Coding for Optical Channels

Ivan Djordjevic • William Ryan • Bane Vasic

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with Chapter 8 contributed by
Anantha Raman Krishnan and Shiva K. Planjery

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Ivan Djordjevic
Department of Electrical
& Computer Engineering
University of Arizona
Tucson, AZ 85721
USA
ivan@ece.arizona.edu

William Ryan
Department of Electrical
& Computer Engineering
University of Arizona
Tucson, AZ 85721
USA
ryan@ece.arizona.edu

Bane Vasic
Department of Electrical
& Computer Engineering
University of Arizona
Tucson, AZ 85721
USA
vasic@ece.arizona.edu

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To my parents (Blagoje and Verica), brother Slavisa, and to Milena.
Ivan Djordjevic
To Stephanie, Faith, Grant, Luke, and the Bandii.
William Ryan

Preface

Recent years have witnessed a dramatic resurgence of interest in channel coding within the optical communications community, as evidenced by the increase of the number of publications, and many eye-catching implementations and experimental demonstrations presented at major conferences. The main drivers behind the emergence of channel coding in optical communications are: (1) high demands in bandwidth thanks to the recent growth of Internet usage, IPTV, VoIP, and YouTube; and (2) rapid advance of silicon signal processing capability. In recent years, with the rapid growth of data-centric services and the general deployment of broadband access networks, there has been a strong demand driving the dense wavelength division multiplexing (DWDM) network upgrade from 10 Gb/s per channel to more spectrally efficient 40 Gb/s or 100 Gb/s per channel, and beyond. The 100 Gb/s Ethernet (100 GbE) is currently under standardization for both local area networks (LANs) and wide area networks (WANs). The 400 Gb/s and 1 Tb/s are regarded to be the next steps after 100 Gb/s and have started already attracting research community interests. Migrating to higher transmission rates comes along with numerous challenges such as degradation in the signal quality due to different linear and nonlinear channel impairments and increased installation costs. To deal with those channel impairments novel advanced techniques in modulation and detection, coding, and signal processing should be developed. Such topics will be described in detail in this book.

The introduction of sophisticated electronic digital signal processing (DSP), coherent detection, and coding could fundamentally alter the optical networks as we see them today. DSP has played a vital role in wireless communication and has enabled so-called software-defined radio (SDR). Thanks to the recent resurgence of coherent detection and the recent drive toward dynamically reconfigurable optical networks with transmission speeds beyond 100 Gb/s, DSP and forward error correction (FEC) are becoming increasingly important. Regardless of the data destination, an optical transport system (OTS) must provide the predefined bit-error rate (BER) performance. To achieve a target BER regardless of the data destination, the future OTS should be able to adjust the FEC strength according to the optical channel conditions. Such an approach leads us toward the *software-defined optical transmission* (SDOT) in which the transponder can be adapted or reconfigured to multiple standards, multiple modulation formats, or code rates, a concept very similar to SDR.

Although channel coding for optical channels has gained prominence and emerged as the leading ultra-high-speed optical transmission enabling technology, FEC seems to be rather alien to many optical engineers. The optical engineers are aware that FEC potentially hold the keys to solving many major problems for today's "fragile" and "rigid" optical networks, but feel intimidated by sophisticated coding terminology. This book is intended to give a coherent, self-contained, and comprehensive introduction to the fundamentals of channel coding and DSP for optical communications. It is designed for three diverse groups of researchers: (1) optical communication engineers who are proficient in the optical science and are interested in applying coding theory and DSP, but not familiar with basic coding concepts, (2) wireless communication engineers who are very much adequate with their DSP and coding skill sets, but are disoriented by the perceived huge gap between optical and RF communications worlds, and (3) coding experts interested in entering the world of optical communications. An attempt has been made to make the individual chapters self-contained as much as possible while maintaining the flow and connection between them.

This book is organized into 11 chapters, and treats topics related to modulation, DSP and coding for optical channels starting from the fundamentals of optical communication and major channel impairments and noise sources, through DSP and coding, to various applications, such as single-mode fiber transmission, multimode fiber transmission, free space-optical systems, and optical access networks. This book presents interesting research problems in the emerging field of channel coding, constrained coding, coded-modulation, and turbo equalization and touches on the intriguing issue related to future research topics in coding for optical channels. The main purpose of this book is: (1) to describe the FEC schemes currently in use in optical communications, (2) to describe different classes of codes on graphs of high interest for next-generation high-speed optical transport, (3) to describe how to combine multilevel modulation and channel coding optimally, and (4) to describe how to perform equalization and soft decoding jointly, in a so-called turbo equalization fashion.

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Tucson, AZ

Ivan Djordjevic
William Ryan
Bane Vasic

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About the Authors

Ivan B. Djordjevic is an Assistant Professor in the Department of Electrical and Computer Engineering at the University of Arizona, Tucson, where he is directing the Optical Communications Systems Laboratory (OCSL). He is the author or coauthor of more than 100 journal publications and more than 100 conference papers. Dr. Djordjevic is also the author, together with Dr. William Shieh, of the book *OFDM for Optical Communications*, Elsevier, 2009. His current research interests include optical networks, error control coding, constrained coding, coded modulation, turbo equalization, OFDM applications, and quantum error correction. He is an Associate Editor for the *Research Letters in Optics* and the *International Journal of Optics.*

William E. Ryan is a Professor in the Department of Electrical and Computer Engineering at the University of Arizona. He has published numerous papers in the leading conferences and journals in the area of communication theory and channel coding. He is also the author (with Shu Lin) of the graduate textbook *Channel Codes: Classical and Modern*, Cambridge University Press, 2009. His research interests are in coding and signal processing with applications to magnetic data storage and data communications.

Dr. Bane Vasic received his B.Sc., M.Sc., and Ph.D. from the University of Nis, Serbia. He is currently a Professor of Electrical and Computer Engineering and Mathematics at the University of Arizona, Tucson. Prior to this appointment, he was at Bell Laboratories. He is a Member of the Editorial Board of the IEEE Transactions on Magnetics, and was a chair or technical program chair for several workshops and conferences including: IEEE CTW 2003 and 2007, DIMACS Workgroup and Workshop on Theoretical Advances in Information Recording, 2004, LANL Workshop on Applications of Statistical Physics to Coding Theory, 2004, Communication Theory Symposium within ICC 2006. He has authored a number of journal and conference articles, book chapters and edited three books, and his patents are implemented in Bell Labs chips. His research interests include coding theory, communication theory, constrained systems, and digital communications and recording.

