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INTRODUCTION

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1.1 HIGH-CAPACITY FIBER TRANSMISSION TECHNOLOGY EVOLUTION

Since the first demonstration of an optical fiber transmission system in 1977 [1], the demands for higher capacity and longer reach have always been the dominant driver behind the evolution of this new communication technology. In less than four decades, single-fiber transmission capacity has increased by more than five orders of magnitude, from the early 45 Mb/s, using direct modulation and direct detection [2], to more than 8.8 Tb/s by using the digital coherent optical transmission technology [3]. In the meantime, optical transmission reach has increased from only a few kilometers to more than 10,000 km [4]. Such dramatic growth in capacity and reach has been enabled by a series of major breakthroughs in device, subsystem, and system techniques, including lasers, modulators, fibers, optical amplifiers, and photodetectors, as well as various modulation, coding, and channel impairment management methods.

The first generation of optical fiber communications was developed during the late 1970s, operating near 0.8 μm using GaAs semiconductor lasers [2] and multimode fibers (MMF). Although the total capacity of the first commercial system was only running at 45 Mb/s, with an optical reach or repeater spacing of 10 km, this capacity is now much greater than that of comparable coax systems (assuming identical reach or repeater spacing).

With breakthroughs in InGaAsP semiconductor lasers/photodetectors and single-mode fiber manufacturing technologies, the *second generation* shifted the

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wavelength to 1.3 μm by taking advantage of the low attenuation (<1 dB/km) and low dispersion of single-mode fibers. A laboratory experiment in 1981 demonstrated transmission at 2 Gb/s over 44 km of single-mode fiber [5]. By 1987, second-generation optical fiber communication systems, operating at bit rates of up to 1.7 Gb/s with a repeater spacing of about 50 km, were commercially available.

The optical transmission reach of second-generation fiber communication systems was limited by fiber losses at the operating wavelength of 1.3 μm (typically 0.5 dB/km). Losses of silica fibers approached minimum near 1.55 μm. Indeed, a 0.2-dB/km loss was realized in 1979 in this spectral region [6]. However, the introduction of *third-generation* systems operating at 1.55 μm was delayed by large fiber dispersion near 1.55 μm. Conventional InGaAsP semiconductor lasers (with Fabry–Perot type resonators) could not be used because of pulse spreading occurring as a result of simultaneous oscillation in several longitudinal modes. Two methods were developed to overcome the dispersion problem: (i) a dispersion-shifted fiber was designed to minimize the dispersion near 1.55 μm and (ii) a single longitudinal mode laser, that is the widely used distributed feedback (DFB) laser, was developed to limit the spectral width. By using these two methods together, bit rates up to 4 Gb/s over distances in excess of 100 km were successfully demonstrated in 1985 [7]. Third-generation fiber communication systems operating at 2.5 Gb/s became available commercially in 1990 with a typical optical reach of 60–70 km. Such systems are capable of operating at a bit rate of up to 10 Gb/s [8].

To further increase optical transmission reach and reduce the number of costly optical–electrical–optical (O–E–O) repeaters for long distance transmission, efforts were focused on coherent optical transmission technology during the late 1980s. The purpose was to improve optical receiver sensitivity by using a local oscillator (LO) to amplify the received optical signal. The potential benefits of coherent transmission technology were demonstrated in many system experiments [9]. However, commercial introduction of such systems was postponed with the advent of erbium-doped fiber amplifiers (EDFAs) in 1989. The *fourth generation* of fiber communication systems makes use of optical amplification for increasing O–E–O repeater spacing and of wavelength-division multiplexing (WDM) for increasing total capacity. The advent of the WDM technique in combination with EDFAs started a revolution that resulted in doubling of the system capacity every 6 months or so and led to optical communication systems operating at >1 Tb/s by 2001. In most WDM systems, fiber losses are compensated for by spacing EDFAs 60–80 km apart. EDFAs were developed after 1985 and became available commercially by 1990. A 1991 experiment showed the possibility of data transmission over 21,000 km at 2.5 Gb/s, and over 14,300 km at 5 Gb/s, using a recirculating-loop configuration [10]. This performance proved that an amplifier-based, all-optical, submarine transmission system was feasible for intercontinental communications. By 1996, not only had transmission over 11,300 km at a bit rate of 5 Gb/s been demonstrated by using actual submarine cables [11], but commercial trans-Atlantic and trans-Pacific cable systems also became available. Since then, a large number of submarine fiber communication systems have been deployed worldwide.

