as the specification of PMD, chromatic dispersion and dispersion slope become less stringent. This increased freedom might be exploited to design fiber types that are even better suited for 100G-optimized transmission systems. For example, fiber types that can provide an improved transmission performance (compared to SSMF) are super large effective area (SLA) fiber types such as *Draka LongLine* [16] and low-loss pure silica fiber types such as *Corning SMF-ULL* [17]. LongLine increases the effective area from the typical 85 µm^2 of SSMF to 120 µm^2, which translates into a nonlinear tolerance improvement of roughly 1.5 dB. SMF-ULL, on the other hand, lowers the attenuation coefficient from typically 0.19 dB/km of SSMF to 0.175dB/km. This lowers the span loss of a 100 km span from 19 dB to 17.5 dB, which result in an 1.5 dB OSNR improvement. Ideally, one could combine both improvements with a high effective area pure-silica fiber. Such a fiber type would allow for a total margin improvement (nonlinear tolerance and OSNR) of approximately 3 dB compared to SSMF.

Receiver complexity of digital coherent detection

Compared to direct-detection receivers, coherent detection and the associated digital signal processing imply a significant *shift in system complexity from the transmission link to the transmitter and receiver*. The optical components in a POLMUX-QPSK transmitter and receiver require a higher complexity compared to more conventional direct-detection modulation formats (e.g. DPSK). *Optical integration* might therefore be one of the promising directions to reduce footprint, power consumption and improve optical specifications. For example, a single POLMUX-QPSK Mach-Zehnder modulator at the transmitter or an integrated quad photo-diode array combined with a 90^0 hybrid structure at the receiver are promising directions of optical integration.

In addition, there is a *shift in complexity from the optical into the electrical domain*. In particular the ADCs are a key component for any digital coherent receiver. Ideally the optical signal is converted to the electrical domain using a factor of two over-sampling, which implies that ~60-Gsample/s ADCs are required to realize a 100G coherent receiver. The design of 60-Gsample/s ADCs that allow for a >18-GHz electrical bandwidth, effective vertical resolution of at least 4 bits, and a power consumption of only a couple of Watts is truly challenging and requires state-of-the-art mixed signal design [18]. The same is true for the receiver-side digital signal processing, which may consist of as many as 40 to 100 million gates and therefore requires state-of-the-art 40 nm or 65 nm CMOS processes. In addition, to limit the power consumption associated with inter-chip communication both the ADCs and digital signal processing are preferably integrated on a single-chip.

Finally, an important consideration for 100G transmission is the implementation of *advanced FEC coding and de-coding schemes*. Due to the 25-Gbaud symbol rate it is possible to add up to 20% FEC overhead without incurring significant optical filtering penalties in cascaded PXCs. The use of low-density parity check codes (LDPC) with ~20% overhead combined with soft-decision decoding enables a coding gain of up to 11 dB at a 10^{-15} BER, which is a 2-3 dB improvement in effective coding gain over the FEC codes used today at 43-Gb/s line rates [19].

Conclusions

Within the next few years, coherent detection and digital signal processing will drastically change the way optical communication systems are designed. The advantages this technology offers in optical performance and operation simplicity will truly enable the next-generation of long-haul 100G transmission systems.

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