Chapter 1
Introduction

We live in a time officially proclaimed as the information era, which is closely related to Internet technology and characterized by never-ending demands for higher information capacity [1]. Optical transmission links are established around the globe, and the optical fiber connection extends from the global backbone to access networks, all the way down to the curb, building, home, and desk [1–9]. Despite of the Internet "bubble" occurred in the early 2000s, the Internet traffic has been growing at astonishing rate ranging from 75 to 125% per year [6]. Given the recent growth of Internet usage, IPTV, and VoIP, it has become clear that current 10-Gb/s Ethernet rate is insufficient to satisfy the bandwidth demands in near future. For example, Internet2 has announced 2 years ago a capacity upgrade of its next-generation IP network from 10 Gb/s to 100 Gb/s [7]. According to some industry experts, 100-Gb/s transmission is needed by the end of 2009, while 1 Tb/s should be standardized by the year 2012–2013 [7].

The performance of fiber-optic communication systems operating at these high rates is degraded significantly due to several channel impairments including intra- and interchannel fiber nonlinearities, the nonlinear phase noise, and polarization mode dispersion (PMD). These effects constitute the current limiting factors in efforts to accommodate demands for higher capacities/speeds, longer link lengths, and more flexible wavelength switching and routing capabilities in optical networks. To deal with those channel impairments, novel advanced techniques in modulation and detection, coding, and signal processing should be developed, and some important approaches will be described in this book. The book represents a coherent and comprehensive introduction to the fundamentals of optical communications, digital signal processing (DSP), and coding for optical channels.

In this chapter, we provide a historical overview on optical communications (Sect. 1.1), introduce basics of optical communication and networking (Sect. 1.2), describe the current optical communication trends (Sect. 1.3), and explain why the coding in optical channels is of utmost importance (Sect. 1.4). In Sect. 1.5, we describe the organization of the book.

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1.1 Historical Perspective of Optical Communications

The earliest optical communications systems consisted of fire or smoke signals, signaling lamps, and semaphore flags to convey a single piece of information [3]. For example, a relatively sophisticated ancient communication system, along the Great Wall of China, was composed of countless beacon towers. In this ancient communication system, the number of lanterns or the color of smoke was used as a means to inform the size of an invading enemy, which represents a crude form of multilevel signaling. By using the beacon towers, with the guards in each tower, positioned at regular distances along the Great Wall, a message could be transmitted from one end of the Great Wall to the other, more than 7,300 km, in slightly more than 1 h [9]. Therefore, this ancient communication system has many similarities with today's relay or regeneration systems, in which the beacon towers can be considered as relays. Relay or regeneration systems were further studied by Claude Chappe in 1792 to transmit coded messages over a distance of 100 km [3].

Thanks to the success of telegraphy, telephony, and radio communications in the first half of twentieth century, the optical communication systems were actually forgotten. However, in the late twentieth century, different communication systems came to saturation in terms of reach and capacity. For instance, a typical coaxial cable-based transport system operating at 155 Mb/s requires the regeneration at approximately every 1 km, which is costly to operate and maintain. The natural step was to study the optical communication systems, which can dramatically increase the total capacity. The research in optical communication was boosted upon demonstration of a laser principle [10]. The first step was to fabricate an appropriate optical transmission medium. Kao and Hockman [11] proposed to use the optical fiber as the medium, although at the time it had unacceptable fiber loss. Their argument was that attenuation mostly was coming from impurities, rather than any fundamental physical effect such as Rayleigh scattering, which could be reduced by improving the fabrication process. Their prediction was that an optical fiber with attenuation of 20 dB/km should be sufficient for telecom applications, which surprisingly was developed within 5 years since initial proposal, by researchers from Cornell. This invention opens up opportunities for development of fiber-optic communication systems. Several generations of optical communication systems were developed since then. The *first generation* appeared in 1980s, and the operating wavelength was 0.8 μm with 45 Mb/s data rate. Repeater spacing was 10 km, which was much greater than that for comparable coax systems. Lower installation and maintenance costs resulted from fewer repeaters.

The *second generation*, which was focused on a transmission near 1.3 μm to take advantage of the low attenuation (<1 dB/km) and low dispersion, was deployed during the early 1980s. Sources and detectors were developed that use InGaAsP semiconductor. The bit rate of these systems was limited to <100 Mb/s due to dispersion in multimode fibers (MMFs). *Single-mode fiber* (SMF) was then incorporated. By 1987 the second generation systems were operating at 1.7 Gb/s at 1.3 μm with repeater spacing of 50 km.

The *third generation* systems were based on the use of 1.55-μm sources and detectors. At this wavelength the attenuation of fused silica fiber is minimal. The deployment of these systems was delayed, however, due to the relatively large dispersion at this wavelength. Two approaches were proposed to solve the dispersion problem. The first approach was to develop single-mode lasers and the second was to develop dispersion shifted fiber (DSF) at 1.55 μm. In 1990, 1.55-μm systems operating at 2.5 Gb/s were commercially available and were capable of operating at 10 Gb/s for distances of 100 km [1–3]. The best performance was achieved with DSFs in conjunction with single-mode lasers. A *drawback* of these systems was the need for *electronic regeneration* with repeaters typically spaced every 60–70 km. Coherent detection methods were investigated in late 1980s and early 1990s to increase receiver sensitivity. However, this approach was super ceded by the development of the optical amplifier.

The *fourth generation* systems are based on the use of *optical amplifiers* to increase repeater spacing and *wavelength division multiplexing* (WDM) to increase the aggregate bit rate. Erbium-doped fiber amplifiers (EDFAs) were developed to amplify signals without electronic regeneration during the 1980s [1–3]. In 1991, signals could be transmitted 14,300 km at 5 Gb/s without electronic regeneration [1–3]. The first transpacific commercial system went into operation sending signals over 11,300 km at 5 Gb/s and other systems are being deployed [1–3]. System capacity is increased through use of WDM. Multiple wavelengths can be amplified with the same optical amplifier. In 1996, $20 \times 5\,\text{Gb/s}$ signals were transmitted over 9,100 km providing a total bit rate of 100 Gb/s and a bandwidth–length (B–L) product of 910 (Tb/s) km. [1–3] In these broad band systems, dispersion becomes an important issue to be addressed.

In the *fifth generation* systems, the effort is primarily concerned with the fiber dispersion problem. Optical amplifiers solve the loss problem but increase the dispersion problem since dispersion effects accumulate over multiple amplification stages. An ultimate solution is based on the novel concept of *optical solitons* [1–3]. These are pulses that preserve their shape during propagation in a lossless fiber by counteracting the effect of dispersion through fiber nonlinearity. Experiments using stimulated Raman scattering (SRS) as the nonlinearity to compensate for both loss and dispersion were effective in transmitting signals over 4,000 km [1–3]. EDFAs were first used to amplify solitons in 1989 [1–3]. By 1994 a demonstration of soliton transmission over 9,400 km was performed at a bit rate of 70 Gb/s by multiplexing seven 10-Gb/s channels [1–3]. In parallel, dispersion compensating fibers (DCFs) were invented to deal with chromatic dispersion, and various dispersion maps were proposed [1–3] (see Sect. 1.3.4 for more details).

