Modulation and Detection Techniques for Optical Communication Systems

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Abstract: Performance and implementation complexity of various binary and nonbinary modulation methods with coherent, differentially coherent and noncoherent detection are compared. Nonbinary modulation with coherent detection maximizes spectral efficiency and improves tolerance to transmission impairments, while enabling effective, low-complexity electrical compensation of these impairments.

1. Introduction

Currently deployed fiber and free-space optical communication systems use on-off keying (OOK) with direct detection, and some are beginning to use differential phase-shift keying (DPSK) with interferometric detection. The further evolution of modulation and detection techniques will increase spectral efficiency in wavelength-division-multiplexed (WDM) systems, improve robustness against transmission impairments, and facilitate electrical compensation of such impairments. As explained in this paper, nonbinary modulation with coherent detection yields the best performance in all of the above respects, but at the cost of increased implementation complexity.

Throughout this paper, we consider fiber or free-space systems that use optical amplifiers and/or nonlinear optical wavelength converters, and assume that that amplified spontaneous emission (ASE) is the dominant noise source. We follow the notation used in [1], to which the reader is referred for further details and references.

2. Detection and Modulation Techniques

Detection methods for digitally modulated optical signals are classified most logically using traditional distinctions [2], as given in Table 1. In *noncoherent detection*, only the presence or absence of energy is ascertained, and no phase information is recovered. We consider noncoherent detection of M-level intensity modulation, referred to as M-ary pulse-amplitude modulation (M-PAM). OOK is the special case of 2-PAM. In *differentially coherent detection*, the phase in one symbol is compared to the phase in the previous symbol. We consider differentially coherent detection of M-ary differential phase-shift keying (M-DPSK). In *coherent detection*, a signal is detected using a carrier phase reference generated at the receiver. We consider coherent detection of M-ary phase-shift keying (M-PSK) or M-ary quadrature-amplitude modulation (M-QAM). Any of the three detection methods can be implemented using heterodyne or homodyne downconversion by a local-oscillator (LO) laser and balanced optical receiver(s), followed by the appropriate electrical-domain detector. But noncoherent detection can be implemented at lower complexity using simple direct detection, while differentially coherent detection can be implemented at lower complexity using interferometer(s) in conjunction with balanced optical receiver(s). Under our assumption that ASE dominates, these simpler implementations achieve the same performance as heterodyne or homodyne [3].

Table 1. Classification of detection techniques.

Detection Technique	Heterodyne or Homodyne Implementation	Direct Detection Implementation	Modulation Techniques Considered	Class of Technique
Noncoherent	Envelope detection	Direct detection	PAM	Asynchronous
Differentially coherent	Delay-and-multiply detection	Interferometric detection	DPSK	
Coherent	Coherent detection	—	PSK, QAM	Synchronous

Fig. 1 compares the spectral efficiencies and receiver sensitivities of various modulation and detection methods. Achievable spectral efficiency is proportional to $\log_2(M)$, the number of bits encoded per symbol. The receiver sensitivity n_b/n_{eq} is the average number of photons per bit n_b, divided by the equivalent ASE noise factor of the optical amplifier chain n_{eq} [1]. Binary modulation can achieve spectral efficiency up to 1/b/s/Hz (per polarization). 2-DPSK with interferometric detection is an attractive scheme for its excellent sensitivity and relatively low implementation complexity. Quaternary modulation can double spectral efficiency, while achieving higher tolerance to impairments, such as fiber chromatic dispersion (CD) and polarization-mode dispersion (PMD). 4-DPSK with interferometric detection is attractive for its reasonable sensitivity and complexity, while 4-PSK with coherent detection offers better sensitivity. Going to still higher spectral efficiencies ($M > 4$), QAM with coherent detection offers the best sensitivity among the various schemes. The superior performance of QAM can be traced to the fact that QAM encodes information in two degrees of freedom (two quadrature phases), while PSK, DPSK or PAM encode information in only one degree of freedom (phase, phase or magnitude).

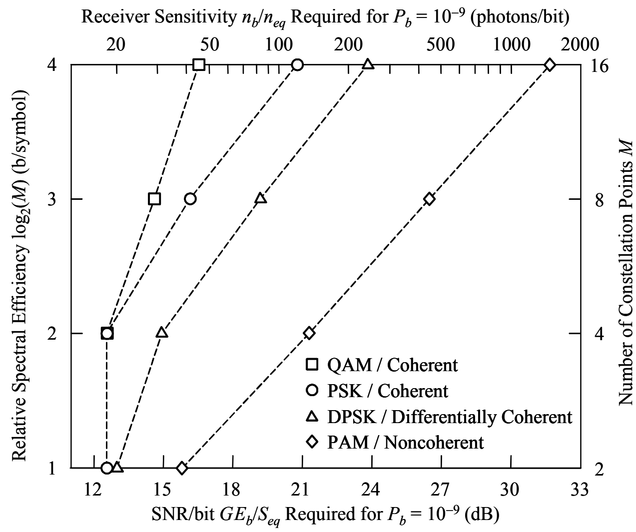

Fig. 1. Spectral efficiency vs. required receiver sensitivity (or SNR/bit) of various modulation/detection techniques.

