

MODULATION AND DETECTION TECHNIQUES FOR DWDM SYSTEMS*

Invited Paper

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Abstract: Various binary and non-binary modulation techniques, in conjunction with appropriate detection techniques, are compared in terms of their spectral efficiencies and signal-to-noise ratio requirements, assuming amplified spontaneous emission is the dominant noise source. These include (a) pulse-amplitude modulation with direct detection, (b) differential phase-shift keying with interferometric detection, (c) phase-shift keying with coherent detection, and (d) quadrature-amplitude modulation with coherent detection.

Key words: optical fiber communication; optical modulation; optical signal detection; differential phase-shift keying; phase-shift keying; pulse amplitude modulation; heterodyning; homodyne detection.

1. INTRODUCTION

Currently deployed dense wavelength-division-multiplexed (DWDM) systems use binary on-off keying (OOK) with direct detection. In an effort to improve spectral efficiency and robustness against transmission impairments, researchers have investigated a variety of binary and non-binary modulation techniques, in conjunction with various detection techniques. In this paper, we compare the spectral efficiencies and signal-to-noise ratio (SNR) requirements of several modulation and detection techniques. We assume that amplified spontaneous emission (ASE) from optical amplifiers is the dominant noise

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source. We do not explicitly consider the impact of other impairments, such as fiber nonlinearity (FNL), chromatic dispersion (CD), or polarization-mode dispersion (PMD).

The information bit rate per channel in one polarization is given by

$$R_b = R_s R_c \log_2 M, \quad (1)$$

where R_s is the symbol rate, $R_c \leq 1$ is the rate of an error-correction encoder used to improve SNR efficiency, and M is the number of transmitted signals that can be distinguished by the receiver. For an occupied bandwidth per channel B , avoidance of intersymbol interference requires $R_s \leq B$ [1]. If the channel spacing is Δf , the spectral efficiency per polarization is

$$S = \frac{R_b}{\Delta f} = \frac{R_s R_c \log_2 M}{\Delta f} \leq \frac{B R_c \log_2 M}{\Delta f} \quad (2)$$

Our figure of merit for spectral efficiency is $\log_2 M$, the number of coded bits per symbol, which determines spectral efficiency at fixed $R_s/\Delta f$ and fixed R_c . Binary modulation ($M = 2$) can achieve spectral efficiency up to 1 b/s/Hz, while non-binary modulation ($M > 2$) can achieve higher spectral efficiencies.

Non-binary modulation can improve tolerance to uncompensated CD and PMD, as compared to binary modulation, for two reasons [2, 3]. At a given bit rate R_b , non-binary modulation can employ lower symbol rate R_s , reducing signal bandwidth B , thus reducing pulse spreading caused by CD. Also, because non-binary modulation employs longer symbol interval $1/R_s$, it can often tolerate greater pulse spreading caused by CD and PMD.

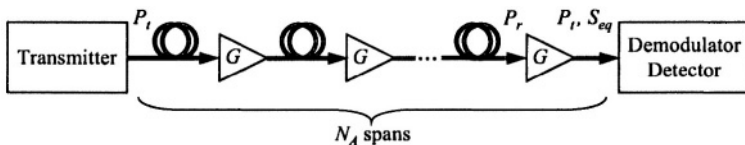


Figure 1. Equivalent block diagram of multi-span system,

In comparing SNR efficiencies, we consider the reference system shown in Fig. 1. The system comprises N_A fiber spans, each of gain $1/G$, and each followed by an amplifier of gain G . The average transmitted power per channel is P_t , while the average power at the input of each amplifier is $P_r = P_t/G$. We assume that for all detection schemes, ASE dominates over other noise sources, thereby maximizing the receiver signal-to-noise ratio (SNR) [4]. At the output of the final amplifier, the ASE in one polarization has a power spectral density

(PSD) given by

$$S_{eq} = N_A(G - 1)n_{sp}h\nu = (G - 1)n_{eq}h\nu, \quad (3)$$

where n_{sp} is the spontaneous emission noise factor of one amplifier, and we define the equivalent noise factor of the multi-span system by $n_{eq} = N_A n_{sp}$.

