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This book is dedicated
to my wife Kate and
my daugther Caroline.

Contents

Preface

Currently, virtually all commercially available optical communication systems use on-off keying to carry information by the presence or absence of light. Neither the phase nor frequency of an optical signal is used to carry information. Phase-modulated optical communications, or coherent optical communications, have been studied for a long time since the early date of optical communications. However, early works focused on improving receiver sensitivity that have became less relevant after the widely deployment of optical amplifiers.

In the *Optical Fiber Communication Conference 2002 (OFC '02)*, Gnauck et al. (2002) and Griffin et al. (2002) revived phase-modulated optical communication systems based on direct-detection of return-to-zero differential phase-shift keying (RZ-DPSK) and differential quadrature phase-shift keying (DQPSK) signal. With 3 dB better receiver sensitivity and improved tolerance to fiber nonlinearities, RZ-DPSK signal becomes the emerging transmission format for long-haul and ultra-long-haul lightwave transmissions. DQPSK signal also improves the spectral efficiency of the lightwave systems.

Because the usage of optical amplifiers to maintain a high optical power along the fiber link, current optical communication systems are fundamentally limited by the balancing of both optical amplifier noises and fiber nonlinearities. Our initial studies focus on the impact of nonlinear phase noise to DPSK signal. The topics of nonlinear phase noise came to us by accident. Also in *OFC '02*, we published a paper about the capacity of constant-intensity modulation in lightwave systems (Ho and Kahn, 2002), mainly to clarify our comments of Kahn and Ho (2001) on the important paper of Mitra and Stark (2001). In Mitra and Stark (2001), the capacity of multichannel wavelength-division multiplexed (WDM) systems is limited by cross-phase modulation. Ideally, constant-intensity modulation, including phase and frequency modulation, gives a constant phase shift to other channels through cross-phase modulation. Constant-intensity modulation is more likely to be limited by four-wave mixing than cross-phase modulation. Because of Gnauck et al. (2002), many people mentioned that nonlinear phase noise of Gordon and Mollenauer (1990) is the major limitation to constant-intensity modulation. Without the knowledge of both Liu et al. (2002b) and Xu and Liu (2002) to compensate nonlinear phase noise using the received intensity, most people believed that nonlinear phase noise was the primary limitation with no practical solution.

Back to San Jose, within days, we realized that nonlinear phase noise is correlated with the received intensity and may be compensated by the received intensity using electronic circuits, functionally the same as both Liu et al. (2002b) and Xu and Liu (2002). After many revisions, the paper was published as Ho and Kahn (2004a), even after some of our contributions to other topics related to nonlinear phase noise had been published. Ho and Kahn (2004a) began our works on the research on phase-modulated signal for lightwave communications.

This book is originated from the notes for a seminar style class on coherent optical communications. The students in the class provided a great help on improving the manuscript and selecting the materials. For system in linear regime, the performance of phase-modulated signal is mainly studied for system dominated by amplifier noises. Nonlinear phase noise is the unquestionable limitations when the signal pulse maintains its shape along the fiber link. When the optical pulse is broadened by fiber chromatic dispersion, pulse overlap and the subsequent pulse-to-pulse interaction also degrades a DPSK signal. However, pulse-to-pulse interaction usually has less effect then nonlinear phase noise.

The materials of this book are suitable for researchers in the field of lightwave communications and graduate students in the class of advanced optical communication systems.

KEANG-PO HO

Acknowledgments

In my career in optical communications, Prof. Joseph Kahn is my mentor in UC Berkeley, colleague in StrataLight, and good friend outside business. He taught me the method and aesthetic to approach and solve problems. Earlier in my career, I would like to thank both Chinlon Lin and Paul Shumate as my manager in Bellcore (currently Telcordia Technologies), Frank Tong as my supervisor in IBM and colleague in the Chinese University of Hong Kong, and Lian Chen, Tony Lee, Robert Li, Kok Cheung, Wing Wong, and Raymond Yeung as my colleagues in the Chinese University of Hong Kong. The co-founding with Joseph Kahn and Terry Smith of StrataLight Communications was also a very exciting and rewarding experience. I would like to also thank Ted Schmidt, Gary Wang, and Anhui Liang as my colleagues in StrataLight. Gary was the one who made a copy of Gordon and Mollenauer (1990) from Stanford Library to me.