Table 2 compares the three detection techniques, including maximum number of degrees of freedom and receiver sensitivities for binary and quaternary modulations. Noncoherent or differentially coherent detection can be implemented using direct detection, avoiding the need for a LO laser and polarization control or diversity. Any of the three techniques can be implemented using heterodyne or homodyne downconversion, yielding two potential advantages. First, by using a fast-tunable LO laser, one can construct a frequency-agile receiver to enable wavelength-routed switching or frequency-hopped transmission. Second, fiber CD appears as a linear distortion, facilitating its effective, low-complexity compensation in the electrical domain.

Table 2. Comparison of detection techniques. Shading denotes an advantage. Noncoherent and differentially coherent detection assume single-polarization filtering at the receiver. Receiver sensitivities are the values of n_b/n_{eq} required for $P_b = 10^{-9}$.

Attribute	Noncoherent		Differentially Coherent		Coherent
Maximum number of degrees of freedom (per polarization)	1 (magnitude)		1 (phase)		2 (two quadrature components)
Receiver sensitivity for binary	38 photons/bit (2-PAM)		20 photons/bit (2-DPSK)		18 photons/bit (2-PSK)
Receiver sensitivity for quaternary	134 photons/bit (4-PAM)		31 photons/bit (4-DPSK)		18 photons/bit (4-PSK)
	Heterodyne / Homodyne	Direct Detection	Heterodyne / Homodyne	Direct Detection	Heterodyne / Homodyne
Electrical filtering can be used to select channel (enables frequency-agile receiver)	Yes	No	Yes	No	Yes
Chromatic dispersion is linear distortion (enables effective electrical compensation)	Yes	No	Yes	No	Yes
Local oscillator laser required at receiver	Yes	No	Yes	No	Yes
Polarization control or diversity required at receiver	Yes	No	Yes	No	Yes

3. Implementation Issues

Table 3 compares homodyne to heterodyne downconversion. Homodyne requires the optical receiver to have an electrical bandwidth of the order of the symbol rate R_s, while heterodyne requires a bandwidth of about $2R_s$, which can be prohibitive at high symbol rates. For many applications, it is necessary to downconvert two quadrature phases of an optical signal: (a) demodulation of quadrature modulation, (b) synchronous demodulation in the electrical domain (as opposed to using an optical PLL), (c) asynchronous demodulation in the electrical domain, (d) electrical compensation of CD in fiber, or (e) electrical compensation of nonlinear phase noise (NLPN) in fiber. In such cases, homodyne requires two balanced optical receivers, while heterodyne requires only one. Heterodyne downconversion requires narrowband filtering or image rejection to avoid image-band interference (in WDM systems) and a 3-dB noise penalty from image-band ASE [4], while homodyne avoids these complications.

Table 3. Comparison of homodyne and heterodyne and downconversion. Shading denotes an advantage. R_s denotes the symbol rate.

Attribute	Homodyne	Heterodyne
Electrical bandwidth requirement of balanced optical receiver	$\sim R_s$	$\sim 2R_s$
Number of balanced optical receivers for required (per polarization) for quadrature detection	2	1
Narrowband filtering or image rejection required to avoid image-band interference and noise	No	Yes

Table 4 compares the laser linewidths required to implement various modulation and detection methods. While 2- and 4-DPSK and 2-PSK can be implemented using typical distributed-feedback lasers, other modulation/detection methods require narrower-linewidth lasers [11].

Table 4. Laser linewidth requirements for various modulation and detection techniques, assuming a 0.5 dB penalty. Differentially coherent detection assumes an interferometric implementation, so the transmitter laser has linewidth $\Delta\nu$, while for coherent detection, each of the transmitter and local oscillator lasers has linewidth $\Delta\nu$.

Modulation	Detection	$\Delta\nu/R_b$	$\Delta\nu$ for R_b = 10 Gb/s	Reference
2-DPSK	Differentially coherent	3.0×10^{-3}	30 MHz	[5]
4-DPSK	Differentially coherent	5.0×10^{-4}	5 MHz	[6]
2-PSK	Coherent	8.0×10^{-4}	8 MHz	[7]
4-PSK	Coherent	2.5×10^{-5}	250 kHz	[8]
8-PSK	Coherent	1.5×10^{-6}	15 kHz	[9]
16-PSK	Coherent	2.4×10^{-7}	2.4 kHz	[9]
8-QAM	Coherent	9.0×10^{-6}	90 kHz	[10]
16-QAM	Coherent	6.9×10^{-7}	6.9 kHz	[10]

Electrical signal processing is useful for carrier phase synchronization, compensation of CD, PMD and NLPN in fiber, or compensation of atmospheric turbulence and Doppler shifts in free-space links. Some operations, such as carrier phase synchronization, can be done easily in the analog domain. But over time, we expect to see increased use of analog-to-digital conversion and digital signal processing (DSP). DSP-based processing is particularly useful to track time-varying perturbations, or when it is necessary to compensate multiple perturbations simultaneously.

4. References

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