# Chapter 12
# Optical Communications and Modulation Techniques in 5G

**Yinglu Hu, Yong Wang and Kuan W. A. Chee**

**Abstract** Wired and wireless communication technologies are widely leveraged for bilateral communications between the utility and end user in smart grid environments. With mobile technologies evolving, optical communications are projected to play an essential role in emerging fifth-generation (5G) networks. In this chapter, we first introduce fiber-optic communications and briefly address optical attenuation, dispersion, and nonlinear effects for a variety of modulation devices in present and future fiber-optic transmission and multiplexing technologies. Second, the development of optical wireless communications is introduced, including free-space optical communication and visible-light communication (VLC) systems. Third, waveform designs and modulation techniques in 5G for the smart grid are addressed, including amplitude shift keying (ASK), differential phase shift keying (DPSK), quadrature phase shift keying (QPSK), multiple quadrature amplitude modulation (MQAM), polarization shift keying (PolSK), plus other digital modulation and pulse modulation formats, as well as coding technologies. Finally, an overview of the prospects is given for future development, application fields, and socioeconomic influence.

**Keywords** 5G networks · Optical fiber communications · Wireless communications · Modulation and demodulation · Encoding and decoding · Fiber optics · Dispersion and nonlinear effects · Amplitude shift keying (ASK) ·

Y. Hu · Y. Wang · K. W. A. Chee (✉)
Laser Research Institute, Qilu University of Technology (Shandong Academy of Sciences), Shanyisuo Building, 37 Miaoling Road, Laoshan District, Qingdao 226100, Shandong, China
e-mail: kuan.chee@nottingham.edu.cn

Y. Hu
e-mail: yingluhu@sdlaser.cn

Y. Wang
e-mail: yongwang@sdlaser.cn

K. W. A. Chee
Department of Electrical and Electronic Engineering, Faculty of Science and Engineering, The University of Nottingham, Sir Peter Mansfield Building, 199 Taikang East Road, Ningbo 315100, Zhejiang, China



E. Kabalci and Y. Kabalci (eds.), *Smart Grids and Their Communication Systems*, Energy Systems in Electrical Engineering,
https://doi.org/10.1007/978-981-13-1768-2_12

Differential phase shift keying (DPSK) · Quadrature phase shift keying (QPSK) · Quadrature amplitude modulation (QAM)

## 12.1 Introduction

With the advent of massive Internet of Things (IoT) and the coming era of big data, a wider range of device connections, more extensive data processing, and more complex environments, higher requirements are presented for new communication technologies. Marked by the emergence of cloud services, augmented/virtual reality, the Internet of Vehicles (IoV), and other new services, revolutionary fifth-generation (5G) technology is poised to handle the burgeoning network requirements to transmit, process, and operate a massive increase in data owing to the proliferation of connected devices. Compared with fourth-generation wireless (4G) long-term evolution (LTE), 5G networks aim to have the following characteristics [1]:

(a) **Data traffic growth**. 5G networks need to be able to support large amounts of data flow, more than three orders of magnitude the capacity of 4G networks, while also enabling up to 100 Gbit/s/km$^2$ transmission.
(b) **Substantially increased equipment networking**. As the growth of IoT devices and connections is anticipated, 5G network coverage will be more extensive, involving a large number of device-to-device, machine-to-machine, etc., applications with a connection density from 200 thousand up to 1 million per square kilometer, all supported by a network infrastructure scaled up a 100-fold compared to the 4G predecessor.
(c) **Greatly improved data transmission rates**. The transmission speed of 5G networks is two to three orders of magnitude higher than that of 4G, reaching up to 10 Gbps, and in some special cases, up to 100 Gbps.
(d) **Superior spectrum efficiency**. With 5G Internet handling more users and data transfer and providing wider coverage, faster transmission speeds and so on, higher spectral efficiency is expected of a factor of 5–10 that of 4G, which requires channel multiplexing and compression technologies to improve the signal source and channel performance.
(e) **Higher reliability and availability and reduced latency**. A major challenge to network operators is to handle an increased number of services and data generated by end users, and to support even the various industrial and emergency information systems. With the network undertaking more social functions and social responsibilities, there is a need to further reduce inefficient consumption of resources and network delay time. The network delay in 5G needs to be mitigated by a factor of 5–10 that of 4G, especially for related sectors such as public security and safety, with reliability being required to reach at least 99.99%. For 5G, the time delay needs to be less than 1 ms, while tight equipment time synchronization needs end-to-end phase error limits as low as 400 ns, or 100 ns in joint transmission and reception.

(f) **More green, energy conserving, and environmentally friendly**. The network energy consumption will increase by approximately three orders of magnitude compared to that of 4G. 5G networks put forward higher requirements to the communication system's information transmission rate, channel capacity, information processing speed, and so on. Finally, in 5G networks, from the smallest personal terminal to the largest conglomerates, anything digital-related, interconnection anytime, anywhere for any device, and all kinds of infrastructure, users and Internet-compatible equipment, realize the IoT.

Three application scenarios have been defined for the 5G networks [2]: enhanced mobile broadband (eMBB), massive machine-type communication (mMTC) and ultra-reliable low-latency communication (uRLLC), in which case, optical communication technologies will play an important role. eMBB concerns improved data rate, latency, user density, capacity, and coverage of mobile broadband access. mMTC allows communications between low-cost, low-power highly connected devices for applications such as smart metering and body sensors. uRLLC enables communication between devices and machines with high reliability, very low latency and high availability, for smart grids, vehicular communication, industrial control, factory automation, and public security applications.

To date, optical communication technology development far surpasses that of other communication technologies, by dint of higher transmission rates, the ability to process information faster, as well as possessing greater broadband channel capacity, and is therefore absolutely adequate to accommodate 5G network technology demands. Optical communications have heretofore proven to be instrumental in 4G networks, as they are widely deployed whether in long-haul communication cables, short- and medium-length links for data center designs, or short-distance fiber to the home (FTTH), as well as in local area network (LAN) connections and hot-spot areas. Long-haul trunk line designs, including terrestrial and undersea or submarine optical fiber cables, mainly utilize a large range of optical fiber cables that prioritize the C and L bands in the telecoms window. Generally, single-mode fiber is used, but if necessary, an assortment of fiber types can be combined in a given cable [3]. Wavelength division multiplexing (WDM) enables multi-channel transmission [4] and polarization division multiplexing (PDM)-multiple quadrature amplitude modulation (MQAM) improves the single-channel utilization rate, which may be combined with polarization mode dispersion (PMD) compensation or relay technologies to achieve the desired broadband capacity for high-speed and long-range transmission.

5G may also introduce all-optical networks (AONs), soliton-based optical communications, and other technologies to improve data transmission rate, reliability and transmission range. The design and development of data center infrastructure have evolved under the weight of big data, cloud computing, virtualization, mobility, post-operating system, and other emerging technologies. Modern data center strategies can be implemented in collaboration with utilities to realize energy efficiency, and IT enterprises can customize the required services according to the client's individual needs without having to worry about space or energy wastage and excessive configuration. Data centers need to establish an independent unified network architecture starting from 10 gigabit Ethernet, hence a large number of multimode fiber (MMF) communication links are required for synchronization [5], and to transmit and process data between data centers and end users. Short-distance FTTH includes fiber to the desktop, fiber to the curb, fiber to the office, fiber to the zone, and fiber to the feeder, which are part of the family of fiber to the x (FTTX) broadband network architecture. It is popular to implement the "last mile" between the backbone network and LAN or home user, using a point-to-multipoint passive optical network (PON).

Optical communication systems can be classified into wired and wireless. The former generally refers to the adoption of the optic-fiber medium. In 2017, the number of users in China has reached more than two hundred million, while that worldwide probably around a billion, and this number is set to increase manifold for 5G networks. Hence, a large number of single-mode fiber cables will be deployed to maintain such a massive scale of network connectivity. Furthermore, optical wireless networking is also essential to support 5G. In addition to the traditional wireless fidelity (Wi-Fi) technology for wireless LAN interconnection and hot-spot communication, light fidelity (Li-Fi), which uses visible light for wireless data transmission instead of radio waves, is gaining commercial foothold after trials in offices and industrial environments. Potentially, Li-Fi may complement Wi-Fi, or may even replace it in the foreseeable future. Hence, wireless optical communications will play a crucial role in supporting 5G connectivity where it may not be practicable to lay optical fiber cable links for applications such as interstellar communication, vehicular networking, smart cities, etc. Among the most popular optical wireless communication systems, there are free-space optical communication and visible-light communication (VLC) technologies.

Fiber-optic communications rely on digital modulation formats such as amplitude shift keying (ASK), differential phase shift keying (DPSK), quadrature phase shift keying (QPSK), MQAM, etc., whereas VLC is supported by pulse modulation technologies such as pulse position modulation (PPM) and differential pulse position modulation (DPPM). The modulation technology for free-space optical communications is contingent on the optical source. To improve channel capacity, transmission rate and reliability, specialized encoding techniques will be applied in conjunction with various modulation formats. In 2016, 3GPP has determined that for 5G wireless standards, low-density parity-check (LDPC) is the appropriate data channel encoding scheme along with polar codes to increase the spectrum efficiency. Furthermore, improved coding performance and decreased decoding complexity allow more energy efficient mobile terminals and increased coverage to support a larger number of users.

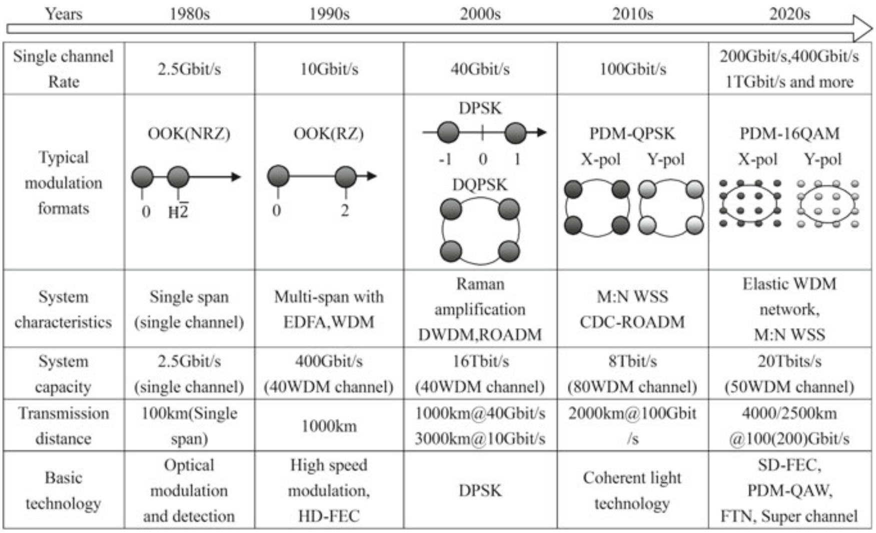
In this chapter, optical fiber communications, free-space optical, VLC, as well as digital modulation, pulse modulation, and encoding technologies for 5G networks will be introduced. Power line communications designs are an alternative to fiber-optic communications to eliminate additional system installations, for example, in renewable smart grids [6], but which are utilized in areas where aging-induced performance degradation is not a severe constraint. To complement the comprehensive survey on power electronics and renewable energy sources integrated into 5G [7], this chapter will introduce and review the applicable waveform designs and modulation formats based on wired and wireless communications infrastructure for point-to-point communications in the smart grid environment.

## 12.2 Optical Fiber Communications

In 1870, John Tyndall, an Irish physicist, gave a public lecture in the Royal Society lecture hall on the principle of total internal reflection of light, and included a simple demonstration: he drilled a hole into the base of a water-filled bucket, and then shone a beam of light onto the water surface to demonstrate the bending of light along the water column outflowing from the hole into another bucket below. This was one of the many early initiatives in controlling the most visible form of energy: light. In 1955, Narinder Kapany prototyped an ultra-thin optical fiber made of glass for light transmission based on the basic principles of refraction [8]. Since then, there have been several attempts to use glass fiber for data transmission, but their success was inhibited by a high loss rate owing to the attenuation of light in long-haul transmission. In 1966, Charles Kao and George Hockham, of The Standard Telecommunication Laboratories in England, published a paper entitled “Dielectric-fiber surface waveguides for optical frequencies,” which proposed for the first time the principle of low-loss optical fiber through impurities/contamination removal, thereby opening the door to the optical fiber communication industry [9]. By 1970, scientists in Corning Incorporated (then Corning Glass Works) in the USA, through doping silica glass with titanium, finally achieved the world’s first ultra-low-loss fiber: a 30-m fiber sample with attenuation less than 20 dB/km [10]. In the early 1970s, Bell Laboratories developed an enhanced chemical vapor deposition (CVD) standard for fiber-optic cable manufacturing. Thereafter, fiber-optic technology continued to flourish, and optical attenuation dropped from 4 dB/km as of 1972 down to 1.1 dB/km by 1974 [11]. In 1976, Bell Laboratories established the world’s first practical communication line from Atlanta to Washington, transmitting at a data rate of 45 Mb/s using MMF and a light-emitting diode (LED) optical source with a 0.85 $\mu$m emission wavelength and a repeater spacing of up to 10 km. Also by 1976, NTT Electronics Corporation reduced optical fiber losses to 0.47 dB/km (at 1200 nm) [12]. Upon further investigations, two low-loss windows were established at 1.31 and 1.55 $\mu$m. By 1979, AT&T and NTT have successfully developed continuous-wave semiconductor lasers with an emission wavelength of 1550 nm, and then NTT developed very low-loss single-mode fibers (SMF) with 0.2 dB/km attenuation at 1550 nm [13]. In 1980, the multimode optical fiber communication system was first commercialized (140 Mb/s), and experimental work also began on the single-mode optic-fiber communication system. In 1990, the first single-mode fiber-optic telecommunication systems were commercialized (565 Mbps), and synchronous digital hierarchy (SDH) was formulated as the technical standard. In 1995, 2.5-Gbps SDH products entered the market, followed by 10-Gbps in the following year. In 1997, 20- and 40-Gbps SDH products were demonstrated with zero dispersion-shifted fiber and WDM, and thus achieving a significant breakthrough. Around the turn of the century, Japan and the USA began to enter the commercial FTTH market. In 2005, 42.8-Gbps single-channel transmission was established between Shanghai and Hangzhou, and 100-Gbps between Paris and Frankfurt. Between 2007 and 2008, the US company Verizon built 3.1-Tbps experimental lines [14]. In 2009, Corning commercially launched an ultra-low-attenuation optical fiber with a loss of 0.16 dB/km at 1550 nm [15, 16]. Also in the same year, Telstra and Nortel Networks have successfully completed a long-haul optical fiber network transmission test between 40 and 100 Gbps. In January 2014, British Telecom deployed the world's first Tbps fiber links based on commercial platforms, at 1.4 Tbps over a distance of 410 km between London and Ipswich. At the 2015 OFC, Corning announced a new fiber with 0.146 dB/km attenuation [17]. Since then, single-channel 400-Gbps optical fiber communication systems were deployed. In 2017, Sumitomo Electric launched a kind of low-loss fiber with an attenuation coefficient of 0.1419 dB/km at a wavelength of 1560 nm [18]. At the OFC that year, AT&T announced the successful completion of a 400-gigabit Ethernet connection field trial between New York and Washington DC using a software-defined network (SDN) controller. Also at the same OFC, Acacia Communications demonstrated the ball grid array (BGA) photonic chip and the next-generation (dual core) Pico digital signal processing (DSP) chip for coherent applications, supporting a wide range of 100G and 400G client interfaces. Meanwhile, advances in physical technologies, such as high-performance semiconductor lasers and modulators, low-noise optical amplifiers, broadband receiver devices, large-scale and ultra-large-scale integrated circuits and microprocessors, continue to underscore the development of the optical fiber communication system.

Optical fiber telecommunications, considered a revolutionary technology in the history of electrical communications, have thus developed rapidly over the past three decades [19–23]. To date, fiber optics are widely employed by virtue of various advantages such as having much lower attenuation, large bandwidth, long-distance relay, outstanding anti-interference properties/electromagnetic immunity, non-conductive behaviour, high security, low-cost, lightweight characteristics, high transmission quality, and so on. The first-generation MMF optics operated at a shorter wavelength (850 nm), low bit rate (34 or 45 Mbps), and a transmission distance relay of about 10 km. Second-generation single-mode fiber-optic systems operated at 1310 nm and enabled a transmission rate of 140–565 Mbps, and with repeater spacing of 50–100 km. Third-generation fiber-optic systems adopted dispersion-shifted single-mode fiber links for operation at 1550 nm with a repeater spacing of 100–150 km and an external modulation technology to realize 2.5–10 Gbps. Fourth-generation fiber-optic systems employ WDM to increase data system capacity up to 20 Tbps, and optical amplifiers enable distance relays in excess of few hundred kilometers, hence reducing reliance on repeaters. Fifth-generation fiber optics focus on extending the wavelength range for deployment of WDM, and other new technology developments involve optical solitons.

The single-channel data rate of optical fiber links has increased from 2.5 Gbps in 1985 to 400 Gbps in 2015. The main techniques include high-speed electro-



| Years | 1980s | 1990s | 2000s | 2010s | 2020s |
|---|---|---|---|---|---|
| Single channel Rate | 2.5Gbit/s | 10Gbit/s | 40Gbit/s | 100Gbit/s | 200Gbit/s,400Gbit/s 1TGbit/s and more |
| Typical modulation formats | OOK(NRZ) 0 H2 | OOK(RZ) 0 2 | DPSK -1 0 1 DQPSK | PDM-QPSK X-pol Y-pol | PDM-16QAM X-pol Y-pol |
| System characteristics | Single span (single channel) | Multi-span with EDFA,WDM | Raman amplification DWDM,ROADM | M:N WSS CDC-ROADM | Elastic WDM network, M:N WSS |
| System capacity | 2.5Gbit/s (single channel) | 400Gbit/s (40WDM channel) | 16Tbit/s (40WDM channel) | 8Tbit/s (80WDM channel) | 20Tbits/s (50WDM channel) |
| Transmission distance | 100km(Single span) | 1000km | 1000km@40Gbit/s 3000km@10Gbit/s | 2000km@100Gbit/s | 4000/2500km @100(200)Gbit/s |
| Basic technology | Optical modulation and detection | High speed modulation, HD-FEC | DPSK | Coherent light technology | SD-FEC, PDM-QAW, FTN, Super channel |

**Fig. 12.1** Technology development of fiber-optic communication transmission over the past three to four decades. Reproduced from Cui et al. [38]

optic modulation, high-speed optical detection, hard decision forward error correction, DPSK, differential quadrature phase shift keying (DQPSK), coherent detection, optical DSP, soft decision forward error correction, polarization multiplexing (PM), MQAM and faster-than-Nyquist (FTN) modulation and demodulation [24–32].

With the introduction of super channel technology [33–35], the channel rate has exceeded 1 Tbps [36]. Meanwhile, the introduction of broadband fiber-optic amplifiers, such as erbium-doped fiber amplifier (EDFA) and Raman fiber amplifier (Raman amplifier), has enabled WDM to become a reality. The fiber-optic link is also developed from an early single span to today's multi-span, freely switched transparent WDM and flexible-grid WDM networks [37], as shown in Fig. 12.1 [38].

Fiber-optic communications will be the foundation for 5G networks within the physical layer, for which the service-based architecture (SBA) was identified as the basic architecture for 5G core networks at the recent 3GPP conference in June 2017. The future for 5G is in the evolution of optical fiber communication technologies, incorporating advanced multiplexing, chromatic dispersion (CD) compensation, and PMD compensation schemes, that will target high-capacity, high-speed, and ultra-long-haul performance capabilities. Modified fiber manufacturing techniques enable the all-wave fiber to expand on traditional communication channels, and in conjunction with soliton-based optical communications, electro-optic modulators are developed to boost single-channel transmission up to Tbps rates, and establish greater capacity and reliability in AON technologies for fiber-optic communications.

The ensuing section first introduces the sources of loss and dispersion which limit performance in fiber-optic communication, then introduces optical modulation schemes and devices in fiber-optic systems. Multiplexing technologies including higher-order multiplexing will be discussed, in terms of their benefits to the system capacity and data transmission rates. Finally, this section will introduce several important directions in the research and development of fiber-optic communications in 5G.

## *12.2.1 Fiber Characteristics for Communications*

In fiber-optic telecommunication systems, laser diodes or LEDs are used as optical transmitters, which convert electrical signals into optical signals that are coupled into optical fibers for transmission. At the receiving end, PIN photo diodes or avalanche photodiodes (APD) are employed, which recover the electrical signals from detected optical signals. However, in long-haul systems and high-speed fiber-optic networks, signal loss and dispersion are major challenges for fiber performance especially at high data rates, for example, in excess of 100 Gbps. CD and PMD effects limit fiber links, even in spite of high-powered lasers and fiber amplifier regenerators. In particular, nonlinear effects occur when the optical signal power is boosted to mW levels in an attempt to increase the unrepeated transmission range. Hence, a variety of CD, PMD, and nonlinear compensation techniques have been proposed, with modulation formats centered on reducing dispersion. Here, we discuss attenuation, dispersion, and nonlinear effects in fiber optics.

### 12.2.1.1 Optical Fiber Loss

Optical power loss caused by fiber attenuation is very important to characterize in fiber optics as it largely determines the maximum length of fiber that the signal can be relayed without regeneration. Spectral attenuation, which is low at long wavelengths, is due to absorption and scattering, which in turn depend on temperature, pressure, humidity, the surrounding environment, and other physical factors. Absorption in the optical fiber includes UV absorption, infrared absorption, transition metal absorption, and hydroxide absorption, while scattering includes Rayleigh scattering and scattering from imperfect structures.

### 12.2.1.2 Optical Fiber Dispersion

As an optical fiber is composed of a normally dispersive media, a propagating optical pulse will consist of different group velocities depending on the wavelength, and different mode field diameters and modal path lengths, thereby resulting in pulse broadening and/or jitter in the received signal which is cumulative over the length of the fiber link. Consequently, pulse spreading beyond allotted time intervals in digital communications may lead to interference of one symbol with subsequent symbols, or inter-symbol interference (ISI), thereby introducing errors in the decision device at the receiver output due to signal distortion. With pulses overlapping into adjacent pulses, their distinguishability at the receiver end is reduced, and thus the error rate increases. Hence, fiber dispersion limits the bandwidth or data transmission capacity of the fiber because bit rates cannot be too high, and pulses need to be further apart to tolerate dispersion effects. There are three main types of dispersion in an optical fiber: material dispersion, waveguide dispersion, and modal dispersion, the former two causing CD in single-mode optical fibers. Material dispersion is due to the varying wavelength-dependent refractive index in the transmission medium; the longer wavelengths travel faster. Waveguide dispersion results from light traveling faster in the cladding (lower refractive index) than in the core (higher refractive index); longer wavelengths travel in a larger mode field diameter, and are therefore more prone to material dispersion. Material and waveguide dispersion have opposite frequency response characteristics, therefore judicious design of fiber material and index profiles enables zero dispersion wavelength in single-mode fibers. Modal dispersion occurs only in MMFs, due to the varying modal path lengths in the fiber. To reduce modal dispersion, the core diameter can be reduced to, e.g., 9 $\mu$m or less at 1.55 $\mu$m, where only one mode is able to propagate efficiently (i.e., single-mode fiber). Hence for the single-mode optical fiber, there is no modal dispersion since only one mode is permitted for transmission.