In the late 1990s and early 2000s, several efforts were made to further increase single-fiber capacity. The first effort focused on increasing system capacity by transmitting more and more channels through WDM. This was mainly achieved by reducing channel bandwidth through (i) better control of the laser wavelength stability and (ii) development of dense wavelength multiplexing and demultiplexing devices. At the same time, new kinds of amplification schemes had also been explored, as the conventional EDFA wavelength window, known as the C band, only covers the wavelength range of 1.53–1.57 μm. The amplifier bandwidth was extended on both the long- and short-wavelength sides, resulting in the L and S bands, respectively. The Raman amplification technique, which can be used to amplify signals in all S, C, and L wavelength bands, had also been intensely investigated. The second effort attempted to increase the bit rate of each channel within the WDM signal. Starting in 2000, many experiments used channels operating at 40 Gb/s. Such systems require high-performance optical modulator as well as extremely careful management of fiber chromatic dispersion (CD), polarization-mode dispersion (PMD) and fiber nonlinearity [12]. To better manage fiber CD, dispersion compensating fiber (DCF) has been developed and various dispersion management methods have also been explored to better manage fiber nonlinearity. These efforts led in 2000 to a 3.28-Tb/s experiment in which 82 channels, each operating at 40 Gb/s, were transmitted over 3000 km. Within a year, the system capacity was increased to nearly 11 Tb/s (273 WDM channels, each operating at 40 Gb/s) but the transmission distance was limited to 117 km [13]. In another record experiment, 300 channels, each operating at 11.6 Gb/s, were transmitted over 7380 km [14]. Commercial terrestrial systems with the capacity of 1.6 Tb/s were available by the end of 2000.

Until early 2000s, all the commercial optical transmission systems used the same direct modulation and direct detection on/off keying non-return-to-zero (NRZ) modulation format. The impressive fiber capacity growth was mainly achieved by advancement in photonics technologies, although forward error correction (FEC) coding also played a significant role in extending the reach for 10 Gb/s per channel WDM systems. Starting from 40 Gb/s per channel WDM systems, it became evident that more spectrally efficient modulation formats were needed to further increase the fiber capacity to meet the ever-growing bandwidth demands.

High spectral-efficiency (SE) modulation formats can effectively increase the aggregate capacity without resorting to expanding the optical bandwidth, which is largely limited by optical amplifier bandwidth. Using high-SE modulation formats also help reduce transceiver speed requirements. Furthermore, high-SE systems are generally more tolerant of fiber CD and PMD, since they use smaller bandwidths for the same bit rate. CD and PMD tolerance are particularly attractive for high-bit-rate transmission, since dispersion tolerance is reduced by a factor of 4 for a factor-of-2 increase in bit-per-symbol [15].

Early efforts in achieving high SE used direct detection. The first widely investigated modulation format with SE > 1 bit/symbol was the optical differential quaternary phase-shift keying (DQPSK) with differential detection. This is a constant intensity modulation format, which can transmit 2 bits/symbol, corresponding to a theoretical SE of 2 bits/s/Hz [16, 17]. This modulation format also exhibits excellent fiber nonlinearity tolerance due to the nature of constant intensity. To go beyond 2 bit/s/Hz, polarization-division multiplexing (PDM) has been suggested to further increase SE in combination with DQPSK [18]. However, as the state of polarization of the light wave is not preserved during transmission, dynamic polarization control is required at the receiver to recover the transmitted signals.

The need for higher SE and the advancement in digital signal processing (DSP) eventually revives coherent optical communication. The concept of digital coherent communication was proposed by several research groups around 2004–2005 [19–22]. Quickly, this technology was recognized as the best technology for 40 Gb/s, 100 Gb/s and beyond WDM transmission systems, mostly due to the following reasons: (i) coherent technology preserves both amplitude and phase information, allowing all four dimensions of an optical field (in-phase and quadrature components in each of the two orthogonal polarizations) to be retained for information coding and thus offering much greater spectral efficiency than intensity-modulated direct detection (IMDD) systems; (ii) coherent technologies include powerful DSP that helps to solve the problems of chromatic and polarization-mode dispersion suffered by IMDD systems above 10 Gb/s, and thereby deliver vastly increased capacity over the same, or even better distances; and (iii) coherent detection offers better sensitivity than IMDD systems.

