Performance comparison of optical 8-ary differential phase-shift keying systems with different electrical decision schemes

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Abstract: We examine the performance of optical 8-ary differential phase-shift keying transmission systems according to the type of receiver structure and modulation format. Compared with the approach based on a multilevel decision, we found that a bilevel receiver provides 3-dB gain in optical signal-to-noise ratio sensitivity and is more robust against chromatic dispersion for either nonreturn-to-zero or return-to-zero modulation.

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References and links
1. Introduction

Multilevel (ML) optical transmission systems have many critical advantages in the design of optical transmission links. With their smaller bandwidth, wavelength channels can be packed more closely within the limited transmission band. For the same reason, the ML optical transmission format enables much robust transmission of the signal against fiber penalties, such as chromatic dispersion or polarization mode dispersion [1].

Among the different techniques to expand optical signals into the ML domain, phase-shift keying (PSK) has received much interest recently as the most promising candidate for the next-generation multilevel transmission format. Recent notable progress in the research of multilevel PSK includes the demonstration of optical 4-ary, differential quadrature PSK (DQPSK) [1,2] and 8-ary (D8PSK) systems, by use of a combination of delay interferometers (DIs) with proper electrical processing either at the transmitter side [3,5,6] or the receiver side [4].

For a deeper extension of optical DPSK above DQPSK, there could be two different approaches distinguished by their strategy for the detection of a differential phase [6]: complete optics only or partial optics with an electrical multilevel decision. Here we examine and compare the performances of two possible implementation schemes [bilevel (BL) versus ML electrical decision] for an optical D8PSK receiver and discuss the transmission characteristics related to the choice of modulation format [return to zero (RZ) versus nonreturn to zero (NRZ)]. Results show a 3-dB advantage in optical signal-to-noise ratio (OSNR) sensitivity for a BL receiver, with better tolerance against chromatic dispersion for both NRZ and RZ formats. We discuss the observed OSNR enhancement and increased dispersion tolerance.

2. Receiver structures

In principle, the M-ary optical DPSK signaling format has \( M \) phase codes that require \( M/2 \) phase thresholds. Figure 1(a) illustrates the direct-form implementation of such receiver hardware for an optical D8PSK system, constructed by use of as many \( M/2 \) DIs in parallel with each DI operated at the required optical phase threshold. Even if the structure can be considered as a simple extension of an optical DQPSK receiver, the output electrical signals from the DIs now have four specific levels. Nevertheless, in the current implementation, we treat each decision variable as a BL signal and process the signal with a single threshold in its respective clock-and-data recovery (CDR) module. Note that this is possible because all the required phase thresholds are already realized in the optics of the receiver as shown in Fig. 2(a). The final step consists of recovering the original data by use of the decoding table that we propose in Table 1(a) [4], which is implemented in the logic circuitry following the CDR modules.

As an alternative approach that uses the minimum number of DIs, Fig. 1(b) shows a

![Fig 1. Implementations of optical D8PSK receiver incorporating (a) bilevel electrical decision (BL D8PSK) and (b) multilevel electrical decision (ML D8PSK)](image)
receiver structure that uses a ML electrical decision technique for the optical D8PSK system, similar to the quadrature receiver scheme commonly used in an electrical PSK system [7]. In this structure, the missing phase information from an insufficient number of DIs can be fulfilled in the electrical domain by increasing the number of electrical decision thresholds. Also shown in Fig. 2(b) and Table 1(b) are the associated constellation graph with detection (optical and electrical) thresholds and a decoding table for the ML receiver, respectively.

Table 1. Phase decoding tables of optical D8PSK for (a) bilevel (BL) and (b) multilevel (ML) receiver; a + or – mark represents the polarity of the decision variable, and the number of marks indicates the expected signal level

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It should be mentioned that inevitable surplus sets exist that are not matched to the constellations of the optical D8PSK signals. Note that the number of all the possible decision sets is 16 (2⁴ for a BL receiver and 4² for a ML receiver). Even though the redundant sets also represent symbol errors, they can be corrected to the nearest symbols in a maximum-likelihood manner [4,7]. Such a bit-error-rate (BER) enhancement technique is not included in the current analysis.

3. Analysis methodology

To estimate the performance of an optically preamplified M-ary optical DPSK receiver exactly, we utilized the well-known Karhunen–Loève series expansion technique formulated in the frequency domain [8]. To analyze the effect of intersymbol interference (ISI), we also used a semianalytical BER calculation [9,10], including a pseudorandom bit sequence (PRBS) with a sufficient code length to take account of ISI caused by the symbol patterning effect.

The decision error rate of each DI obtained with the above step is utilized to calculate the system’s BER as follows:

\[
BER = \left[1 - \prod_{r=1}^{N_r} (1 - ER^r)\right] / \log_2 M
\]

where \( ER^r \) is the decision error rate of the \( r \)-th DI, and \( N_r \) is the number of DIs in each receiver structure (\( M/2 \) for the BL receiver and 2 for the ML receiver).
For approximation (1), it is obvious that approximations exist for mutual independence among the DIs in the receiver and Gray coding [11]. It can easily be shown that the approximations hold for all the practically meaningful BER levels (e.g., less than $10^{-3}$). In fact, the BER results obtained from the above method showed excellent agreement with the Monte Carlo error counting method to within 0.5 dB of the estimation error (Fig. 3).

