# 40G/100G long-haul optical transmission system design using coherent receivers



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# 40G/100G long-haul optical transmission system design using digital coherent receivers

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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 40G/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. 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 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] as well as improved possibilities for optical performance monitoring [3]. 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 40G/100G optical transmission systems. We focus in this discussion on 40G/100G transmission using *polarization-multiplexed quadrature phase shift keying* (POLMUX-QPSK) modulation, often also referred to as CP-QPSK, PDM-QPSK or DP-QPSK, which is likely to become the next standard for long-haul optical transmission systems.

**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 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 $90^o$ hybrid (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) [1,2].
Fig. 1 shows the constellation diagram of POLMUX-QPSK modulation, represented as a 4-dimensional hypercube (in-phase and quadrature on two polarizations). The use of a 4 bits/symbol modulation format results in a low symbol rate of 10.75 Gbaud (43-Gb/s line rate) and 28 Gbaud (112-Gb/s line rate), respectively. Note that the 43-Gb/s and 112-Gb/s line rate result in 40-Gb/s resp. 100-Gb/s *net data rate* when forward-error correction (FEC) and Ethernet overhead are subtracted. The lower symbol rate improves the tolerance to linear transmission impairments as well as making it possible to use lower-frequency electrical components. In addition, the combination of POLMUX-QPSK modulation and coherent detection allows for an OSNR requirement close to the theoretical optimum [1].

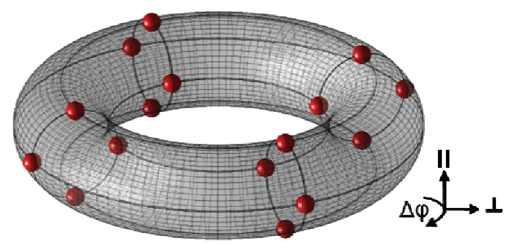


*Fig.1: POLMUX-QPSK constellation diagram.*

**System design using digital coherent detection**
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) [4]. 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 43-Gb/s or 112-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 or fiber Bragg gratings [FBGs]) [5] as well as a limited optical bandwidth

through cascaded filtering in photonic cross-connects (PXC) [1]. Transmission links with high-PMD fiber or multiple cascaded PXCs are straight-out challenging for 43-Gb/s DPSK modulation, resulting in a reduced transmission reach. For such links, 43-Gb/s DQPSK is a promising alternative as the lower symbol rate (21.5 Gbaud) significantly improves the tolerance to both PMD and narrowband optical filtering. However, at an 112-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-deployed transmission systems. Digital coherent receivers combined with either 43-Gb/s or 112-Gb/s POLMUX-QPSK modulation, on the other hand, can compensate for dispersion map deviations, PMD, FBGs induced phase ripples, as well as being more tolerant to the optical filtering resulting from cascaded PXCs on a 50-GHz grid. Hence, this will enable field-deployed transmission links to *upgrade* to 43-Gb/s and 112-Gb/s line rates without an exchange in installed equipment.

On newly deployed transmission links, which generally use high-quality fibers, the optical performance of 43-Gb/s DPSK is roughly equivalent to 43-Gb/s POLMUX-QPSK modulation. In this case not the optical performance, but *simplicity* of the transmission link is the most important advantage of using digital coherent receivers. It negates the need for dispersion management along the transmission link, which in turn offers advantages in transmission latency, sparing of dispersion compensation modules, and allows for simpler amplifier structures. In addition, the optical performance monitoring capabilities that a digital coherent receiver offers reduces the number of required measurements on the installed fiber base and simplifies monitoring of transmission performance.

Regretfully, coherent detection does not simplify all aspects of transmission link design. In particular the *nonlinear tolerance* of 43-Gb/s POLMUX-QPSK modulation is significantly reduced compared to DPSK modulation as it is very sensitive to XPM-induced nonlinear phase shifts. This would have a significant impact on the maximum transmission reach, where it not for the fact that the improved OSNR requirement offsets the reduced nonlinear tolerance. As a result both modulation formats have a comparable transmission reach. For 112-Gb/s POLMUX-QPSK modulation, the nonlinear tolerance is significantly higher compared to a 43-Gb/s line rate as the higher symbol rate reduces the impact of XPM. 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 112-Gb/s line rate. Still, careful system design is required when 43-Gb/s or 112-Gb/s POLMUX-QPSK modulated channels co-propagate with other modulation formats (in particular 10-Gb/s on-off-keying) on the same fiber.

**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 optical to the electrical domain*. In particular the ADCs are a key component for any digital coherent receiver implementation. 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 a 60-Gsample/s ADC that allows 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 [6]. The same is true for the receiver-side digital signal processing, which may consist of as many as 40 to 100 million gates. It therefore requires state-of-the-art 40nm or 65nm CMOS processes in order to reduce power consumption. In addition, the ADC and digital signal processing are preferably integrated on a single-chip in order to limit the power consumption associated with inter-chip communication.

The optical components in a POLMUX-QPSK transmitter and receiver represent as well a higher complexity compared to more conventional direct-detection modulation formats (e.g. DPSK). *Optical integration* might 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 and an integrated quad photo-diode array combined with a $90^0$ hybrid structure at the receiver are both promising directions of optical integration.

Finally, an important consideration for 100G transmission systems 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, a problem which prevents the use of high overhead FEC for 43-Gb/s DPSK modulation. The use of low-density parity check codes with ~20% overhead combined with soft-decision decoding enables a 2-3 dB improvement in effective coding gain over the class of FEC codes typically used at 43-Gb/s line rates (~11 dB coding gain at $10^{-15}$ BER) [7].

**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 40G/100G transmission systems.

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