PMD is related to the different transmission rates, or differential group delay, between two orthogonal polarized modes in the optical fiber due to material birefringence and waveguide birefringence. Variations in random physical characteristics of each fiber in the link, such as concentricity or ellipticity (inducing waveguide birefringence), and/or variations in ambient temperature or stress on the fiber (inducing material birefringence), lead to PMD.

In the laying of optical fiber link lengths surpassing 1,000 km, the influence of PMD will be amplified; hence, PMD compensators should be deployed. The wavelength of light near 1.55 $\mu$m is in a low-loss region; hence, the general transmission wavelength is between 1.28 and 1.6 $\mu$m in the optical fiber. It is possible to produce single-mode fibers with a total dispersion of less than 1.6 ps/km/nm in this wavelength range. Dispersion compensation technologies are mainly divided into two categories: one is based on optical techniques, and the other based on electrical techniques. The former is through the design and manufacture of optical compensation devices, such as the dispersion compensating fiber (DCF) that can be added in optical fiber links. Negative dispersion compensation is provided at 1.55 $\mu$m, so that the net dispersion is approximately zero; while the DCF consists of a complicated structure at a high cost, the technology is relatively mature. The latter does not need to add extra optical parts, and hence it is a low-cost and simple solution, but not as mature due to limitations in the development of electrical techniques.

#### 12.2.1.3 Nonlinear Effects in Optical Fibers

Nonlinear effects are other performance limiting factors in optical fibers. In conventional telecommunication systems, optical fibers usually exhibit linear transmission characteristics due to the fact that quartz is a relatively weak nonlinear medium. However, when the optical signal power is larger than a few mW, the intensity per unit core area can reach up to the order of $MW/m^2$, as the optical waves are confined within the small diameter of the fiber core. When a sufficiently intense optical beam is coupled into the fiber exceeding the threshold level, a nonlinear response will be exhibited via Brillouin scattering with most of the light backscattered in the opposite direction to that of transmission; in other words, the influence of the optical fiber parameters on the light intensity is no longer constant. Especially in long-haul optical fiber links, the cumulative nonlinear and attenuation effects are substantial. There are two major kinds of nonlinear effects in fiber optics, namely stimulated scattering and refractive index perturbation, which can result in signal degradation through signal attenuation, power saturation, back-propagation, etc.

Stimulated scattering in optical fibers occurs when the light and one of the crystalline lattice waves—acoustic mode (phonons), charge displacement mode (polarons), or magnetic spin oscillation mode (magnons)—interact, causing a fraction of the transmitted lightwave to change its momentum (thus wavelength) through an inelastic process. The most important types of nonlinear scattering within optical fibers are: stimulated Brillouin scattering (SBS) and stimulated Raman scattering (SRS). The former may be caused when the electric field variations in an intense optical beam induce acoustic phonon vibrations in the dielectric-fiber medium via electrostriction or radiation pressure, thereby resulting in frequency shifts through energy loss (gain) to generate (absorb) the quasi-particles (phones, polarons, or magnons). Generated acoustic waves interacting with the pump wave lead to, through alteration of refractive index, a backscattered optical wave called Stokes wave. The propagation of acoustic waves through the optical fiber in turn induces spatially periodic local compressions/expansions that cause local changes in the refractive index (photoelastic effect). As a consequence of backscattering, SBS limits the maximum signal power that can be transmitted through a fiber link. In contrast, SRS involves only the interaction of electromagnetic waves with random and incoherent thermal fluctuations (or optical phonons) generated by spontaneous Raman scattering, and results in scattering in both the forward and reverse directions [39]. In a single-channel optical fiber communication system, SRS is generally not an issue because the threshold power for its onset is about 500 mW at 1.55 $\mu$m, well above the typical optical power of about 10 mW [40]. However, in the WDM system, as long as the wavelength difference is within the Raman gain profile, SRS effects are significant, resulting in energy transfer from shorter to longer wavelength signals. This process induces power depletion in short wavelength channels and power amplification in long wavelength channels, for interchannel separation reaching as high as 200 nm in the presence of fiber nonlinearities. Thus, interchannel interference (ICI) can be caused by nonlinear Raman crosstalk, and signal-to-noise ratio degradation is most severe in the shortest wavelength channel. Without careful evaluation of the SRS induced power depletion and suitable mitigation schemes, the maximum transmission range and capacity in WDM systems will be heavily constrained. SRS restricts the maximum transmission power in the optical fiber and limits the transmission capacity, leading to inter-channel interference (ICI) in the WDM system, generate SRS noise, cause error codes and reduce the communication quality.

Refractive index perturbation in a material in response to an applied electric field is known as the optical Kerr effect. The second-order nonlinear refractive index of quartz glass is relatively small, hence the nonlinear effect is correspondingly very small. However, its compounded effect significantly affects fiber performance in very long-haul communications fiber links. The nonlinear refractive index change resulting from the temporal change in optical signal intensity leads to phase shifts, known as self-phase modulation (SPM), as well as cross-phase modulation (XPM) between the two pulses. XPM is so-called when the optical power from one wavelength of light modifies the refractive index, and through the optical Kerr effect, affects the phase of another wavelength. In addition, four-wave mixing (FWM) is an intermodulation phenomenon that may occur particularly with decreased channel spacing, e.g., in dense wavelength division multiplexing (DWDM) systems, or at high signal power levels, due to interactions between two or three wavelengths that produce one or two new wavelengths. At high optical power, when three different frequencies of incident photons interact in a nonlinear medium, they give rise to scattering that produces the fourth photon frequency. As the optical transmission speed increases, besides the nonlinear effects between channels, intra-channel cross-phase modulation (IXPM) and intra-channel four-wave mixing (IFWM) become more significant between pulses. SPM, IXPM and IFWM are collectively referred to as intra-channel nonlinear interactions [41–43].

With the adoption of high-speed optical fiber communication systems based on DWDM, high data rate transmission, high optical signal power, and high channel density, can cause adverse fiber nonlinearities, ICI and other issues, which crucially limit the performance of optical communication systems [44]. Compensation of unwanted nonlinearities and suppression of phase shift caused by nonlinearity is key to further improve the quality of optical fiber transmission. In fact, the compensation of nonlinear effects in optical fibers should be distinguished from dispersion compensation, though it is difficult to describe quantitatively its very complex interaction with the signal. Scientists have studied ways to eliminate nonlinear effects in optical fibers and have developed nonlinear electrical equalization [45–47], precoding [48], digital backward propagation [49, 50], and other, techniques. Nevertheless, a principal means to control SBS is by broadening the spectral light source or raising the SBS threshold power above 20 dBm. The threshold power can be increased either by optical phase modulation (dithering) or initial pulse modulation and spectrum scattering by transmission in a double-clad fiber. An appropriate design of fiber Bragg grating (FBG) can also be applied within the optical fiber for SBS suppression. Spectral broadening of the signal due to XPM induced by the pump suppresses the SBS effect in a Raman fiber amplifier. In WDM systems, the effect of SRS is to amplify the long wavelength channels at the expense of short wavelength channels, but this can be considerably reduced by properly configuring the number of channels, channel spacing, optical signal power, and transmission distance [51]. Especially in long-distance transmission, the difference in optical signal power between long and short wavelengths due to SRS imposes a received power limitation [52]. Nevertheless, spectral inversion techniques followed by compensation for fiber loss can be implemented to determine the optical signal power to be launched at the different wavelength channels; this can minimize spectral distortions and attenuations introduced by SRS and the wavelength-dependent linear loss coefficient of the optical fiber, respectively. In addition, reducing the input power at each channel can mitigate SRS-induced crosstalk, and a fiber-optic relay system can be utilized to extend the transmission distance. For DWDM networks without optical generators, optical signal power equalization can be applied at the input to increase the high-frequency signal power so as to ensure homogeneity of the output optical power at each channel [53]. Furthermore, optical and electrical equalization technologies can effectively reduce the impact of SPM [54–57]. Especially with regards to the phase shift keying (PSK) system, because the nonlinear phase shift caused by SPM is related to the signal strength, a phase shift proportionate to the received signal can be applied to partially offset the influence of SPM [56, 57]. For 10-Gbps WDM as well as 10- and 40-Gbps hybrid systems, XPM has an adverse impact on system performance [58, 59]. The effect of XPM can be effectively mitigated by appropriate dispersion management technologies [60]. In G.653 optical fiber systems and dense multi-user systems, FWM is yet more serious. Predistortion techniques [61] and electro-domain post compensation techniques [62] based on coherent detection are currently used to reduce the influence of FWM. The effects of intra-channel nonlinear interactions are more serious than that of XPM and FWM, and are thus dominant in 40-Gbps systems [63]. IXPM and IFWM only occur in the overlapping regions of the pulses in the channel, which can be suppressed by appropriate dispersion management schemes [64–66], new modulation formats [67, 68], or optical (electrical) equalization technologies [69, 70].

### *12.2.2 Optical Modulation and Modulators*

In telecommunications, modulation is the process of varying the properties of the carrier signal, which is a transmitting electromagnetic pulse or wave (or a laser-generated light beam), with a modulating signal containing information to be transmitted. This carrier signal may be carried over free space, or propagated through an optical waveguide. Optical modulators are devices that modulate beams of light in fiber optics. The following section is to introduce the concept of light modulation and several optical modulation devices.

#### 12.2.2.1 Optical Modulation

In fiber-optic communication systems, the optical pulse emitted by the light source can be used as a carrier signal. An optical modulator is required to load the information-bearing signal onto the carrier wave so that the resulting optical beam can be physically transmitted and deciphered at the receiving end of the transport

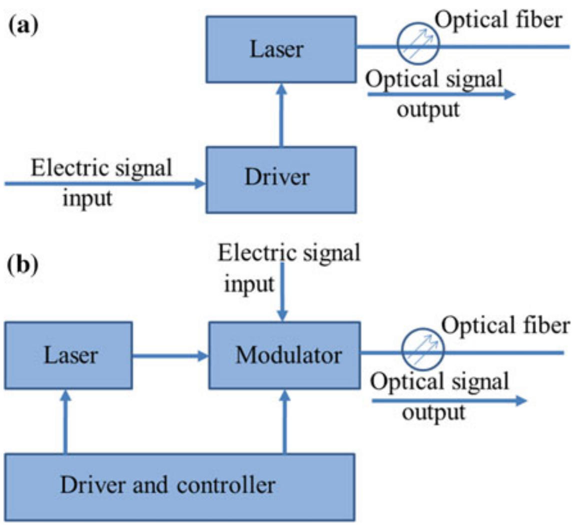



**Fig. 12.2** **a** Direct and **b** external modulation of optical signal

medium. There exists a large range of modulation techniques, which can be divided into two categories, internal (direct) modulation and external modulation, as shown in Fig. 12.2.

Direct modulation is relatively easy: by modulating the electrical signal (current or voltage) driving the light source (e.g., semiconductor laser diode). The disadvantage in this is that a narrow linewidth is required from the laser diode, and high bandwidth chirp may occur when applying and removing the drive current; hence, it is suitable only in low data rate and short-distance communication systems. External modulation involves light modulator devices that can mainly be categorized into two groups based on the material properties modified: absorptive modulators (absorption/attenuation coefficient) and refractive modulators (refractive index). In electro-absorptive modulators, the absorption coefficient of the material can be controlled by the quantum-confined Stark effect, Franz–Keldysh effect, excitonic absorption, Fermi-level changes, or free carrier concentration changes. Refractive modulators employ an electro-optic effect (electro-optic modulator), or acousto-optic effect (acousto-optic modulator), or magneto-optic effect (magneto-optic modulator), or exploit polarization changes in liquid crystals to modify the phase of an optical beam, which can in turn be amplitude modulated using an interferometer or directional coupler. Spatial light modulators (SLMs) can alter the two-dimensional distributions of amplitude and/or phase of a light wave.

What follows is a brief introduction to these modulators. If the modulation is imposed on the amplitude, frequency, phase, or polarization of the light beam to represent the quantized digital signal “1” or “0”, we can transmit information by using modulation techniques such as on-off keying (OOK), frequency shift keying (FSK), DPSK, DQPSK, quadrature amplitude modulation (QAM) and PolSK, all of which will be discussed in detail below. However, FSK is gradually less used in high-speed optical fiber communications due to limitations from fiber dispersion and narrow band filtering effects. Amplitude and phase modulation technologies are important to support high-speed optical fiber telecommunication systems, especially in 5G.

#### 12.2.2.2 Electro-Optic Modulator

Electro-optic modulators exploit the electro-optic effect that is due to the material's refractive index change resulting from the application of a DC or low-frequency electric field. Electrostatic forces can modulate the refractive index by distorting the position, orientation, or shape of the molecules constituting the material.

Either of two types of effects may dominate in an electro-optic medium: Kerr effect or Pockels effect (Fig. 12.3). The effect dominating in the optical modulator determines whether it is a Kerr cell or Pockels cell. For the Kerr effect, the refractive index change (or birefringence) is proportional to the square of the electric field intensity. When no voltage is applied to the Kerr cell, the optical medium is transparent, and the polarization state of the light propagating through it is unaltered so that no output of light can pass through as the linear polarization is perpendicular to the optical axis of the polarization analyzer Q. With an electric field applied, the polarization state of the incident light is modulated, resulting in a corresponding intensity of the beam output; an optimum electric field will allow nearly all the light to be transmitted through. Periodic changes in applied voltage can modulate both the polarization and intensity of the optical beam. By the Pockels effect, the birefringence produced is linearly proportional to the electric field. Two kinds of modulation are possible in the Pockels cell depending on the orientation of the applied electric field in relation to the light beam: longitudinal and transverse (see Fig. 12.3). P is a polarizer, and Q is a polarization analyzer in Fig. 12.3.

#### 12.2.2.3 Acousto-Optic Modulator

An acousto-optic modulator consists of two parts: acousto-optic medium and a piezoelectric transducer attachment (Fig. 12.4). The typical acousto-optic medium may be made from lead molybdate crystals, tellurium oxide crystals, fused quartz, etc. When an oscillating electric signal drives the transducer, ultrasonic waves are generated that propagate through the cell structure with the refractive index changed by moving periodic planes of expansion and compression. The periodic refractive index change in the optical medium is known as acoustic grating. The grating pitch is equal to the wavelength of the acoustic wave. When a light beam is incident on the acoustic grating, both diffraction and shifting of the light frequency occur, which is called the acousto-optic effect, and represents the operating principle of acousto-optic modulators (or Bragg cells). Light beam modulation can occur in five ways: (i) **Diffraction**. The angular diffraction depends on the wavelength of the incident light relative to the pitch of the acoustic grating. (ii) **Intensity**. The amount of light diffracted by the

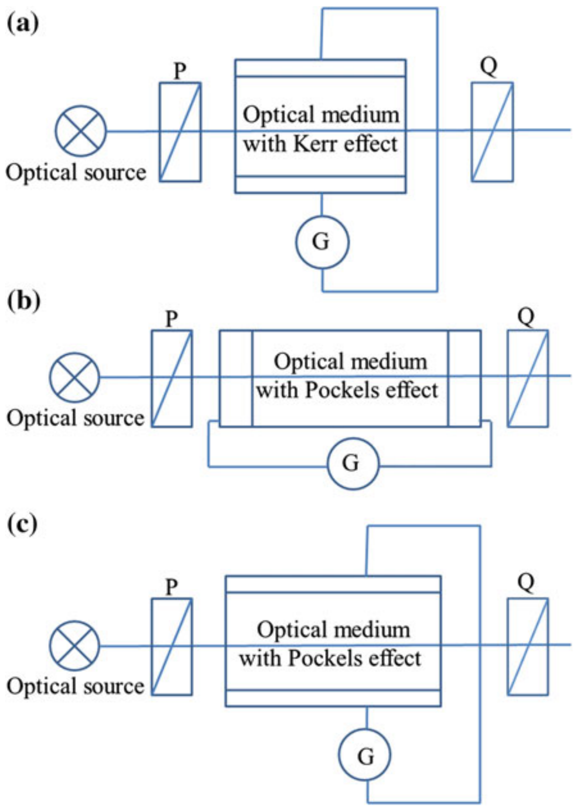



**Fig. 12.3** Basic structures of electro-optic modulators, such as **a** Kerr cell, and Pockels cell with an electric field applied, **b** longitudinally, and **c** transversely to the propagating light beam

acoustic grating depends on the intensity of the ultrasonic wave. (iii) **Frequency**. When the incident light is scattered from the moving planes of ultrasound waves, the frequency of the diffracted beam will be Doppler-shifted by an amount equal to the acoustic frequency. (iv) **Phase**. The phase of the diffracted light beam will be shifted by the phase of the sound waves. (v) **Polarization**. The acoustic waves induce a birefringent phase shift, much akin to the Pockels effect.

#### 12.2.2.4 Magneto-Optic Modulator

In a magneto-optic modulator (Fig. 12.5), a crystalline medium having properties that can be modified by the presence of a magnetic field is utilized. Gyromagnetic materials are exploited in this case, wherein the plane of polarization can be rotated for a linearly polarized light on passing through the crystal, known as the Faraday effect. The amount of Faraday rotation is related to the direction of the incident light, the permittivity tensor, and the thickness of the gyromagnetic crystal. Left- or right-hand circular polarization therefore depends on the crystal medium. By

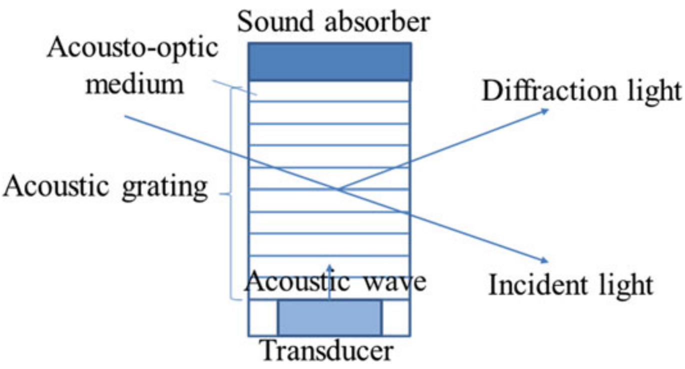



**Fig. 12.4** Structure of an acousto-optic modulator

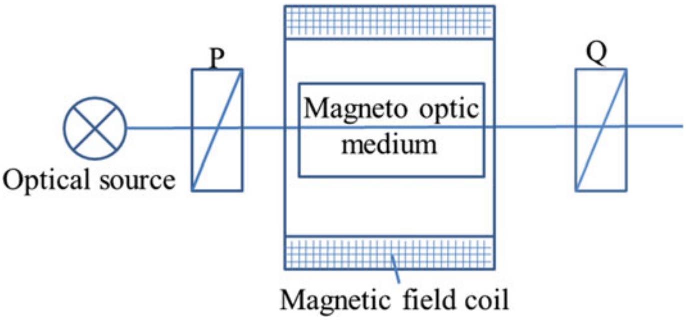



**Fig. 12.5** Structure of a magneto-optic modulator with magnetic field applied perpendicularly to the light propagation direction

changing the intensity of the applied magnetic field, the polarization and intensity of the propagating light can be modulated, a principle similar to that of the electro-optic modulator. The magneto-optic effect can also be deployed to design an optical isolator through which the optical wave passes only in one direction but not in the other. P is a polarizer, and Q is a polarization analyzer in Fig. 12.5.

#### 12.2.2.5 Mach–Zehnder Modulator

By using a Mach–Zehnder interferometer, a phase-modulated electro-optic modulator can be deployed as an amplitude modulator. In a Mach–Zehnder modulator (MZM) shown in Fig. 12.6, the laser beam can be split into two paths, one of which is phase modulated. The refractive index changes linearly with applied voltage in the electro-optic material, so that there is a phase difference when the two beams recombine. Changing the electric field on the phase modulating path will determine whether the two beams interfere constructively or destructively at the output, thereby

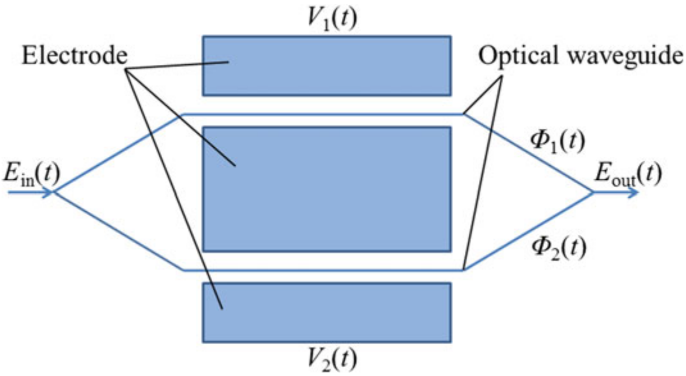



**Fig. 12.6** Operational principle of MZM

controlling the amplitude (intensity) of the exiting beam. If the optical path difference of the two beams is an integer multiple of the wavelength, constructive interference occurs; if the optical path difference is a half integer multiple of the wavelength, then destructive interference occurs. Thus, the intensity and phase modulation of the optical wave can be realized using an MZM.

### *12.2.3 Multiplexing Technologies in Optical Fiber Telecommunications*

On one hand, the requirements for high-capacity optical fiber communications are increasing, and 400-Gbps single-carrier technology is popular. On the other hand, 5G networks will require Tbps technology for a sufficiently large bandwidth, which necessitates the application of various multiplexing technologies to cope with increasing transmission capacity. With the evolution of high-capacity optical transmission technology based on electrical time division multiplexing (TDM) in the early 1990s to that based on optical WDM by the end of the 1990s, transmission capacity increased from 2.5 to 10 Gbps. WDM technology improved from coarse WDM to DWDM. PDM allows doubling of the transmission capacity by utilizing waves of two orthogonal polarization states so that two channels of information can be transmitted on the same carrier frequency, thereby doubling the spectral efficiency. Furthermore, code division multiplexing (CDM) has emerged in which multiple data signals are combined for simultaneous transmission over a common frequency band, thereby making full use of code domain resources to improve the bandwidth capacity. Using higher-order modulation formats such as MQAM or orthogonal frequency-division multiplexing (OFDM) can increase the spectral efficiency as well. For example, PDM-16QAM and 256QAM-OFDM transmissions achieved a spectral efficiency of 6.3 bit/s/Hz [71] and 14 bit/s/Hz [72], respectively. OFDM technology performs well in suppressing CD and PMD effects, and can resolve the problem of multi-path fading in signal transmission. With the adoption of higher-order modulation formats, the minimum Euclidean distance between constellation points decreases, accompanied by a reduction in both dispersion and nonlinear tolerance. For increased optical signal-to-noise ratio (OSNR) requirements, higher optical power is required in optical fiber links, but which induces susceptibility to nonlinear effects that limit the system performance. Therefore, there is much focus on other multiplexing schemes to further expand the transmission bandwidth in single-mode fiber links. Owing to advances in multi-core fiber processing technology, multi-core space division multiplexing (SDM) has also gained a lot of attention.