The advent of digital coherent detection has resulted in remarkable SE and fiber capacity improvement in the past few years. In lab experiments, the SE of optical communication systems has been increased from 0.8 b/s/Hz to more than 14.0 b/s/Hz [23] in single-mode fiber, and >100 Tb/s single-fiber capacity has been demonstrated [24]. The use of digital coherent detection technology also enables us to explore a few new avenues to further increase the optical network capacity or performance. For example, fiber capacity can be further increased by using few-mode fibers through mode-division multiplexing (MDM), which is enabled by coherent detection and DSP. Coherent technology and DSP also enable rate-adaptable optical transmission, which is critical for future elastic optical networks. Since coherent detection offers higher receiver sensitivity than direct detection, this technology may also facilitate the development of silicon-photonics-based photonic integration technologies, which suffer a significantly higher optical loss than the conventional discrete optical systems.

1.2 FUNDAMENTALS OF COHERENT TRANSMISSION TECHNOLOGY

1.2.1 Concept of Coherent Detection

In coherent optical communication, information is encoded onto the electrical field of a lightwave; decoding entails the direct measurement of the complex electrical field. To measure the complex electrical field of lightwave, the incoming data signal (after fiber transmission) interferes with a local oscillator (LO) in an optical 90° hybrid as schematically shown in Figure 1.1. If the balanced detectors in the upper branches measure the real part of the input data signal, the lower branches, with the

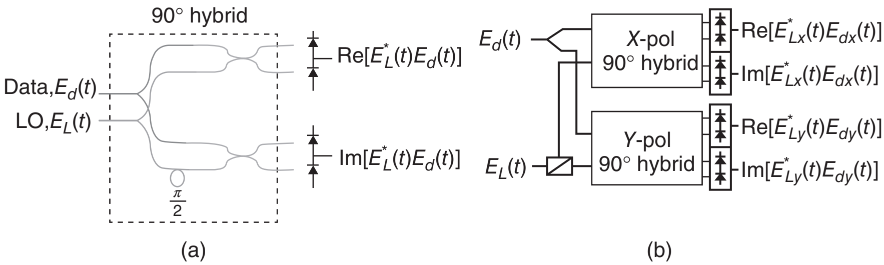

FIGURE 1.1 Coherent detection principle illustration. (a) Phase-diverse coherent detection. (b) Polarization- and phase-diverse coherent detection.

LO phase delayed by 90°, will measure the imaginary part of the input data signal. For reliable measurement of the complex field of the data signal, the LO must be locked in both phase and polarization with the incoming data. In order to realize phase and polarization synchronization in the electrical domain through DSP, a polarization- and phase-diverse receiver is required as is shown in Figure 1.1(b). Such a receiver will project the baseband complex electrical field of the incoming signal into a four-dimensional space vector using the LO as the reference frame.

A coherent receiver requires careful phase and polarization management, which turned out to be the main obstacle for the practical implementation of a coherent receiver using optical-based management methods. The state of polarization of the lightwave is random in the fiber. Dynamic control of the state of polarization of the incoming data signal is required so that it matches that of the LO. Each dynamic polarization controller is bulky and expensive [25], and for WDM systems, each channel needs a dedicated dynamic polarization controller. The difficulty in polarization-management alone severely limits the practicality of coherent receivers, and phase locking is challenging as well. All coherent modulation formats with phase encoding are usually carrier suppressed; therefore, conventional techniques such as injection locking and optical phase-locked loops cannot be directly used to lock the phase of the LO. Instead, decision-directed phase-locked loops must be employed [26, 27]. At high symbol rates, the delays allowed in the phase-locked loop are so small that it becomes impractical [27].

But the advancement of high-speed DSP changed the whole picture. By digitizing the coherently detected optical signals, both phase and polarization can be managed in the electrical domain through advanced DSP. Coherent detection in conjunction with DSP also enables compensation of several major fiber-optic transmission impairments, opening up new possibilities that are shaping the future of optical transmission and networking technology.

1.2.2 Digital Signal Processing

Figure 1.2 shows the functional block diagrams for a typical DSP-enabled coherent transmitter (a) and receiver (b). In principle, the coherent transceiver shown in