4. Numerical results and discussion

To analyze the performance of ML and BL D8PSK, we performed a numerical analysis by utilizing the method described in Section 3. Two of the most popular transmission formats were tested at a fixed bit rate of 40 Gbits/s: an NRZ format with constant power and ideal rectangular phase shape [10] and an RZ (33% duty cycle) generated from an additional pulse carver, a Mach–Zehnder modulator complementarily driven by a sinusoidal clock at half of the symbol rate [9]. For an NRZ transmitter with a nonideal phase shape (with a rise time of as much as 25% of the symbol period), we observed similar performances as those with an ideal NRZ, which is consistent with previous reports [10]. Each transmitter was assumed to be chirp free. To include the ISI effect caused mainly by three-symbol patterns, we used PRBSs at code lengths of $2^{16-1}$ ($= 83^{16-1}$) for optical D8PSK and $2^{6-1}$ ($= 43^{6-1}$) for DQPSK.

Optical amplified spontaneous emission (ASE) from the preamplifier was modeled as additive white Gaussian noise. To characterize the optical noise, the OSNR was calculated with unpolarized ASE power within a reference bandwidth of 0.1 nm. To simulate the frequency response of an arrayed waveguide grating, we assumed a first-order Gaussian optical bandpass filter. Electrical noise from photodiodes was ignored; we focused instead on the ASE noise-limited systems. After we used balanced photodetectors, fifth-order Bessel electrical low-pass filters were used. For all the numerical analyses, electrical decision thresholds (in CDR modules) were optimized to minimize the BER.

To determine the optimum receiver design and to study the effects of filtering in the D8PSK receivers [9] at the same time, we evaluated the OSNR penalty in a back-to-back condition as a function of optical ($B_o$) and electrical ($B_e$) bandwidths for both ML and BL D8PSKs, with NRZ and RZ modulation formats (Fig. 4). The results are referenced to the minimum OSNR to achieve a $10^{-12}$ BER for each format: 22.4, 25.4, 23.5, and 26.6 dB for RZ BL, RZ ML, NRZ BL, and NRZ ML D8PSK, respectively.

Figure 4 also shows that the NRZ D8PSK format suffers from suboptimum filtering more severely than RZ modulation. A comparison of the BL and ML receivers showed that the BL receiver was more resistant to filtering-induced ISI for both modulation formats.

It is important to note the existence of a 3-dB gain in OSNR sensitivity for BL D8PSK (compared with that for ML D8PSK). We attribute this observation to the difference in the distances between error-dominant levels. Note that, in Fig. 5, $f_p$ and $f_g$ govern the BER for ML D8PSK, and $f_g$ governs the BER for BL D8PSK. As the distance for ML D8PSK is 2 1/2 times smaller than that for BL D8PSK, the ML D8PSK signals require 3 dB more OSNR than the...
BL D8PSK signals to achieve the same BER. Note that OSNR \( \propto Q^2 \propto |d_{ed}|^2 \) [12], where \( Q \) is the Q factor and \( d_{ed} \) is the distance between error-dominant levels. Here, we assume an ASE noise-limited condition with a fixed received optical power, ignoring the data dependency of the beat noise power that can be justified for M-ary DPSK with ordinary optical filtering [13].

Expressed in mathematical terms, we obtain

\[
\Delta OSNR_{\text{ed}} = 10 \log_{10} \left[ \frac{2 \sin (\pi/8)}{\sin (3\pi/8) - \sin (\pi/8)} \right]^2 = 3 \text{ (dB)}
\]  

in agreement with the observed OSNR gain.

To investigate the transmission performance associated with accumulated chromatic dispersion, we calculated the OSNR penalty at a 10^{-12} BER for different multilevel optical DPSK systems, as shown in Fig. 6. For each system type, the filter bandwidths have been selected to their optimal point. The figure also shows the dispersion penalty for an optical DQPSK system, which is in good agreement with a previous report [10].

By comparing BL and ML receivers we observed that the BL receiver exhibited greater dispersion tolerance than the ML receiver: 1.05 and 1.3 times larger for RZ and NRZ D8PSK, respectively, with a 1-dB OSNR penalty. As inferred from Fig. 5, we attribute this to the relatively larger margin of the central eye around the electrical ground, which is the dominant factor on the performance of a BL receiver.

By comparing the NRZ and RZ formats, the RZ D8PSK format exhibited much stronger robustness against chromatic dispersion: 1.9 and 1.5 times for ML and BL receivers, respectively. This observation is somewhat counterintuitive at first glance because the RZ system, with its wider spectrum, is known to be more susceptible to chromatic dispersion. However, when we examined the results closely, for example, the OSNR penalty of DQPSK in Fig. 6, it is possible to determine the existence of a crossover point (~ 150 ps/nm), where the NRZ starts to outperform the RZ in terms of dispersion tolerance, meeting our intuitive picture. For the RZ and NRZ D8PSK, the crossover was observed at approximately 440 ps/nm.

Fig 4. OSNR penalty due to optical and electrical filtering for (a) NRZ ML D8PSK, (b) RZ ML D8PSK, (c) NRZ BL D8PSK, and (d) RZ BL D8PSK.
of the dispersion value (with a large OSNR penalty of 8 dB, which is above our range of interest). This result is in agreement with the previous report by Wang and Kahn [10].

Summarizing the above analysis, we conclude that the BL receiver with RZ modulation is the best design choice over other D8PSK schemes in terms of its strong dispersion tolerance as well as its low OSNR sensitivity.

5. Conclusion

We investigated the performance of an 8-ary optical DPSK transmission system by comparing different receiver structures (bilevel versus multilevel) and signal modulation (RZ versus NRZ) formats. We proved the existence of a 3-dB gain in OSNR sensitivity of the BL D8PSK structure both numerically and analytically. In the future, we expect the RZ BL D8PSK system to be used in spectrally efficient high-capacity transmission systems.