In *sixth generation* systems, the efforts have been directed toward realizing greater capacity of fiber systems by multiplexing a large number of wavelengths. These systems are referred to as dense wavelength division multiplexing (DWDM) systems. Systems with wavelength separation of 0.8 nm are currently in operation and efforts are pushing to reduce this to <0.5 nm. Controlling wavelength stability and the development of wavelength demultiplexing devices are critical to this effort. Systems are currently operating at 10 Gb/s and 40 Gb/s.

The current research focus is related to 100 Gb/s per wavelength optical transmission and beyond, by employing various multilevel modulation and coding schemes, polarization-multiplexing, DSP, and coherent detection. The orthogonal frequency division multiplexing (OFDM) appears to be an excellent candidate to deal with chromatic dispersion and PMD, but is sensitive to four-wave mixing (FWM) between subcarriers due to fiber nonlinearities [9].

1.2 Optical Transmission and Optical Networking

An exemplary WDM optical network, which can be used to identify the key optical components, concepts, and system parameters is shown in Fig. 1.1. The end-to-end optical transmission involves both electrical and optical signal paths. To perform conversion from electrical to optical domain the optical transmitters are used, while to perform conversion in opposite direction (optical to electrical conversion) the optical receivers are used. The SMF serves as a foundation of an optical transmission system because the optical fiber is used as medium to transport the optical signals from source to destination. The optical fibers attenuate the signal during transmission, and someone has to use optical amplifiers, such as EDFAs, Raman amplifiers, or parametric amplifiers, to restore the signal quality. Unfortunately, the amplification process is accompanied with the noise addition. For better exploitation of enormous bandwidth of SMF, the WDM concept is introduced, which corresponds to the scheme with multiple optical carriers at different wavelengths that are modulated by using independent electrical bit streams, as shown in Fig. 1.1, and then transmitted over the same SMF. During transmission of WDM signals, occasionally several wavelengths have to be added/dropped, which is performed by the optical add–drop multiplexer (OADM), as shown in Fig. 1.1. The optical networks require

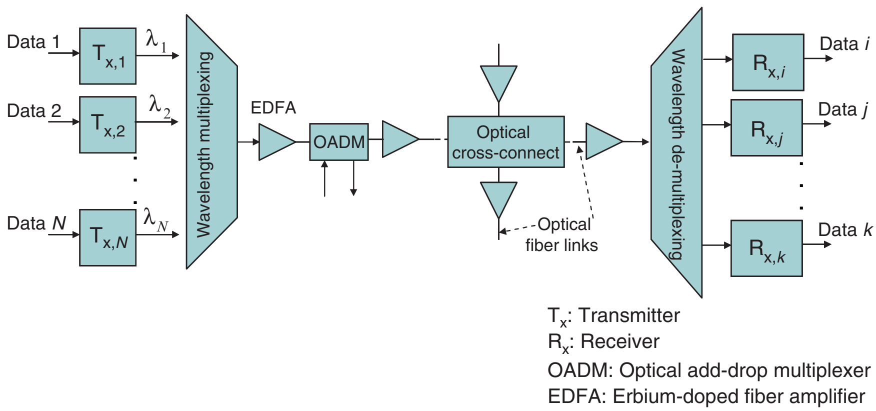

Fig. 1.1 An exemplary WDM optical network identifying key optical components, concepts, and parameters

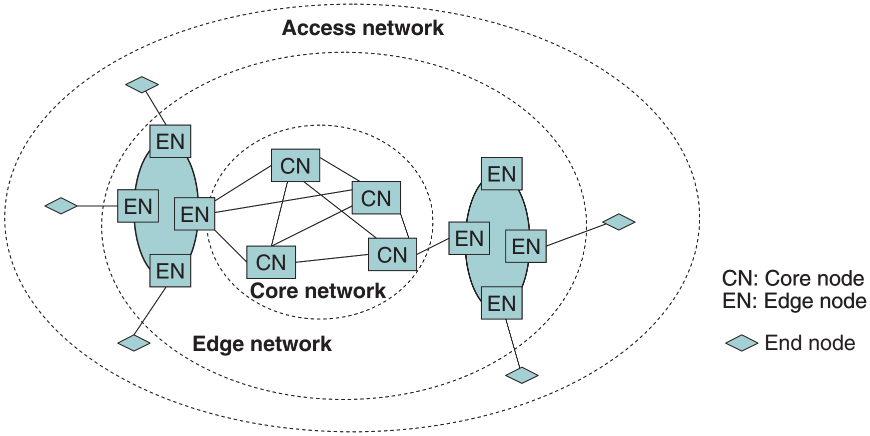

Fig. 1.2 A typical optical networking architecture

the switching of information among different fibers, which is performed by the optical cross-connect (OXS). To combine several distinct wavelength channels into composite channel the wavelength multiplexers are used. On the other hand, to split the composite WDM channel into distinct wavelength channels, the wavelength demultiplexers is used. To impose the information signal (be in digital or analog form) optical modulators are used. The optical modulators are commonly used in combination with semiconductor lasers.

To provide a global picture, we describe a typical optical network shown in Fig. 1.2. We can identify three ellipses representing the *core network*, the *edge network*, and the *access network* [1]. The long-haul core network interconnects big cities, major communications hubs, and even different continents by means of submarine transmission systems. The core networks are often called the wide area networks (WANs) or interchange carrier networks. The edge optical networks are deployed within smaller geographical areas and are commonly recognized as metropolitan area networks (MANs) or local exchange carrier networks. The access networks represent peripheral part of optical network and provide the last-mile access or the bandwidth distribution to the individual end-users.

The optical transmission systems can be *classified* according to different criterions. If *transmission length* is used for classification, we can identify very short reach (hundreds of meters), short reach (several kilometers), long reach (tens and hundreds of kilometers), and ultra-long reach (thousands of kilometers) optical transmission systems. When *bit rate* is used as classification criteria, the optical transmission systems can be classified as low-speed (tens of Mb/s), medium-speed (hundreds Mb/s), and high-speed (Gb/s). Finally, from *application perspective* point of view the systems can be either power budget (loss) limited or bandwidth (transmission speed) limited.

