Conventional DPSK Versus Symmetrical DPSK: Comparison of Dispersion Tolerances

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***Abstract*—Differential phase-shift keying (DPSK) encodes information in the phase difference $\Delta\phi$ between successive symbols. In conventional DPSK (CDPSK), $\Delta\phi$ assumes values in the set $\{0, \pi\}$, while in symmetrical DPSK (SDPSK), $\Delta\phi$ assumes values in the set $\{\pi/2, -\pi/2\}$. It is shown by numerical analysis that return-to-zero (RZ)-CDPSK is more robust to chromatic dispersion, while RZ-SDPSK is more robust to first-order polarization-mode dispersion if strong optical filtering is applied.**

***Index Terms*—Chromatic dispersion (CD), differential phase-shift keying (DPSK), modulation format, optical fiber communication, polarization-mode dispersion (PMD).**

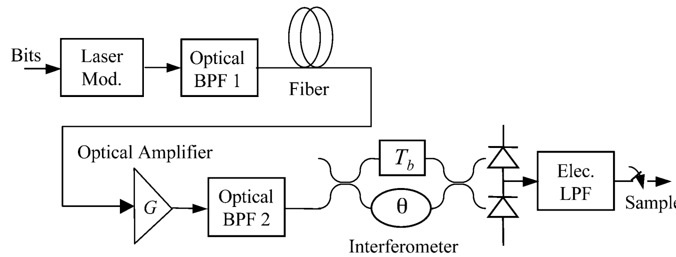

Fig. 1. Schematic diagram of CDPSK and SDPSK system. The phase shift is $\theta = 0$ for CDPSK and $\theta = \pi/2$ for SDPSK.

I. Introduction

DIFFERENTIAL phase-shift keying (DPSK) is a class of modulation techniques encoding information in the phase difference $\Delta\phi$ between successive symbols. When $\Delta\phi$ assumes values in the set $\{0, \pi\}$, we have (binary) conventional DPSK (CDPSK), and when it assumes values in the set $\{\pi/2, -\pi/2\}$, we have symmetrical DPSK (SDPSK) [1] (also called $\pi/2$-DPSK recently [2]). The comparison between CDPSK and SDPSK was performed in the context of satellite communication during the 1980s [1], [3]. It was found that SDPSK has better bit-error-ratio (BER) performance than CDPSK in the presence of intersymbol interference (ISI). These studies considered ISI arising from electrical filtering, timing errors, and hard limiting.

DPSK modulation has been used in several high-capacity long-haul optical transmission experiments over the past two years. Initial experiments used only CDPSK [4]–[7], in part, because of the ease of generating $\{0, \pi\}$ phase differences using a Mach–Zehnder modulator (MZM). Recent optical transmission experiments using SDPSK [2] showed that SDPSK outperforms CDPSK in the presence of strong optical filtering and polarization-mode dispersion (PMD). In this letter, using numerical analysis, we compare the performance of CDPSK and SDPSK using return-to-zero (RZ) pulses and in the presence of optical filtering, chromatic dispersion (CD) and first-order PMD. We show that SDPSK is indeed superior to CDPSK in combating PMD if strong optical filtering is used. We show, however, that SDPSK is inferior to CDPSK in its tolerance to CD. We explain in detail the origins of these differences.

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II. System Model and BER Calculation

Fig. 1 illustrates the structure of an optical system using CDPSK or SDPSK modulation. We assume that an appropriate modulator is used to modulate the CDPSK or SDPSK signal. Examples of CDPSK modulators are described in [4]–[7], while an SDPSK modulator is given in [2]. The modulated signal is then passed through an optical bandpass filter (BPF 1), which corresponds to the multiplexer in a multichannel system, and is launched into the fiber, which is assumed to be lossless. In the fiber, the optical signal is assumed to be affected by CD and first-order PMD, but not by fiber nonlinearity.

The received optical signal passes into a lumped optical amplifier, which adds amplified spontaneous emission (ASE) noise. The amplifier output is filtered by a second optical bandpass filter (BPF 2), corresponding to the demultiplexer in a multichannel system, and is passed into an optical delay-line interferometer, which demodulates the received DPSK signal. For reception of either CDPSK or SDPSK, the upper branch of the interferometer provides a delay equal to the bit duration T. For CDPSK, the lower branch provides an optical phase shift $\theta = 0$, while for SDPSK system, the phase shift is $\theta = \pi/2$. The interferometer outputs are detected by a balanced photodetector, and the differential photocurrent is lowpass filtered and sampled at the bit rate. We assume that ASE noise is the dominant noise in the receiver.