Prof. Jingshown Wu and Hen-Wai Tsao brought me to the field of optical communications in early 90's, especially introduced me to the field of coherent optical communications. Both Prof. Wu and Prof. Tsao are currently my senior colleagues in National Taiwan University. Prof. Tsao especially gave me with great encouragement during the preparation of this book. I also would like to thank my students in National Taiwan University, including to Hsi-Cheng Wang, Jen-An Huang, Alien Chen, Terry Yuan, Kevin Chen, Po-Yu Chen and others.

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Figures 6.1, 9.19, 11.1 are adapted from some initial drawings of Prof. Joseph Kahn. Ms. Hsiu-Huei Yen also provided lots of clerical supports in this book project.

Chapter 1

INTRODUCTION

Fiber-optic communication systems have been deployed worldwide and certainly revolutionized the current and future telecommunication infrastructures. Currently, virtually all telephone conversations, cellular phone calls, and Internet packets must pass through some pieces of optical fiber from source to destination. While initial deployment of optical fiber was mainly for long-haul or submarine transmission, lightwave systems are currently in virtually all metro networks. The future deployment of optical fiber is moving toward the home for broadband access. Fiber-to-the-premise (FTTP) and fiber-to-the-home (FTTH) are being considered seriously in most parts of the World right now (Abrams et al., 2005).

Since Kao and Hockham (1966) first proposed the usage of optical fiber to guide light for information transmission, the fiber loss has been reduced from the early date of 20 dB/km (Kapron et al., 1970) to about 0.15 dB/km (Kaiser and Keck, 1988, Kanamori et al., 1986, Murata and Inagaki, 1981, Nagayama et al., 2002). Most of the commercially available optical fiber has a loss of about 0.2 dB/km at the low-loss window around 1.55 μm[1]. Optical signal can be transmitted for a long distance without regeneration owning to the low-loss characteristic of optical fiber.

With great physical properties, Erbium-doped fiber amplifiers (EDFA) also provide gain at the low-loss window of 1.55 μm (Becker et al., 1999, Desurvire, 1994). Optical amplifiers are used to periodically amplify an optical signal to compensate for fiber loss. The low-loss window of optical

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[1] Product information of optical fiber are available from `http://www.corning.com/opticalfiber/`, `http://www.ofsoptics.com`, and `http://www.alcatel.com/products`.

fiber can also partition to many channels for dense wavelength-division-multiplexed (WDM) systems. Only adding noise to the signal, EDFA amplifies many WDM channels together without crosstalk and distortion. Before the usage of phase-modulated signals, very high throughput fiber link has been constructed without electronic regeneration for trans-oceanic distances (Bakhshi et al., 2004, Bergano and Davidson, 1996, Cai et al., 2002, 2003b, Golovchenko et al., 2000, Suzuki and Edagawa, 2003). With the usage of phase-modulated signals, the system performance is further improved (Becouarn et al., 2003, Cai et al., 2004, Charlet et al., 2004b, Rasmussen et al., 2003, 2004). In all commercially available lightwave transmission systems, only the intensity of optical signal is used to carry information. Neither the phase nor frequency of an optical carrier is used. In order to transmit more information in a single optical carrier or a single WDM channel, the phase of an optical carrier must be explored. In this chapter, we will briefly explain the basic architecture of intensity modulated optical communication systems and the reason the phase should be used to converse information in an optical carrier.