Since the popularity of FTTX broadband networks in the previous century, multiplexing technologies have been extensively employed in PONs, thereby driving the development of TDM-PON, WDM-PON, OFDM-PON, TDM-WDM-PON, etc. The main multiplexing schemes for optical signal transmission in optical fiber links are WDM, OFDM, TDM, CDM, PDM, SDM and mode division multiplexing. The growing data traffic resulting from the convergence of various network services can be better handled through an evolution in DWDM, whereby a plurality of coherent optical carriers are combined to form a super channel. This is one of the most essential technologies for 5G high-speed data transmission. In fact, DWDM, TDM, and CDM are the foremost multiplexing technologies to increase channel bandwidth and data transmission rate; WDM is to increase the number of channels, whereas TDM and CDM are to increase the data capacity of single-channel links. WDM, TDM, OFDM and other various multiplexing technologies can be combined to greatly enhance the fiber-optic system capacity.

#### 12.2.3.1 Optical Wavelength Division Multiplexing

WDM is a technology that multiplexes two or more different optical carrier signals onto a single strand of optical fiber at the same time, essentially by using different wavelengths of the light beam, or frequency-division multiplexing (FDM), as shown in Fig. 12.7. Carrier signals in the wavelength range between 1.26 and 1.6 $\mu$m can be employed since the corresponding optical loss is relatively low in optical fiber links. Figure 12.8 shows the structures of typical WDM and WDM with optical add-drop multiplexers (OADMs). Prisms and diffraction gratings, which are passive devices and are thus highly reliable, can be used in WDM optical systems to combine (multiplex) or split (demultiplex) different wavelength signals. With WDM, the extremely high bandwidth (~25 THz) in the 1.55 $\mu$m low-attenuation band of single-mode fiber can be fully utilized when a plurality of non-synchronous signals can be transmitted along the same optical fiber link. WDM systems are popular because they allow the capacity of the network to be expanded without having to lay extra fiber links. WDM has been used to expand the capacity of installed point-to-point transmission systems through the addition of wavelengths. There is no need to overhaul the backbone network through new technology development in the optical fiber infrastructure since using WDM and optical amplifiers is sufficient to achieve bidirectional communi-

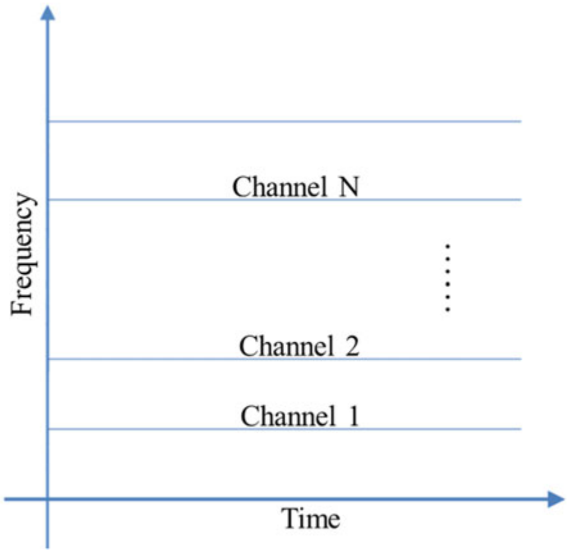



**Fig. 12.7** Schematic diagram illustrating FDM

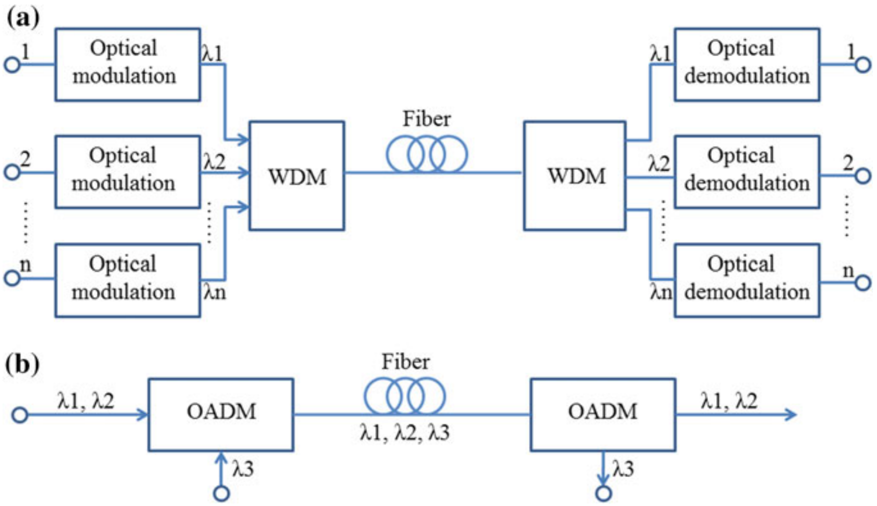



**Fig. 12.8** Operational principle of WDM. **a** Typical WDM structure and **b** WDM structure with OADM

cations, upscale the capacity at great flexibility, and avoid high installation costs.

Coarse WDM, which uses wavelengths from 1271 through 1611 nm with a channel spacing of 20 nm, allows less sophisticated and less expensive transceiver designs. Advances in high-precision lasers and (de)multiplexing devices permit an increase in the total number of channels in a single fiber by using very narrowly-spaced channels, in what is known as DWDM. Typical channel spacings range from 0.4 to 4 nm, providing a greatly improved bandwidth of between 50 and 500 GHz.

Advanced optical transmission technologies, such as coherent optical OFDM to combat dispersion in optical media, Nyquist-WDM and arbitrary waveform generators, are identified as enablers of flexible-grid optical networks. The enhanced spectral efficiency, operational flexibility, and network capacity by spectrum on-demand allocation and adaptive modulation may be widely deployed in 5G networks.

#### 12.2.3.2 Optical Orthogonal Frequency-Division Multiplexing

OFDM is a multi-carrier modulation technique, based on the principle of dividing a channel into several parallel sub-channels (frequencies), thereby converting high-speed data signals into parallel low-speed data streams. Essentially, it is a technique of encoding digital data on multiple carrier frequencies, so that individually, each optical sub-carrier is more dispersion-tolerant. OFDM has traditionally been adopted in RF wireless systems; in the 1950s, it had been deployed in military data transmission systems. Thereafter, with the rapid development of multi-chip modules and integrated circuits, it has since been widely employed in high-speed digital communications, and has even become the core technology in 4G networks. In 1996, Pan and Green published the first paper on optical OFDM, which referred to the idea that OFDM technology can be applied to optical fiber communications [73], and since 2001, OFDM technology has been employed in fiber-optic communications. In 2006, Lowery et al. [27] showed that OFDM can be applied to adaptively mitigate CD in ultra-long-haul single-mode fiber links. Overall, optical OFDM technology has many advantages compared to traditional OFDM:

(1) **Higher spectral utilization rate**. A large number of closely spaced orthogonal sub-carrier signals can be used to carry data on several parallel data streams, but unlike DWDM, the sub-carrier spectra can even overlap, as shown in Fig. 12.9, hence the spectral efficiency is superior. By extracting the phase and amplitude of each sub-carrier, Fast Fourier Transform (FFT) is used to separate the sub-carriers, which are orthogonal in the frequency space, without crosstalk. Studies have shown that the OFDM spectrum utilization rate can reach at least 2.9 bit/s/Hz, and if combined with other multiplexing technologies, can achieve more than 10 bit/s/Hz.
(2) **Complex processing of rare earth elements for CD and PMD compensation in fiber links not needed**. As each sub-carrier data rate is much lower, CD in an optical fiber, being inversely proportional to the square of the baud rate, is significantly low. Hence, ISI caused by multi-path propagation can be eliminated. In addition, a cyclic prefix can be added to the data block for resilience against inter-channel interference.
(3) **Digital equalization can be performed at the receiver using mature DSP technology**. Efficient phase and amplitude equalization can compensate vari-

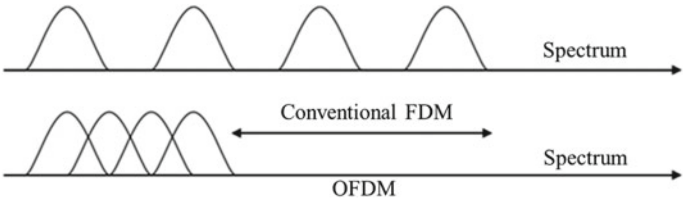



**Fig. 12.9** OFDM improves the spectral efficiency greatly compared with conventional FDM

ations in dispersion along the fiber link, which is a significant advantage over electronic pre-compensation in traditional OFDM.

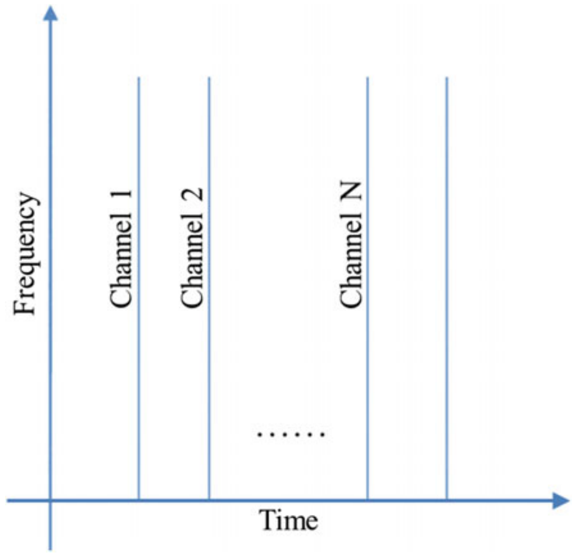
#### 12.2.3.3 Optical Time Division Multiplexing

TDM is a technique that divides a channel into multiple time slots using synchronized switches at each end of the optical fiber link. An optical pulse consisting of different baseband signals is distributed to occupy each time slot, so that N baseband channels are multiplexed into a single transmission line, as shown in Fig. 12.10. Due to single wavelength transmission, the management of cascaded amplifiers and dispersion is greatly simplified because each node in the network of electronic devices operates locally at a low data rate, therefore improving the transmission capacity of a single channel. Each encoded TDM frame comprises a time slot for each sub-channel, a synchronization channel, and may also include an error-correcting channel. In this modulation technology, a stable, ultra-narrow pulse laser is key for high-speed and long-haul optical fiber telecommunication systems.

#### 12.2.3.4 Optical Code Division Multiplexing

CDM or synchronous code division multiple access (CDMA) evolved from those used in simple radio transceivers and is widely adopted in second-generation (2G) and third-generation (3G) of wireless mobile telecommunications technologies. CDMA is a technology that employs CDM to allow multiple users to share the same multipoint transmission medium or communications channel. A typical CDMA system setup is shown in Fig. 12.11. The system consists of users' data sources, ultra-short pulse lasers, optical switches, adjustable optical CDMA encoders, optical star couplers, adjustable optical CDMA decoders, photodetectors, and electrical threshold detectors, etc. In CDM technology, the transmitter encodes the signal using a pseudo-random spreading sequence whereby each channel is assigned its own code to separate it from one another. In other words, each user in synchronous CDMA may use a code orthogonal to that of others for signal modulation. Multiplexing with a spreading code increases the bandwidth by spreading it out over the available spectrum for the signal. When the underlying spreading codes are decoded at the receiving

**Fig. 12.10** Schematic diagram illustrating TDM



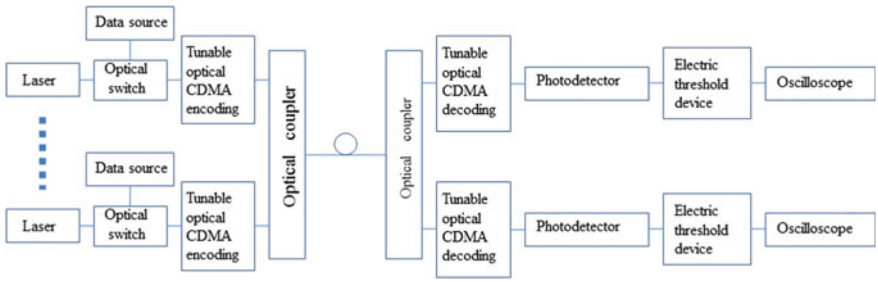




**Fig. 12.11** Schematic diagram illustrating a CDMA system

device, the original data signals are demultiplexed and restored from the transmitted signal. Orthogonal codes have zero cross-correlation, which means that they do not interfere with one another. Hence, CDM allows efficient practical utilization of the fixed frequency spectrum, and high security and flexible resource allocation due to channel coding, as well as having excellent anti-interference properties. Moreover, the stability and linewidth requirement of the light source is less stringent than that for WDM. Other advantages of CDM include asynchronous access, the ability to deal with information transmission in an emergency, and the simplified manner of optical information processing without requirement of highly selective frequency filters, and freedom from nonlinear FWM effects.

#### 12.2.3.5 Other Division Multiplexing Technologies

I. Polarization division multiplexing

PDM doubles the fiber link system capacity and improves the spectrum utilization rate through transmitting two channels of information on the same carrier frequency by virtue of using optical waves of two orthogonal polarization states [74, 75]. Further, the separate left and right circularly polarized light beams can be transmitted through the same optical fiber. The key devices involved are the polarization beam combiner, polarization beam splitter, polarization controller, and filter, etc. In practice, the polarization states of the signals may continuously drift during transmission owing to the influence of physical changes in the fiber such as external pressure and temperature. Therefore, it is important to be able to achieve dynamic demultiplexing of two orthogonal polarization states at the receiving end of the communication link. At present, polarization demultiplexing is based on two major technologies: direct demultiplexing in the optical domain and coherent detection in the digital domain. Compared with the latter, direct demultiplexing in the optical domain has the advantage of not requiring high-speed DSP circuits or high-speed interfaces from ADC to DSP, and the use of highly multilevel modulation formats to obtain ultra-high per channel bit rates can be managed more efficiently.

II. Mode division multiplexing

MDM benefits the system bandwidth by exploiting the spatial modes of waveguides to carry multiple signals simultaneously. The excitation of higher-order modes with high efficiency, low complexity, and high resolution is the premise of MDM. Different waveguide modes are orthogonal to one another, thereby providing independent spatial dimensions for data transmission. Therefore, the development of long-haul MDM systems requires fibers and optical components that support multiple spatial modes, such as modal and wavelength (de)multiplexers, wavelength-selective switches, and high-performance multiple-input multiple-output (MIMO) signal processing architectures. Long-distance propagation over fiber links may result in intra-group or inter-group mode coupling due to random or intentional index perturbations, bends, twists, or stresses, but the received signals can be demultiplexed by MIMO processing. When combined with WDM, a data rate higher than 4 Tbps may be expected via a single multimode optical fiber link.

The present mode conversion and (de)multiplexing methods are based on employing waveguide structures of multimode long-period fiber gratings, planar waveguides, photonic lanterns, and directional couplers; or are based on employing free-space optics involving phase masks, phase plates, SLMs, beam splitters, mirrors, and lenses. The approach using all-fiber/waveguide structures are considered to provide higher mode conversion efficiency, besides being highly integrable and compact. On the other hand, free-space optics systems are generally polarization insensitive and demonstrably broadband.

III. Space division multiplexing

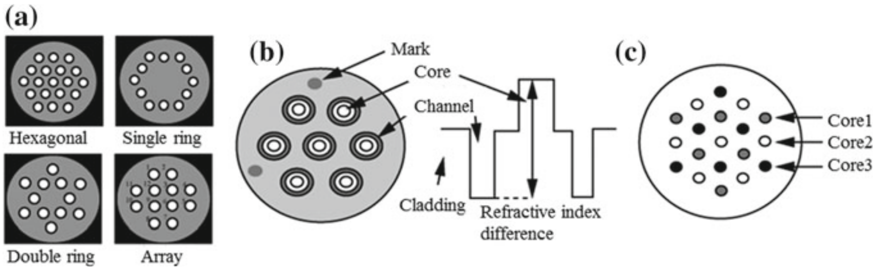



**Fig. 12.12** Typical MCF structures. **a** Air-hole distributions, **b** channel-assisted MCF structure, and **c** heterogeneous fiber core structure. Reproduced from Lai et al. [76]

The maximum transmission capacity of SMF is about 100 Tbps, constrained by nonlinear effects and the Shannon limit. SDM technology is a breakthrough that, by modulating each data channel into individual spatial or polarization modes, increases the number of parallel channels to realize ultra-high-capacity long-haul transmission. Multi-core fiber (MCF) multiplexing is an intuitive way to enhance the capacity of a single fiber, and therefore SDM technologies include MDM utilizing few-mode fibers (FMF), MCF, or multi orbital angular momentum (OAM) fibers, etc. [76]. Though the maximum capacity of a standard SMF is about 100 Tbps [77, 78], mode multiplexing can achieve a capacity exceeding 115 Tbps [79], and 2.15 Pbps is possible with multi-core multiplexing [80]; combining multiple cores and modes can further improve the transmission capacity and spectral efficiency and eclipse the performance records previously held [81, 82].

The multiplexing of multiple SMFs in the same transmission link increases the spatial fiber density and constitutes the MCF [83]. Representative MCFs are schematized in Fig. 12.12, which are typically utilized for increased spatial diversity. The bandwidth can be multiplied, and with a larger core diameter, a substantially higher spectral efficiency and power threshold can be achieved in SDM transmission compared to that of SMF. To support multiple spatial paths, the key technologies in an MCMM system include MCF design, fan-in and fan-out multiplexing, wavelength-selective switching, inline optical amplification, multi-core alignment, and extensive photonic and electronic integration. Increasing the number of cores and decreasing the core spacing in MCFs will result in a linear increase in inter-core crosstalk, which in turn varies linearly with transmission distance [84]. For 100 Gbps dual polarization QPSK systems, inter-core crosstalk should not exceed −50 dB for a 1,000-km MCF transmission [85]. A 14,350 km transmission experiment by TE SubCom using a 12-core fiber [86] showed that MCFs can simultaneously improve capacity and power efficiency for transmission at 105.1 Tbps and achieve a record capacity-distance product of 1.51 Pb/s*km.

FMF multiplexing allows the propagation of a finite number of higher-order spatial modes in tandem with the fundamental mode. FMF with a higher cutoff frequency and larger mode field diameter can be achieved through judicious design of the fiber core and cladding refractive indices (index contrast almost doubling) for the

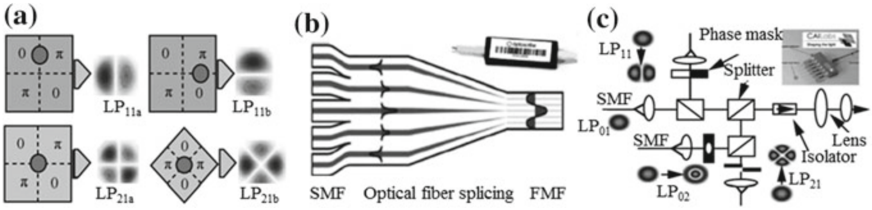



**Fig. 12.13** Mode conversion and multiplexing/demultiplexing using **a** phase mask, **b** photon lantern, and **c** spatial optical coupler. Reproduced from Lai et al. [76]

simultaneous transmission of several linearly polarized modes. The high transmission capacity can be supported not only through the optimization of refractive index profiles in the FMF, but through MIMO digital signal processors at the receiver in long-haul SDM systems to control and compensate the adverse effects associated with mode coupling (intermodal crosstalk) and dispersion (differential mode group delay) [87]. Phase masks, photonic lanterns and spatial optical couplers are used to realize mode conversion and multiplexing/demultiplexing as shown in Fig. 12.13. Few-mode multi-core conversion and multiplexing technology combines MCF and FMC multiplexing technology, which not only places a number of fiber cores in the fiber cladding, but also transfers several linear polarization modes in each fiber core.

The photon possesses two vital properties that can be exploited in fiber optics: spin angular momentum (SAM) and OAM [88], as illustrated in Fig. 12.14. SAM is the angular momentum component related to the quantum spin and continuous (counter)clockwise rotation of the perpendicular planes of circularly or elliptically polarized electric and magnetic fields around the beam axis during wave propagation. OAM is another component of angular momentum related to the quantum spin and the field spatial distribution in lieu of polarization. By controlling the rotational direction, angle and radius of beam wavefronts using spiral phase plates, SLMs or q-plates, etc., OAM multiplexing can be realized with different orthogonal signals, and is therefore projected to add capacity when used in concert with the existing modulation and multiplexing schemes [89]. Unlike SAM that offers only two orthogonal quantum states associated with the two states of polarization, OAM can access a potentially unbounded set of quantum states, and thus offers an unmatched number of channels. The key techniques of OAM multiplexing systems include mode conversion and control, mode multiplexing and switching, optical fiber system transmission, and so on.

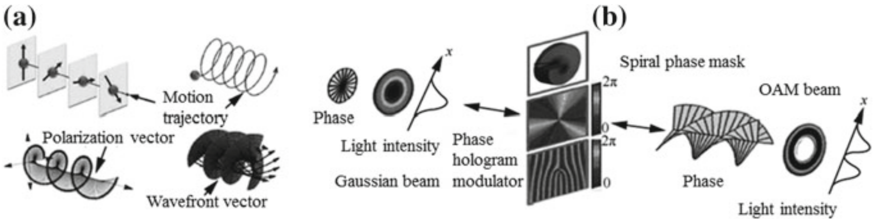



**Fig. 12.14** OAM multiplexing. **a** OAM compared with SAM and **b** OAM mode conversion using spatial light modulation. Reproduced from Lai et al. [76]

## *12.2.4 Features of Optical Fiber Communications in 5G Networks*

### 12.2.4.1 Ultra-large Capacity, Ultra-long-Haul, and Ultra-high Data Rate Optical Fiber Communication Systems

Due to the maturity of fiber-optic communication technologies operating at around 1.55 μm, and the development of coherent optical systems, transmission capacity and data rates have significantly improved. Ultra-long-haul optical fiber communications can be achieved with low-loss and low dispersion optical fiber technology, performance improvements in a variety of optical signal amplifiers and repeater devices, and development of dispersion and nonlinearity compensation technologies.

At the 2012 OFC, NTT reported an SMF transmission experiment with 224 wavelengths using the WDM-PDM-64QAM modulation method, at a total capacity of 102.3 Tbps, spectral efficiency of 9.1 bit/s/Hz, and transmission distance of 204 km. In 2014, researchers in the Eindhoven University of Technology and University of Central Florida have jointly developed a new type of optical fiber to achieve single-channel transmission up to 5.1 Tbps in a single fiber, and 50-channel transmission up to 255 Tbps (net 200 Tbps) over a fiber link of at least 1 km. In 2016, optical fiber communications magazine reported the realization of 105-Tbps transmission over 14,350 km using a 12-core optical fiber [86]. In 2017, FiberHome Technologies Group in China achieved a capacity of 560 Tbps in a WDM and SDM optical transmission experiment using single-mode seven-core optical fibers, which also represents the ability to support simultaneous phone calls by 13.5 billion people, hence marking a new level of the nation's ultra-large capacity, ultra-long-distance, ultra-high data rate optical communications systems [90].