In order to explain the principles of CDPSK and SDPSK reception, similar to [2], we assume that the complex amplitude of the nth pulse is $E_n = A\exp(j\phi_n)$, where A is a real constant and ϕ_n is the phase of the nth pulse. Bit "0" is encoded by $\phi_n = \phi_{n-1} - \theta$ and bit "1" by $\phi_n = \phi_{n-1} - (\theta + \pi)$. Recall that $\theta = 0$ for CDPSK and $\theta = \pi/2$ for SDPSK. When the two interferometer branches are phased as described previously, the amplitudes at the upper and lower output ports are given by

$$E_1 = [A\exp(j\phi_{n-1}) + A\exp(j\phi_n + j\theta)]/2 \quad (1)$$

and

$$E_2 = [A\exp(j\phi_{n-1}) - A\exp(j\phi_n + j\theta)]/2 \qquad (2)$$

respectively. Thus, the differential current in the balanced photodetector is expressed as

$$i = |E_1|^2 - |E_2|^2 = A^2\cos(\phi_{n-1} - \phi_n - \theta). \qquad (3)$$

In the case of either CDPSK or SDPSK, the differential current is A^2 for bit "0" and $-A^2$ for bit "1." Decisions are made using a threshold set near zero.

The BERs of CDPSK and SDPSK in the presence of CD and PMD are computed using the numerical method described in [8] and [9]. Briefly, this method expresses the optical noise in a Fourier series using a Karhunen–Loeve series expansion (KLSE) and uses matrix techniques to express the decision sample as a noncentral quadratic form of Gaussian random variables, which follows a noncentral chi-square distribution. Then, the moment-generating function of decision samples is obtained, allowing the BER to be evaluated using an inverse Laplace transform. We refer to this procedure as the KLSE method, following [9], which describes in detail its application to DPSK systems with CD and first-order PMD.

III. CD and PMD Power Penalties of CDPSK and SDPSK

In this section, we compare the power penalties caused by CD and first-order PMD in 40-Gb/s systems using CDPSK and SDPSK. The system configuration is as follows. Both optical bandpass filters BPF 1 and BPF 2 have second-order super-Gaussian frequency responses. BPF 1 and BPF 2 have 3-dB bandwidths (full-width at half-maximum) specified by the parameter B. The electrical lowpass filter is a fifth-order Bessel type with 3-dB cutoff of 32 GHz.

In both CDPSK and SDPSK transmission, the elementary pulses are either 33% or 66% duty-ratio RZ pulses, both of which can be generated by driving an MZM with a clock signal at half the bit rate $1/(2T)$, but with different DC biases. The modulated signal is launched into the fiber with equal projection into the two principal states of PMD, causing the worst-case PMD effect. First-order PMD is parameterized in terms of τ, the differential group delay. CD is characterized by the product DL (ps/nm), where D is the fiber CD parameter and L is the fiber length. The optical amplifier noise figure is taken to be 3 dB.

Fig. 2 presents the power penalties at 10^{-9} BER for CDPSK and SDPSK with 33% and 66% RZ pulses. Both BPF 1 and BPF 2 have bandwidths $B = 50$ GHz, corresponding to strong optical filtering. All power penalties are referred to the quantum-limited receiver sensitivity for binary DPSK, which is 21.8 photons/bit at 10^{-9} BER. The decision threshold is always optimized to minimize BER; we find that the optimal threshold often deviates from zero by as much as 0.5% of the peak-peak excursion of decision samples.