1. Intensity-Modulated/Direct-Detection Systems

Currently, virtually all deployed fiber systems use the simple intensity modulation system in which the information is carried in the light intensity and recovered using a photodiode, so called on-off keying or intensity-modulated/direct-detection (IMDD) systems. Most textbooks of optical communications focus mainly on IMDD systems (Agrawal, 2002, Einarsson, 1996, Iannone et al., 1998, Kazovsky et al., 1996, Keiser, 1999, Kolimbiris, 2004, Mynbaev and Scheiner, 2001, Senior, 1992). Both transmitter and receiver for on-off keying systems are very simple, may be the simplest among all possibilities.

Figure 1.1 shows a typical long-haul IMDD system. The transmitted data are modulated into the optical carrier using an external intensity modulator that is basically a very fast switch to turn-on and -off the light path to carry either “0” or “1”. After the modulator, the optical signal passes through an EDFA to boost up the power and then is launched into the optical fiber. In Fig. 1.1, EDFA is used periodically to compensate for fiber loss span after span.

After many spans of optical fiber, the optical signal is further amplified using a low-noise EDFA preamplifier. The optical signal is converted to electrical signal using a fast photodiode. Ideally, a photodiode converts a photon to an electron, i.e., the optical intensity to electrical current. Information in the phase or frequency of the optical carrier losses in the photodiode. The photodiode is followed by an electrical amplifier,

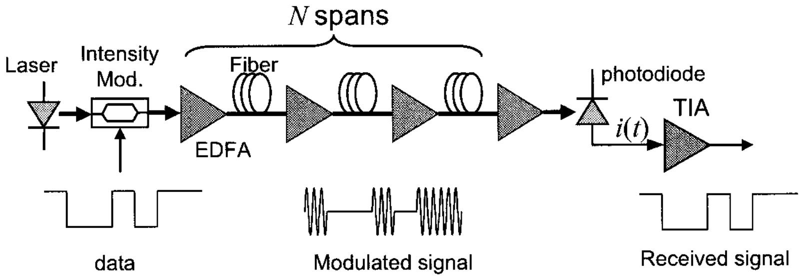


Figure 1.1. Typical configuration of an intensity-modulated/direct-detection (IMDD) system.

usually a trans-impedance amplifier (TIA) to convert photocurrent to voltage. The received signal after the TIA is the same as the transmitted signal but with noise mostly from optical amplification and the receiver circuitry.

The IMDD system illustrated schematically in Fig. 1.1 is very simple. The receiver decides whether the transmitted bits are either "0" or "1" based on the presence or absence of light. This class of system can use either non-return-to-zero (NRZ) or return-to-zero (RZ) pulses for digital transmission. Subcarrier multiplexing (Way, 1998) is also IMDD system to transmit either digital or analog modulated frequency-division multiplexed (FDM) channels in the intensity of the optical carrier. Subcarrier multiplexing is mostly for video distribution, but may also be used for high-speed digital data (Hui et al., 2002). Hybrid WDM systems can transmit some on-off keying and some subcarrier multiplexed channels (Ho et al., 1998b, Lee et al., 2002a, Way et al., 1990).

Some short distance IMDD systems do not need the usage of optical amplifiers. Typical semiconductor laser is also a very simple device in which light is generated with current injection. With inferior signal quality, direct-modulated semiconductor laser is a simple form of low cost transmitter. Light-emitting diode can also be used for low-speed applications, mostly for multimode fiber with a large core to alleviate the alignment requirement.

