Ultimate Spectral Efficiency Limits in DWDM Systems

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***Abstract*—We summarize current knowledge of spectral efficiency limits in DWDM transmission systems for various modulation techniques (unconstrained, constant-intensity, binary), detection techniques (coherent, direct), and propagation regimes (linear, nonlinear). We briefly review technologies required to approach these limits in practice.**

I. Introduction

The overall capacity (b/s) of a DWDM transmission system is governed by the available bandwidth (Hz) and by the achievable spectral efficiency (b/s/Hz). Ultimate limits to the spectral efficiency are determined by the information-theoretic capacity per unit bandwidth [1]. While closely approaching these limits may require exponentially increasing complexity and delay, establishing accurate estimates of the limits can yield insights useful in practical system design. In this paper, we summarize current knowledge of spectral efficiency limits in amplified DWDM systems, and briefly review technologies required to approach these limits.

II. Spectral Efficiency Limits

The spectral efficiency limit depends on choice of modulation technique (e.g., unconstrained, constant-intensity, or binary), detection technique (coherent or direct), and propagation regime (linear or nonlinear). Unless otherwise noted, we assume no constraints on modulation technique. Initially, we consider propagation in a single polarization; polarization effects are briefly addressed in Section III below. We use the following notation: B denotes occupied bandwidth per channel (Hz), $\Delta\nu$ denotes channel spacing (Hz), SNR denotes optical signal-to-noise ratio (W/W), C denotes capacity per channel (b/s), and $S = C/\Delta\nu$ denotes spectral efficiency limit (b/s/Hz).

A. Coherent Detection, Linear Regime

In the case of coherent detection[1], the optical signal is modeled as a complex-valued electric field. Noise arising from optical amplifiers and the local oscillator can be modeled as additive, signal-independent, complex circular Gaussian noise [1]. When optical nonlinearities are negligible, the optimal transmitted field is also complex circular Gaussian-distributed, and the spectral efficiency limit is given by the well-known Hartley-Shannon formula

$$S_{\text{coh, lin}} = (B/\Delta\nu)\log_2(1 + SNR). \tag{1}$$

Note that at high SNR, the spectral efficiency (1) is given asymptotically by

$$S_{\text{coh, lin}} \sim (B/\Delta\nu)\log_2 SNR. \tag{2}$$

The spectral efficiency limit (1) is shown in Fig. 1(a).

B. Constant-Intensity Modulation, Coherent Detection, Linear Regime

Various modulation techniques, such as differential phase-shift keying (DPSK) and continuous-phase frequency-shift keying (CPFSK), encode information in optical signals having nominally constant intensity. Spectral efficiency limits under a constant-intensity constraint, assuming coherent detection and linear propagation, have been computed in [2] for arbitrary SNR. At high SNR, the spectral efficiency is given asymptotically by

$$S_{\text{const-int, coh, lin}} \sim (B/\Delta\nu)(0.5\log_2 SNR + 1.1). \tag{3}$$

The spectral efficiency limit (3) is shown in Fig. 1(b). Observe that the limit (3) is 1.1 b/s/Hz more than half the Hartley-Shannon limit (2), assuming $B/\Delta\nu = 1$.

C. Direct Detection, Linear Regime

In the case of direct detection, the optical signal is modeled as a non-negative, real electric field magnitude.[2] Typically, the dominant noise is signal-spontaneous beat noise, which is additive and signal-dependent. To date, spectral efficiency limits have not been derived for arbitrary SNR. At high SNR [3], the optimal transmitted field magnitude follows a half-Gaussian distribution, and the spectral efficiency limit is given asymptotically by

$$S_{\text{dir, lin}} \sim (B/\Delta\nu)(0.5\log_2 SNR - 1.0). \tag{4}$$

The spectral efficiency limit (4) is shown in Fig. 1(c). Note that (4) is 1.0 b/s/Hz less than half the Hartley-Shannon limit (2), assuming $B/\Delta\nu = 1$. Intuitively, the factor-of-two reduction results from discarding one quadrature phase of the field, and the additional 1.0 b/s/Hz loss is caused by discarding the sign of the field.

D. Coherent Detection, Nonlinear Regime

In typical DWDM systems, the dominant nonlinear impairments arise from the Kerr effect. Kerr nonlinearities include four-wave mixing (FWM), which

[1] In this paper, "coherent detection" denotes photoelectric mixing of the signal with a phase-locked local oscillator.

[2] In practice, one may not only modulate the magnitude, but also modulate the phase, either intentionally (e.g., duobinary encoding) or unintentionally (e.g., chirp). While phase modulation affects the spectrum, it does not affect the detected photocurrent, provided that dispersion is well-compensated and the receiver does not employ an interferometer to convert phase modulation to intensity modulation.

