Advanced Optical Modulation Formats

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2 AUTHORS, INCLUDING:

Rene-Jean Essiambre

Alcatel Lucent

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Peter J. Winzer and René-Jean Essiambre

Bell Laboratories, Alcatel-Lucent, Holmdel, NJ, USA

2.1 INTRODUCTION

Since the publication of the fourth volume of the book series *Optical Fiber Telecommunications* in 2002, high-speed optical transmission systems have increasingly been building on techniques that are well established in radio-frequency (RF) communication systems, and in particular in wireless communication. Examples are advanced modulation formats, line coding, enhanced forward error correction (FEC), and digital signal processing at transmitter and receiver. The adoption and extension of these techniques from the Mb/s regime into the multi-Gb/s realm is driven by the desire to steadily lower the cost per end-to-end networked information bit in an environment of continuously increasing data traffic. This is being done by extending the regeneration-free reach of optical line systems at the highest possible per-fiber transmission capacities, while at the same time allowing for optical wavelength routing in optically transparent mesh networks. In this context, *communication engineering techniques* are now supplementing established methods from optical physics to increase transmission reach, system capacity, and network flexibility. Today, research and commercial implementation of digital optical communication techniques fall into two main areas, distinguished by the per-wavelength symbol rates they operate at:

- At per-channel symbol rates of 10 Gbaud, *electronic signal processing* ranging from simple feed-forward and decision-feedback equalizers (FFE, DFE) at the receiver all the way to maximum-likelihood sequence estimation (MLSE) is commercially available today [1–3], and FEC is found in most commercial 10-Gb/s transport products [4, 5]. Digital signal predistortion at the transmitter is being actively pursued [6], and coherent detection is

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experiencing renewed[1] interest [14–16]. In contrast to widely deployed direct detection, coherent detection allows electronic signal processing to make use of the full optical field (magnitude *and* phase), which can be exploited for more efficient mitigation of fiber transmission impairments such as chromatic dispersion (CD) or polarization mode dispersion (PMD). Coherent detection research is also aiming at increasing the bit rate through multilevel modulation and polarization multiplexing while keeping the signal bandwidth similar to that of a 10-Gb/s binary signal to reuse 10-Gb/s optical line infrastructure and to increase the system's spectral efficiency (SE). In general, narrow signal bandwidths are desired in high-SE optically routed networks to minimize excessive filtering penalties due to the concatenation of reconfigurable optical add/drop multiplexers (ROADMs) and to avoid excessive cross talk between adjacent wavelength-division multiplexed (WDM) channels.

- At per-channel symbol rates of 40 Gbaud, and up to 100 Gbaud, the capabilities of electronic equalization are still limited to low complexity electronic [17–21] and optical [22–24] FFE structures. In this area, *modulation formats* and *line coding* are at the center of interest. They are used to mitigate linear and nonlinear impairments of fiber-optic transmission, as well as to achieve high SEs in optically routed networks. At 40 Gb/s, FEC is a standard feature of commercially deployed optical transport systems [25].

Despite the many benefits brought by electronic signal processing and digital communication techniques, it should be noted that an optical fiber network differs substantially from an RF communication link, both *fundamentally* and *technologically*. Some key differences relevant to the discussions in this chapter are summarized in Table 2.1.

Fiber Nonlinearities

The most important fundamental difference between optical and RF communications is the presence of nonlinear distortions in the optical fiber communication channel. The high transversal confinement of the optical signal field in a fiber core with effective areas between 20 and 110 μm^2 causes light intensities to reach or exceed a megawatt/cm^2. At such high optical intensities, the fiber's index of refraction is affected by the presence of optical signals through the optical *Kerr effect* [26], and signal-induced refractive index changes translate into changes of the signals' optical phases. Over optically amplified distances of many hundred or even several thousand

[1] Coherent detection using advanced optical modulation formats was widely discussed in the context of *unamplified* lightwave systems in the 1980s [7–12], where attenuation-limited single-span transmission required utmost receiver sensitivities. With the advent of efficient optical amplifiers, allowing for comparable direct-detection receiver sensitivities [9, 13], coherent systems research decayed in the early 1990s.

kilometers, these phase rotations, in conjunction with fiber dispersion, result in a host of different waveform distortions that increase with signal power. As a consequence, and in stark contrast to classical RF systems, the performance of an optical communication link exhibits a maximum at a certain signal power level, which represents the optimum trade-off between optical amplifier noise (amplified spontaneous emission, ASE) and fiber Kerr nonlinearity. As an example, Figure 2.1(a) [27] shows the

Table 2.1

Optical vs radio-frequency communication systems.

	Optical communications	RF communications
Fundamental		
Noise	Quantum noise	Thermal noise
Interference	Multipath, WDM crosstalk	Multipath, multiuser
Channel	Fiber nonlinearity + dispersion	Linear channel, fading
Channel dynamics	~kHz (const. for~10^7 bits)	~kHz (const. for ~10^1–10^3 bits)
Technological		
Electrical bandwidth	~60 GHz – limited by technology (bandwidth/carrier~10^{-4} to 10^{-6})	Limited by spectral regulations (bandwidth/carrier~10^{-2} to 10^{-4})
Detection	Predominantly square-law	Predominantly coherent (I/Q) demodulation
Digital processing	Fairly simple equalization and FEC	Extensively used, sophisticated
Processing power per information bit	Fairly low	Very high

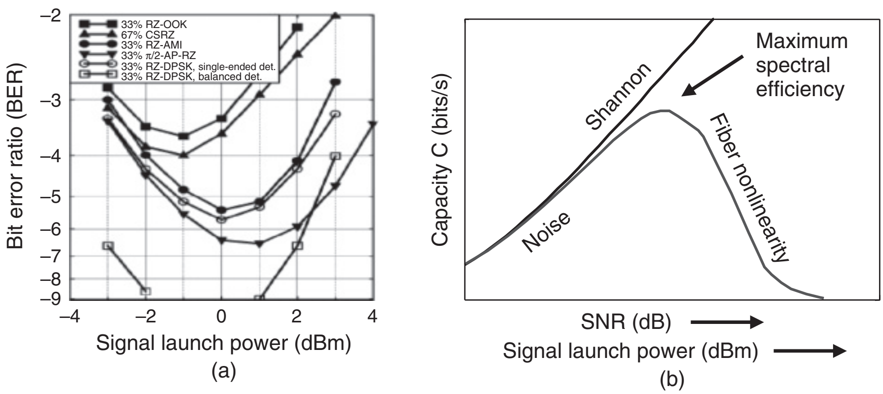

Figure 2.1 (a) Measured BER vs signal launch power for various optical modulation formats transmitted over 1980 km of SSMF [27]; (b) Schematic representation of fiber channel capacity vs received SNR. Both cases exhibit maximum performance at a specific signal power level, representing the optimum trade-off between optical amplifier noise and fiber Kerr nonlinearity (this figure may be seen in color on the included CD-ROM).