The ultimate goal of an optical signal transmission system is usually defined as achieving desired bit error rate (BER) performance between two end users or between two intermediate nodes in network reliably and at affordable cost. In order to achieve so, an optical transmission system needs to be properly designed, which includes the management of key optical communication systems engineering parameters. These parameters can be related to power, time, wavelength, or be interrelated. The parameters related only to power are power level, fiber loss, insertion loss, and extinction ratio (the ratio of powers corresponding to bit "1" and bit "0"). The parameters related only to time are jitter, first-order PMD, and bit/data rate. The parameters related to wavelength include optical bandwidth and wavelength stability. The parameters, signal impairments and additive/multiplicative noise sources, related to both power and wavelength are optical amplifier gain, optical noise [such as amplified-spontaneous emission (ASE) noise], different crosstalk effects, FWM, and SRS. The parameters related to time and wavelength are laser chirp, second-order PMD, and chromatic dispersion. The parameters related to power and time are BER, modulation format, polarization-dependent loss (PDL), and quantum noise. Finally, the channel impairments related to time, power, and wavelength simultaneously are self-phase modulation (SPM), cross-phase modulation (CPM), and stimulated Brillouin scattering (SBS). Any detection scenario must include electronic noise, such as thermal noise, which is associated with receiver design. These different parameters, noise sources, and channel impairments are subject of Chaps. 2 and 3.

Different high-speed optical transmission *enabling technologies* can either be related to the usage of novel/better *devices*, such as Raman and parametric amplifiers, PMD and chromatic dispersion compensators, and modulators, or be related to the novel *methods*, such as advanced modulation formats (various multilevel modulation schemes with both direct and coherent detections and OFDM), forward error correction (FEC), coded modulation, constrained (modulation/line) coding, advanced detection schemes [maximum likelihood sequence detection/estimation (MLSD/E) and maximum a posteriori probability (MAP) detection (Bahl–Cocke–Jelinek–Raviv (BCJR)-algorithm-based equalizers)], and various multiplexing schemes [polarization-multiplexing, optical time division multiplexing (OTDM), subcarrier multiplexing (SCM), code division multiplexing (CDM), and OFDM]. These various enabling technologies will be described in the following chapters.

An important concept to be introduced here is related to the so-called *lightwave path*, which can be defined as the trace that optical signal passes between the source and destination without experiencing any opto-electrical-opto (O-E-O) conversion [1]. Generally speaking, the lightwave paths may differ in lengths and in the information capacity that is carried along and can traverse though different portions of an optical network. The lightwave path can be considered as bandwidth wrapper for lower speed transmission channels, which form virtual circuit services [1]. The time division multiplexing (TDM) technique is applied to aggregate the bandwidth of virtual circuits before it is wrapped in the lightwave path. TDM of virtual circuits can be either *fixed* (each circuit receives a guaranteed amount of the bandwidth – a bandwidth pipe) or *statistical* (in packet-switching the data content is divided into data packets, which can be handled independently). The fixed multiplexing of

Table 1.1 Bit rates for different synchronous/asynchronous optical channels

Synchronous (TDM) channels	Bit rate	Asynchronous (data) channels	Bit rate
DS-1	1.544 Mb/s	10-BaseT Ethernet	10 Mb/s
E-1	2.048 Mb/s	100-BaseT Ethernet	100 Mb/s
OC-1	51.84 Mb/s	FDDI	100 Mb/s
OC-3=STM-1	155.52 Mb/s	ESCON	200 Mb/s
		Fiber Channel-I	200 Mb/s
OC-12=STM-4	602.08 Mb/s	Fiber Channel-II	400 Mb/s
		Fiber Channel-III	800 Mb/s
OC-48=STM-16	2.488 Gb/s	Gb Ethernet	1 Gb/s
OC-192=STM-64	9.953 Gb/s	10-Gb Ethernet	10 Gb/s
OC-768=STM-256	39.813 Gb/s	40-Gb Ethernet	40 Gb/s

Table 1.2 The wavelength bands for fiber-optics communications

Wavelength band	Descriptor	Wavelength range (nm)
O-band	Original	1,260–1,360
E-band	Extended	1,360–1,460
S-band	Short	1,460–1,530
C-band	Conventional	1,530–1,565
L-band	Long	1,565–1,625
U-band	Ultra-long	1,625–1,675

virtual circuits is defined by SONET/SDH standards. Bit-rates of different bandwidth channels, for both synchronous and asynchronous transmission, are given in Table 1.1, due to Cvijetic [1].

Optical fiber is the key point of an optical transmission system because it has much wider available bandwidth, lower signal attenuation, and smaller signal distortions compared with any other wired or free-space physical media. The total bandwidth is approximately 400 nm, or around 50 THz, when related to the wavelength region with fiber attenuation being bellow 0.5 dB/km. The usable optical bandwidth is commonly split into several wavelength bands, as shown in Table 1.2 due to Ramaswami and Sivarajan [2]. The bands around the minimum attenuation point, usually referred to as C and L bands, are the most suitable for high channel count DWDM transmission. The wavelength region around 1,300 nm is less favorable for optical signal transmission because signal attenuation is higher than attenuation in S, C, and L bands. On the other hand, it is quite suitable for CATV signals, and the course-WDM (CWDM) technique is usually employed in this region.

The key optical components, which will be described in Chap. 2, can be classified as follows (1) semiconductor light sources [light-emitting diodes (LEDs) and semiconductor lasers: Fabry–Perot (FP), distributed feedback (DFB), distributed Bragg reflector (DBR), vertical cavity surface emitting (VCSEL), and tunable lasers (external cavity laser, mutilaser chip, three-section tunable)]; (2) optical modulators [direct optical modulators and external modulators: Mach–Zehnder modulator

(MZM) and electroabsorption modulator]; (3) optical fibers (MMFs and SMFs); (4) optical amplifiers [semiconductor optical amplifier (SOA), EDFA, Raman amplifiers, and parametric amplifiers]; (5) photodiodes [PIN, avalanche photodiodes (APDs), and metal–semiconductor–metal (MSM) photodetectors]; and (6) various optical components [optical isolators, optical circulators, optical filters, optical couplers, optical switches, and optical multiplexers/demultiplexers].

A monochromatic electromagnetic wave, which is commonly used as a signal carrier, can be represented through its electric field as $\boldsymbol{E}(t) = \boldsymbol{p}A\cos(\omega t + \phi)$ (A – amplitude, ω – frequency, ϕ – phase, $\boldsymbol{p}$ – polarization orientation), for which each parameter can be used to impose the message signal. If the message signal is analog, the corresponding modulation formats are amplitude modulation (AM), frequency modulation (FM), phase modulation (PM), and polarization modulation (PolM). On the other hand, when the modulating signal is digital then the carrier signal duration is limited to symbol duration, and corresponding modulation formats are amplitude shift keying (ASK), frequency shift keying (FSK), phase shift keying (PSK), and polarization shift keying (PolSK).