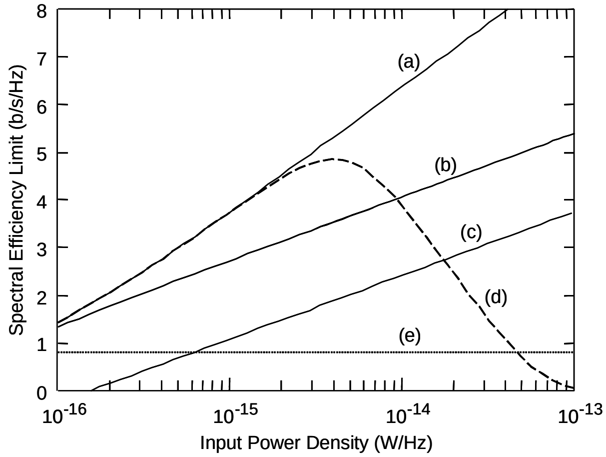

Fig. 1. Spectral efficiency limits versus input power density in amplified DWDM systems: (a) coherent detection, linear [1], (b) constant-intensity modulation, coherent detection, linear [2], (c) direct detection, linear, high-SNR asymptote [3], (d) coherent detection, nonlinear [5], (e) binary modulation limit [1]. We assume: single polarization, λ = 1.55 µm, 25 fiber spans, 80 km span length, α = 0.20 dB/km, distributed Raman amplification, G = 16 dB, NF_{eff} = –1 dB, occupied bandwidth per channel B = 40 GHz, channel spacing $\Delta\nu$ = 50 GHz. Curve (b) further assumes: 80 channels, D = 4 ps/(nm-km), nonlinear coefficient γ = 1.4 1/(W-km), $l_{eff} = 1/\alpha$.

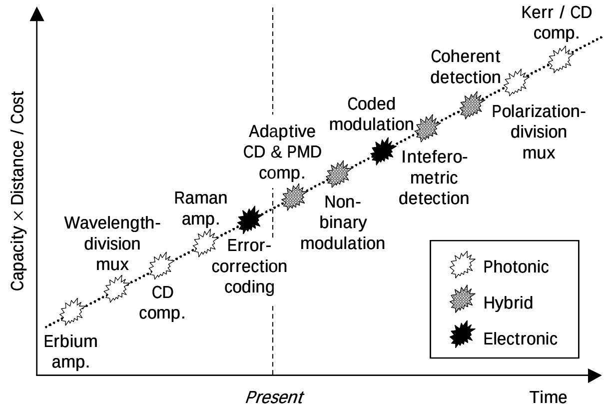

Fig. 2. Schematic roadmap of key technologies for high-capacity DWDM transmission. Hybrid technologies may be implemented using photonics and/or electronics. CD and PMD denote chromatic and polarization-mode dispersion, respectively.

gives rise to additive noise, and self-phase modulation (SPM) and cross-phase modulation (XPM), which cause multiplicative noise. To date, spectral efficiency limits in the nonlinear regime have been derived only for coherent detection. In [4], Narimanov and Mitra derive the capacity of a single-channel system. Their work shows that Kerr nonlinearities always reduce capacity, so the capacity of a soliton-based system will always be lower than its linear counterpart. Mitra and Stark [5] have studied the capacity of DWDM systems, considering XPM and neglecting SPM and FWM. Their spectral efficiency limit is shown in Fig. 1(d). They show that at low input power densities, the spectral efficiency increases logarithmically with input power. As the input power density exceeds a critical value, the spectral efficiency decreases exponentially with input power. They show that the critical input power density, and thus the spectral efficiency limit, increases with chromatic dispersion D and with channel spacing $\Delta\nu$, because walk-off decreases the impact of XPM. Note, however, that in the limit of large D, SPM may cause irreversible distortion, and should not be neglected.

III. Discussion

Next-generation DWDM systems are expected to achieve spectral efficiencies of 0.4 b/s/Hz. Using binary modulation, spectral efficiency cannot exceed $B/\Delta\nu \leq 1$ b/s/Hz (see Fig. 1(e)). Fig. 2 outlines the technologies required to approach fundamental spectral efficiency limits shown in Fig. 1(a)-(d).

Non-binary modulation, such as multilevel amplitude and/or phase encoding, is essential for approaching these limits. While non-binary constant-intensity modulation is less spectrally efficient than unconstrained modulation, its spectral efficiency can significantly exceed that of binary modulation.

Direct detection incurs a significant loss of spectral efficiency, and coherent detection is required to approach the fundamental spectral efficiency limits.

While Kerr nonlinearities impose limits on spectral efficiency, these limits far exceed the spectral efficiency of current and next-generation systems. In any case, techniques such as mid-span spectral inversion can extend the limits imposed by Kerr nonlinearities [6].

Polarization-mode dispersion (PMD) has no fundamental impact on spectral efficiency limits[3]. In principle, the spectral efficiency limits described above can be doubled using polarization-division multiplexing, i.e., launching pairs of signals in orthogonal polarizations, and employing polarization-resolved detection.

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[3] By making B sufficiently small, we can always restrict attention to first-order PMD, and by launching a signal into one of the principal states of polarization (which vary slowly with time), we can avoid PMD-induced distortion.