### 12.2.4.2 Coherent Optical Communications

The high sensitivity of coherent receivers in coherent optical fiber communications permits a longer unrepeated transmission range, and with preservation of phase information, electrical post-processing functions can be realized flexibly such as compensation for CD and PMD in the digital domain after coherent detection. Nevertheless, coherent systems are more complicated compared to that of traditional intensity modulation and direct detection (IMDD) systems by virtue of their sensitivity to the phase and polarization states of the optical signal. In coherent schemes, homodyne and heterodyne detection are typical, the former implying a single frequency, whereas the latter deals with multiple frequencies. Homo- and hetero-dyne detections refer to the extraction of information encoded as modulation of the phase and/or frequency of the optical signal, by determining the fixed offset in frequency and/or phase compared with a reference waveform from a local oscillator that would be identical to the signal if it carries null information. The key features of coherent technologies include optical in-phase and quadrature (IQ) modulation and optical delay detection, and high-speed DSP operation at the transmitter and receiver. Optical amplitude modulation (AM) and optical IQ modulation can be realized using the respective Mach–Zehnder configurations, and the IQ modulator—that enables any kind of modulation formats—can modulate the IQ components of the optical carrier. Using two optical delay detectors in parallel, the optical signal IQ components can be demodulated separately without the need for the local oscillator. Hence, many obvious advantages compared to traditional IMDD systems are as follows:

(1) Any kind of multilevel modulation format can be handled using the phase-diversity homodyne (heterodyne) receiver which mixes the optical signal with that from the local oscillator and distinguishes the IQ components. This means that greatly improved spectral efficiency can be supported without any increase in system complexity. Moreover, by introducing the polarization diversity scheme into the receiver, polarization demultiplexing and post-processing functions such as compensation for group velocity dispersion (GVD) or PMD are possible through DSP techniques.
(2) The ability to combine coherent detection with DSP can provide new capabilities for optical communication systems with phase detection of the optical signal. The carrier phase is recovered after homodyne (heterodyne) detection by means of DSP. Electrical post-processing functions after detection can be performed on the optical carrier, such as optical filtering and dispersion compensation. Transmission impairments such as CD, PMD, nonlinearities and phase noise can be compensated. Therefore, as optical compensators (such as DCFs) are not needed, the cost of the transmission system is reduced.
(3) High-speed digital-to-analog and analog-to-digital circuits employed at the transmitter and receiver, respectively, as well as DSP supported by application-specific integrated circuits before (transmitter) and after (receiver) data conversion, provide a simple and efficient means of carrier phase tracking, and drastically improve system stability.
(4) Conventionally, high-capacity WDM systems deploy EDFA and semiconductor optical amplifiers (SOAs) as repeaters. However, for long-haul optical fiber cables installed in very harsh environments such as at the bottom of the sea or in hot deserts, repeater equipment are highly susceptible to damage. On the

other hand, the transmission range of coherent optical communications without repeaters is far greater, and is therefore deployable under severe conditions.

(5) Finally, coherent optical communication systems have excellent anti-jamming and anti-interception features, and therefore communications security is greatly enhanced. With a large transmission bandwidth and relatively low power consumption, there is potential for its development in inter-satellite communications.

#### 12.2.4.3 All-Wave Fiber Communications

There are only two transmission windows, from 1260 through 1360 nm and from 1510 through 1610 nm in conventional SMFs that are favorable for long-haul optical fiber communications, whereby attenuation and dispersion effects are minimal. Attenuation increases at wavelengths near 1380 nm due to the absorption by OH-groups in conventional SMF. Therefore, the removal of OH-groups such as moisture during fiber manufacturing reduces attenuation at these wavelengths in the all-wave fiber (AWF), hence allowing broadband deployment over 1280 through 1625 nm, popularly known as the “all-wave window”; the water absorption peak at 1385 nm is eliminated [91]. The biggest advantage of AWF is that it greatly widens the optical fiber bandwidth, providing more than a 100-nm bandwidth compared to that of conventional SMF. For example, if the wavelength interval is 0.8 nm in WDM systems, this is equivalent to an increase by at least 125 channels, meaning a greatly improved data transmission capacity.

#### 12.2.4.4 All-Optical Network and Optical Amplifiers

AONs, also called high-speed broadband optical networks, are based on optical wavelength-selective switching and routing in WDM optical communications networks. Established practices based on electronic circuitry to implement TDM networks cannot cope with the growing demand for bandwidth, operational speed, reliability and simplified operation and management. In AONs, data traffic relies on the propagation of optical signals throughout the entire network from the source to destination node without optical–electrical and electrical–optical conversion. No photoelectric conversion bottleneck is expected, and data rates will not be limited by electronic device performance. Therefore, AONs are scalable and reconfigurable, and efficient AONs are at the forefront of optical fiber communication technologies, which represent the information highway of the 21st century; many countries regard AONs as a foundation for the construction of the “information superhighway,” and in their information technology strategic plans, designate it as an essential national capability. In order to realize AON communications, a key technology is the optical amplifier [39], which is a device that directly amplifies an optical signal without having to first convert it into an electrical signal. SOAs employ a semiconductor such as GaAs/AlGaAs, InP/InGaAs, etc., as the gain medium, and have a structure similar to the Fabry–Perot laser diode but with anti-reflection designs at the end faces akin to that adopted in photovoltaics, for example [92]. Doped fiber amplifiers utilize an optical fiber doped with rare earth elements as the gain medium, such as EDFAs for C-band (1525–1565 nm) and L-band (1570–1610 nm), thulium-doped fiber amplifiers for S-band (1450–1490 nm) and praseodymium-doped fiber amplifiers in the 1300 nm region. These can cover the entire band of wavelengths for optical fiber communications.

#### 12.2.4.5 Optical Soliton Communications

For large networks covering huge geographical areas, the use of soliton propagation allows optical pulse compression induced by nonlinear SPM effects to neutralize group velocity dispersion effects. The soliton refers to any optical field that is unaltered during propagation due to the delicate balance between nonlinear and dispersion effects in the medium. Under specific conditions, such as a sufficiently high pulse power density and in anomalously dispersive media, solitons can transmit for long distances and are therefore suitable for AONs with reduced reliance on repeaters. Transmission capacity at one to two orders of magnitude higher than that in a traditional communication system can be achieved. Soliton-based optical communication systems are superior to that of traditional IMDD systems and coherent optical communications in high fidelity long-distance transmission performance. Applying ultra-short pulse control and TDM or WDM transmission [93], the data rate can be increased to at least the order of Tbps. Further, through reduction of amplified spontaneous emission (ASE) noise using an optical filter, a transmission distance up to 100,000 km or more can be achieved.

#### 12.2.4.6 Quantum Secure Optical Communications

With the development of the Internet, various security issues also manifest in spite of advances in classical computing. In 2012, the LinkedIn website was compromised, resulting in information thefts from more than 117 million LinkedIn user accounts. In 2015, the Ukrainian power grid was hacked into, shutting down power supplies for nearly 700 thousand homes. In the same year, supposedly due to a security breach in the US general elections, about 191 million voter registration records were leaked. In 2016, Los Angeles county was targeted in a phishing cyber attack, which compromised the private information of 760,000 people. These scenarios are part of the general paradigm that information security is largely a critical issue not only for large companies, banks, and defense organizations, but small business enterprises and individual consumers. Fortunately, quantum computing and Shor's algorithm [94, 95] have emerged, and are finding applications in the fields of classical cryptography, weather forecasting, drug design, financial analysis, and so on. Owing to its ability to perform a range of useful tasks more rapidly and securely compared to classical computing, quantum computing is expected to take the place of traditional encryption methods (RSA algorithm, Digital Signature Algorithm, etc.), emailing, electronic payment, Internet, IoT and a range of other services having security implications. On the other hand, more and more attention is being paid to the security of optical communication networks, with the consequential need to appropriately encrypt the data transmitted in optical cables. Secure quantum communication technologies based on post-quantum cryptography arose at a historic moment, and since it uses the optical quantum states carrying information to distribute the quantum keys, its security is impregnable because quantum states are indivisible, and cannot be cloned [96].

In recent years, many countries around the world have been devoted to ushering in the second quantum revolution and actively building ultra-secure national quantum communication networks. The UK launched a flagship quantum communications hub in 2015 at an expenditure of £ 270 million, and built Bristol and Cambridge quantum metropolitan area networks in 2016. Japan built the quantum communication Tokyo metropolitan area network in 2015, and planned to build national high-speed quantum communication networks between 2020 and 2030. In 2016, the USA built a 650-km quantum link between Ohio and Washington, with a secure communications backbone network spanning tens of thousands of kilometers long in the blueprint. The European Union issued a “Quantum Manifesto” in 2016, and within the European H2020 research and innovation framework programme, invested € 1 billion for a start in 2018 to support a flagship-scale initiative in quantum technology; this targets development within 5–10 years a quantum secure communication network linking distant cities, and a pan-European quantum secure Internet by 2035. Also in 2016, South Korea built the Seoul, Pentang and Suwon Phase I networks, with an aggregate link length of 256 km, and secure communications will be adopted in all government networks by 2020 and in all commercial networks by 2025. In China, the world’s longest quantum communication network spanning 2,000 km long, dubbed the “Beijing-Shanghai trunk line,” had passed the acceptance test and was opened in September 2017; this established a wide area space-to-Earth quantum communication network when combined with the world’s first quantum science satellite “Mo-tse” launched in the previous year, thus no sooner allowing the first practical demonstration of an intercontinental ultra-secure quantum-encrypted video chat between Beijing and Vienna. Also by September 2017, China has set up its first commercial quantum network in Shandong province. Furthermore, international telecommunications and hi-tech business leaders have been investing heavily in ultra-secure communications in the era of quantum computing. For example, BT Group plc has long been leading its own research into quantum communications, focusing on quantum key distribution (QKD). In October 2016, BT and Toshiba opened the UK’s first quantum communication showcase, with the latter company having by then already applied quantum cryptography to secure transmission of genome data in Japan. Deutsche Telekom AG and SK Telecom Co. Ltd. have co-established a “quantum alliance” in February 2017, and by June 2017, SK Telecom had developed a powerful quantum repeater that can dramatically extend the distance of quantum communication up to a distance record of 112 km for QKD. Since announcing in October 2015 its first quantum cryptography cloud security solution (that increases data transmission security in networks), AliCloud has teamed up with NVDIA to invest US$1 billion in cloud computing research and development, and also with QuantumCTek to co-establish the China Quantum Communication Industry Alliance. In March 2017, AliCloud became the first cloud computing company in the world to provide quantum-encrypted transmission of information with cloud services for industry, for example, in a case of long-distance cloud-based quantum cryptography communication for MyBank's business credit data. IBM, Hewlett-Packard, Siemens, Philips, Alcatel Lucent, Hitachi, Huawei, ZTE, and other multinational companies have also joined this quantum communication industry.

Encryption technologies, based on post-quantum cryptography, error-correcting codes, lattice, hash, multi-variable, and so on, will become an important direction for quantum-encrypted communications in the next few years. However, research into the multiplexing of QKD and strong classical data signals continues to be crucial to deliver quantum and classical signals in one fiber link, and pertinent to the integration of quantum communication networks with gigabit-capable passive optical networks in existing telecommunications infrastructure to implement ultra-secure quantum communications.

#### 12.2.4.7 Wavelength Conversion in Optical Networks

The explosion in data traffic and an associated high bandwidth demand has made viable the use of multiple wavelengths in optical fiber links to increase network capacity. Wavelength converters are essential in dynamically reconfigurable optical networks and are parsimoniously utilized at key network nodes, enabling more efficient exploitation of optical bandwidth under dynamic traffic patterns and permitting transparent interoperability, wavelength routing, wavelength reuse, path protection and restoration, as well as contention resolution and scalability. Therefore, the implementation of all-optical wavelength conversion (AOWC) will be a key feature in next-generation AONs based on WDM. Furthermore, for 5G, the ability of wireless networks to be adaptive, autonomous, scalable, stable, and sufficiently agile to maintain their services under all potential conditions is expected by default. Self-healing networks are thus envisioned to be crucial, providing autonomous fault management including performance monitoring, fault detection, active compensation and recovery, and outcome evaluation. Existing wavelength conversion technologies to support this framework for 5G can be grouped into the following: those based on SOAs including cross-gain modulation (XGM), XPM and FWM [97–99]; or those that employ, cross-absorption modulation in an electro-absorption modulator (EAM) [100], difference frequency generation/sum frequency generation (DFG/SFG) using periodically poled lithium niobate (PPLN) optical waveguides [101–103], FWM or degenerate FWM in highly-nonlinear fiber (HNLF) or silicon waveguide [104, 105], or injection-locked semiconductor lasers [106], etc.

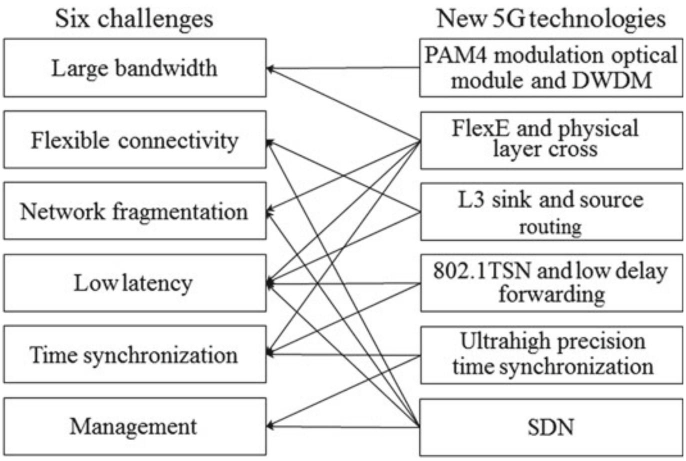



**Fig. 12.15** Network challenges correlated with new 5G technologies to mitigate them

### *12.2.5 Key Technologies of 5G Optical Transmission Networks*

Communication networks can be classified into core networks, convergence networks, access networks, and customer premises networks according to the logic function; and 5G networks must be constructed based on the classical optical transmission network. Six foreseeable future needs/challenges will have to be handled by 5G optical transmission networks, i.e., (i) large bandwidth, (ii) flexible connectivity, (iii) network fragmentation, (iv) low latency, (v) time synchronization, and (vi) management of operation and maintenance. In order to maintain the advantages of packet transport network (PTN), the SDN architecture needs to be extended to meet future development requisites. Key 5G-related technologies include the 4-level pulse amplitude modulation (PAM4) optical module and DWDM technologies, Flexible Ethernet (FlexE) and physical layer cross-technologies, layer 3 sink and source routing technologies, IEEE 802.1 time sensitive networking (TSN) and low delay forwarding technologies, ultra-high-precision time synchronization, and SDN technologies, etc. (see Fig. 12.15).

DWDM has already been introduced earlier, and PAM4 will be introduced in Sect. 12.4. FlexE is a communications protocol maintained by the Optical Internetworking Forum, and is the third generation of Ethernet compatible with the 5G era that, allows data center providers to utilize bandwidth more flexibly, possesses low added latency, and reuses several mechanisms from Ethernet. Service isolation and network slicing on the bearer network can also be implemented. Lightweight enhancements to Ethernet have been achieved by adding a middle FlexE shim layer between the layer 2 Ethernet medium access control (MAC) layer and layer 1 physical layer, which schedules client interface data to different channels via a TDM-based distribution mechanism. One or more channels can be used as needed by each client interface to isolate services. For example, the FlexE shim layer can divide a 400GE interface into 20 channels working at 20 Gbps, meaning that full use is made of the existing optical transport network in channelized isolation for 5G services. FlexE can also increase interface capacity through interface bonding, without resorting to multiple interfaces that result in wasted capacity and unbalanced service traffic distribution, or requiring service adjustment and cutover. Furthermore, FlexE can slice a physical Ethernet interface into multiple elastic Ethernet hard pipes based on timeslot scheduling, bringing about twin properties of improved service isolation and high network efficiency, as well as statistical multiplexing. Therefore, when combined with DWDM, FlexE not only provides high bandwidth capacity, but also permits flexible bandwidth adjustment and data isolation features that fully meet 5G service requirements and drive industry development.

When routing at layer 3 using SDN as its core technology, individuals or subnets may be configured for intercommunication and resource sharing between layer 2, in which individuals or several user groups must access the same access network(s) without interference with one another. The IEEE 802.1 TSN standards guarantee packet transport with bounded low latency, low packet delay variation and low packet loss. For example, this means that the PTN processing delay can be reduced from about 50 $\mu$s to about 5–10 $\mu$s.

Ultra-high-precision time synchronization between two remote sites is desirable for large-scale, flexible networks that support the 5G-industry chain by improving accuracy and reducing cost in measurement and control systems. However, the precision of currently prevailing timeservers is around $\pm$100 ns, but which needs to be reduced to $\pm$30 ns for 5G and IoT. In December 2017, ZTE Corporation had announced its completion of tests for a high-precision time source device based on the principle of satellite common view, achieving a time precision of $\pm$10 ns.

Ultra-high-precision bidirectional time-frequency transfer is needed over high-speed, long-haul fiber-optic links, with propagation delays associated with forward and backward transmissions expected to be the same (symmetrical) over the same fiber link using identical wavelengths. Nevertheless, each node and link may introduce asymmetries through fiber dispersion effects and their temperature dependence that affect the time/phase accuracy over networks. For 5G compatibility, the time precision requisite for each link and node should be reduced from $\pm$1000 to $\pm$100–300 ns and $\pm$30 to $\pm$5–10 ns, respectively. Different factors responsible for the uncertainty of time transfer include precision and stability of the transmitted wavelengths, the power dependence of the transceiver delay, Sagnac effect, etc. WDM-based schemes have been adopted to successfully suppress the impact of Rayleigh backscattering on signal timing jitter in bidirectional propagation.

The SDN technology is a novel cloud computing approach that facilitates network management and efficient network configuration for high-level system performance and diagnostics. Network functions virtualization (NFV) and virtual private networks (VPN) are enabled, with the core technology characterized by open flow via dissociation of the network device control plane (routing process) from data plane (forwarding process of network packets) so as to expand the smart capability of the network. The control plane constitutes the centralized intelligence, as bearer networks and wireless networks require a central orchestration and management system for flexible control of network traffic.

As stated earlier, the 3GPP officially confirmed in June 2017 that 5G core networks will be assimilated into the unified infrastructure; this is in accordance with the SBA architecture proposed jointly by China Mobile and 26 other operator and network equipment manufacturing companies. The SBA architecture is compatible with SDN/NFV technology, allowing the 5G network to adopt cloud computing (cloud native), and therefore convenient for rapid network upgrading, as well as enhancing the network resource utilization rate and ushering in new network capabilities. Indeed, the service-oriented 5G core network aims to support a very diverse range of services with very different levels of performance requirements, incorporating use cases such as industrial control, augmented/virtual reality, interconnected vehicles, etc. Therefore, this calls for end-to-end network slicing to support a rich range of services and industries on one physical network infrastructure. Taken together, network operators can flexibly enable new services in neighboring sectors and incorporate their networks into new industry value chains.

## 12.3 Optical Wireless Communications in 5G

Wireless communication technology has developed at an unprecedented pace in recent decades and is playing an important role in modern society. Wireless communications usually imply the adoption of radio waves. The electromagnetic spectrum is a scarce resource that is managed and regulated by governmental bodies and international agencies. With the coming era of 5G, the demands for higher data rates and ultra-high-capacity networks are ever-soaring, but the existing radio spectrum resources are limited in capacity and challenged to keep up. Hence to resolve the backhaul bottleneck, other viable options for wireless communications include the upper frequency portions of the electromagnetic spectrum, and not just RF. For example, optical wireless communications (OWC) refer to transmission in unguided propagation media or wireless data transmission for telecommunications or computer networking, through the deployment of optical carriers in the visible, infrared, and ultraviolet bands. When terrestrial point-to-point OWC systems operate at the near IR frequencies (750–1600 nm), they are referred to as free-space optical communications, whereas when operating in the visible range (390–750 nm), they are referred to as VLC. There has also been an upsurge of interest in operation within a solar-blind UV spectrum (200–280 nm), known as UV communication. Categories of OWC applications according to the transmission range include: (i) the ultra-long-range inter-satellite and deep-space links; (ii) long-range terrestrial inter-building connections; (iii) medium-range wireless local area networks (WLANs) and inter-vehicular and vehicle-to-infrastructure networks; (iv) short-range wireless body area network, wireless personal area network and underwater communications; and (v) ultra-short-range chip-to-chip communications [38]. In 5G networks, OWC can complement optical fiber communication, wireless Internet and mobile broadband services, and can penetrate environments which prohibit the installation of optical fibers or which contain RF shielding enclosures.

### 12.3.1 Free-Space Laser Communications

The free-space laser communication system is an OWC system that uses the laser output as a carrier wave, and vacuum, outer space or air, as the transmission medium; this is projected to become one of the important technologies to support 5G communication networks. Free-space lasers can have applications in deep-space telecommunication networks, or inter-satellite or satellite-ground networks, as well as terrestrial networks. Ultra-high-capacity and high data rates can be achieved using laser transmitters and cost-effective transparent links without requiring the installation of optical fibers [107–109]. The general long-haul transmission distance ranges from one to hundreds of thousands of kilometers. In 2013, NASA's Lunar Laser Communication Demonstration [81] achieved two-way communications between the ground station and the lunar satellite at a record-breaking error-free data rate of more than 20 and 600 Mbps for uplink and downlink, respectively, by using a pulse laser beam to transmit data over the 380,000 km between the moon and Earth. In 2015, the European Space Agency in its European Data Relay System achieved data transmission at 1.8 Gbps across 45,000 km between spacecrafts in low earth and geostationary earth orbits, using a new generation laser communication terminal. Early last year, a satellite was launched in China for a high-speed coherent laser communication experiment at a satellite-ground distance of 1600 km, yielding 20 Mbps uplink to the moon and 5.12 Gbps downlink from the moon supported by PPM, and bringing about a transmission capacity consistent with streaming video on demand [82].