In order to better utilize the enormous bandwidth of the optical fiber, we have to transmit simultaneously many channels over the same bandwidth through *multiplexing*. The commonly used methods of multiplexing in optical communications are given below as follows:

- *Wavelength-division multiplexing* (WDM) is already introduced in Fig. 1.1.
- *Time-division multiplexing* (TDM), in which many lower-speed signals are time-interleaved to generate a high-speed signal. The multiplexing can be performed either in electrical domain, when is known as electrical TDM (ETDM), or in optical domain, when is known as optical TDM (OTDM).
- *Frequency-division multiplexing* (FDM), in which continuous-wave (CW) modulation is used to translate the spectrum of the message signal into a specific frequency slot of the passband of optical channel. The optical version of FDM is commonly referred to as WDM.
- *Orthogonal frequency-division multiplexing* (OFDM) is a particular version of FDM in which the orthogonality among subcarrier is obtained by providing that each subcarrier has exactly an integer number of cycles in the symbol interval. The number of cycles between adjacent subcarriers differs by exactly one.
- *Subcarrier multiplexing* (SCM) is again a particular version of FDM in which different independent data streams are first microwave multiplexed and then transmitted using the same wavelength carrier.
- *Code-division multiplexing* (CDM), in which each message signal is identified by a unique *signature sequence* ("code"), with signature sequences being orthogonal to each other.

During the transmission over an optical fiber, the transmitted signal is impaired by various noise sources and channel impairments. The noise sources can be additive in nature (dark current noise, thermal noise, ASE noise, and crosstalk noise) or be multiplicative in nature [mode partition noise (MPN), laser intensity noise (RIN), modal noise, quantum shot noise, and avalanche shot noise]. Different channel impairments can be related to fiber attenuation, insertion loss, dispersion effects, or fiber nonlinearities. Fiber attenuation originates from material absorption, which can be intrinsic (ultraviolet, infrared) or extrinsic (water vapor, Fe, Cu, Co, Ni, Mn, Cr, various dopants: GeO_2, P_2O_5, B_2O_3), Rayleigh scattering, and waveguide imperfections (Mie scattering, bending losses, etc.). The dispersion effects can originate from intermodal (multimode) dispersion (in MMFs), chromatic dispersion (material and waveguide dispersion effects present in SMF), PMD, and PDL. The fiber nonlinearities can originate from nonelastic scattering effects (SBS, SRS) or Kerr nonlinearities (SPM, XPM, FWM). Various noise sources and optical channel impairments are described in Chap. 3.

1.3 Optical Communications Trends

The invention of Internet has fundamentally changed the underlying information communication infrastructure and has lead to the world-wide telecom boom in the late 1990s and early 2000s [9]. This development coincided with the development and deployment of WDM optical amplified systems. Surprisingly, the Internet traffic has continued its rapid growth despite the so-called "Internet bubble" in the equity market. Namely, some new applications, such as IPTV and YouTube, have emerged, which continued to drive the high bandwidth demands so that the growth of the Internet does not seem to saturate any soon. Moreover, the CISCO's projection of the Internet traffic growth, up to 2012, shows an exponential dependence from 2002 to 2012 [9]. This exponential Internet traffic growth places an enormous pressure to the underlying information infrastructure at every level, from core to access networks. In the rest of this section, we describe several trends in optical communications arising from rapid IP traffic growth.

1.3.1 Migration to 100 Gb/s Ethernet and Beyond

Over the past decades the Ethernet (IEEE 802.3) has expanded from original share-medium LAN technology to a reliable standard across all level of the networks [9]. Ethernet has become the undisputed communication technology of choice in terms of cost and reliability. Because the IP backbones have grown so quickly that some large ISPs already reported router-to-router trunk connectivity exceeding 100 Gb/s in 2007; some industry experts believe that the 100-Gb/s Ethernet (100 GbE) standard is too late, while 1-Tb/s Ethernet standard should be available by 2012–2013 [8]. The migration of the line rate from 10 Gb/s to 100 Gb/s is expected to help in reduction of capital and operational costs. Since the migration to 100 GbE leads to fewer pipes, but of larger bandwidth among the IP routers, it is expected to simplify the traffic management.

The deployment of transmission systems based on data rates of 100 Gb/s is advantageous for many reasons [12] (1) smaller number of high-speed channels for a given bandwidth results in better spectral efficiency because no bandwidth is wasted on separating the channels; (2) a single high-speed transponder may replace many low-speed ones resulting in reduction of the number of optoelectronic devices and easier monitoring; and (3) a reduced number of channels for a given bandwidth permits using simpler optical switching devices and simpler routing algorithms. However, increasing data rates of fiber-optics communication systems is associated with numerous technological obstacles [10–15] such as increased sensitivity to fiber nonlinearities, high sensitivity to PMD, and increased demands in dispersion accuracy.

1.3.2 Dynamically Reconfigurable Optical Networks

The explosive growth of bandwidth-rich Internet video applications places tremendous strain on the traditional communication networks [9]. Although the link capacity can be enhanced by migration to 40 Gb/s or 100 Gb/s or by employing more WDM channels, such simplistic approach works very well in only a point-to-point communication. In order to be able to adjust to ever changing requirements for the bandwidth demand, the optical networks must be able to dynamically add, drop, and route the wavelength channels at individual nodes. If this operation is performed in optical domain, the transponder cost related to optical-to-electrical and electrical-to-optical conversions will be eliminated. This type of wavelength management in optical domain is performed by reconfigurable optical add–drop multiplexer (ROADM) [16].

Current limitations of photonics-enabled networks also result from the heterogeneity of the infrastructure and consequential bottlenecks at different boundaries and interfaces. In optically routed networks, neighboring DWDM channels carry random traffic patterns in which different lightwave paths experience different penalties due to the deployment of ROADMs and wavelength cross-connects (WXCs). Different wavelength channels carrying the traffic to different destinations can have quite different signal-to-noise ratios (SNRs) and spectral distortions due to cascaded filtering effects, as illustrated in Fig. 1.3a. The Internet of the future should be able to support a wide range of services containing a large amount of multimedia over different network types at high speed.

