Quadrature Duobinary Modulation for 100G Transmission Beyond the Nyquist Limit

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Abstract: Quadrature duobinary (QDB) modulation with coherent detection is proposed for 112-Gb/s transmission systems. With proper system design for maximum spectral efficiency, we show that dual polarization QDB can achieve 112-Gb/s transmission on 25-GHz channel spacing.

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1. Introduction

Increasing spectral efficiency and bit rate per channel are major drivers in modern fiber optic communications, with recent research efforts focused on so-called 100G systems to enable efficient transport of 100 Gb/s Ethernet traffic. The transmission of 100G channels (107-112 Gb/s including overhead for FEC) on existing optical line systems designed for 50 GHz or even 25 GHz channel spacing presents a difficult challenge due to the limited optical bandwidth available for each channel. Moreover, any optical networking functions, such as optical add-drop multiplexing (OADM), narrow the effective optical bandwidth even further due to spectral truncation from optical filtering. Advanced multilevel modulation formats, in combination with polarization multiplexing, can offer a solution to this problem by increasing signal spectral efficiency. In particular, dual polarization differential quadrature phase shift keying (DP-DQPSK) has received considerable attention recently [1, 2]. The theoretical spectral efficiency of DP-DQPSK is 4 bits/s/Hz, which is sufficient to achieve 112 Gb/s (28 Gbaud) transmission on 50 GHz channel spacing. However, 112 Gb/s DP-DQPSK reaches its Nyquist limit at a channel spacing of 28 GHz, complicating upgrades of existing optical line systems designed based on a 25 GHz channel spacing ITU grid.

In this paper, we propose and analyze a method for compressing the DP-DQPSK spectrum to provide a more efficient 100G transmission. The method is based on a generalization of the duobinary technique, as illustrated in Figure 1a). The in-phase (I) and quadrature (Q) tributaries are differentially pre-coded, and then passed through an electrical duobinary generating low-pass filter (LPF). The filtered electrical drive signals are then applied to the electrodes of an I-Q modulator, thus producing an optical quadrature duobinary (QDB) format. Note that an optical multiplexing filter, if sufficiently narrow, may also play a useful role in creating the duobinary correlation, as discussed below. The QDB signal constellation is illustrated in Figure 1b). Duobinary coding results in signal degeneracy: the 4 corner constellation points are degenerate, all representing the dibit (1,1), as are the opposite points on the real and imaginary axis, representing dibits (1,0) and (0,1) respectively. This degeneracy in the QDB signal constellation is not wasted. Rather, it is used to shape a narrower signal spectrum. As we show next, the DP-QDB format with coherent detection enables 112 Gb/s WDM transmission on a 25 GHz channel spacing, while requiring essentially the same hardware complexity as a DP-DQPSK system.

2. Simulation Results

As with DQPSK, the optimum reception of QDB requires coherent detection. The theoretical matched filter performance for coherent duobinary systems is developed in [3]; this analysis can be easily generalized to coherent QDB systems. Figure 2 a). plots the theoretical ideal performance curves of BER versus OSNR (defined in 0.1 nm noise bandwidth) for 112 Gb/s DP-QDB. The theoretical ideal performance of DP-DQPSK is also shown for both coherent and interferometric detection. DP-QDB with coherent detection shows about the same OSNR sensitivity as DP-DQPSK with interferometric detection. However, the DP-QDB format suffers a ~ 2 dB penalty compared with DP-DQPSK based on coherent detection; this is the price we must pay to achieve a narrower signal spectrum. Note that the alternative approach to achieving narrower signal spectrum by going to a higher level modulation, such as 8-PSK or 16-QAM, would also suffer a significant OSNR penalty compared with DQPSK, while also increasing system complexity.

In order to obtain good performance with QDB using realistic filters, the duobinary generating filter must be carefully optimized. In particular, to realize the matched filter performance for QDB, we employ a system design where the duobinary filter function is equally divided between transmitter (Tx) and receiver (Rx) [4]. There are actually two filter pairs to consider: a matched pair of electrical LPFs at Tx/Rx, and a matched pair of optical band-pass filters (BPFs) at Tx/Rx. The LPF at Tx effectively sets the modulator bandwidth, while the LPF at Rx sets the receiver electrical bandwidth. The pair of optical BPFs corresponds to the WDM multiplexing and de-multiplexing functions. Electrical LPFs are modelled as 4th order Bessel filters, while optical BPFs are modelled as 2nd order Super Gaussian filters. In our simulations, the ASE noise is loaded between the two optical BPFs to emulate a realistic transmission system where ASE noise accumulates along the optical transmission line, while the optical multiplexing and de-multiplexing filters are located at Tx and Rx, respectively.