2. Phase-Modulated Optical Communications

The low-loss window of optical fiber transmits optical signal with a carrier frequency of about 190 THz at the wavelength around 1.55 μm. As an oscillator, laser for communication purpose is highly coherent with very pure spectrum. In digital communications (Proakis, 2000),

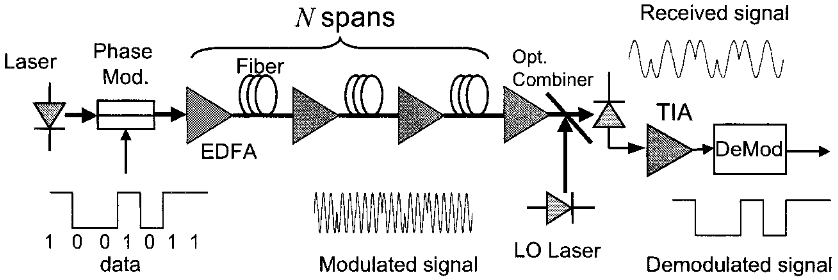


Figure 1.2. Typical schematic of a phase-modulated optical communication system.

the phase of the carrier is generally used in most wireline or wireless communication systems. While the coherence of the laser does not seriously affect the performance of an IMDD system, when the phase or frequency of an optical carrier is used to transmit information, the phase or frequency noise of the transmitter laser adds directly to the phase and frequency of the optical carrier. Both phase or frequency noise of a laser must be reduced for phase-modulated or coherent optical communications.

Figure 1.2 shows a typical schematic of a phase-modulated optical communication system based on phase-shift keying (PSK). In the transmitter, digital data are generally modulated to the amplitude, phase, or frequency of an optical carrier. More complicated system can modulate data into the combination of amplitude, phase, and/or frequency. In the receiver, the optical signal is first mixed with the light of a local oscillator (LO) laser to downconvert the signal from the optical carrier frequency to microwave carrier frequency in the range of GHz or tens of GHz. When the received signal is mixed with LO laser, an optical beating signal is generated at the photodiode, giving a beating signal having a frequency equal to an intermediate frequency (IF) that is the frequency difference between the optical carrier of the transmitter and the LO laser.

If the optical frequency of the signal is the same as that of the LO laser, the system is called a homodyne system. If the optical frequency of the signal differs with that of the LO laser, the system is called a heterodyne system with an IF of

$$\omega_{\mathrm{IF}} = \omega_c - \omega_{\mathrm{LO}}, \tag{1.1}$$

where ω_c and ω_{LO} are the optical frequency of the transmitted signal and LO laser, respectively. In homodyne systems, $\omega_{\mathrm{IF}} = 0$. Typical heterodyne systems have an IF larger than the data-rate. If the IF is less than the data rate, the system is called an intradyne system (Derr, 1992).

Compared the IMDD system of Fig. 1.1 with the PSK system of Fig. 1.2, the optical signal in the optical fiber for an IMDD system looks the same as that of the transmitted or received signal but that of a PSK system looks significantly different with the transmitted signal. In PSK systems, after the mixing of received signal with LO laser at the photodiode, the transmitted data are recovered using a demodulator. The demodulator generally converts an amplitude, phase or frequency modulated signal back to digital data.

In the 80's to early 90's, there were active researches on coherent optical communications to carry information in either the phase or frequency of the optical carrier. Some of those works were summarized in the books by Betti et al. (1995), Cvijetic (1996), Hooijmans (1994), Okoshi and Kikuchi (1988), and Ryu (1995), and reviewed by the papers of Brain et al. (1990), Kazovsky (1989), Linke and Gnauck (1988), Okoshi (1982, 1984, 1987), and Saito et al. (1991, 1993), and the collections by Henry and Personick (1990) and Shimada (1995). In that time, the goal was to achieve better receiver sensitivity and longer unregenerated distance using a coherent receiver, even for an intensity-modulated or amplitude-shift keying (ASK) signal. Beating with the LO laser to enhance the signal, the receiver sensitivity can be improved by up to 20 dB compared with simple direct detection. To certain extend, the mixing with LO laser serves as a signal amplifier. With the advances of optical amplifiers, especially EDFA (Desurvire et al., 1987, Mears et al., 1987, Nakazawa et al., 1989), longer unregenerated distance can be achieved by periodically amplifying the optical signal and better sensitivity can be achieved by optically preamplifing the received signal. Although coherent optical communication techniques may allow more efficient usage of optical bandwidth, fiber based coherent communications had lost its favor and relevant by the advances of optical amplifiers.