The ROADMs are commonly used to provide interconnection of many distribution networks (see Fig. 1.3b). Since their introduction in 2003, ROADMs have become a mainstream for use in core networks. Unfortunately, the use of reconfigurable networks with the transport speed exceeding 100 Gb/s imposes big challenges to the network designers, because at such high speeds the transmitted signal is very sensitive to PMD, residual chromatic dispersion, ROADMs concatenation filtering effect, and imperfections in electrical and optical components. It is therefore mandatory to perform per channel optical dispersion compensation. For long-haul

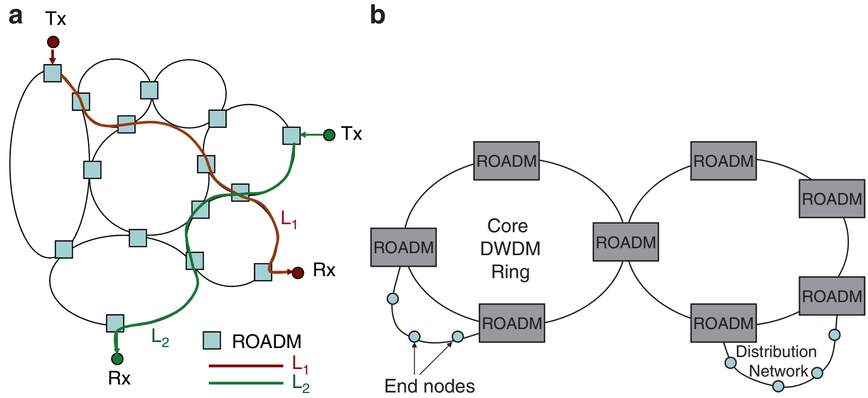

Fig. 1.3 (**a**) Different lightwave paths (L_1 and L_2) in an optically routed network; (**b**) optical distribution networks connected by ROADMs

transmission, it is also necessary to perform PMD compensation at 100 Gb/s. The optical PMD compensators usually have large footprint and are highly lossy and expensive. It is quite clear that such a "brute-force" migration from 10 GbE to 100 GbE cannot achieve at all the original goal of the cost saving.

1.3.3 Software-Defined Optical Transmission

In response to the emergence of analog and digital standards in wireless communications during 1980s, the concept of software-defined ratio (SDR) has been introduced [17–19]. SDRs are capable of changing scrambling and encryption coding in an ad hoc manner. Additionally, they can change their modulation format, data rate, channel coding, and voice codecs, while providing flexible and interoperable communication. The flexibility to adapt to major transmission parameters in accordance to the existing channel/traffic conditions is another key benefit. When channel conditions are favorable, SDRs can increase the signal constellation size or decrease it when channel conditions become poor, therefore giving SDRs the advantage of improved noise immunity. Channel coding schemes of SDRs can also be adapted to better deal with the effects of fading and interference.

As expected, similar challenges arise in modern optical communications [9]. A number of various "advanced" modulation formats have been proposed for the next generation 100-Gb/s Ethernet optical transport [20–26]. We envision an optical network in which all packets are error protected at edge nodes and can provide a target BER performance regardless of the packet destination. Because in this network the encoding and decoding is performed in edge nodes, it is compatible with existing modulation and multiplexing and switching techniques and can be used in different network environments. To enable the long-haul transmission, the employed codes must have good error correction capabilities. On the other hand, short links and/or highfidelity lightwave paths can utilize lower overhead and offer lower decoding latency. In order to optimize error correction overhead, complexity and latency it is of crucial importance that codes offer flexible error protection capability, so that packets traveling further or through the error prone network are protected better. Error protection flexibility can be achieved by encoding user data in packets with different destinations using different codes, each having different error protection capabilities. Information about the code employed for a particular packet can be included in the packet header together with other information necessary to provide active routing. In general, the use of different codes for different destinations would be costly to implement due to increased hardware complexity. Such complexity can be avoided if a unified encoding and decoding architecture can be used for all destinations. The structured quasicyclic (QC) low-density parity-check (LDPC) codes [27] provide us with this unique feature. Such an approach leads toward the *software-defined optical transmission* (SDOT) in which the transponder can be adapted or reconfigured to multiple standards, multiple modulation formats, or code rates, the concept very similar to SDR. In addition, the SDOT system should be able to (1) dynamically set up the physical link without any human intervention, (2) assign an optimal line rate and signal constellation size in accordance with the optical link conditions, (3) select between multicarrier mode and single-carrier mode, (4) chose an optimum code rate, and (5) accurately report various channel parameters (optical SNR, chromatic dispersion, PMD, electrical SNR) so to predict the fault and alarm before it causes the traffic interruption.

The concept of SDOT is illustrated in Fig. 1.4a. A key difference with respect to a conventional optical transmission system is the presence of DAC/ADC and DSP in the architecture of the SDOT. The SDOT promotes the migration from analog to digital domain to enhance the optical transmissions by providing a dynamic adaptation to the optical channel conditions and reconfiguration to an appropriate modulation format and code rate.

The electronic dispersion compensation (EDC) is a key point important for the success of SDOT concept. The very early approaches of EDC are essentially hardware based including feed-forward equalizer (FFE) and decision feedback equalizer (DFE), with limited performance improvement [28]. The EDC by DSP means has shown much better tolerance to various channel impairments. SDOT shown in Fig. 1.4 provides a generic architecture applicable to various EDCs by DSP techniques. For example, for conventional optical front ends and intensity modulation/direct detection (IM/DD) systems, the MLSD/E or turbo equalization can be used [13, 15]. The precompensation can be used together with optical in-phase/quadrature (IQ) modulator and direction detection, which is illustrated in Fig. 1.4b. For a coherent detection front end, digital phase estimation can be used instead of conventional optical phase-locked loop (OPLL). For coherent detection and optical IQ modulator (see Fig. 1.4b), coherent optical OFDM can be used to compensate for chromatic dispersion and PMD. Although the front ends in these examples are different, they all take the advantage of DSP to improve the chromatic dispersion and PMD tolerance.

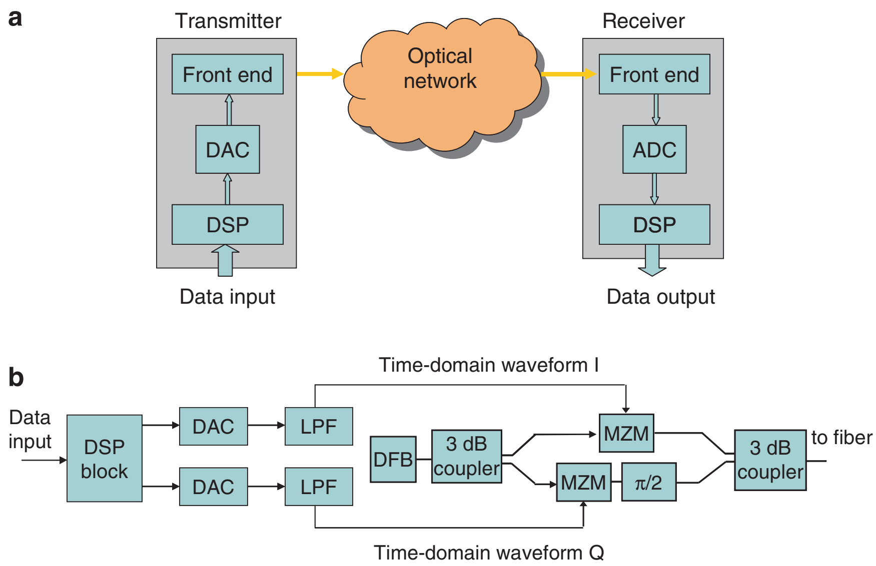

Fig. 1.4 (**a**) Conceptual diagram of software-defined optical transmission concept; (**b**) a typical transmitter front-end architecture (for single polarization) applicable to both direct and coherent detections. *DAC* Digital-to-analog converter, *ADC* analog-to-digital converter, *MZM* Mach–Zehnder modulator