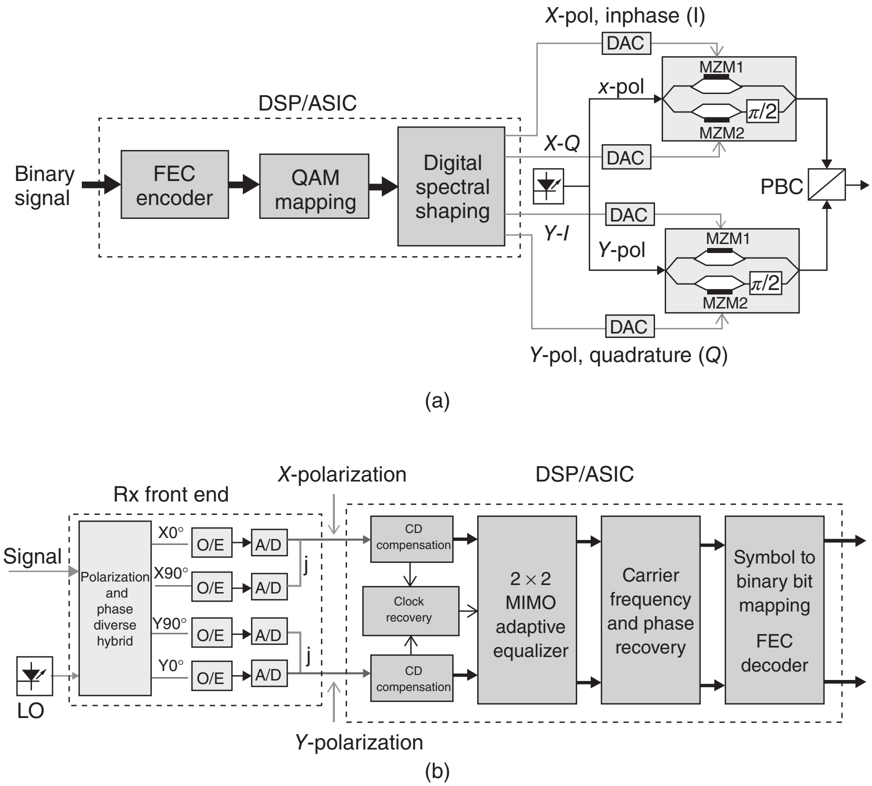

FIGURE 1.2 DSP-enabled coherent transmitter (a) and receiver (b). CD: chromatic dispersion. ASIC: application-specific integrated circuit.

Figure 1.2 can be used to generate and detect any four-dimensional coded-modulation formats. For the DSP-enabled transmitter shown in Figure 1.2(a), the binary client signal first goes through an FEC encoder, and then the FEC-coded binary signals are mapped into the desired multilevel modulated symbols such as the common quadrature amplitude modulation (QAM) symbols. After that, various digital spectral shaping techniques may be applied to the QAM-mapped signals to improve the transmission performance or to reduce transmission impairments. For example, the Nyquist pulse-shaping technique, which is presented in detail in Chapter 4, can be an effective method to improve the WDM spectral efficiency without resorting to the use of higher-order modulation formats. After digital spectral shaping, the in-phase and quadrature components of the digital QAM signal are converted into two analog signals, which are used to drive an *I*/*Q* modulator to up-convert the baseband electrical signal into an optical signal for transmission. For such a DSP-enabled transmitter, a single *I*/*Q* modulator can be used to generate various QAM formats.

Figure 1.2(b) shows a typical digital coherent receiver. The incoming optical field is coherently mixed with a local oscillator through a polarization- and phase-diverse

90° hybrid. This hybrid separates the in-phase and quadrature components of the received optical field in both *X*- and *Y*-polarizations, which are then detected by four balanced photodetectors. The detected analog electrical signals are digitized by four analog-to-digital converters (ADCs) and the digitized signals are then sent to a DSP unit. For such a digital coherent receiver, the front end can be used to receive any quadrature amplitude-modulated signal, because modulation-specific demodulation and decoding are carried out in the DSP unit.

The post-transmission DSP consists of five major functional blocks: (i) fiber CD compensation, (ii) clock recovery, (iii) 2×2 multiple-input-multiple-output (MIMO) adaptive equalization, (iv) carrier frequency and phase recovery, and (v) QAM and FEC decoding. Fiber CD is typically compensated for by using a frequency domain-based phase-only digital spectral shaping technique, and this function can be moved to the transmitter side or split between the transmitter and receiver for ultra-long-haul transmission, where the required computational load may be too heavy for either a single transmitter or receiver DSP chip. The 2×2 adaptive equalization performs automatic polarization tracking, polarization-mode dispersion, and residual CD compensation. This adaptive equalization also helps mitigate impairments from narrow-band filtering effects from the reconfigurable optical add-drop multiplexers (ROADMs) that are widely deployed in today's wavelength-routing optical networks.

Both the transmitter and the receiver DSP units are usually implemented in application-specific integrated circuits (ASICs) for best overall performance (i.e., footprint, power consumption, latency, etc.). Because the computational requirement is substantial for a high-coding-gain soft-decision FEC, an independent ASIC dedicated to FEC has been used in the first generation 100-Gb/s per wavelength coherent transmission systems.