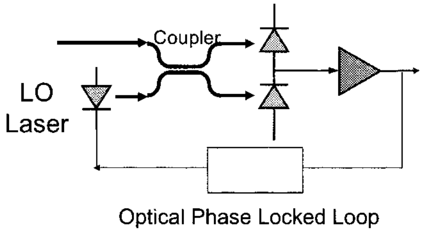
In digital communications (Proakis, 2000), a coherent demodulated system requires carrier recovery. In a homodyne system, carrier recovery requires phase-locking the LO laser to the received signal. In a heterodyne system, carrier recovery is conducted in the microwave signal at the IF of ω_{IF}. A heterodyne optical system is functionally the same as the superheterodyne receiver invented by Armstrong around 1920 (Brittain, 2004, Douglas, 1990) that is the dominant receiver in radio frequency (RF) communications for years. Homodyne RF receiver has become more popular for its low-power consumption (Abidi, 1995, Razavi, 1997).

Coherent optical communication systems use different terminology than that in digital communications. Conventionally, an optical communication system is called "coherent" as long as there is optical signal mixing even without carrier recovery. Even if the demodulator of Fig. 1.2 does not use carrier recovery but noncoherent or envelope detection, the system is called coherent optical communication systems. For example, differential phase-shift keying (DPSK) system is a noncoherent digital communication system (Proakis, 2000) but a coherent optical communication system (Betti et al., 1995, Henry and Personick, 1990, Okoshi and Kikuchi, 1988, Ryu, 1995). Following the traditional terminology of coherent optical communications, a coherent optical receiver with and without phase tracking is called synchronous and asynchronous receiver, respectively. Asynchronous receiver is usually based on power or envelope detection.

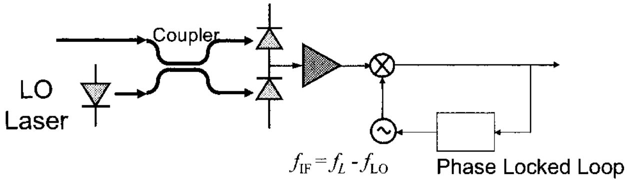
The mixing or heterodyning of two lasers for communication purpose was considered in the earliest date of optical communications (Goodwin, 1967, Oliver, 1961). Early systems operated in free space and used high power long-wavelength laser sources (DeLange, 1972, Goodwin, 1967, Nussmeier et al., 1974, Peyton et al., 1972). Even until today, coherent space communication still has its advantage as compared with on-off keying, especially for inter-satellite communications (Chan, 1987, 2000, 2003, Rochat et al., 2001). Coherent optical communication is also used for ultra dense radio-on-fiber signal (Kikuchi and Katoh, 2002a,b, Kuri and Kitayama, 2002, 2003).

Coherent optical communications in optical fiber were first proposed in early 80's (Favre et al., 1981, Favre and LeGuen, 1980, Kikuchi et al., 1981, Okoshi and Kikchi, 1980, Saito et al., 1980, 1981, Yamamoto, 1980, Yamamoto and Kimura, 1981). Although coherent optical communications were virtually disappear after the successful introduction of EDFA in early 90's, direct-detection DPSK has received renewed interested recently since the pioneer works of Gnauck et al. (2002) and Griffin et al. (2002). While early works focused on improving the receiver sensitivity, phase-modulated or coherent systems may be a candidate for advanced modulation scheme to improve the spectral efficiency. Direct-detection DPSK just provides a sensitivity gain of about 3 dB to on-off keying, significantly lower than the early claims of 10 to 20 dB in the 80's before the available of optical amplifiers (Okoshi and Kikuchi, 1988).