At the input of the final amplifier, the average energy per information bit is $E_b = P_r/R_b$. At the output of the final amplifier, the average energy per information bit is $GE_b = GP_r/R_b = P_t/R_b$, identical to the average transmitted energy per information bit. Our figure of merit for SNR efficiency is the value of the received SNR per information bit GE_b/S_{eq} required to achieve an information bit-error ratio (BER) $P_b = 10^{-9}$. This figure of merit indicates the average energy that must be transmitted per information bit for fixed ASE noise, making it appropriate for systems in which transmitted energy is constrained by FNL. Defining the average number of photons per information bit at the input of the final amplifier $n_b = E_b/h\nu$, and using (3), the figure of merit for SNR efficiency is

$$\frac{GE_b}{S_{eq}} = \left(\frac{G}{G - 1} \right) \frac{n_b}{n_{eq}} \approx \frac{n_b}{n_{eq}}, \quad (4)$$

which is equal to the receiver sensitivity at the final amplifier input divided by the equivalent noise factor of the multi-span system.

The modulation techniques described below can be employed with various elementary pulse shapes, including non-return-to-zero (NRZ) or return-to-zero (RZ), and with various line codes, such as duobinary or carrier-suppressed RZ. In the absence of fiber nonlinearity, with proper CD compensation and matched filtering, the elementary pulse shape and line code do not affect the spectral efficiency and SNR figures of merit considered here.

2. DIRECT DETECTION OF PAM

When used with direct detection, M -ary pulse-amplitude modulation (PAM) encodes a block of $\log_2 M$ bits by transmitting one of M intensity levels. Henry [5] and Humblet and Azizoglu [6] analyzed the performance of 2-PAM (OOK) with optical preamplification and direct detection. In order to achieve $P_b = 10^{-9}$, 2-PAM requires $n_b/n_{eq} = 38$ with single-polarization filtering and $n_b/n_{eq} = 41$ with polarization diversity.

We are not aware of an exact performance analysis of M -PAM for $M \geq 4$. Neglecting all noises except the dominant signal-spontaneous beat noise, at each intensity level, the photocurrent is Gaussian-distributed, with a variance

proportional to the intensity. Setting the $M - 1$ decision thresholds at the geometric means of pairs of adjacent levels approximately equalizes the downward and upward error probabilities at each threshold. In order to equalize the error probabilities at the $M - 1$ different thresholds, the M intensity levels should form a quadratic series [7]. Assuming Gray coding, the BER is given approximately by

$$\begin{aligned} P_b &\approx \frac{1}{\log_2 M} Q \left(\sqrt{\frac{3 \log_2 M}{(2M - 1)(M - 1)} \frac{GE_b}{S_{eq}}} \right) \\ &= \frac{1}{\log_2 M} Q \left(\sqrt{\frac{3 \log_2 M}{(2M - 1)(M - 1)} \frac{n_b}{n_{eq}}} \right). \end{aligned} \quad (5)$$

For $M = 2$, (5) indicates that $n_b/n_{eq} = 36$ is required for $P_b = 10^{-9}$, which is lower by 0.2 dB than the exact requirement $n_b/n_{eq} = 38$. For $M \geq 4$, (5) indicates that the SNR requirement increases by a factor $(3 \log_2 M)/[(2M - 1)(M - 1)]$, corresponding to penalties of 5.5, 10.7 and 15.9 dB for $M = 4, 8, 16$, respectively. To estimate SNR requirements of M -PAM with single-polarization filtering, we assume the exact requirement $n_b/n_{eq} = 38$ for $M = 2$, and add the respective penalties for $M = 4, 8, 16$.

3. INTERFEROMETRIC DETECTION OF DPSK

Both M -ary phase-shift keying (PSK) and differential phase-shift keying (DPSK) use signal constellations consisting of M points equally spaced on a circle. While M -PSK encodes each block of $\log_2 M$ bits in the phase of the transmitted symbol, M -DPSK encodes each block of $\log_2 M$ bits in the phase change between successively transmitted symbols [1].

For interferometric detection of 2-DPSK, a Mach-Zehnder interferometer with a delay difference of one symbol compares the phases transmitted in successive symbols, yielding an intensity-modulated output that is detected by a balanced optical receiver. In the case of M -DPSK, $M \geq 4$, a pair of Mach-Zehnder interferometers (with excess phase shifts of 0 and $\pi/2$) and a pair of balanced receivers are used to determine the in-phase and quadrature components of the phase change between successive symbols.

Tonguz and Wagner [8] showed that the performance of DPSK with optical amplification and interferometric detection is equivalent to standard differentially coherent detection [1]. 2-DPSK requires $n_b/n_{eq} = 20$ with single-polarization filtering and $n_b/n_{eq} = 22$ with polarization diversity to achieve $P_b = 10^{-9}$ [8]. The performance of M -DPSK for $M \geq 4$ with single-polarization polarization filtering is described by the analysis in [1].