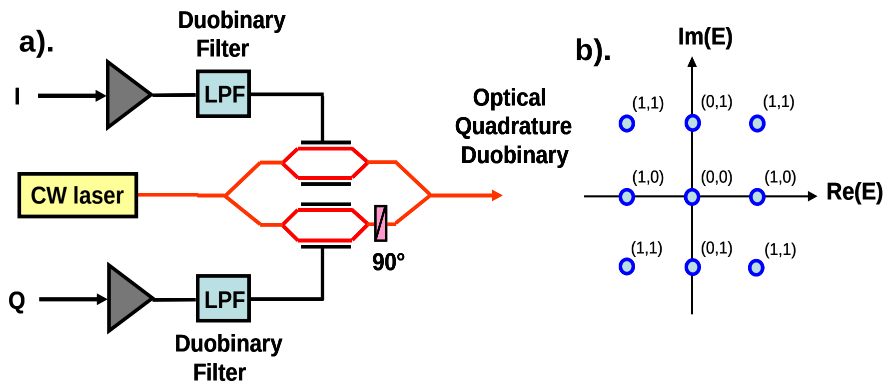

Fig. 1. Schematic diagrams for a). QDB transmitter (only one polarization of DP-QDB modulator is shown); and b). QDB signal constellation.

Figure 2b). shows our Monte-Carlo simulation results for optimizing the LPF bandwidth. The optimum LPF bandwidth depends on the optical BPF bandwidth. In systems designed for 50 GHz channel spacing, where the optical BPF bandwidths are typically near ~ 40 GHz, the optimum LPF bandwidth is ~ 34% of baud rate. However, significantly better performance can be achieved with narrower optical filters, as long as the LPF bandwidth is scaled appropriately. The simulations results in Figure 2 b). show that a properly optimized QDB system based on realistic filters can approach to within ~ 0.2 dB of the theoretical ideal performance; this occurs at an optical BPF bandwidth of ~ 22.5 GHz, and a corresponding LPF bandwidth ~ 50% of baud rate or 14 GHz. In this case the duobinary partial response filter function is dominated by the matched pair of optical filters. As the optical BPF bandwidth is further reduced to 20 GHz, the optimum LPF bandwidth approaches the baud rate, indicating that all of the partial response filter function is performed in the optical domain. Note that the regime of narrow optical filtering, corresponding to optical bandwdiths ~ 20-25 GHz, provides the best performance for QDB. This is also the typical regime of optical filter bandwidths in 10 Gb/s WDM systems designed for 25 GHz channel spacing; a fortunate coincidence which can be exploited to realize 112 Gb/s DP-QDB transmission on 25 GHz channel spacing.

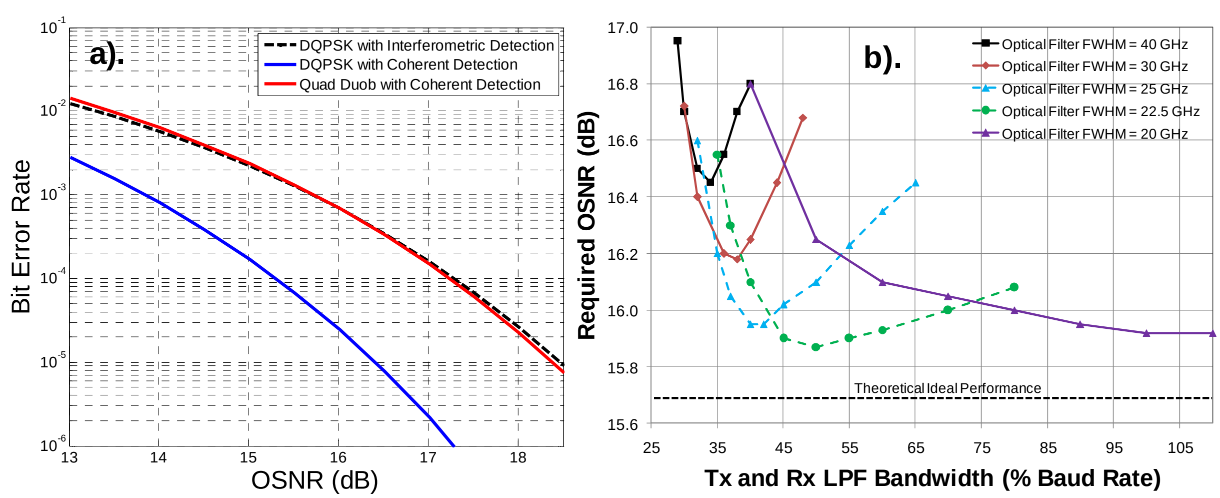

Fig. 2. a). Ideal theoretical performance for DP-QDB versus DP-DQPSK; b). Monte-Carlo simulations on required OSNR to achieve BER = 10^{-3} for DP-QDB system, showing optimum LPF bandwidths for a range of typical WDM optical filter bandwidth designs.