1.3.4 Digital Signal Processing and Coherent Detection

The conventional optical systems employ a dispersion map to deal with accumulated chromatic dispersion of SMF. In dispersion maps, the DCF modules are deployed at the amplifier stage to compensate for the accumulated dispersion of the transmission link. The DCF could be placed at the optical amplifier site within double-stage amplifier, which is typical for terrestrial applications (see Fig. 1.5a), or be distributed in a dispersion mapped span, which is typical for submarine systems (see Fig. 1.5b). Such dispersion maps work very well for transmission systems operating at 10 Gb/s and below, but become extremely tedious at 40 Gb/s and beyond, requiring both the dispersion and dispersion slope of the DCF to be matched precisely. Any residual mismatched dispersion needs to be compensated using a fixed or tunable optical dispersion module, and this is performed on per channel basis. On the other hand, the electron equalizer has the advantages of lower cost, small footprint, and ease of adaption and is suitable for employment in SDOT scenario [9]. The electronic equalizers employ the classical equalization approaches such as FFE, DFE, Viterbi equalizer, and turbo equalizer. The early stage electrical equalizers mostly utilized SiGe or InP/AlGaAs technology with the channel memory limited to 2 or 3 bits and have successfully been commercial deployed [29]. The major breakthrough in electronic signal processing took place when researchers from Nortel promoted their predistortion equalizer supporting 5,000-km transmission over SMF

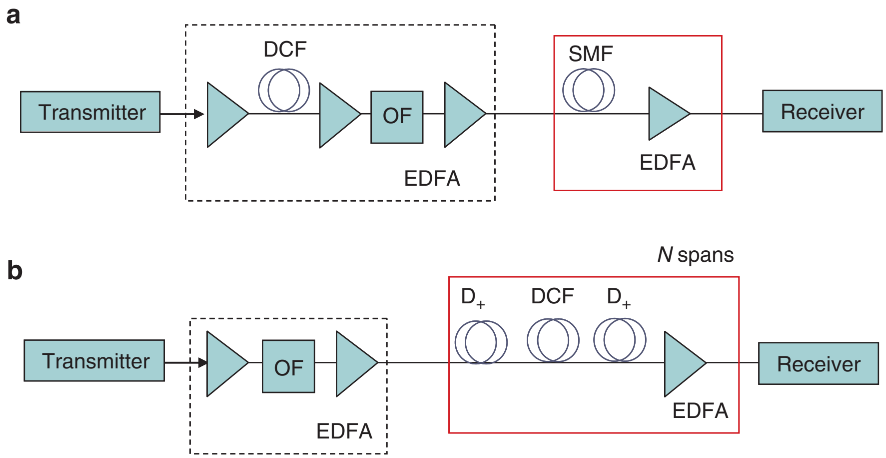

Fig. 1.5 Dispersion maps: (**a**) discrete DCF module based maps and (**b**) dispersion managed maps. *OF* Optical filter

without any optical dispersion compensator [30]. This work raised an interesting and fundamental question to the optical community whether it is necessary at all to use the dispersion maps, such as those shown in Fig. 1.5. The "era" of electronic DSP-assisted optical transmission has arrived, followed by the subsequent dramatic revival of the coherent optical communications [9].

1.3.5 OFDM for Optical Communications

OFDM is an efficient approach to deal with intersymbol interference (ISI) due to chromatic dispersion and PMD. By providing that the guard interval is larger than the combined delay spread due to chromatic dispersion and maximum differential group delay (DGD), the ISI can be eliminated successfully [9]. In the early of the 2006, three groups independently proposed two flavors of optical OFDM for long-haul application that were also aimed at eliminating the need for dispersion management in optical transmission systems [9], including direct-detection optical OFDM [31, 32] and coherent optical OFDM (CO-OFDM) [33]. CO-OFDM provides the superior performance in terms of spectral efficiency, receiver sensitivity, and polarization-dispersion resilience, but requires a little bit higher implementation complexity compared to that of direct detection OFDM [9]. The transmission experiments of CO-OFDM conducted in the research laboratories have reached 100-Gb/s transmission over 1,000 km of SMF [34–36].

The block diagram of an OFDM system with direct detection for transmission over MMF links is shown in Fig. 1.6, as an illustration. The demultiplexer converts incoming information data stream into parallel form. Constellation mapper maps

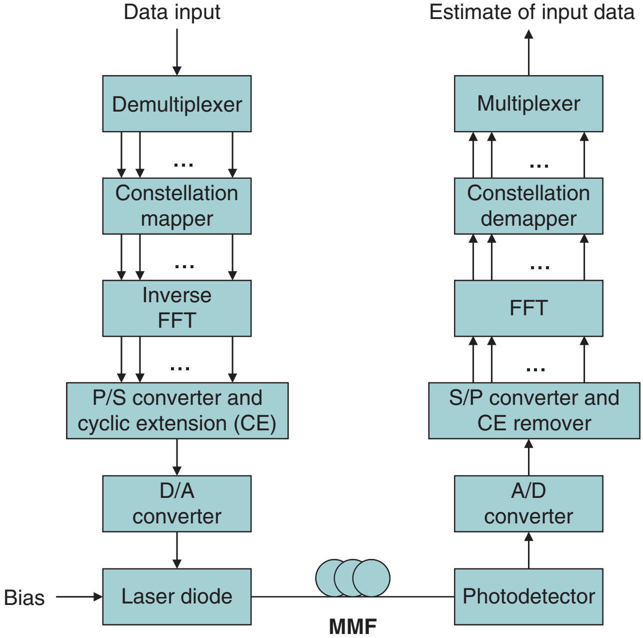

Fig. 1.6 The block diagram of an OFDM system with direct detection suitable for transmission over MMF links. *P/S* Parallel-to-serial, *S/P* serial-to-parallel

parallel data into N subcarriers using quadrature amplitude modulation (QAM). The modulation is performed by applying the inverse fast Fourier transform (IFFT), which transforms frequency-domain parallel data into time-domain parallel data. The digital-to-analog (D/A) converter performs the conversion from digital to analog domain. Typically, D/A converter contains a transmit filter. As shown in Fig. 1.6, to reduce the system cost direct modulation of laser diode can be used. Because the negative signals cannot be transmitted over an intensity modulation with direct detection, the bias voltage is used to convert the negative portion of OFDM signal to positive. Since this approach is power inefficient, the clipping can be used. At the receiver side, upon optical-to-electrical conversion by photodetector, DC bias blocking, analog-to-digital (A/D) conversion, cyclic removal, and serial-to-parallel (S/P) conversion, the demodulation is performed by the FFT. With sufficient number of subcarriers, the OFDM symbol duration can be made arbitrarily small increasing therefore the tolerance to ISI due to chromatic dispersion and PMD. By providing that the cyclic extension guard interval (see Fig. 1.6) is longer than total delay spread due to chromatic dispersion and maximum value of DGD, chromatic dispersion and PMD can be completely (at least in principle) compensated for. The cyclic extension can be performed by inserting the last $N_G/2$ samples of the IFFT effective portion of symbol at the beginning of the OFDM symbol and appending the first $N_G/2$ samples at the end.