In terrestrial free-space laser communications between buildings, the atmosphere is the transmission medium, but absorption and scattering of the signal can occur with the variety of gas molecules, solid particles, and water vapor present in the atmosphere, thus resulting in signal attenuation. Hence, the transmission range for terrestrial applications is generally limited to a few tens of kilometers and is also influenced by atmospheric turbulence-induced fading and sensitivity to the weather conditions and gradual changes in air temperature and pressure as well as platform motion. Terrestrial free-space laser communications can be implemented for last mile broadband access and other communication solutions. This terrestrial technology first emerged in the 1980s, with the US Naval Academy having developed low data rate atmospheric laser communication links between islands and the mainland for secure and reliable bidirectional data transmission; but the system only had an 8-MHz bandwidth using a limited number of optoelectronic devices [110]. In 1994, ThermoTrex Corporation established a data transmission rate of 1.13 Gbps with less than $10^{-6}$ bit error rate (BER) at elevations from 1.8 to 2.1 km above sea level using a free-space laser link between mountain summit observatories 42 km apart [111]. In 1998, Lucent Technologies Inc. prototyped a free-space optical communication system achieving a data transmission rate of 2.5 Gbps over a transmission distance of 2.5 km. In February of the same year, Lucent implemented a testbed, with a data transmission rate reaching 10 Gbps. In 2000, Lucent collaborated with Astro Terra Corporation to further develop the prototype, enabling 10 Gbps at a transmission distance of 5 km [111]. In 2004, No. 34 Research Institute of China Electronics Technology Group Corporation developed a commercial free-space laser communication system with data transmission rates ranging from 11 to 155 Mbps over a distance of 8 km [112]. In the same year, LightPoint Communications Inc. and Huawei Corporation configured wireless optical communication systems for African operators. In 2008, a high-speed atmospheric laser communications team in Wuhan University developed a free-space optical communication experimental prototype using WDM technology, which was capable of a transmission data rate of 2.5 Gbps over a range of 16 km. By 2010, the data transmission rate reached 7.5 Gbps over a distance of 40 km through further improvements to the light source [113]. The National Institute of Standards and Technology in USA demonstrated optical time-frequency transfer over free-space via bidirectional exchange between coherent frequency combs phase-locked to local optical oscillators (clocks), achieving femtosecond-scale timing deviation, a residual instability below $10^{-18}$ at 1000s, and systematic offsets below $4 \times 10^{-19}$ across a 2-km link. In 2016, researchers from the Institute of Optics and Electronics, Chinese Academy of Sciences, adopted adaptive optics to improve the quality of atmospheric laser communications. A coherent laser light source was used in the atmospheric laser communication link, yielding a data transmission rate of 5 Gbps. Modulation techniques for free-space laser communications are basically the same as for fiber optics, notably allowing modulation by amplitude, polarization, phase, and so on. [114]. In addition, other intensity modulation techniques can be used with direct detection, such as PPM and DPPM, which will be explained in detail in the next section.

### *12.3.2 Visible-Light Communications*

As a subset of the OWC technologies, VLC uses fluorescent lamps to transmit signals at 10 Kbps, or LEDs at up to 500 Mbps, over typical distances between 1 and 2 km. To support 5G networks, VLC can be used as a communications medium for ubiquitous computing. Light-producing devices for indoor/outdoor lighting, TVs, traffic signs, etc., are pervasive, and therefore wired links are not needed to simultaneously support multiple computers or mobile phone terminals on the Internet, without adversely affecting speed. The advantages of VLC include high bandwidth, and secure and reliable transmission with high energy efficiency, and without electromagnetic interference when using larger scale optics and more powerful LEDs, as well as the fact that the system is safer for high-power applications because humans can perceive the optical beam and avoid possible harm.

Hence, VLC can be deployed as Li-Fi in indoor wireless communications, train and aircraft wireless communications, vehicular networking, intelligent transportation, secure electronic transactions, IoT, etc., and particularly useful in electromagnetic sensitive areas such as aircraft cabins, hospitals, and nuclear power plants. In 2000, Tanaka et al. of Keio University in Japan proposed using LEDs in communication base stations, and carried out various experimental modulation techniques for VLC systems [115–117]. In 2012, the team credited for coining the popular Li-Fi terminology led by Professor Harald Haas at University of Edinburgh, patented a technology using flashlights to transmit digital information [118]. In 2013, researchers at Fudan University reported successful realization of the technology in the laboratory, whereby the network signal was powered by a 1 W LED lamp, which interconnected four computers at the same time, achieving a maximum data rate of 3.25 Gbps and average Internet speed of 150 Mbps [119]. The modulation schemes suitable for VLC include PPM, DPPM, OOK or digital pulse interval modulation (DPIM), which will be introduced in the next section.

## 12.4 Modulation Technologies in 5G

Analog modulation aims to transfer analog baseband signals over an analog bandpass channel at a different frequency, whereas digital modulation aims to transfer a digital bit stream over an analog bandpass channel or over a limited RF band. Typical methods of analog modulation are AM, frequency modulation (FM) and phase modulation, while typical methods of digital modulation are ASK, FSK PSK, DPSK, etc.

Modulation technologies have a long history of evolution with the development of communication networks. The first-generation wireless cellular networks were analog telecommunication standards that first emerged in Tokyo in the late 1970s, and relied on FM with a bandwidth ranging from 10 to 30 kHz and data rates around 10 Kbps, suitable only for speech and data transmission. Around the same time, fiber optics was used extensively by network operators to build their telecommunications infrastructure. Sprint Corporation in the USA was the first carrier to operate a fully digital fiber-optic network in the mid-1980s. Commercial SMF systems and the SDH transmission protocol appeared in the 1990s, and Sprint was again the first to deploy synchronous optical networks, a variant of SDH. The 2G cellular technology networks that emerged in the 1990s are digital, offering a bandwidth of 200 kHz and peak data rate of at least 300 Kbps. Moreover, the digitization permits less energy consumption and enhances voice clarity and mitigates noise. As 2G systems were far more spectrally efficient, they were launched based on CDMA standards, or on the global system for mobile communications (GSM) standards based on time division multiplexing access, depending on the type of multiplexing used. Gaussian minimum shift keying, a subset of FSK, is most notably used in GSM cellular technology, but while its spectral efficiency is high, a higher power level is required than that of QPSK, a subset of PSK, in order to transmit the same amount of data reliably. The 2G networks in Japan and North America use another PSK known as DQPSK. By the end of the 1990s, the USA, Japan, Britain, France, and more than 20 other countries together pledged a commitment to optical fiber communications, and to vigorously develop optical modulation technologies, and adopt WDM for increased data system capacity. Coherent optical fiber communications had been extensively studied in the 1980s, but due to the success and rapid progress in high-capacity WDM systems using EDFAs, concerted interest in the former was interrupted for almost 20 years. OOK was widely adopted in IMDD schemes, and for improved spectral efficiency and data rates in WDM systems, modulation techniques such as binary phase shift keying (BPSK), DPSK, QPSK, DQPSK, etc., were developed. In 2002, Bell Labs developed DPSK, which when coupled with other technologies such as extended L-band amplifiers, Raman amplifiers, forward error correction, and optical dispersion compensation, allowed the doubling of error-free, high bandwidth transmission distance to over 4000 km at 2.56 Tbps using a 64-channel DWDM system.

At the 2002 OFC, a British team reported on a 10-Gbps coherent detection transmission system based on DQPSK modulation [120]. Interest in coherent optical communications was soon revived after a demonstration in 2005 of digital carrier phase estimation in digital coherent receivers which enable a variety of spectrally efficient modulation formats to be employed, such as multiple phase shift keying (MPSK) and QAM without dependence on the somewhat complicated optical phase-lock loop. Encoding formats for transmission such as those based on non-return-to-zero (NRZ) and return-to-zero (RZ), were adopted in communications interfaces. For example, carrier-suppressed return-to-zero (CSRZ) was used to generate specific optical modulation formats, such as CSRZ-OOK or CSRZ-DPSK, in which data are encoded on the signal intensity or differential phase, respectively, using a binary scheme. Others include RZ-DPSK, RZ-DQPSK.

3G wireless networks also emerged at the outset of the 21st century, with new frequency bands to support the services that provide a data rate of at least 2 Mbps, thereby ensuring wireless voice telephony, mobile Internet access, fixed wireless Internet access, video calls, and mobile TV. Packet switching was used rather than the circuit switching in 2G for data transmission. The first commercial networks were live in South Korea by January 2002, on the CDMA-based evolution-data optimized telecommunications standards.

In 2008, a set of criteria for what is marketed as 4G, known as the international mobile telecommunications advanced (IMT-Advanced) standard, was specified by the international telecommunications union-radio communications sector. Since 2009, LTE was commercially deployed, and LTE-Advanced is a candidate targeting to outperform the IMT-Advanced compliant T-advanced standard, which will make use of additional frequency bands and multiplexing to achieve higher data rates. Mobile worldwide interoperability for microwave access Release 2 and LTE-Advanced were standardized in 2011, and are IMT-Advanced compliant, allowing speeds up to the order of 1 Gbps. The 4G system uses an all-Internet protocol (IP)-based communication such as IP telephony. Multiple access schemes are available; examples are orthogonal frequency-division multiple access multi-carrier transmission that allows simultaneous low data rate transmission from several users, or single-carrier frequency-division multiple access as an attractive alternative especially where low peak-to-average power ratio (PAPR) in uplink communications means increased transmission efficiency and reduced power amplifier costs. Other new access schemes, such as interleaved frequency-division multiple access, multicarrier CDMA and beam-division multiple access, are also gaining more importance for next-generation systems.

For single-channel transmission reaching 100 Gbps, advanced digital modulation formats such as differential 8-phase PSK (D8PSK), PM 16-QAM, and other multilevel signaling schemes began to be widely used. In optical communications, PolSK is a novel modulation technique that is preferentially adopted for increased reliability in free-space optical systems than for fiber optics because the polarization state fluctuates due to birefringence in optical fibers, thereby presenting a challenge for detection. Multilevel digital coherent optical modulation formats such as multilevel PolSK have been proposed due to the higher data rates advantage compared to binary modulation counterparts. Hence in optical communications, multilevel modulation schemes have been widely used in combination with polarization multiplexing, such as polarization multiplexed-QPSK (PM-QPSK), or PM 16-phase QAM. To enable capacity scaling of WDM optical networks, it is necessary to increase spectral efficiency. PM-QPSK has been applied to a 100-Gbps system, with a theoretical spectral efficiency of 4 bit/s/Hz, though the spectral efficiency of 16QAM doubles that of PM-QPSK.

In 2009, Bell Labs reported coherent optical communications performance for a 10-channel WDM transmission with 112-Gbps PDM-16QAM and a 15-channel WDM with 100 Gbps PM-QPSK over a fiber link distance of over 620 and 7200 km, respectively [121, 122], with the former achieving a spectral efficiency of 6.2 bit/s/Hz. In the following year, Bell Labs again reported at the OFC conference, $10 \times 224$-Gbps WDM transmission of 28-Gbaud PDM-QAM over 1200 km of fiber link, achieving a spectral efficiency of 4 bit/s/Hz [123]. At the same conference the year after, Fraunhofer Institute for Telecommunications (Berlin) presented a serial 10.2-Tbps transmission system employing a 1.28-Tbaud RZ-16QAM signal, polarization multiplexing, and ultra-fast coherent demultiplexing, which achieved an error-free data rate of 9.5 Tbps and transmission over 29 km long [124].

5G networks may involve more advanced optical modulation formats, and in fiber-optic communication systems, direct detection will be entirely replaced by coherent detection. More advanced modulation formats are being intensively researched, such as 64QAM, 256QAM, 512QAM, 1024QAM, and 4096QAM, or MQAM [125, 126]. Another modulation scheme for beyond-4G cellular wireless communication systems is frequency and quadrature amplitude modulation (FQAM), which is a combination of FSK and QAM [127]. In ultra-high data rate communications, such as 400-Gbps client-side data links covering distances from 100 m to 10 km, higher-order modulation formats, such as PAM4 are adopted due to the simplicity and power efficiency to replace conventional NRZ in order to reduce the need for high bandwidth devices. In lieu of NRZ that relies on 2-level amplitude detection, PAM4 uses 4-level amplitude detection, thereby doubling the transmission capacity with the same bandwidth optical devices, though at a penalty of signal-to-noise performance [128]. Many currently deployed fiber and free-space optical systems (or VLCs) use together with direct detection, common intensity modulation schemes such as OOK, PPM, DPPM, DPIM or color shift keying. With a visible-light spectrum 10,000 times larger than the RF spectrum, Li-Fi represents a massive capacity expansion, and with data rates exceeding 224 Gbps, and is expected to complement, if not replace, Wi-Fi in many applications of short-range wireless communications.

The increase in data transmission speed and number of channels will inevitably require greater reliability. To reduce the BER, appropriate channel coding is needed for 5G. In addition to the Turbo codes used extensively in 3G and 4G, other coding schemes were proposed for 5G, such as LDPC codes, also known as Gallager codes, polarization and polar codes, etc. At the 3GPP conference in 2016, polar codes and LDPC were slated to be adopted in the eMBB control channels for the 5G New Radio interface and for the corresponding data channel, respectively.

The following section will briefly introduce a variety of digital modulation and pulse modulation technologies, and several coding schemes that may be adopted in 5G networks.

## *12.4.1 Digital Pulse Modulation*

### 12.4.1.1 Amplitude Shift Keying

The simplest and most common form of ASK modulation is OOK. The presence of an optical carrier for a specific duration denotes a binary "1" while its absence for the same duration symbolizes a binary "0". At the transmitter, the electrical data signal is loaded onto the optical carrier using the optical modulator to output the intensity modulated signal. At the receiving end, a photo-detector is used to transform the optical signal into an electrical signal for sampling and decision based on direct detection. The decision threshold is set to half the optical signal intensity of binary "1". Within the sampling time where the intensity is greater than the threshold, the signal is judged to be binary "1", otherwise binary "0", thus restoring the data signal. More sophisticated encoding schemes, such as 4ASK and 8ASK, have been developed using additional amplitude levels, i.e., when a finite number of amplitudes are used, each assigned a bit value (or an equal range of bits).

There are two kinds of OOK waveforms: NRZ-OOK and RZ-OOK (see Fig. 12.16). The NRZ-OOK format, with a 100% duty cycle and a symbol period equalling the pulse width, can be generated using direct modulated lasers and electro-absorption modulators for short- and intermediate-reach transmission, or using MZMs for long-haul systems, at data rates up to 10 Gbps [129]. However, the modulation is affected by Kerr nonlinearities such as SPM, XPM or FWM in the optical fiber, thus impairing the transmission bandwidth and BER performance. Hence, NRZ-OOK is suitable only for lower data rates and shorter-range transmission. On the other hand, RZ-OOK has a duty cycle less than 100% (common duty cycles are 33, 50 and 67%) with temporal spacing between adjacent pulses, and a symbol period not equalling the pulse width. As long as the delay spread is smaller

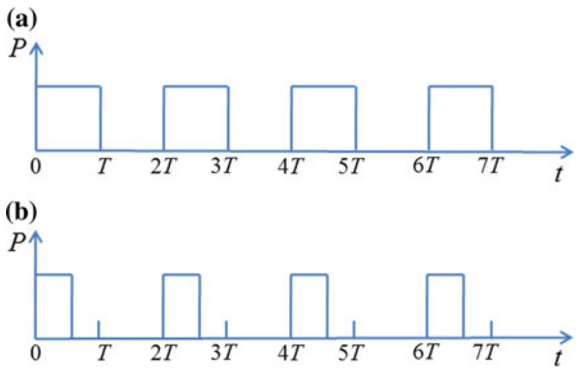



**Fig. 12.16** Two kinds of optical waveforms: **a** NRZ-OOK modulation and **b** RZ-OOK modulation

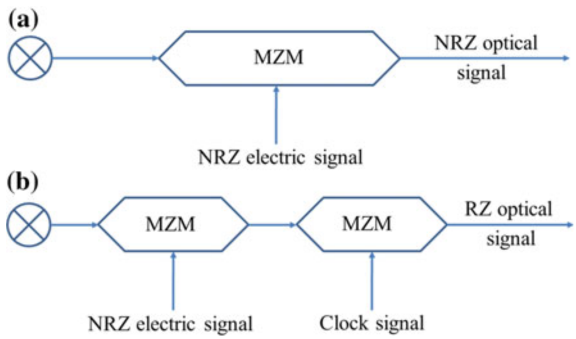



**Fig. 12.17** **a** NRZ and **b** RZ code generation using the Mach-Zehnder modulator

than the symbol period, ISI is very small, and RZ-OOK possesses greater tolerance to nonlinearities, CD and PMD effects. Figure 12.17 shows the generation of the NRZ and RZ codes using the MZM.

#### 12.4.1.2 Differential Phase Shift Keying

PSK is a digital modulation scheme, in which the carrier phase is correlated with the data signal, while the amplitude and frequency are constant. In the BPSK waveform, two phases are used and separated by 180°, hence the so-called 2PSK, which is functionally equivalent to 2-QAM. In a coherent system, when the modulated signal has the same phase as the carrier, the transmitted digital baseband signal is “1”. Otherwise, the baseband signal is “0” when the modulated signal has a reverse phase with respect to the carrier signal. As it takes the highest amount of noise or distortion for an incorrect decision by the demodulator, this digital modulation is the most robust of all the PSKs. However, due to an arbitrary phase shift introduced by the communications channel or phase ambiguity existing in the recovery of 2PSK signals, the demodulated signal and the transmitted digital baseband signal become confused, i.e., “1” becomes “0” and “0” becomes “1”, resulting from an incorrect

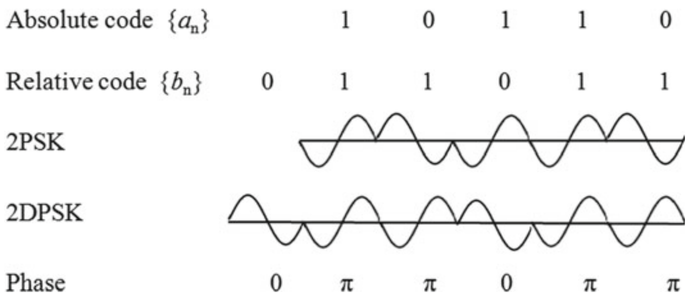



**Fig. 12.18** DPSK signal waveform

decision by the demodulator. This is known as the "inverted π phenomenon." To overcome this problem, DPSK is used. Instead of using the data to set the phase, they are used to change the phase of the carrier wave. Data are digitally transmitted depending on the difference between successive phases, or encoded in the optical phase change between adjacent bits [130]. The DPSK demodulator relies on one-bit delay interferometers to detect phase information by comparing the phases of two adjacent bits in the entire bit period. If "0" and "π" phase shift are used to represent the binary data "0" and "1", respectively, then the 2DPSK waveform can be obtained according to the coding principle illustrated in Fig. 12.18 [131].

It is known that compared to OOK, DPSK provides much higher sensitivity and robustness to nonlinear impairments in high data rate optical fiber communications. Approximately 3 dB lower OSNR is required by DPSK to reach a given BER. For the same average optical power, the optical peak power is 3 dB lower for DPSK than for OOK. Furthermore, the optical power is more evenly distributed in DPSK with power present in every bit, hence reducing bit pattern dependent nonlinear effects. Therefore, due to these reasons, DPSK has good resilience to nonlinearity [132]. DPSK can also be classified into NRZ and RZ formats, with similar characteristics to that of OOK. The NRZ code structure is compact and simple, with the optical power in each bit occupying the entire bit slot; but the average transmission power is relatively high and nonlinear distortion is serious, thereby limiting applications to shorter-range transmission. In RZ format, the optical power in each bit appears as an optical pulse, and because the average optical power is lower, the OSNR requirement for a given BER is low, hence it has better dispersion (besides nonlinearity) tolerances compared to that of NRZ. Three commonly used methods of pulse carving by applying a sinusoidal drive signal to an MZM-based pulse carver result in RZ duty cycles of 33, 50, and 67%. Carving at half the duty rate, or 67% duty cycle, results in CSRZ combined with an OOK optical modulator, which can be applied to long-haul high-capacity transmission due to higher tolerance to drive phase errors. The implementation of the RZ- and CSRZ-DPSK transmitter using MZMs is illustrated in Fig. 12.19. CSRZ-DPSK, which was proposed by NTT Corporation in Japan in 2002, has enhanced ability to suppress PMD effects because of the more evenly dis-

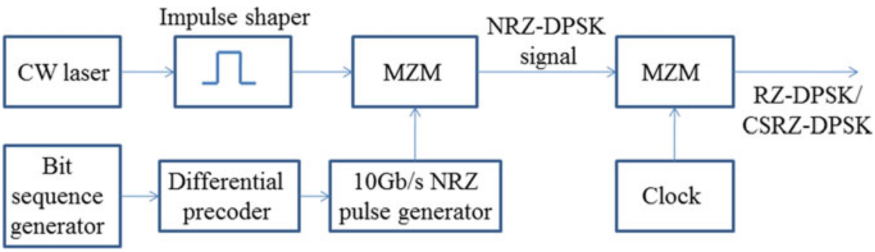



**Fig. 12.19** Schematic diagrams illustrating RZ-DPSK and CSRZ-DPSK modulation

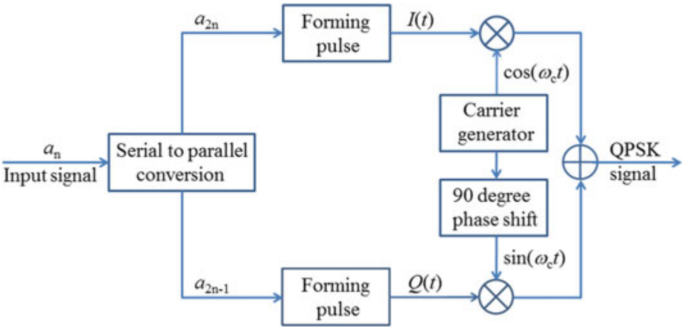



**Fig. 12.20** Structure of the QPSK signal transmitter system

tributed optical power in the time domain [133]. Moreover, the spectral efficiency is improved.

### 12.4.1.3 Quadrature Phase Shift Keying

QPSK is a digital modulation technique that takes into account efficient band utilization and power utilization with anti-interference features; hence, it is widely exploited in optical communication systems. Modulating the carrier phase using 4-state or 2-bit encoding per symbol accomplishes transmission of information. Figure 12.20 shows the conceptual transmitter structure for QPSK. The transmitter has a local oscillator that generates the carrier wave. Two MZMs and a 90° phase shifter are typically used to shape the I and Q waveforms.

The principle of the receiver structure underlying the detection of QPSK signals is illustrated in Fig. 12.21. The QPSK waveform is usually composed of two orthogonal binary phase states, so that the system bandwidth for QPSK is the same as that for BPSK but doubles the data rate. At the receiver, two signals are usually multiplied by the respective local oscillator-generated orthogonal coherent carrier signals, to separate the two baseband signals before conversion into the original waveform by low pass filtering, sampling, and parallel to serial conversion. Two sets of 45°

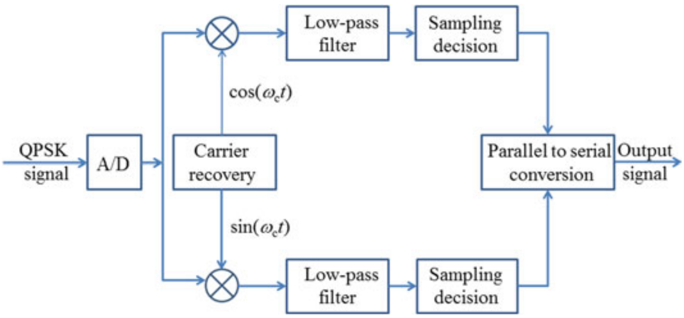



**Fig. 12.21** Structure of the QPSK receiver system

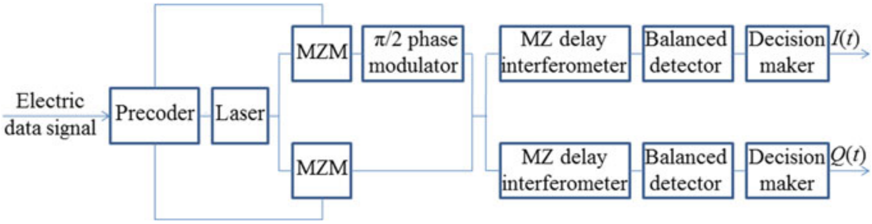



**Fig. 12.22** Schematic diagram illustrating principle of DQPSK

Mach–Zehnder delay interferometers, balanced detectors and decision-making circuits, are used in a QPSK demodulation module.