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Figure 3 shows Monte-Carlo simulation result on the required OSNR for BER = 10^{-3} as a function of WDM channel spacing, including the impact of WDM crosstalk. We use a simple design rule for scaling the optical filter bandwidth: the optical FWHM bandwidth is set to 80% of channel spacing, e.g. taking the values of 40 and 20 GHz at the channel spacing of 50 and 25 GHz, respectively. The Tx and Rx LPF bandwidth is optimized for each value of optical filter bandwidth in accordance with Figure 2b). Since both narrow optical filtering and crosstalk play a role in limiting the smallest feasible channel spacing, we include the single channel case (dashed curves) to separate out the impact of the optical filtering. As shown in Figure 3, the DP-DQPSK format can support a channel spacing of 50 GHz without penalty from WDM crosstalk. In this case, DP-DQPSK with coherent detection is the preferred solution due to a ~ 2 dB advantage in OSNR sensitivity. However, a significant WDM crosstalk impairment begins to be visible for DP-DQPSK at ~ 40 GHz, and practical operation at < 35 GHz channel spacing is problematic due to rapidly rising penalties from both WDM crosstalk and spectral truncation due to narrow optical filtering. Thus, we conclude that in practice, the spectral efficiency of DP-DQPSK systems is limited to somewhere significantly below the theoretical limit of 4 bits/s/Hz. In contract, the DP-QDB system, designed with smooth physically realizable filters, can achieve a spectral efficiency of 4 bits/s/Hz with only a small penalty from WDM crosstalk. In fact the overall performance of DP-QDB improves as channel spacing is scaled down to 28 GHz due to the beneficial effects of narrow optical filtering. The DP-QDB format may even support 112 Gb/s transmission on a 25 GHz ITU grid, thus breaking the Nyquist limit, with a modest penalty from WDM crosstalk. To ensure that we have not under-estimated the WDM crosstalk penalty, the DP-QDB simulation at channel spacing of 25 GHz was performed with 100 different random seeds, each seed setting different timing shifts and optical phases of the WDM aggressor channels. The resulting histogram is included in the inset of Figure 3. It shows an average WDM crosstalk penalty of 0.8 dB with a standard deviation of 0.06 dB. We believe this OSNR penalty is acceptable, especially considering that the overall OSNR penalty compared with 50 GHz channel spacing is only ~ 0.3 dB.

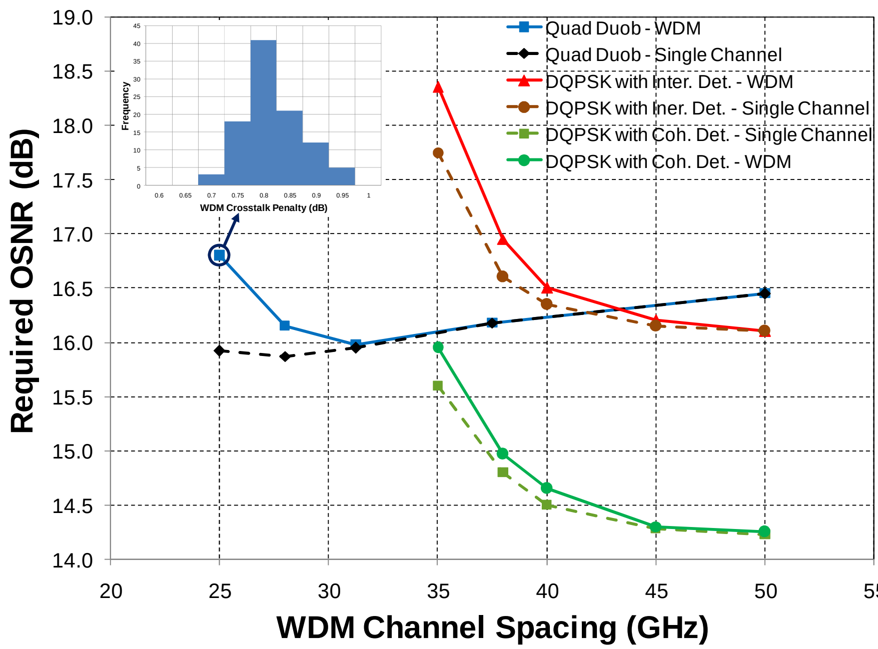

Fig. 3. Monte-Carlo simulations on required OSNR as a function of WDM channel spacing, comparing DP-QDB with DP-DQPSK systems.

3. Conclusions

We proposed and analyzed the DP-QDB format for 112 Gb/s transmission. Simulation analysis shows that a properly designed DP-QDB system based on coherent detection can achieve transmission beyond the Nyquist limit.

4. References

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