4. COHERENT DETECTION OF PSK AND QAM

In optical communications, “coherent detection” has often been used to denote any detection process involving photoelectric mixing of a signal and a local oscillator [9]. Historically, the main advantages of coherent detection were considered to be high receiver sensitivity and the ability to perform channel demultiplexing and CD compensation in the electrical domain [9]. From a current perspective, the principal advantage of coherent detection is the ability to detect information encoded independently in both in-phase and quadrature field components, increasing spectral efficiency. This advantage can be achieved only by using synchronous detection, which requires an optical or electrical phase-locked loop (PLL), or some other carrier-recovery technique. Hence, we use the term “coherent detection” only to denote synchronous detection, which is consistent with its use in non-optical communications [1].¹

In ASE-limited systems, the sensitivity of a synchronous heterodyne receiver is equivalent to a synchronous homodyne receiver provided that the ASE is narrow-band-filtered or that image rejection is employed [10]. Most DWDM systems use demultiplexers that provide narrow-band filtering of the received signal and ASE, in which case, image rejection is not required for heterodyne to achieve the same performance as homodyne detection.

Both homodyne and heterodyne detection require polarization tracking or polarization diversity. Our analysis assumes tracking, as it requires fewer photodetectors. Coherent system performance is optimized by using high amplifier gain G and a strong local-oscillator laser, so that local-oscillator-ASE beat noise dominates over receiver thermal noise and other noise sources [4]. This corresponds to the standard case of additive white Gaussian noise [1].

M -ary PSK uses a constellation consisting of M points equally spaced on a circle. In the case of uncoded 2- or 4-PSK, the BER is given by [1]

$$P_b = Q \left(\sqrt{\frac{2GE_b}{S_{eq}}} \right) = Q \left(\sqrt{\frac{2n_b}{n_{eq}}} \right), \quad (6)$$

where the Q function is defined in [1]. Achieving a BER 10^{-9} requires $n_b/n_{eq} = 18$. The BER performance of M -PSK, $M > 4$ is computed in [1].

M -ary quadrature-amplitude modulation (QAM) uses a set of constellation points that are roughly uniformly distributed within a two-dimensional region. In the cases $M = 2^{2m}$ ($M = 4, 16, \dots$), the points are evenly arrayed in a

¹We do not consider heterodyne or phase-diversity homodyne detection with differentially coherent (delay) demodulation of DPSK, since the interferometric detection scheme described in Section 3 is mathematically equivalent [8] and is easier to implement. Likewise, we do not consider heterodyne or phase-diversity homodyne detection with noncoherent (envelope) demodulation of PAM, since the direct detection scheme described in Section 2 is mathematically equivalent [8] and is more easily implemented.

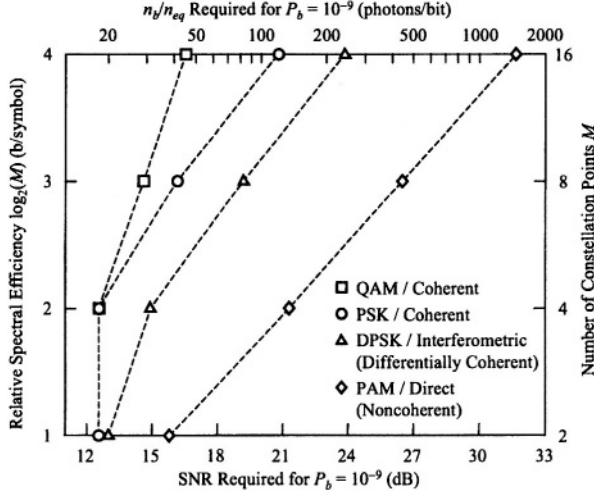


Figure 2. Spectral efficiency vs. SNR requirement for various techniques.

Table 1. Comparison of modulation and detection schemes. Numbers given represent the values of $GE_b/S_{eq} = n_b/n_{eq}$ (photons/bit) required for $P_b = 10^{-9}$. Numbers in parenthesis are the corresponding values of $10 \log_{10}(GE_b/S_{eq}) = 10 \log_{10}(n_b/n_{eq})$.