As both single-carrier coherent system and CO-OFDM have made rapid progress toward 100-GbE transport, there naturally arises an intriguing question about the superiority between CO-OFDM and single-carrier coherent system [9]. Although OFDM has gained popularity in the previous decade and has already widely been implemented in a number of communication standards, there has been an on-going debate on the superiority between OFDM and single-carrier FDE. OFDM has two fundamental problems (1) large peak-to-average-power ratio (PAPR) and (2) sensitivity to phase noise. The debates sometimes do not provide the clear-cut answer and the result can be a split decision in standards. For example, the Europe, Japan, and most of the countries in the world have selected OFDM, while the USA has chosen single-carrier 8-level vestigial sideband modulation (8VSB) as the digital TV standard. However, the same arguments used in wireless communication are not quite applicable to the optical domain. Given the fact that the communication channel, devices, and systems are quite distinct compared to RF domain, it is imperative to understand thoroughly the problems at hand and clarify the context in which the debate is being conducted, which was addressed in [9]. From the comparison provided in [9], we conclude that the CO-OFDM is advantageous because of its scalability to the ever increasing data rate and transponder adaptability.

1.4 Forward Error Correction for Optical Communications and Networks

The state-of-the-art fiber-optics communication systems standardized by the ITU employ concatenated BCH/RS codes [37, 38]. The RS(255,239) in particular has been used in a broad range of long-haul communication systems, and it is commonly considered as the first-generation of FEC [41, 42]. The elementary FEC schemes (BCH, RS, or convolutional codes) may be combined to design more powerful FEC schemes, e.g., RS(255,239) + RS(255,233). Several classes of concatenation codes are listed in ITU-T G975.1. Different concatenation schemes, such as the concatenation of two RS codes or the concatenation of RS and convolutional codes, are commonly considered as second generation of FEC [41]. In recent years, iteratively decodable codes, like turbo codes [38–41] and LDPC codes [13–15, 42, 44–50], have generated significant research attention. In [40], Sab and Lemarie proposed an FEC scheme based on block turbo code for long-haul DWDM optical transmission systems. In recent papers [13–15, 44–48], we have shown that iteratively decodable LDPC codes outperform turbo product codes (TPCs) in BER performance. The decoder complexity of these codes is comparable (or lower) to that of TPCs and is significantly lower than that of serial/parallel concatenated turbo codes. For reasons mentioned above, LDPC code is a viable and attractive choice for the FEC scheme for 100-Gb/s optical transmission systems. The soft iteratively decodable codes (turbo and LDPC codes), also known as codes on graphs, in optical community are commonly referred to as the *third generation* of FEC [41, 43].

Codes on graphs have revolutionized communications and are becoming standard in many applications. LDPC codes, invented by Gallager [42] in 1960s, are linear block codes for which the parity check matrix has low density of ones. LDPC codes have generated great interests in the coding community recently, and this has resulted in a great deal of understanding of the different aspects of LDPC codes and their decoding process. An iterative LDPC decoder based on the *sum–product algorithm* (SPA) has been shown to achieve a performance as close as 0.0045 dB to the Shannon limit [49]. The inherent low complexity of this decoder opens up avenues for its use in different high-speed applications, including optical communications.

In Fig. 1.7, we show the recent progress in FEC for high-speed optical communications; the figure is adopted and modified from [51]. The horizontal axis denotes the year, while the vertical axis denotes the net coding gain (NCG). The first generation FEC schemes appeared during 1987–1993 and RS(255,239) of code rate 0.93 (overhead 7%) shows the NCG of 5.8 dB. The second generation FEC was developed during 2000–2004, with the best performing concatenated code showing the NCG of 9.4 dB for code rate of 0.8 (25% of redundancy) [51]. Focus, since then was on codes on graphs, turbo and LDPC codes, with potential NCG above 10 dB. The codes on graphs are commonly referred to third generation FEC for optical communications, as indicated above.

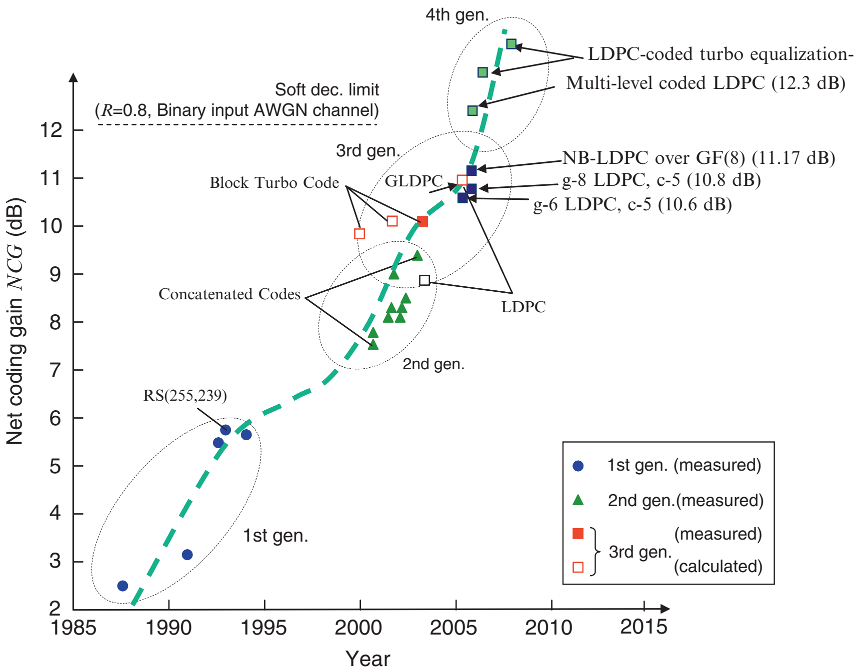

Fig. 1.7 Recent progress in FEC for optical communication systems. (Modified from ref. [51]; © IEEE 2006; reprinted with permission.)