As observed in Fig. 2, when both CD and PMD are absent, SDPSK has a slightly lower penalty than CDPSK. In the presence of significant CD, CDPSK has a much lower penalty than SDPSK, while in the presence of PMD, SDPSK has a lower penalty than CDPSK, in qualitative agreement with the results of [2] (note, however, that [2] did not use strong optical filtering at the receiver). These observations suggest that when strong optical filtering is used, the choice between CDPSK and SDPSK

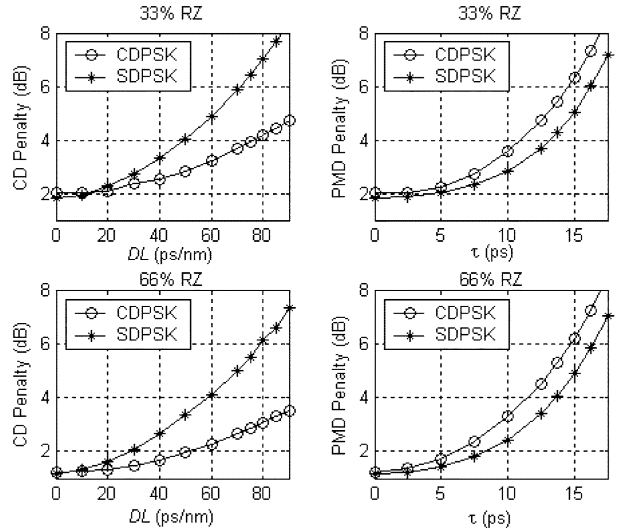

Fig. 2. CD and PMD power penalties of CDPSK and SDPSK.

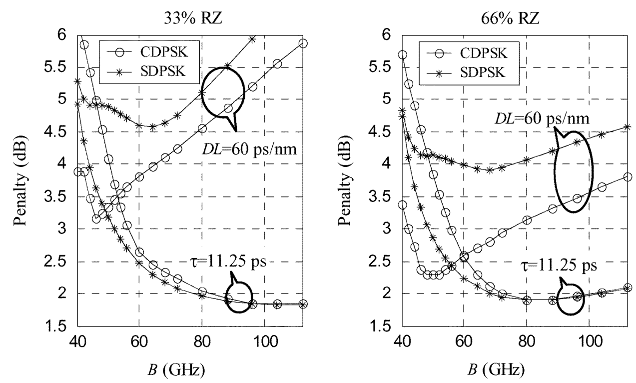

Fig. 3. CD and PMD power penalties of CDPSK and SDPSK versus the bandwidth of the optical filters.

will depend on the relative strengths of CD and PMD in a given system.

When the bandwidth of the optical filters is varied, the CD and PMD penalties of both CDPSK and SDPSK will change. Fig. 3 shows the CD penalties at $DL = 60$ ps/nm and the PMD penalties at $\tau = 11.25$ ps versus the bandwidth B of BPF 1 and BPF 2. Focusing on the penalty difference between CDPSK and SDPSK, we see that for both 33% RZ and 66% RZ, the difference in PMD penalties decreases as B increases, and becomes negligible when B exceeds 80 GHz. By contrast, for both 33% RZ and 66% RZ, there is a substantial penalty difference between CDPSK and SDPSK, though the penalty decreases for large B. Therefore, with weak optical filtering, CDPSK is preferable over SDPSK, because the two techniques have similar PMD penalties, while the former technique has a smaller CD penalty.

In order to understand the differences between CDPSK and SDPSK, it is helpful to observe the interference between adjacent bits. We consider a periodic "0011" bit sequence, which includes all two-bit patterns. We use 33%-RZ pulses and strong optical filtering (BPF 1 and BPF 2 have $B = 50$ GHz). Fig. 4 shows the differential current in the balanced photodetector for both CDPSK and SDPSK. We observe several different ISI effects in Fig. 4. In CDPSK, pulses #1 and #2 attract each other and actually merge into one flat-top pulse, while pulses #3 and

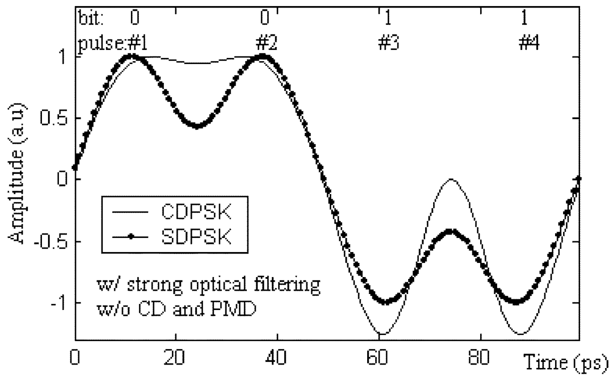

Fig. 4. Differential current when transmitting "0011" bit sequence in the presence of strong optical filtering only.