M	$\log_2 M$	PSK/Coherent One Pol.	QAM/Coherent One Pol.	DPSK/Interferometric		PAM/Direct	
				One Pol.	Two Pol.	One Pol.	Two Pol.
2	1	18 (12.6)	Not applicable	20 (13.0)	22 (13.4)	38 (15.8)	41 (16.1)
4	2	18 (12.6)	18 (12.6)	31 (14.9)	?	134 (21.3)	?
8	3	41 (16.2)	29 (14.6)	83 (19.2)	?	443 (26.5)	?
16	4	119 (20.8)	45 (16.6)	240 (23.8)	?	1472 (31.7)	?

$2^m \times 2^m$ square, while in the cases $M = 2^{2m+1}$ ($M = 8, 32, \dots$), the points are often arranged in a cross. The BER performance of M -QAM is computed in [1].

5. DISCUSSION

Fig. 2 and Table 1 compare the spectral efficiencies and SNR requirements of the various modulation and detection techniques described above. We observe that for $M > 2$, the SNR requirement for PAM increases very rapidly, while the SNR requirements of the other three techniques increase at a more moderate rate. Note that for large M , the SNR requirements increase with roughly equal slopes for PAM, DPSK and PSK, while QAM exhibits a distinctly slower increase of SNR requirement. This behavior can be traced to

Table 2. Comparison of detection techniques. Shading denotes an advantage.

Attribute	Direct	Interferometric	Coherent
Maximum degrees of freedom per polarization	1	1	2
Signal-to-noise requirement for binary modulation (relative to 2-PAM with direct detection)	0 dB (2-PAM)	−2.8 dB (2-DPSK)	−3.2 dB (2-PSK)
Signal-to-noise requirement for quaternary modulation (relative to 2-PAM with direct detection)	+5.5 dB (4-PAM)	−0.9 dB (4-DPSK)	−3.2 dB (4-PSK)
Electrical filtering can select WDM channel	No	No	Yes
Chromatic dispersion is linear distortion, making electrical compensation more effective	No	No	Yes
Local oscillator laser required at receiver	No	No	Yes
Polarization control or diversity required	No	No	Yes

the fact that PAM, DPSK and PSK offer one degree of freedom per polarization (either magnitude or phase), while QAM offers two degrees of freedom per polarization (both in-phase and quadrature field components). Based on Fig. 2, at spectral efficiencies below 1 b/s/Hz per polarization, 2-PAM (OOK) and 2-DPSK are attractive techniques. Between 1 and 2 b/s/Hz, 4-DPSK and 4-PSK are perhaps the most attractive techniques. At spectral efficiencies above 2 b/s/Hz, 8-PSK and 8- and 16-QAM become the most attractive techniques.

Table 2 compares key attributes of direct, interferometric and coherent detection. The key advantages of interferometric detection over direct detection lie in the superior SNR efficiency of 2- and 4-DPSK as compared to 2- and 4-PAM. Coherent detection is unique in offering two degrees of freedom per polarization, leading to outstanding SNR efficiency for 2- and 4-PSK, and still reasonable SNR efficiency for 8-PSK and for 8- and 16-QAM. Coherent detection also enables electrical channel demultiplexing and CD compensation. Coherent detection requires a local oscillator laser and polarization control, which are significant drawbacks.

Laser phase noise has traditionally been a concern for optical systems using DPSK, PSK or QAM. Interferometric detection of DPSK can be impaired by changes in laser phase between successive symbols. In coherent detection of PSK or QAM, a PLL (optical or electrical) attempts to track the laser phase noise, but the PLL operation is corrupted by ASE noise. Linewidth requirements for 2-DPSK, 2-PSK and 4-PSK are summarized in Table 3. At a bit rate $R_b = 10 \text{ Gb/s}$, the linewidth requirements for 2-DPSK and 2-PSK can be accommodated by standard distributed-feedback lasers. 4-PSK requires a much narrower linewidth, which can be achieved by compact external cavity lasers [14].

Table 3. Laser linewidth requirements for various modulation and detection techniques, assuming a 0.5 dB penalty. For interferometric detection, transmitter has linewidth $\Delta\nu$, while for coherent detection, each of the transmitter and local oscillator has linewidth $\Delta\nu$.

Modulation	Detection	$\Delta\nu/R_b$	$\Delta\nu$ for $R_b = 10$ Gb/s	Reference
2-DPSK	Interferometric	3.0×10^{-3}	30 MHz	[11]
4-DPSK	Interferometric	?	?	
2-PSK	Coherent	8.0×10^{-4}	8 MHz	[12]
4-PSK	Coherent	2.5×10^{-5}	250 kHz	[13]

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