The type of QPSK adopted depends on the data rate required. At 2 Mbps, DQPSK is used, such as in the 2G cellular networks in North America and Japan. The DQPSK system is shown in Fig. 12.22. DQPSK was first integrated in optical signal transmission as reported by Groffin et al. at the 2002 OFC [120]; this concerns the relative phase shift between successive symbols rather than the absolute phase of each symbol in QPSK, and has a very narrow spectral width. For a given data rate, the dispersion tolerance is unchanged, but the system capacity is doubled as compared to that of DPSK.

Offset-QPSK (OQPSK) is a modified version of QPSK, using four different phase values to transmit. The OQPSK system has an additional one-half symbol period ($T_s/2$) delay circuit in the Q branch, as shown in Fig. 12.23. The demodulation scheme for OQPSK is basically the same as that for QPSK except for an additional $T_s/2$ delay circuit in the Q branch of the demodulation system, as shown in Fig. 12.24. As a consequence, the two component waves are offset by half a symbol period. In QPSK, the phase can change by 180° at once, while in OQPSK the phase changes are only of the order of 0° and 90°, meaning that the abrupt phase shifts occur about twice as often as for QPSK though the magnitude of fluctuations is less severe—this is occasionally favorable in practice.

If the transmitted signal itself serves as a phase reference instead of using an absolute carrier phase reference, an adaptation of OQPSK can produce a functionally

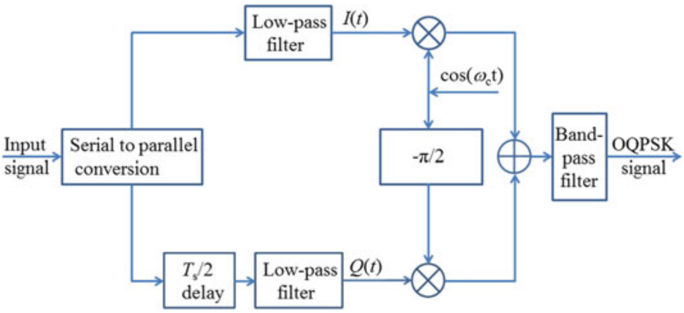



**Fig. 12.23** Principle of OQPSK signal generation

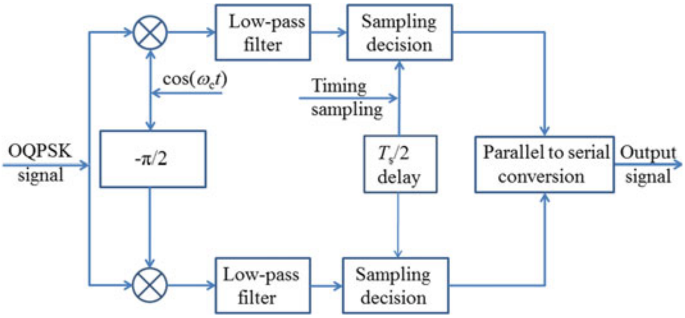



**Fig. 12.24** Schematic diagram illustrating OQPSK demodulation

equivalent D8PSK or D16PSK system [134]. For D8PSK or D16PSK, a π/4 (π/8) phase modulator is needed for signal generation, while a corresponding multi-path delay interferometer is needed at the receiver to perform the demodulation. To recover the original data, the decision circuit (comparator) computes the phase difference between the received signal and the preceding one that is then mapped back to the symbol it represents through a logical operation.

#### 12.4.1.4 Frequency Shift Keying

FSK uses discrete changes in the carrier frequency to transmit digital data. Binary FSK is the simplest form, which uses a pair of discrete frequencies to transmit a binary bit stream (1's and 0's). A binary "1" is called the mark frequency, and "0" is called the space frequency.

The simplest way to realize FSK at the transmitter is through direct modulation of the drive current to the distributed feedback laser light source, for example, 1 GHz frequency shift corresponding to an electric current change about 1–2 mA. As the output power versus drive current is not absolutely constant in the saturation region, the FSK waveform is accompanied by a certain degree of ASK modulation, which reduces the signal quality. Moreover, the bit rate is limited by the modulation response of both the distributed feedback laser and electro-absorption modulator used to compensate the output signal. Complex dispersion management and compensation systems are frequently required to deal with PMD, CD and nonlinear effects for long-haul transmission. The closely-spaced FSK carriers due to the limited drive current range hinder precise signal demodulation and also further limit the modulation data rate because of a high risk of severe crosstalk. The larger frequency FSK signals may be easily filtered out using narrowband optical filters, but the resulting wide spectrum may be susceptible to dispersion and nonlinear effects. Given the frequent high costs and complexity of direct demodulation, it is important to develop simple and inexpensive solutions such as that based on tuning of the frequency tone spacing using lasers to achieve higher receiver sensitivity in high-speed transmission systems and optical label switching networks.

#### 12.4.1.5 Multiple Quadrature Amplitude Modulation

The traditional digital modulation systems, such as Multiple ASK (MASK) , MPSK and Multiple FSK(MFSK), carry information by changing the phase, amplitude, or frequency of the carrier signal in M discrete steps. Different bandwidth efficiencies can be achieved, but at a penalty of power efficiency. Moreover, as the hexadecimal number M increases in M-ary digital transmission, the minimum distance between adjacent points in the I-Q plane (constellation diagram) decreases, hence increasing BER. To fully utilize the bandwidth allocated per channel, MQAM can be adopted for instance, when the amplitude is allowed to vary with the phase, thereby increasing the number of states per symbol whereby each state is defined with a specific variation in amplitude and phase. Hence, higher bandwidth efficiency can be achieved than for MPSK using the same average signal power. MQAM is now universally employed in satellite digital video broadcasting, as well as in cable television networks, with fairly strong ISI suppression and signal-to-noise performance.

In 4G networks, 16QAM, 64QAM, and 256QAM have been utilized, but at present, 1024QAM, 2048QAM, and beyond, such as multidimensional 3D 64QAM are being developed [126]. For domestic broadcasting, 16QAM, 64QAM, and 256QAM are used in digital cable television and cable modem applications through fiber optics and VLC systems. 16QAM and 64QAM are currently adopted in the UK, and 64QAM and 256 QAM are currently standardized in the USA, for digital terrestrial television. Higher-order QAM variants greatly increase data rates and spectral efficiency, but are more susceptible to noise and higher BER. Hence, a balance needs to be struck between obtaining higher data rates and maintaining an acceptable BER with the trade-off improving with fairly sophisticated QAM receivers and demodulators; nevertheless, even with increased complexity these decoder or demodulator systems can be mass-produced at reasonable costs with larger scale ICs.

In 2013, Omiya et al. demonstrated an improved frequency domain equalization technique that extended the transmission distance to about 720 km, for 400 Gbps PDM-256 coherent optical orthogonal frequency-division multiplexing, with higher

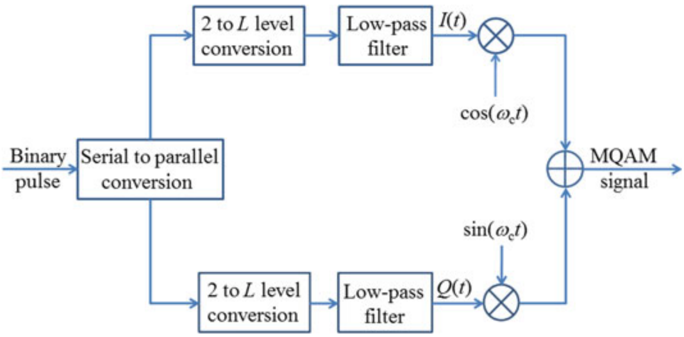



**Fig. 12.25** Structure of the MQAM transmitter system

level QAM sub-carrier modulation (QAM-OFDM) at 14bit/s/Hz spectral efficiency [72]. In 2016, ZTE demonstrated a single-carrier 800G long-haul transmission of 120 Gbaud WDM 16QAM signals over 1200 km terrestrial optical fiber links. In 2016, Khanna et al. reported error-free transmission of 400 Gbps single-carrier DWDM 64QAM and 128QAM over 80 km [135]. In 2017, ZTE reported successful transmission of 34 Gbaud single-carrier PM-256QAM signals over 80 km of standard SMF [136].

The principle of MQAM modulation for wireless communications is as shown in Fig. 12.25. Serial binary input pulses firstly go into the serial to parallel converter, and the data stream is divided into two halves of the data rate, which are then converted from 2 to L levels, where $L^2 = M$. The baseband sequences go into the pulse shaping filters (raised cosine filters) to suppress out-of-band radiation, thus forming the in-phase I (t) and quadrature Q (t) channels. The in-phase channel is multiplied by a cosine, and the quadrature channel is multiplied by a sine wave of the same frequency, resulting in a 90° phase difference, which are finally summed to output the MQAM signal.

The principles underpinning the transmission of optical and RF MQAM signals are basically the same. QAM constellations can be constructed in many different configurations, such as square, rectangle, star, and ring. For example, the star 16QAM format is as shown in Fig. 12.26. Two MZMs are driven by the two laser output pulses, with the first and second pulses driving $MZM_1$ to generate the $QPSK_1$ signal, and the third and fourth pulses driving $MZM_2$, the output for which is phase-shifted by 45° to produce the $QPSK_2$ signal. The star 16QAM signal is then generated by vector superposition of $QPSK_1$ and $QPSK_2$. The demodulation for star is more complex than for square, but it has lower OSNR and attenuation loss. The square 16QAM format is as shown in Fig. 12.27, in which a 6-dB attenuator replaces the phase shifter in the lower branch for the star configuration. In this case, the constellation points are evenly arranged in the $4 \times 4$ grid. Modulation/demodulation for the square constellation is relatively simple, but the BER is marginally worse.

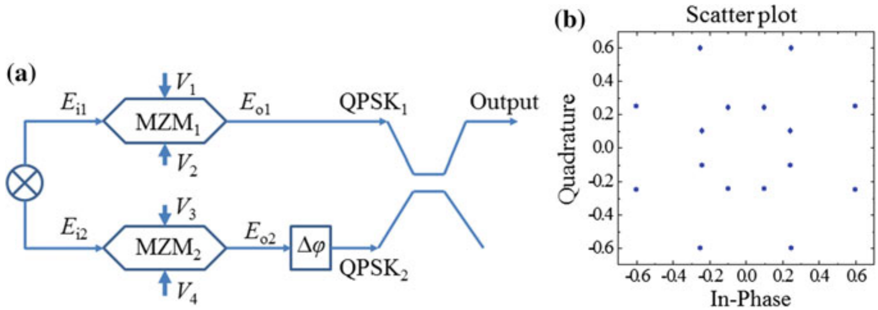



**Fig. 12.26** Schematic diagram illustrating star 16QAM. **a** System to generate star QAM signals and **b** constellation diagram for star QAM

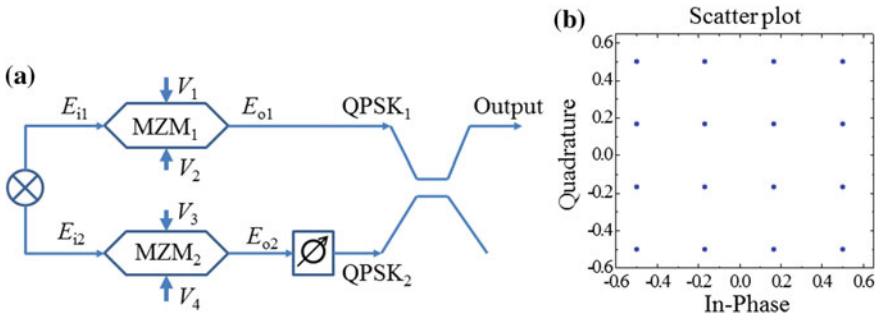



**Fig. 12.27** Schematic diagram illustrating square 16QAM. **a** System to generate square QAM signals and **b** constellation diagram for square QAM

The constellation points for ring 16QAM are evenly distributed in concentric circles as shown in Fig. 12.28, thereby achieving maximal angular spacing for a given energy. Therefore, ring MQAM allows better BER performance for a given bandwidth than that of square, having reduced nonlinear distortion but requiring more complex modulation/demodulation schemes.

The MQAM signals are prone to noise in optical fiber or wireless transmission. In moving to higher-order QAM constellations for higher data rates and modes, multi-path interference typically increases. The constellation points spread out, therefore decreasing the spacing between adjacent states, hence making it challenging for signal decoding at the receiver. The noise immunity is thus reduced with a smaller OSNR, or carrier-to-noise ratio, which in turn results in a higher BER. Figure 12.29 shows noise effects on the constellation points for 64QAM and 256QAM. Therefore, as M increases, the susceptibility to interference significantly increases, as seen by the markedly reduced spacings between adjacent constellation points [125]. Figure 12.30 shows the theoretical error rates for MQAM simulated on MATLAB [126]. It can be expected that if noise or dispersion compensation techniques are improvised in the

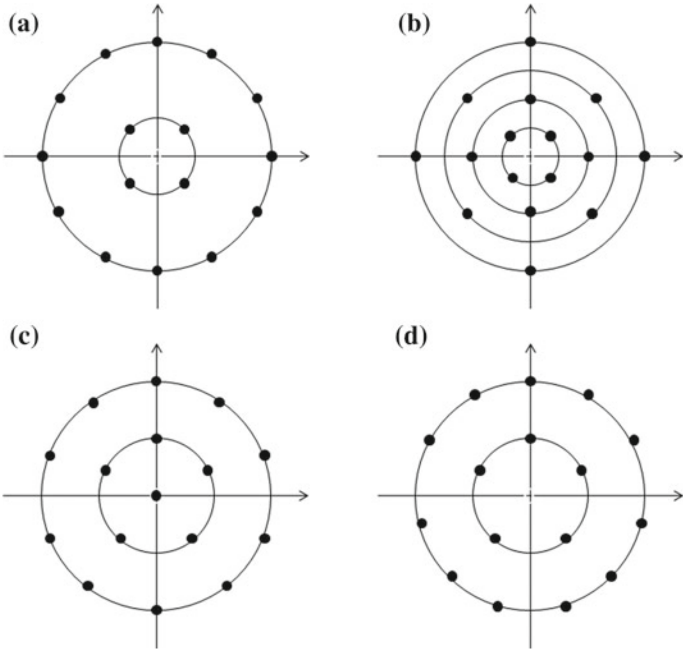



**Fig. 12.28** Circular 16QAM signal constellation. **a** Circular 16QAM(4,12), **b** circular 16QAM(4,4,4,4), **c** circular 16QAM(1,5,10), and **d** circular 16QAM(5,11)

transmission medium such as optical fibers, the benefits in higher spectral efficiency afforded by higher-order QAM can be reaped.

Multidimensional QAM can be realized in combination with other modulation and multiplexing technologies in order to improve the system bandwidth while maintaining an acceptable BER. For example, combining QAM with FSK creates FQAM, which is touted to be important for 5G networks to mitigate inter-cell interference while providing ubiquitous and high data rate connectivity [127].

Likewise, when combined with PM, PDM-MQAM is possible [137]. Figure 12.31 shows the constellation diagram of three-dimensional 64QAM, which possesses the same BER as for two-dimensional 16QAM, but the bandwidth is equivalent to that of two-dimensional 64QAM, as shown in Fig. 12.32 [126].

#### 12.4.1.6 Polarization Shift Keying

In addition to amplitude, frequency, and phase, polarization is an important parameter of optical waves. With data transmitted by varying polarization states corresponding to the binary "1" and "0", the available degrees of freedom in the polarization domain can be exploited to reduce the size of antenna arrays in conventional MIMO systems. PolSK is therefore one of the important techniques for 5G, which is able to resolve

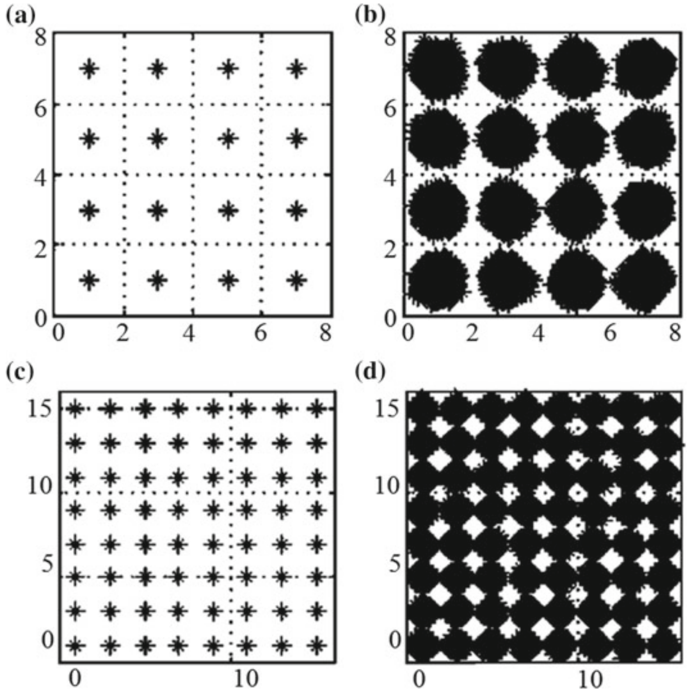
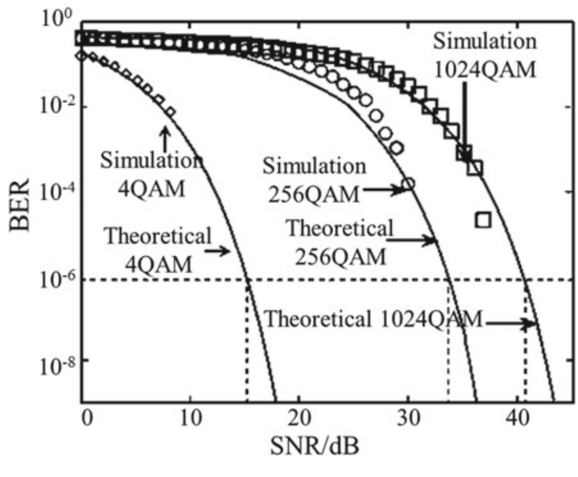



**Fig. 12.29** 1/4 part of 64QAM and 256QAM signal constellations before and after transmission over a channel. **a** Initial (no noise added) and **b** received 64QAM (SNR = 28 dB) signal, and **c** initial (no noise added) and **d** received 256QAM (SNR = 35 dB) signal. Reproduced from Zhang [125]

**Fig. 12.30** Simulation and theoretical error rate curves of MQAM. Reproduced from Zhang [126]




phase noise issues that IMDD systems encounter, or the problem of polarization state fluctuation in the optical domain. Higher optical gain can be achieved while

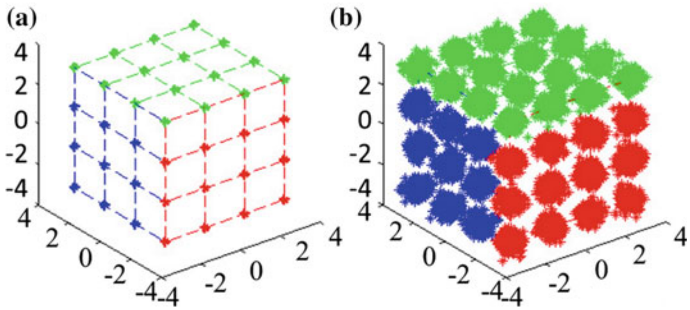
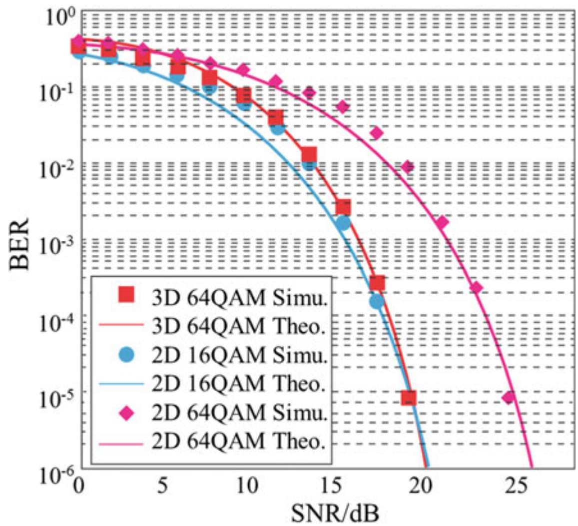



**Fig. 12.31** 3D-64QAM modulation signal constellation. **a** Initial and **b** received signal. Reproduced from Zhang [126]

**Fig. 12.32** Comparison of 2D and 3D QAM modulation Reproduced from Zhang [126]




reducing nonlinear effects (XPM and SPM) in optical fiber, appropriate for binary and multi-level transmission.

In 1964, Niblack and Wolf first proposed the conceptual polarization modulation [138], but because optical communications was at an early stage, it was not yet an attractive solution. In the 1990s, Benedetto et al. introduced PolSK for optical digital transmission, which prompted overwhelming interest for new generation communication systems [139]. In PolSK systems, the polarization modulator, which is used to modulate the polarization state of optical waves, is the most critical component. The most common type is the $LiNbO_3$ polarization modulator, which can generate any polarization, suitable for binary and multi-level PolSK systems, and which operates at a wavelength of 1550 nm. In these systems, a polarization-maintaining optical fiber or a cheaper and low-loss single-polarization fiber can be used to preserve linear polarization during propagation, so that there is little or no cross-coupling of optical power or PMD. Appropriately designed fiber cores can tackle polarization dependent loss (PDL), which occurs when two polarizations suffer different rates of loss in the fiber due to asymmetries, thereby degrading signal quality.

### 12.4.2 Pulse Modulation

Pulse modulation is often used in visible-light and optical wireless communications. To transmit narrowband analog signals over analog baseband channels, pulse modulation schemes encode message information through the control of the amplitude, width or position of a train of carrier pulses. The primary application of pulse width modulation (PWM) is in the control of the power supply to electrical devices, or in maximum power point tracking in photovoltaics. PAM is used in some versions of Ethernet communications, with PAM4 slated for next-generation high-speed data center interconnect applications. PAM4-compatible chips are already required in 200G/400G data center tranceivers. Typically, the encoding mechanism used in serial communications is the binary NRZ, whereby 0 is a low level and 1 is a high level. To encode more data into the same timeframe, PAM4 adopts multi-level signalling, using 4 distinct levels to encode 2-bit data so that the bandwidth is doubled. For future technology development, PAM8 or even PAM16 may be adopted, requiring more advanced or more complex hardware. Indeed, PAM may also be adopted in the control of LEDs in VLC systems, whereby improved energy efficiency can be achieved over other common driver modulation techniques such as PWM.

