DQPSK modulation for robust optical transmission

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Abstract: The feasibility of long-haul transmission using differential quadrature phase shift keying (DQPSK) modulation is discussed. We focus in particular on the trade-off between spectral efficiency and reach in optical transmission systems using DQPSK modulation.

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1. Introduction

Next-generation optical transmission systems are expected to transmit ever higher bit rates in densely spaced wavelength division multiplexed (WDM) channels. Especially the recent drive towards a 100G Ethernet standard and burgeoning traffic demand indicates that solutions are required for long-haul transmission with high spectral efficiency. Such a carrier-grade 100G Ethernet standard would likely require a bit rate of 111-Gb/s and preferably use a single wavelength [1]. It is challenging to realize such bit rates with binary formats, as the required bandwidth of the electrical components in the transponder is difficult and costly to realize. Multi-level formats, such as differential quadrature phase shift keying (DQPSK) [2] and polarization-multiplexed (POLMUX)-DQPSK [3, 4] provide a promising alternative as they operate at a lower symbol rate for the same total bit rate. Hence, they require lower-speed, but generally more, transponder components compared to binary formats.

A second important application of multi-level modulation is in transparent optical networking. Transmission links are rapidly evolving from point-to-point links to interconnected optical networks. This requires the flexibility to pass multiple optical add-drop multiplexer (OADM) nodes along the transmission link. Today, most transmission systems have a 50-GHz WDM channel spacing, which implies a 0.8-bit/s/Hz spectral efficiency for 40-Gb/s transmission. For binary formats, such as duobinary or differential phase shift keying (DPSK), this is close to the theoretical limit which makes it is difficult to cascade multiple OADM along a transmission link [5]. The narrower optical spectrum of multi-level formats therefore enable both a high spectral efficiency as well as the possibility to cascade multiple OADMs [6]. In addition, the tolerance against linear transmission impairments, such as chromatic dispersion and polarization-mode dispersion (PMD), increases significantly due to the lower symbol rate [7].

Long-haul transmission experiments with a spectral efficiency of 1.0-bit/s/Hz [8], 1.6-bit/s/Hz [4, 9] and 2.0-bit/s/Hz [10] and with a sound tolerance towards narrowband filtering have recently been demonstrated. For shorter transmission distances, the highest spectral efficiency demonstrated so far is 3.2-bit/s/Hz, which enables a 25.6-Tb/s total capacity [11]. In this paper, we review the use of DQPSK and POLMUX-DQPSK modulation in long-haul transmission systems. In particular we address the realization of both long-haul transmission and high spectral efficiency, and point out some techniques that can enable this challenging combination.

![Fig. 1](image_url)

Fig. 1: (a) DQPSK modulation and signal constellation, (b) POLMUX-DQPSK signal constellation.

2. DQPSK modulation

Fig. 1a depicts the concept of DQPSK modulation using a so called ‘Super Mach-Zehnder’ structure [2]. The signal is split and each tributary is, in effect, DPSK modulated. DQPSK modulation is subsequently obtained by interfering the two tributaries with a suitable phase shift (either -$\pi/2$ or $\pi/2$). For experimental evaluation of DQPSK modulation, a pseudo random quaternary sequence (PRQS) can be used to ensure that all possible sequences up to a given length are tested [12]. A commercial transponder, on the other hand, requires pre-coding of the transmitted data [13, 14]. In the receiver, DQPSK modulation is usually combined with direct detection. Mach-Zehnder delay
interferometers (MZDI) [15] first demodulates the signal, to obtain the in-phase (I) and quadrature (Q) tributaries. This is possible by suitably choosing the phase difference between the two arms of the MZDI (−π/4 or π/4) to select either the I or Q tributary. In most reported transmission experiments, two separate MZDIs are used, although it is also possible to demodulate both tributaries at the same time [16]. Note that DQPSK modulation is much more sensitive to phase offsets in the interferometer than DPSK modulation, and hence the phase difference between the two arms should be precisely controlled [17].

Ideally, DQPSK modulation has the same OSNR requirement as DPSK modulation, as it uses two orthogonal signaling dimensions (I and Q). However, for direct detected DQPSK, the demodulation with a MZDI is suboptimal and results in an OSNR penalty compared to DPSK. For a bit-error rate (BER) close to the forward error correction (FEC) limit this penalty is ~1.3 dB and it increases to 1.9 dB for a 10^-8 BER [18]. But electrical post-processing algorithms such as multi-symbol phase estimation (MSPE) can compensate for this OSNR penalty [19, 20]. Combined with coherent detection, DPSK and DQPSK modulation have the same OSNR requirement [18].

3. POLMUX-DQPSK modulation

DQPSK modulation can be extended beyond 2-bits/symbol by using polarization-multiplexing to encode 4 bits/symbol. In comparison to other multi-level formats, POLMUX-DQPSK modulation is particularly interesting as it uses four orthogonal signaling dimensions (I and Q on each of the polarizations). A representation of the 4-dimensional signal constellation of POLMUX-DQPSK modulation is depicted in Fig. 1b. The POLMUX-DQPSK transmitter consists of two separate DQPSK modulators. Afterwards, both DQPSK tributaries are multiplexed together on two orthogonal polarizations to generate POLMUX-DQPSK. In the receiver, POLMUX requires polarization de-multiplexing in order to separate both polarization tributaries. This can be realized in the optical domain, using a polarization controller followed by a polarization beam splitter [4]. The polarization de-multiplexing splits up the POLMUX-DQPSK signal into two DQPSK tributaries that can be demodulated separately with the previously described DQPSK receiver. However, a significant drawback of optical polarization de-multiplexing is the reduced PMD tolerance [21] and the impact of XPM induced cross-polarization modulation [22].