1.2.3 Key Devices

Digital coherent optical transmission technology opens new opportunities to increase the fiber capacity by employing spectrally efficient higher-order modulation formats such as PDM-16QAM, PDM-32QAM, and PDM-64QAM. But these higher-order modulation formats not only require a higher signal-to-noise ratio (SNR), but also become much less tolerant to various impairments from optical devices along the optical links.

One critical device to enable high-SE transmission is narrow linewidth lasers. The widely used DFB laser typically exhibits a Lorentz-type linewidth of about 1 MHz, which is too large to be used for these higher-order modulation formats. External cavity-based tunable lasers exhibit a much more narrow linewidth (~100 kHz) and have been extensively used in recent high-SE transmission system demonstrations. Recently, some progress has been made toward reducing the linewidth of DFB lasers and DBR (distributed Bragg reflector) lasers by employing improved cavity design and a laser linewidth of <500 kHz has been reported [28, 29].

Another critical device for high-SE systems is the so-called *I*/*Q* modulator as shown in Figure 1.2(a). It basically consists of two Mach–Zehnder modulators

(MZMs) built in a parallel configuration, with one MZM for in-phase signal modulation and another MZM for quadrature-phase signal modulation. Such an *I*/*Q* modulator in combination with DSP and digital-to-analog converters (DACs) can be used to generate arbitrary QAM. Since a regular MZM exhibits a nonlinear cosine or sine transfer function, digital precompensation of the nonlinear MZM transfer function may be needed in a practical system. Alternatively, some efforts have been made toward developing linear *I*/*Q* modulators [30].

As shown in Figures 1.1 and 1.2, a polarization- and phase-diverse coherent mixer or a hybrid in combination with four pair of balanced photodetectors is needed in a coherent receiver. It should be noted that the four balanced photodetectors may be replaced by four single-ended photodetectors for lower-order modulation formats such as PDM-QPSK, as long as the optical power of the LO is significantly higher than the received optical signal. Several technologies have been used to develop low-loss, small footprint coherent hybrid, including free-space optics, InP or silicon photonics-based photonic integration technology.

To digitize the received analog electrical signal, high-speed ADCs are critical for modern high-speed coherent systems. By using 28-nm CMOS and a successive-approximation-register (SAR)-based architecture, ADCs with >92 Gs/s sampling rate, 8-bit digital resolution, and >25 GHz analog bandwidth have been commercially available since 2014.

1.3 OUTLINE OF THIS BOOK

This book contains 16 chapters. Chapter 2 reviews the modulation formats, starting from basic definitions and performance metrics for modulation formats that are common in the literature to more complicated high-dimensional coded modulation and spectrally efficient modulation. Chapter 3 focuses on detection and error correction technologies for coherent optical communication systems. The chapter shows that the use of differential coding does not decrease capacity and describes how capacity-approaching coding schemes based on LDPC and spatially coupled LDPC codes can be constructed by combining iterative demodulation and decoding. Chapters 4 and 5 are devoted to two spectral-efficient multiplexing techniques, Nyquist WDM and orthogonal-frequency-division multiplexing (OFDM), which use the orthogonality feature either in the time domain or the frequency domain to achieve close to symbol rate channel spacings. In Chapter 6, polarization and nonlinear impairments in coherent optical communication systems are discussed, including PMD and polarization-dependent loss (PDL) impairments and interchannel nonlinear effects in dispersion-managed systems with different configurations. The fiber nonlinear effects in a non-dispersion-managed system is covered in Chapter 7, which shows that fiber nonlinearities in such systems can be accurately described by some analytical models such as GN-EGN model. The next two chapters present impairment equalization and mitigation techniques. Chapter 8 describes linear impairment equalization and Chapter 9 discusses various nonlinear mitigation techniques. Signal synchronization is covered in Chapters 10 and 11, with Chapter 10 focusing on the methods and techniques used to recover timing synchronization and Chapter 11 on carrier phase and frequency recovery in modern high-speed coherent systems. Chapter 12 describes the main constraints put on the DSP algorithms by the hardware structure, and gives a brief overview on technologies and challenges for prototype and commercial real-time implementations of coherent receivers. Chapter 13 addresses the fundamental concepts and recent progress of photonic integration, with a special emphasis on InP- and silicon-based photonic integrated technologies. To increase network efficiency and flexibility, elastic optical network technology and optical performance monitoring have attracted further attention. These are the subjects of Chapters 14 and 15. Chapter 16 discusses spatial-division multiplexing and MIMO processing technology, a potential solution to solve the capacity limit of single-mode fibers.

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