In PPM, data are transmitted in short pulses having the same amplitude and width, but the pulse delay is moodulated according to the information signal. At the transmitter, the blocks of M message bits are encoded in a single pulse by one of the required $2^{\mathrm{M}}$ possible time shifts [114]. Increasing the size of the message bits increases the transmission data rate, but also risks increasing the BER. Usually, direct modulation is adopted for PPM, whereby the electrical drive current modulates the pulse signal output from the LED or laser diode. A key advantage of PPM is that it is a multiple modulation scheme that can be implemented in optical direct detection systems, such that a phase-locked loop is not required at the receiver to track the carrier phase. PPM is mainly useful for optical communications systems where there is little or no multi-path interference, and has recently been largely replacing PAM in non-baseband applications, or may be used in conjunction with PAM. All in all, PPM is currently being used in fiber-optic communications, deep-space communications, and radio-control systems. Specifically, PPM has been widely used in IR communication systems and is adopted for the IEEE 802.11 infrared physical layer standard, and is also used in Infrared Data Association (IrDA) serial data links operating at 4 Mbps.

Multiple pulse position modulation (MPPM) is an improved form of the traditional PPM, whereby two or more pulses are used to transmit information in each channel symbol. More than one pulse can be placed in all possible ways among the $n = 2^{\mathrm{M}}$ time slots, thereby generating a much larger number of usable channel symbols. ($n$,

**Table 12.1** Encodings of 4-PPM, 4-DPPM, and (4,2)MPPM

| 2 bits | 4-PPM | 4-DPPM | (4,2)MPPM |
|---|---|---|---|
| 00 | 1000 | 1 | 1100 |
| 01 | 0100 | 01 | 1010 |
| 10 | 0010 | 001 | 1001 |
| 11 | 0001 | 0001 | 0101 |

*R*) MPPM denotes a system of M message bits encoded in *R* pulses. The number of symbols generated by *R* pulses arranged in all possible permutations among n slots is $\binom{n}{R}$. If $\binom{n}{R} \geq 2^{M}$, M message bits can be transmitted at the same time. For example, (5,2)MPPM has a total of $\binom{5}{2} = 10$ symbols, which is more than $2^3 = 8$, therefore meaning that (5,2)MPPM can simultaneously transmit three bit messages. In order to adapt to the dimming function, the number of pulses should be determined with the brightness of light (duty cycle), namely *R*/*n*. The number of pulses per symbol is determined from *R*/*n*. Therefore, it is clear that *R*-pulse MPPM increases the amount of information throughput as the number of pulses per symbol increases. Compared to traditional PPM, MPPM can achieve the same transmission rate within the same symbol time interval, hence enhancing the spectral efficiency.

In addition to MPPM, another method to improve spectral efficiency is through DPPM. In DPPM, each pulse position is encoded with respect to the previous one, such that the receiver must only measure the difference in the arrival times of successive pulses, therefore side-stepping the need to synchronize the receiver to align the local clock with the beginning of each symbol. The principal idea is to eliminate as many redundant time slots as possible without affecting the transmitted message. Table 12.1 shows 2 bit encoding by 4-PPM and 4-DPPM and (4,2)MPPM. DPPM is obtained after deletion of null binary digits in the PPM signal, hence the average symbol length for L-DPPM is $(L+1)/2$.

Certainly, in order to improve the spectral utilization, PPM can also be combined with other pulse modulation methods, such as DPPM combined with PAM that creates differential amplitude pulse position modulation, in which the pulse position can vary with amplitude. PPM can also be combined with PWM, to create pulse position width modulation, in which the pulse position can vary with pulse width [141]. In order to improve transmission capacity and power efficiency, pulse intervals can eliminated in each PPM frame, such as through DPIM, dual header pulse interval modulation (DH-PIM), or reverse dual header pulse interval modulation (RDH-PIM) [141]. In DPIM, information is encoded by changing the number of empty slots between adjacent pulses. The pulse intervals that are essentially redundant in each PPM frame are removed when adopting DPIM. DH-PIM not only eliminates the redundant pulse intervals in a PPM frame, but also reduces the average frame duration to around half that of DPIM and a quarter that of PPM. However, for VLC applications [142], DH-PIM brings about some limitation, such as dimming or flickering, which affects the lighting efficiency. In RDH-PIM, no pulse time slot is used to represent message bits, but the LED is kept in the working state at binary “1” for as long as possible. It is known that RDH-PIM has the highest average transmission power and spectral efficiency eclipsing that of DPIM and PPM, and therefore is best suited for optical wireless communication systems in 5G.

### *12.4.3 Channel Coding Technologies*

In telecommunications, information theory and computer technology, encoding is the process of putting a sequence of characters into a special format for transmission or storage. In high data rate transmission, random noise, interference, device impairment, etc., may degrade the reliability of the signal during propagation through communication links, therefore resulting in corruption of the original data stream at the receiving end. Through channel coding techniques that employ a specialized set of algorithmic operations on the data stream at the transmitter, errors can be detected, controlled, or corrected in data transmission over unreliable or noisy communication channels. This is done by encoding the message in a redundant way using an error-correcting code (ECC) . Decoding operations need to be performed at the receiver end for error correction. For 5G services, the physical layer design should thus include an efficient channel coding scheme that is able to provide robust performance and flexibility. Ever since the discipline of information theory was established by the publication of Claude Shannon’s seminal paper, linear ECCs shortly emerged, such as the Hamming code, convolutional code, cyclic code, Golay code, BCH code, RS code, GOPPA code, RM code, etc., which gradually refine error correction in the channel [143, 144]. Later, scientists began seeking out optimal coding techniques that could approach the Shannon limit, such as the forward error correction (FEC) LDCP [145] and Turbo codes [140, 146]. Turbo codes are a class of high-performance FECs that have a capacity extremely close to the Shannon limit, and can be realized with minimal complexity, so that they are used in 3G/4G mobile communications and in deep-space satellite communications. LDCP codes were not initially well regarded because of the lack of sufficiently advanced supporting hardware, which was why its implementation lagged behind that of other codes, notably Turbo codes. However, with advancement in large-scale IC technologies over the decades, LDPC codes rose in significance. LDPC codes are now finding increasing usage in applications requiring reliable and highly efficient information transfer over bandwidth-limited channels in the presence of corrupting noise. To date, developments in LDPC codes allowed them to surpass Turbo codes in terms of error floor and performance in the higher code rate range. Qualcomm Research has demonstrated that LDPC codes have advantages in terms of complexity and implementation when scaling to ultra-high throughputs and block lengths. Furthermore, LDPC coding has been shown to be ideal to combat wireless fading channels. Consequently, at the 87th meeting of 3GPP RAN1, advanced LDPC was unanimously decided as the coding scheme for the eMBB data channel. Advanced, flexible LDPC channel coding will therefore make the global 5G standard a reality. On the other hand, Huawei Corporation announced the achievement of 27-Gbps performance in 5G field trial tests using polar codes for channel coding. In the following month, 3GPP decided to adopt polar codes for the eMBB control channels for the 5G New Radio (NR) interface. These latter coding techniques are employed to enhance code domain utilization toward the Shannon limit, and efficiency and performance can be improved to realize ultra-high-speed and reliable data transmission by combining with FTN throughput.

#### 12.4.3.1 Turbo Codes

Turbo codes were developed around 1990–1991, but was first introduced in 1993 by Berrou et al. [140, 146]. The basic encoding principle is through parallel concatenation of the code words from each of the two recursive systematic convolutional component encoders and interleaver, which respectively output the corresponding parity bit. In a typical communication receiver, soft decisions produced by a demodulator are transferred to a decoder. Iterative decoding involves feeding outputs from one soft input/soft output decoder to the inputs of other equivalent component decoders, through an interleaver. Turbo codes have excellent error correction performance and capacity close to within 0.7 dB of the Shannon limit for a BER of $10^{-5}$, while the encoding/decoding complexity is not high.

#### 12.4.3.2 LDPC Codes

Robert Gallager conceptually developed LDPC codes, also known as Gallager codes, in his doctoral dissertation in 1960 [145]. However, with limited computing capability at that time, LDPC codes were once considered infeasible. In the 1990s, Mackay and Neal studied the performance of LDPC codes using randomly constructed Tanner graphs [147, 148], and the belief propagation (BP) decoding algorithm was used. It was progressively found that LDPC codes have many advantages over Turbo codes: (1) For large block lengths, LDPC codes perform within 0.04 dB of the Shannon limit at a BER of $10^{-6}$; (2) unlike Turbo, LDPC codes do not require a long interleaver to achieve good performance; (3) the block error-correcting performance of LDPC codes is better; (4) the error floor occurs at lower BER; (5) the decoding complexity is generally less (simpler operations in each iteration step) than that of Turbo codes, and decoding is not based on trellises. However, there are many disadvantages, such as the scale of hardware resources, complex coding, large coding delay, etc., involved. Subsequently, researchers have investigated aspects of code design and optimization, decoding algorithms, and implementation. A variety of code structures have been proposed for enhanced benefits, such as structured LDPC codes, non-binary LDPC codes, cascade two sub graphs of LDPC codes, finite geometry LDPC codes, progressive edge growth LDPC codes, and irregular LDPC codes [149–157]; and decoding algorithms such as BP, message passing, density evolution, offset BP-based, etc. [80, 158, 159].

#### 12.4.3.3 Polar Codes

Erdal Arikan introduced the structure of polar codes based on channel polarization in 2008 [160–162], and since then, polar codes have been considered as the latest major breakthrough in coding theory. The channel performance has now almost reached the Shannon limit and has a great advantage in reduced decoding complexity over LDCP codes and Turbo codes. Different approaches were developed to construct the polar codes. Consider an M-bit message sequence to be transmitted through the virtual channel, in which transformations occur through linear combination and splitting operations. At the transmitter/encoder, channel combining initially maps curated combinations of bits to specific channels. The channel splitting that follows at the receiver translates the bit combinations into time-domain bit streams for the decoder. Conventional successive cancellation decoding then ultimately converts the bit block and associated channels into a polarized bit stream at the receiver, i.e., the received bit and associated channel are classified as “good channel” or “bad channel” poles. As the bit block size increases, the received bit stream polarizes in a manner that the number of “good channels” approaches the Shannon limit; this makes polar codes the first and only directly verifiable capacity-achieving practical channel codes among all other coding technologies. The polar codes can be constructed using Bhattacharyya parameters to efficiently calculate channel reliabilities for binary input erasure channels (BECs), or density evolution with Gaussian approximation for other channels. In developing the decoding algorithm, a BP was introduced with factor graph representation and was shown to outperform successive cancellation decoders [163], but because of the sensitivity of BP decoders to the message-passing schedule, it is not realized on channels other than BEC. Maximum likelihood decoders can only work on short code blocks, but a successive cancellation list (SCL) decoding algorithm was introduced to approach the performance of maximum likelihood decoder with an acceptable complexity [164]. For enhanced performance over standard SCL decoding, cyclic redundancy check assisted SCL decoding was also introduced [165].

The absolutely low-complexity advantage of polar codes has made them a preferred choice over Turbo and LDPC codes, as they have so far replaced Turbo codes in 5G eMBB control channels as well as on the physical broadcasting channel, though these channels typically operate at low data rates. Other potential applications in 5G are uRLLC and mMTC. The state of the art for polar code implementations currently deliver only around 5 Gbps, which remains a challenge for polar codes to be applied to data channels typically having a much higher data rate requirement (around 20 Gbps peak for 5G mobile broadband and Tbps rates beyond-5G).

## 12.5 Conclusions

The future smart grid will need to be supported by broadband networks that connect a large range of intelligent devices as well as power and communication systems that function in real time. Hence, the communication layer is one of the most critical for smart grid applications; communication networks need to meet specific requirements, e.g., bandwidth, security, latency, reliability, etc., depending on the application. 5G networks are emerging and are expected to be available by 2020, bringing about higher capacities and efficiencies than ever. They are expected to be hybrid, where optical fiber and wireless systems co-exist as complementary infrastructure, hence reaping the benefits of the bandwidth and durability of optical fiber, and ubiquity and mobility of wireless networks. Optical communication technologies exploiting the electromagnetic spectrum from visible to infrared will be essential to support fiber-optic and optical wireless communications in 5G, giving rise to cloud networks, mobile networks, IoT, vehicular networks, and other networks that are instrumental for applications in the smart grid, cloud computing, artificial intelligence, and augmented and virtual reality, etc. New higher-order modulation technologies will be developed, including more advanced multiplexing techniques, resulting from technological or manufacturing advancements to benefit the latency, capacity and reliability of the channel. It is crucial to design modulation schemes with simple generation and detection while possessing excellent spectral efficiency, sensitivity and dispersion tolerance, to cope with optical 5G mobile fronthaul. Although much attention has revolved around fiber optics, there have been tremendous developments in optical wireless communications. Optical wireless communications are important to support smart management and smart grid measurement and metering, and other communication methods. Laser-based free-space optical communication systems allow line-of-sight connectivity for short-range data rate transmission up to several Gbps, and are thus suitable as backhaul technology for 5G wireless systems.

## References


1. Y. Sun, Research on 5G communication technology in the situation of Internet of things. China New Telecommun. **14**, 43–44 (2017)
2. 5G White Paper V2.0, Part D-Alternative Multiple access v1, Future mobile communication forum, “Candidate solution for new multiple access”, 3GPP R1-163383, Busan, Korea, Apr. 11–15, 2016
3. China Industry Standard, Specifications of engineering design for line of long-haul optical fiber cable trunk transmission system. YD5102-2003, http://t.cn/RQChL9C
4. M. Hu, A new generation of high speed, large capacity, long distance transmission optical fiber technology. Telecommun. Eng. Technics Stand. **3**, 1–5 (2017)
5. Y. Fang, How to extend your data center multimode optical fiber network. Intell. Build. Smart City **5**, 53–57 (2016)
6. E. Kabalci, Y. Kabalci, A measurement and power line communication system design for renewable smart grids. Measur. Sci. Rev. **13**(5), 248–252 (2013)
7. I. Colak, E. Kabalci, G. Fulli et al., A survey on the contributions of power electronics to smart grid systems. Renew. Sustain. Energy Rev. **47**, 562–579 (2015)
8. H.G. Zhang, Submarine cable transforming the world. City Disaster Reduction **3**, 38–42 (2014)
9. K.C. Kao, G.A. Hockham, Dielectric-fiber surface waveguides for optical frequencies. Proc. Inst. Electr. Eng. **113**(7), 1151–1158 (1966)
10. Y. Usui, S. Murai, S. Kurosaki, et al., Method of producing optical waveguide. US, US4410345 (1983)

11. J.B. Macchesney, P. O'connor, F. Dimarecello, et al., Preparation of low loss optical fibers using simultaneous vapor phase deposition and fusion, in *Proceedings of the International Congress on Glass* (1974)
12. M. Horiguchi, H. Osanai, Spectral losses of low-OH-content optical fibres. Electron. Lett. **12**(12), 310–312 (1976)
13. S. Tomaru, M. Yasu, M. Kawachi et al., VAD single mode fiber with 0.2 dB/km loss. Electron. Lett. **17**(2), 92–93 (1981)
14. Z.S. Zhao, Past, present and future of optical fiber communications. Acta Optica Sinica **9**(31), 99–101 (2011)
15. R.R. Khrapko, H.B. Matthews Iii, Optical fiber containing alkali metal oxide. US, US7536076 (2009)
16. L.J. Ball, B.P.M. Baney, D.C. Bookbinder, et al., Low loss optical fiber and method for making same. US, US7524780 (2009)
17. L.Y. Li, Low loss and ultra-low loss optical fiber review. Mod. Transm. **3**, 10–18 (2015)
18. cableabc.com, 0.1419 dB/km: Sumitomo electric works to refresh the lowest fiber loss record. http://t.cn/RQCZMqE, March 2017
19. I.P. Kaminow, T.L. Koch, *Optical Fiber Telecommunications*, 4th edn. (Academic Press, Salt Lake, 2002)
20. I.P. Kaminow, *Optical Fiber Telecommunications*, 5th edn. (Academic Press, Salt Lake, 2007)
21. I.P. Kaminow, *Optical Fiber Telecommunications*, 6th edn. (Academic Press, Salt Lake, 2013)
22. G. Wellbrock, T. Wang, O. Ishida, New paradigms in optical communications and networks. IEEE Commun. Mag. **51**(3), 22–23 (2013)
23. I. Tomkos, B. Mukherjee, S.K. Korotky et al., The evolution of optical networking. Proc. IEEE **100**(5), 1017–1022 (2012)
24. C. Xu, X. Liu, X. Wei, Differential phase-shift keying for high spectral efficiency optical transmissions. IEEE J. Sel. Top. Quantum Electron. **10**(2), 281–293 (2004)
25. S.L. Jansen, D.V.D. Borne, B. Spinnler et al., Optical phase conjugation for ultra long-haul phase-shift-keyed transmission. J. Lightwave Technol. **24**(1), 54–64 (2006)
26. K.P. Ho, *Phase-Modulated Optical Communication Systems* (Springer, New York, 2005)
27. A.J. Lowery, D. Liang, J. Armstrong, Orthogonal frequency division multiplexing for adaptive dispersion compensation in long haul WDM systems, in *2006 National Fiber Optic Engineers Conference and the National Fiber Optic Engineers Conference*, 5–10 Mar 2006, Anaheim, California (IEEE Press, New Jersey, 2006), pp. 1–3
28. W. Shieh, C. Athaudage, Coherent optical orthogonal frequency division multiplexing. Electron. Lett. **42**(10), 587–589 (2006)
29. S.J. Savory, Digital filters for coherent optical receivers. Opt. Express **16**(2), 804–817 (2008)
30. W. Shieh, I. Diorjevic, *Orthogonal Frequency Division Multiplexing for Optical Communications* (Academic Press, Salt Lake, 2010)
31. T. Wang, G. Wellbrock, O. Ishida, Next generation optical transport beyond 100G. IEEE Commun. Mag. **50**(2), s10–s11 (2012)
32. E.S. Boyden, Z. Feng, B. Ernst, Millisecond-timescale, genetically targeted optical control of neural activity. Nat. Neurosci. **8**(9), 1263–1268 (2005)
33. S. Chandrasekhar, X. Liu, B. Zhu, et al., Transmission of a 1.2-Tb/s 24-carrier no-guard-interval coherent OFDM superchannel over 7200-km of ultra-large-area fiber, in *35th European Conference on Optical Communication*, 20–24 Sept 2009, Vienna, Austria (IEEE Press, New Jersey, 2009), pp. 1–2
34. X. Liu, S. Chandrasekhar, P.J. Winzer, Digital signal processing techniques enabling multi-Tb/s super channel transmission. IEEE Signal Process. Mag. **31**(2), 16–24 (2014)
35. X. Liu, S. Chandrasekhar, Super channel for next-generation optical networks, in *Optical Fiber Communications Conference and Exhibition*, 9–13 Mar 2014, San Francisco, CA, USA (IEEE Press, New Jersey, 2014), pp. 1–33
36. Y.R. Zhou, K. Smith, S. West et al., Field trial demonstration of real-time optical superchannel transport up to 5.6 Tb/s over 359 km and 2 Tb/s over a live 727 km flexible grid link using 64G. J. Lightwave Technol. **34**(2), 805–811 (2015)

37. M. Jinno, H. Takara, B. Kozicki et al., Spectrum-efficient and scalable elastic optical path network: architecture, benefits, and enabling technologies. IEEE Commun. Mag. **47**(11), 66–73 (2009)
38. X.G. Cui, X. Liu, S.Y. Cao et al., Development, challenge and opportunity of optical fiber communication system technologies. Telecommun. Sci. **5**, 1–10 (2016)
39. Y.L. Tan, *Optical Fiber Communication System* (Hunan University Press, 2000)
40. G.P. Agrawal, Fiber-optic communication systems. Nasa Sti/Recon Tech. Rep. A **93**(2), 12–20 (1997)
41. I. Shake, H. Takara, K. Mori et al., Influence of inter-bit four-wave mixing in optical TDM transmission. Electron. Lett. **34**(16), 1600–1601 (1998)
42. R.J. Essiambre, B. Mikkelsen, G. Raybon, Intra-channel cross-phase modulation and four-wave mixing in high-speed TDM systems. Electron. Lett. **35**(18), 1576–1577 (1999)
43. A. Mecozzi, C.B. Clausen, M. Shtaif, Analysis of intrachannel nonlinear effects in highly dispersed optical pulse transmission. IEEE Photonics Technol. Lett. **12**(4), 392–394 (2000)
44. G.P. Agrawal, Nonlinear Fiber Optics, 4th edn (Academic Press, 2010)
45. M. Bertolini, N. Rossi, P. Serena et al., Do's and don'ts for a correct nonlinear PMD emulation in 100 Gb/s PDM-QPSK systems. Opt. Fiber Technol. **16**, 274–278 (2010)
46. M. Li, F. Zhang, Z. Chen et al., Chromatic dispersion compensation and fiber nonlinearity mitigation of OOK signals with diverse-VSB-filtering FFE and DFE. Opt. Express **16**(26), 21991–21996 (2008)
47. H.S. Carrer, D.E. Crivelli, M.R. Hueda, Maximum likelihood sequence estimation receivers for DWDM lightwave systems, in *2004 Global Telecommunications Conference*, 29 Nov.–3 Dec. 2004, Dallas, TX, USA, vol. 2, pp. 1005–1010 (2005)
48. I.B. Djordjevic, L.L. Minkov, L. Xu et al., Suppression of fiber nonlinearities and PMD in coded-modulation schemes with coherent detection by using Turbo equalization. J. Opt. Commun. Networking **1**(6), 555–564 (2009)
49. E. Ip, J.M. Kahn, Compensation of dispersion and nonlinear impairments using digital back propagation. J. Lightwave Technol. **26**(20), 3416–3425 (2008)
50. L.B. Du, A.J. Lowery, Improved single channel back propagation for intra-channel fiber nonlinearity compensation in long-haul optical communication systems. Opt. Express **18**(16), 17075–17088 (2010)
51. X.H. Zhao, B.J. Yang, Limitation of stimulated Raman scattering on the power of wavelength division multiplexed transmission system. J. Beijing Univ. Posts Telecommun. **26**(z1), 13–16 (2003)
52. H.X. Bian, S.H. Hou, Theroy of stimulated Raman crosstall cancellation in WDM systems via wavelength conversion technology. Commun. Technol. **40**(12), 46–47 (2007)
53. X.A. Mei, J.Y. Tao, S. Yuan et al., A comprehensive study of SRS optical power equalization. J. Changsha Univ. **21**(2), 10–12 (2007)
54. R.I. Killey, P.M. Watts, M. Glick et al., Electronic dispersion compensation by signal pre-distortion, in *2006 Optical Fiber Communication Conference and the National Fiber Optic Engineers Conference*, 5–10 Mar 2006, Anaheim, CA, USA, vol. 25, No. 6, p. 3 (2006)
55. G. Goeger, Modulation format with enhanced SPM-robustness for electronically pre-distorted transmission, in 2006 *European Conference on Optical Communications*, 24–28 Sept 2006, Cannes, France, pp. 1–2 (2006)
56. C. Xu, X. Liu, Post nonlinearity compensation with data-driven phase modulators in phase-shift keying transmission. Opt. Lett. **17**(18), 1619–1621 (2002)
57. G. Charlet, QPSK with coherent detection over ultra-long distance improved by nonlinearity mitigation, *Leos Summer Topical Meeting*, 23–25 July 2007, Portland, OR, USA, pp. 43–44 (2007)
58. K.P. Ho, Error probability of DPSK signals with cross-phase modulation induced nonlinear phase noise. IEEE J. Sel. Top. Quantum Electron. **10**(2), 421–427 (2004)
59. G. Charlet, H. Mardoyan, P. Tran, et al., Nonlinear interactions between 10 Gb/s NRZ channels and 40 Gb/s channels with RZ-DQPSK or PSBT format over low-dispersion fiber, in *2006 European Conference on Optical Communications*, 24–28 Sept 2006, Cannes, France, pp. 1–2 (2006)