Fig. 2: (a) OSNR requirement for 43-Gb/s POLMX-NRZ-DQPSK /w coh. det., 43-Gb/s RZ-DQPSK /w direct det., 111-Gb/s POLMUX-RZ-DQPSK /w coh. det., 111-Gb/s POLMUX-RZ-DQPSK /w direct det. and 107-Gb/s RZ-DQPSK /w direct det. (from [1]); (b) BER versus transmission distance for direct detection DQPSK. In the experiment ~95 km spans and hybrid EDFA/Raman amplification are used.

4. Long-haul transmission

Modulation formats suitable for long-haul transmission should have both a low OSNR requirement as well as a sound nonlinear tolerance. Fig. 2a depicts the OSNR requirement for 43-Gb/s and 107-Gb/s RZ-DQPSK modulation, which require 13.0-dB and 18.4-dB OSNR [1] for a 10^-3 BER, respectively. The difference is slightly higher than the 4 dB one would expect by scaling the bit rate. For 111-Gb/s POLMUX-RZ-DQPSK, which has a 27.75-Gbaud symbol rate, the requires OSNR is only 16.4 dB for a 10^-3 BER [23]. This difference is probably due to the more stringent requirements on the electrical components bandwidth for a 55-Gbaud symbol rate compared to a 21.5-Gbaud / 27.74-Gbaud symbol rate.

The nonlinear tolerance of DQPSK modulation is ~2-3 dB lower compared to DPSK modulation [24]. This is a result of the π/2 phase difference between the points in the constellation diagram, which make DQPSK more sensitive to nonlinear phase distortions than DPSK. The high spectral efficiency of DQPSK comes therefore, generally, at the cost of a reduction in feasible transmission distance. Fig. 2b shows a long-haul transmission experiment with RZ-DQPSK modulation with and without POLMUX [4]. For 42.8-Gb/s RZ-DQPSK and 85.6-Gb/s POLMUX-RZ-DQPSK the reach (at the FEC limit) is 4,000 km and 2,500 km, respectively. Taking a 3-dB margin into account, the reach with 85.6-Gb/s POLMUX-RZ-DQPSK modulation is reduced to ~1,200 km. In [8], 107-Gb/s
NRZ-DQPSK with 100-GHz channel spacing has been transmitted over 1,200 km (at the FEC limit). Both experiments indicate that it is challenging to realize long-haul transmission with a ≥1 bits/s/Hz spectral efficiency. For long-haul transmission systems it will therefore be desirable to further improve the OSNR requirement and/or nonlinear tolerance. One such approach is to use digital signal processing algorithms such as intra-dyne coherent detection or MSPE. This potentially improves the OSNR requirement with ~2 dB [19, 23] and it can be used for the compensation of nonlinear impairments [20, 25]. In a intra-dyne coherent receiver, the signal is split into two random polarization components that are mixed with four photo-diodes and subsequently analog-to-digital converted. Polarization de-multiplexing, the compensation of CD and PMD impairments and carrier recovery are all realized in the electrical domain [9, 10, 23, 25-28]. Note that an intra-dyne coherent receiver always requires detection of the full optical field (I and Q on both polarizations), hence the optical front-end of the receiver is transparent with respect to the modulation format. This makes it particularly beneficial to use POLMUX-DQPSK modulation, as it combines a high spectral efficient with a low required OSNR.

The OSNR improvement using coherent detection can be observed in Fig. 2a, where direct-detected 43-Gb/s RZ-DQPSK and coherent detected 43-Gb/s POLMUX-NRZ-DQPSK requires 13.0-dB [4] and 11.2-dB OSNR [28] for a 10^{-3} BER, respectively. At a 111-Gb/s bit rate, the required OSNR with coherent detection is 15.8 dB for a 10^{-3} BER. This relatively small advantage is mainly due to limitations in the analog-to-digital converters. Fig. 3a depicts for 111-Gb/s POLMUX-RZ-DQPSK with coherent detection a measured reach of 3000 km [10].

Fig.3: BER versus transmission distance, ~95 km spans and hybrid EDFA/Raman amplification are used in both experiments.

A second possibility to extend the transmission reach is the optical compensation of nonlinear impairments. One of the most suitable technologies for WDM transmission is optical phase conjugation (OPC). OPC is modulation format and bit rate transparent and a single device can conjugate multiple WDM channels [29]. However, as the OPC should be approximately in the middle of the transmission link, it is most suitable for networks with multiple spans between subsequent OADMs. Fig. 3b shows that for 42.8-Gb/s RZ-DQPSK, the feasible transmission distance is improved with ~50% using a single OPC [30].

6. Conclusions

We reviewed the potential of DQPSK modulation to enable robust long-haul transmission with a high spectral efficiency (0.8 - 2.0 bit/s/Hz). We showed that improvements in OSNR and nonlinear tolerance are key requirements for future high spectral efficient (≥1.0 bit/s/Hz) long-haul transmission systems. Two such approaches are coherent detection and optical phase conjugation.

7. References

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