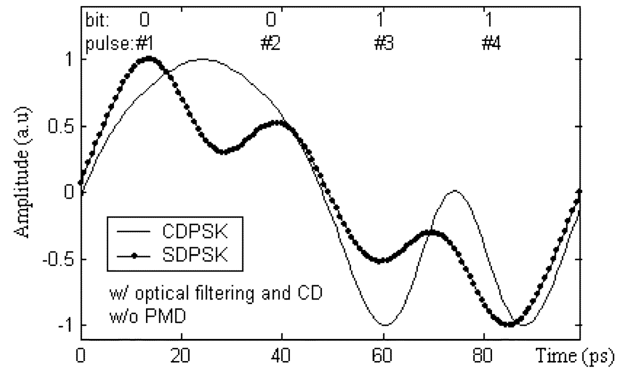

Fig. 5. Differential current when transmitting "0011" bit sequence in the presence of strong optical filtering and CD.

#4 repel each other (the peak–peak interval increases from 25 to 28 ps). In SDPSK, adjoining pulses, such as pulses #1 and #2 or pulses #3 and #4, merely merge their tails. These different types of ISI arise because the impact of strong optical filtering on adjacent pulses depends on the phase difference $\Delta\phi$ between pulses. In CDPSK transmission, the phase difference between pulses #1 and #2 is zero (implying constructive interference will occur) and that between #3 and #4 is π (implying destructive interference will occur); in SDPSK transmission, the phase differences are $\pi/2$ and $-\pi/2$, respectively.

Considering PMD, we recall that the effect of first-order PMD is equivalent to combining the photocurrents of the signal and a τ-delayed copy. Among all of the ISI effects observed in Fig. 4, we expect that the repulsion between pulses #3 and #4 for CDPSK leads to the most degradation. This is because when pulses #3 and #4 repel each other, pulse #3 moves closer to pulse #2. This causes the photocurrents from pulses #2 and #3 to partially cancel each other, pulling both pulses toward zero and significantly increasing the BER. Since the repulsion of pulses occurs only in CDPSK, CDPSK is inferior to SDPSK in combating PMD with strong optical filtering. Note that in the absence of strong optical filtering, all pulses maintain their 33% RZ shape, and PMD induces similar ISI penalties for CDPSK and SDPSK.

Fig. 5 shows the differential current of CDPSK and SDPSK for a "0011" bit sequence in the presence of both CD ($DL =$ 60 ps/nm) and strong optical filtering (BPF 1 and BPF 2 have $B = 50$ GHz). This figure illustrates why SDPSK is inferior to CDPSK in the presence of CD and strong optical filtering. As before, in CDPSK transmission, pulses #1 and #2 attract each other and pulses #3 and #4 repel each other. But in SDPSK, detected pulses of adjacent bits like "00" and "11" no longer have equal amplitudes, with one pulse robbing energy from the other. The direction of the energy transfer depends on whether $\Delta\phi = \pi/2$ or $-\pi/2$. This leads to a severe ISI penalty, because the BER is dominated by the amplitude of the depleted pulses. For this reason, SDPSK is inferior to CDPSK in the presence of CD and strong optical filtering.

In the case of weak optical filtering, CD expands each pulse very significantly, and consideration of a pair of adjacent pulses is not sufficient to explain the performance difference between CDPSK and SDPSK. In fact, it is not sufficient to consider ISI alone, and it is necessary to consider signal-ASE beat noise as well. In the weak-optical filtering regime, we must rely upon detailed numerical calculations as described above to perform even a qualitative performance comparison.

IV. Conclusion

We have compared CD and PMD power penalties of RZ-CDPSK and RZ-SDPSK. We found that with either weak or strong optical filtering, CDPSK has lower CD penalties than SDPSK. With strong optical filtering, SDPSK has lower PMD penalties than CDPSK; at 40 Gb/s, the advantage is about 1 dB for 50-GHz filter bandwidths. In the absence of strong optical filtering, the two techniques have very similar PMD penalties.

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