60. X. Liu, S. Chandrasekhar, Suppression of XPM penalty on 40-Gb/s DQPSK resulting from 10-Gb/s OOK channels by dispersion management, in *2008 Conference on Optical Fiber Communication/National Fiber Optic Engineers Conference*, 24–28 Feb 2008, San Diego, CA, USA, pp. 1–3 (2008)
61. F. Inuzuka, E. Yamazaki, K. Yonenaga, et al., Nonlinear inter-channel crosstalk compensation using electronic pre-distortion in carrier phase locked WDM, in *2008 Conference on Optical Fiber Communication/National Fiber Optic Engineers Conference*, 24–28 Feb 2008, San Diego, CA, USA, pp. 1–3 (2008)
62. X. Li, X. Chen, G. Goldfarb et al., Electronic post-compensation of WDM transmission impairments using coherent detection and digital signal processing. Opt. Express **16**(2), 880–888 (2008)
63. T. Hirooka, M.J. Ablowitz, Intrachannel pulse interactions in dispersion-managed transmission systems: energy transfer. IEEE Photonics Technol. Lett. **14**(3), 316–318 (2002)
64. R.I. Killey, H.J. Thiele, V. Mikhailov et al., Reduction of intrachannel nonlinear distortion in 40-Gb/s-based WDM transmission over standard fiber. IEEE Photonics Technol. Lett. **12**(12), 1624–1626 (2000)
65. J. Martensson, M. Westlund, A. Bernston, Intra-channel pulse interactions in 40Gbit/s dispersion-managed RZ transmission. Electron. Lett. **36**(2), 244–246 (2000)
66. A. Mecozzi, C.B. Clausen, M. Shtaif et al., Cancellation of timing and amplitude jitter in symmetric links using highly dispersed pulses. IEEE Photonics Technol. Lett. **13**(5), 445–447 (2001)
67. X. Wei, A.H. Gnauck, X. Liu et al., Nonlinearity tolerance of RZ-AMI format in 42.7 Gbit/s long-haul transmission over standard SMF spans. Electron. Lett. **39**(20), 1459–1461 (2003)
68. J. Martensson, A. Berntson, A. Djupsjobacka et al., Phase modulation schemes for improving intrachannel nonlinear tolerance in 40 Gbit/s transmission, in *2003 Optical Fiber Communication*, 28–28 Mar 2003, Atlanta, GA, USA, vol. 2, pp. 662–663 (2003)
69. V. Mikhailov, C.R. Doerr, L. L. Buhl, et al., Mitigation of intra-channel nonlinear distortion in 42.7 Gb/s RZ transmission using a single chip optical equalizer, in *2006 Optical Fiber Communication Conference and the National Fiber Optic Engineers Conference*, 5–10 Mar 2006, Anaheim, CA, USA, p. 3 (2006)
70. J. Li, F. Zhang, Z. Chen, Electronic equalization of intrachannel nonlinearities, in *2007 International Nano-Optoelectronics Workshop*, July 29–August 11, 2007, Beijing, China, pp. 108–109 (2007)
71. A.H. Gnauck, P.J. Winzer, C.R. Doerr, et al. 10 × 112-Gb/s PDM 16-QAM transmission over 630 km of fiber with 6.2-b/s/Hz spectral efficiency, in *2009 Optical Fiber Communication—Incudes Post Deadline Papers*, 22–26 Mar 2009, San Diego, CA, USA, pp. 1–3 (2009)
72. T. Omiya, M. Yoshida, M. Nakazawa et al., 400 Gbit/s 256 QAM-OFDM Transmission over 720 km with a 14 bit/s/Hz spectral efficiency using an improved FDE technique. Opt. Express **21**(3), 2632–2641 (2013)
73. R. Yuan, Overview of OFDM for optical communication systems. Opt. Commun. Technol. **8**, 29–33 (2011)
74. A. Sano, H. Masuda, T. Kobayashi, et al., 69.1-Tb/s (432 x 171-Gb/s) C- and Extended L-Band Transmission over 240 Km Using PDM-16-QAM Modulation and Digital Coherent Detection, in *2010 Optical Fiber Communication*, 21–25 Mar 2010, San Diego, CA, USA, pp. 1–3 (2010)
75. X.S. Yao, L.S. Yan, B. Zhang et al., All-optic scheme for automatic polarization division demultiplexing. Opt. Express **15**(12), 7407–7414 (2007)
76. J.S. Lai, R. Tang, B.B. Wu et al., Analysis on the research progress of space division multiplexing in optical fiber communication. Telecommun. Sci. **9**, 118–135 (2017)
77. K. Igarashi, D. Soma, Y. Wakayama et al., Ultra-dense spatial-division-multiplexed optical fiber transmission over 6-mode 19-core fibers. Opt. Express **24**(10), 10213 (2016)
78. A. Sano, T. Kobayashi, S. Yamanaka, et al., 102.3-Tb/s (224 × 548-Gb/s) C- and extended L-band all-Raman transmission over 240 km using PDM-64QAM single carrier FDM with digital pilot tone, in *Optical Fiber Communication Conference and Exposition*, 4–8 Mar 2012, Los Angeles, CA, USA, pp. 1–3 (2012)

79. R. Ryf, N.K. Fontaine, H. Chen et al., Mode-multiplexed transmission over conventional graded-index multimode fibers. Opt. Express **23**(1), 235–246 (2015)
80. ETSI, Digital Video Broadcasting (DVB); User guidelines for the second generation system for broadcasting, interactive services, new gathering and other broad-band satellite applications (DVB-S2), TR 102 376
81. L.H. Guo, L. Zhang, Z.W. Du et al., A survey of lunar laser communications demonstration of NASA. J. Spacecraft TT&C Technol. **34**(1), 87–94 (2015)
82. Z. Zeng, X. Liu, H. Sun et al., Latest developments of space laser communications and some development suggestions. Opt. Commun. Technol. **6**, 1–5 (2017)
83. OFS, Fiber optic cables. http://t.cn/RQl3nFa, June 2017
84. M.J. Li, H. Chen, Novel optical fibers for high-capacity trans-mission system. Telecommun. Sci. **30**(6), 1–15 (2014)
85. K. Saitoh, S. Matsuo, Multicore fiber technology. J. Lightwave Technol. **34**(1), 55–66 (2016)
86. A. Turukhin, O.V. Sinkin, H.G. Batshon, et al., 105.1 Tb/s power-efficient transmission over 14,350 km using a 12-core fiber, in *Optical Fiber Communication Conference 2006*, 20–24 March 2016, Anaheim, CA, USA, pp. 1–3 (2006)
87. N.K. Fontaine, R. Ryf, H. Chen, et al., 30 × 30 MIMO transmission over 15 spatial modes, in 2015 *Optical Fiber Communications Conference and Exhibition*, 22–26 March 2015, Los Angeles, CA, USA, pp. 1–3 (2015)
88. A.E. Willner, A.F. Molisch, C. Bao et al., Optical communications using orbital angular momentum beams. Adv. Opt. Photonics **7**(1), 66–106 (2015)
89. J.S. Lai, B.B. Wu, W.Y. Zhao et al., Orbital angular momentum technology in optical communication and its application analysis. Telecommun. Sci. **30**(5), 46–50 (2014)
90. L.P. Xu, Optical communication industry: opportunities and challenges coexist. Shanghai Informatization **5**, 53–56 (2017)
91. H.F. Jiang, All-wave fiber and its characteristics. Opt. Fiber Electric Cable Their Appl. **3**, 9–11 (2001)
92. K.W.A. Chee, Z. Tang, H. Lü, F. Huang, Anti-reflective structures for photovoltaics: numerical and experimental design. Energy Rep. 4, 266–273 (2018)
93. L. Guo, D.F. Tang, Optical soliton communication technology and its prospects. Electron Technol. **30**(8), 97–99 (2013)
94. P.W. Shor, Algorithms for quantum computation: discrete logarithms and factoring, in *Proceedings 35th Annual Symposium on Foundations of Computer Science*, 20–22 Nov 1994, Santa Fe, NM, USA, pp. 124–134 (1994)
95. M.A. Nielsen, I. Chuang, *Quantum Computing and Quantum Information* (Cambridge Press, 2000)
96. N. Gisin, G. Ribordy, W. Tittel, et al., Quantum cryptography. Rev. Modern Phys. **74**, 145–195 (2002)
97. X. Zhang, D. Huang, J. Sun et al., A novel scheme for XGM wavelength conversion based on single-port-coupled SOA. Chin. Phys. **10**(2), 124–127 (2001)
98. A.M. Clarke, G. Girault, P. Anandarajah, et al., FROG characterisation of SOA-based wavelength conversion using XPM in conjunction with shifted filtering up to line rates of 80 GHz, in *LEOS 2006—19th Annual Meeting of the IEEE Lasers and Electro-Optics Society*, October 29–November 2, 2006, Montreal, Que., Canada, pp. 152–153 (2006)
99. G. Contestabile, M. Presi, E. Ciaramella et al., Multiple wavelength conversion for WDM multicasting by FWM in an SOA. IEEE Photonics Technol. Lett. **16**(7), 1775–1777 (2004)
100. N.E. Dahdah, R. Coquille, B. Charbonnier et al., All-optical wavelength conversion by EAM with shifted bandpass filter for high bit-rate networks. IEEE Photonics Technol. Lett. **18**(1), 61–63 (2005)
101. Y. Wang, C.Q. Xu, Picosecond-pulse wavelength conversion based on cascaded SFG/DFG in a PPLN waveguide. Appl. Opt. **45**(21), 5391–5403 (2006)
102. J. Fonseca-Campos, Y. Wang, B. Chen, 40-GHz picosecond-pulse second-harmonic generation in a MgO-doped PPLN waveguide. IEEE J. Lightwave Technol. **24**(10), 3698–3708 (2006)

103. Y. Wang, C.Q. Xu, Analysis of ultrafast all-optical OTDM demultiplexing based on cascaded wavelength conversion in PPLN waveguides. IEEE Photonics Technol. Lett. **19**(7), 495–497 (2007)
104. M. Takahashi, S. Takasaka, R. Sugizaki, et al., Arbitrary wavelength conversion in entire CL-band based on pump-wavelength-tunable FWM in a HNLF, in *2010 Conference on Optical Fiber Communication*, 21–25 Mar 2010, San Diego, CA, USA, pp. 1–3 (2010)
105. S. Suda, J. Kurumida, K. Tanizawa, et al., Pattern-effect-free wavelength conversion based on FWM in hydrogenated amorphous silicon waveguide, in *2011 Optical Fiber Communication Conference and Exposition, and the National Fiber Optic Engineers Conference*, 6–10 Mar 2011, Los Angeles, CA, USA, pp. 1–3 (2011)
106. J. Horer, E. Patzak, Large-signal analysis of all-optical wavelength conversion using two-mode injection-locking in semiconductor lasers. IEEE J. Quantum Electron. **33**(4), 596–608 (1997)
107. C.J. Wu, C.X. Yan, Z.L. Gao, Overview of space laser communications. Chin. Opt. **06**(05), 670–680 (2013)
108. J. Rong, Y. Hu, The application of optical power amplified technology in intersatellites optical communications. Laser J. **23**(5), 7–9 (2003)
109. C.Z. Wu, Application of FSO system in next generation mobile bearer network. Modern Transm. **02**, 56–66 (2012)
110. Z. Lu, Z. Wu, Closed-form suboptimal maximum likelihood sequence detection for free space optical communications. Appl. Opt. **51**(27), 6441–6447 (2012)
111. K.M. Arun, C.R. Jennifer, *Free-Space Laser Communications Principles and Advances* (Springer Press, New York, 2008)
112. F. Li, Z. Hou, Y. Wu, Experiment and numerical evaluation of bit error rate for free-space communication in turbulent atmosphere. Opt. Laser Technol. **45**, 104–109 (2013)
113. X. Li, S.Y. Yu, J. Ma et al., Analytical expression and optimization of spatial acquisition for intersatellite optical communications. Opt. Express **19**(3), 2381–2390 (2011)
114. X. Zhang, Y. Cao, X.F. Peng et al., Research on coding technology of LT code in free space optical communication. Semicond. Optoelectron. **38**(2), 242–245 (2017)
115. Y. Tanaka, S. Haruyama, M. Nakagawa, Wireless optical transmissions with white colored LED for wireless home links, in *11th IEEE International Symposium on Personal Indoor and Mobile Radio Communications*, 18–21 Sept 2000, London, UK, pp. 1325–1329 (2000)
116. Y. Tanaka, T. Komine, S. Haruyama, et al., Indoor visible communication utilizating plural white LEDs as lighting, in *The 12th IEEE International Symposium on Personal, Indoor and Mobile Radio Communications*, 3 October–30 September 2001, San Diego, CA, USA, pp. F81–F85 (2001)
117. K. Fan, T. Komine, Y. Tanaka, et al., The effect of reflection on indoor visible light communication system utilizing white LEDs, in *The 5th International Symposium on Wireless Personal Multimedia Communications*, 27–30 Oct 2002, Honolulu, HI, USA, pp. 611–615 (2002)
118. H. Haas, *High-speed Wireless Networking Using Visible Light* (Spienewsroom, 2013)
119. Y. Wang, R. Li, Y. Wang, et al., 3.25-Gbps visible light communication system based on single carrier frequency domain equalization utilizing an RGB LED, in *2014 Optical Fiber Communications Conference and Exhibition*, 9–13 Mar 2014, San Francisco, CA, USA, pp. 1–3 (2014)
120. R.A. Griffin, R.I. Johnstone, R.G. Walker, et al., 10 Gb/s Optical differential quadrature phase shift key (DQPSK) transmission using GaAs/AlGaAs integration, in *2002 Optical Fiber Communication Conference and Exhibit*, 17–22 Mar 2002, Anaheim, CA, USA, pp. FD6-1–FD6-3 (2002)
121. A.H. Gnauck, P.J. Winzer, C.R. Doerr, et al., $10 \times 112$-Gb/s PDM 16-QAM transmission over 630 km of fiber with 6.2-b/s/Hz spectral efficiency, in *2009 Optical Fiber Communication—incudes post deadline papers*, 22–26 Mar 2009, San Diego, CA, USA, pp. 1–3 (2009)
122. M. Salsi, H. Mardoyan, P. Tran, et al., $155 \times 100$ Gbit/s coherent PDM-QPSK transmission over 7,200 km, in *2009 European Conference on Optical Communications*, 20–24 Sept 2009, Vienna, Austria, pp. 1–2 (2009)

123. A.H. Gnauck, P.J. Winzer, S. Chandrasekhar, et al., 10 × 224-Gb/s WDM Transmission of 28-Gbaud PDM 16-QAM On A 50-GHz Grid Over 1,200 Km of Fiber, in *2010 Optical Fiber Communication*, 21–25 Mar 2010, San Diego, CA, USA, pp. 1–3 (2010)
124. T. Richter, E. Palushani, C. Schmidtlanghorst, et al., Single wavelength channel 10.2 Tb/s TDM-data capacity using 16-QAM and coherent detection, in *2011 Optical Fiber Communication Conference and Exposition*, 6–10 Mar 2011, Los Angeles, CA, USA, pp. 1–3 (2011)
125. C.Q. Zhang, Analysis of LTE-A high baseband modulation technology 256QAM. Telecommun. Netw. Technol. **11**, 57–61 (2015)
126. C.Q. Zhang, Study on high speed baseband digital modulation techniques for 5G. Designing Tech. Posts Telecommun. **7**(11), 33–38 (2017)
127. X. Li, Research on the application of FQAM modulation technology oriented to 5G. Sci. Technol. Vis. **10**, 53–54 (2017)
128. Q. Jin, Y. Hu, Analysis of 100/400 Gbits/s PAM4 optical transceiver module technology. Study Opt. Commun. **194**, 33–36 (2016)
129. C.H. Yeh, C.W. Chow, C.H. Wang, et al., Using OOK modulation for symmetric 40-Gb/s long-reach time-sharing passive optical networks. IEEE Photonics Technol. Lett. **22**(9), 619–621 (2010)
130. G.W. Lu, T. Miyazaki, Optical phase add-drop for format conversion between DQPSK and DPSK and its application in optical label switching systems. IEEE Photonics Technol. Lett. (2009)
131. T. Dohong, "Differential phase shift keying," *Network Dictionary*, 2007
132. W.Y. Gu, *Ultra Long Haul Optical Transmission Technology* (Beijing University of Posts and Telecommunications Press, 2006)
133. J. Wang, J.M. Kahn, Conventional DPSK versus symmetrical DPSK: comparison of dispersion tolerances. Photonics Technol. Lett. **16**(6), 1585–1587 (2004)
134. A. Castanon, A. Gerardo, I.A. Aldaya Garde. Optical signal phase regenerator for formats of differential modulation with phase changes. US, US 8280261 B2 (2012)
135. G. Khanna, T. Rahman, E. Man, et al., Single-carrier 400G 64QAM and 128QAM DWDM field trial transmission over metro legacy links. IEEE Photonics Technol. Lett. **29**, 189–192 (2017)
136. H.C. Chien, J. Zhang, J. Yu, et al., Single-carrier 400G PM-256QAM generation at 34 GBaud trading off bandwidth constraints and coding overheads, in *2017 Optical Fiber Communications Conference and Exhibition*, 19–23 Mar 2017, Los Angeles, CA, USA, pp. 1–3 (2017)
137. T.J. Richardson, A. Shokrollahi, R. Urbanke et al., Design of capacity-approaching irregular low-density parity-check codes. IEEE Trans. Inf. Theory **47**(2), 619–637 (2001)
138. W. Niblack, E. Wolf, Polarization modulation and demodulation of light. Appl. Opt. **3**(2), 277–279 (1964)
139. S. Benedetto, P. Poggiolini, Theory of polarization shift keying modulation. IEEE Trans. Commun. **40**, 708–721 (1992)
140. C. Berrou, A. Glavieux, Near optimum error correcting coding and decoding: turbo-codes. IEEE Trans. Commun. **44**(10), 1261–1271 (1996)
141. Y.Y. Pan, B. Bai, A.P. Huang et al., Pulse-position-width modulation scheme in wireless optical communication system. Chin. J. Lasers **12**(35), 1883–1887 (2008)
142. Y. Liu, G.A. Zhang, Study on modulation scheme of visible light communications and its performance. Laser Optoelectron. Prog. **9**, 65–71 (2014)
143. D.E. Muller, Application of boolean algebra to switching circuit design and to error detection. Trans. IRE Prof. Group Electron. Comput. EC **3**(3), 6–12 (1954)
144. I. Reed, A class of multiple-error-correcting codes and the decoding scheme. Inf. Theory Trans. IRE Prof. Group **4**(4), 38–49 (1954)
145. R.G. Gallager, Low-density parity-check codes. IEEE Press **8**(1), 3–26 (2011)
146. L. Lopacinski, J. Nolte, S. Buechner, et al., Improved turbo product coding dedicated for 100 Gbps wireless terahertz communication, in *2016 IEEE 27th Annual International Symposium on Personal, Indoor, and Mobile Radio Communications*, 4–8 Sept 2016, Valencia, Spain, pp. 1–6 (2016)

147. D.J.C. Mackay, R.M. Neal, Near Shannon limit performance of low-density parity-check codes. IEEE Lett. **32**(18), 1645–1646 (1996)
148. D.J.C. Mackay, Good error correcting codes based on very sparse matrices. IEEE Trans. Inf. Theory **45**(2), 399–431 (1999)
149. M.C. Davey, D.J.C. Mackay, Low density parity check codes over GF(q). IEEE Inf. Theory Workshop **2**(6), 70–71 (2002)
150. M. Luby, Efficient erasure correcting codes. IEEE Trans. Inf. Theory **47**(2), 569–584 (2007)
151. A. Chakrabarti et al., Low density parity check codes for the relay channel. IEEE Sel. Areas Commun. **25**(2), 280–291 (2007)
152. A. Baynast, A. Sabharwal, B. Azhang, et al., LDPC code design for OFDM channel: graph connectivity and information bits positioning, in *IEEE International Symposium on Signals, Circuits and Systems*, vol. 2, pp. 649–652 (2005)
153. M. Ardakani, F.R. Kschischang, A more accurate one-dimensional analysis and design of irregular LDPC codes. IEEE Trans. Commun. **52**(12), 2106–2114 (2004)
154. K. Fu, A. Anstasopoulos, Analysis and design of LDPC codes for time selective complex-fading channels. IEEE Trans. Wireless Commun. **4**(3), 1175–1185 (2005)
155. N. Wen, J.W. Lu, X. Liu et al., Optimized irregular LDPC codes design for OFDM system. J. Beijing Univ. Posts Telecommun. **29**(4), 107–110 (2006)
156. H. Tang, J. Xu, S. Lin, Codes on finite geometries. IEEE Trans. Inf. Theory **51**(2), 572–596 (2005)
157. X.Y. Hu, E. Eleftheriou, D. M. Arnold, Regular and irregular progressive edge-growth tanner graphs. IEEE Trans. Inf. Theory **51(**1) (2005)
158. M.P.C. Fossorier, M. Mihaljevic, H. Imai, Reduced complexity iterative decoding of low density parity check codes based on belief propagation. IEEE Trans. Commun. **47**, 673–680 (1999)
159. J. Chen, M.P.C. Fossorier, Near optimum universal belief propagation based decoding of LDPC codes. IEEE Trans. Commun. **50**, 406–414 (2002)
160. E. Arikan, A performance comparison of polar codes and Reed-Muller codes. IEEE Commun. Lett. **12**(6), 447–449 (2008)
161. E. Arikan, E. Telatar, On the rate of channel polarization, in *2009 IEEE International Symposium on Information Theory,* June 28–July 3, 2009, Seoul, Korea, pp. 1493–1495 (2009)
162. E. Arikan, Channel polarization: a method for constructing capacity-achieving codes for symmetric binary-input memoryless channels. IEEE Trans. Inf. Theory **55**(7), 3051–3073 (2008)
163. N. Hussami, S.B. Korada, R. Urbanke, Performance of polar codes for channel and source coding, in *IEEE International Symposium on Information Theory*, pp. 1488–1492 (2009)
164. K. Chen, K. Niu, J. Lin, Improved successive cancellation decoding of polar codes. IEEE Trans. Commun. **61**(8), 3100–3107 (2013)
165. Q. Zhang, A. Liu, X. Pan et al., CRC code design for list decoding of polar codes. IEEE Commun. Lett. **21**(6), 1229–1232 (2017)