In term of receiver sensitivity, phase-modulated coherent optical communication systems provide the best performance among all types of modulation scheme. Here both PSK and DPSK systems are discussed further in details for their excellent sensitivity.



(a) Homodyne PSK receiver



(b) Heterodyne PSK receiver

Figure 1.3. Schematic diagram of (a) homodyne and (b) heterodyne PSK receiver.

2.1 PSK Systems

Optical PSK systems carry data in the phase of an optical carrier. Figure 1.2 shows a typical PSK transmitter consisting of a phase modulator following a semiconductor laser or other types of light source. An electrical driver amplifier is used to apply the data to the phase modulator, ideally providing a phase shift of either 0° or 180°. Figures 1.3 show the schematic diagram of both homodyne and heterodyne PSK receivers.

A homodyne PSK receiver uses an optical phase-locked loop (PLL) to lock the phase of the LO laser to that of the transmitter laser. In homodyne receiver, the optical frequency of LO laser should be the same as that of the transmitter laser, for example, by frequency tracking.

All receivers in Fig. 1.3 use a balanced receiver to sum the two beating optical signals after a 3-dB coupler. Among many advantages, a balanced receiver can suppress LO noise and provide larger signal power than single-branch receiver (Abbas et al., 1985). Similar to the combiner of Fig. 1.2, the coupler before the balanced receiver is also an 180° optical hybrid. The optical outputs of the coupler have phase difference of 180°.

A heterodyne receiver beats the optical signal of LO laser with the received signal to generate an IF signal. Frequency locking is necessary to provide a fixed IF. An electrical PLL, operating on the angular frequency of ω_{IF}, is used to recover the transmitted phase.

In the receivers of Fig. 1.3, the polarization of the LO laser must be the same as that of the transmitter laser or otherwise using a polarization-diversity receiver (Kazovsky, 1989). In heterodyne receiver, a 90° optical hybrid can be used for an image-rejection heterodyne receiver (Chikama et al., 1990a, Darcie and Glance, 1986, Glance, 1986b). Optically amplified heterodyne receiver has more or less the same performance as homodyne receiver (Jørgensen et al., 1992, Walker et al., 1990). A heterodyne receiver can also give quadrature components using a quadrature electrical mixer.

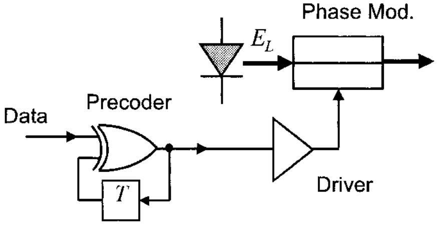
Due to the requirement of an optical PLL, homodyne PSK receiver is difficult to implement. With some successful demonstrations (Kahn et al., 1990, Kazovsky and Atlas, 1990, Norimatsu et al., 1990), homodyne receiver is not an active research area right now. To receive both in-phase and quadrature components, homodyne and heterodyne quadrature receivers in various configurations had also been demonstrated (Derr, 1990, Kahn et al., 1992, Norimatsu et al., 1992).

2.2 DPSK Systems

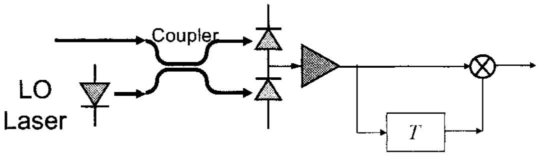
Optical DPSK signal carries data in the phase difference of an optical carrier between two consecutive symbols. Figures 1.4 show the schematic diagram of a DPSK transmitter and receiver. A DPSK transmitter is almost identical to the PSK transmitter in Fig. 1.2 other than the requirement of a precoder. In an RZ-DPSK transmitter, the laser is replaced by a pulse source that emits optical RZ pulses synchronized with the data.

When the differential phase is used to carry data, mathematically, the precoder should be the accumulative phase shift of the data stream. Because the phase of a signal is always confined to $[-\pi, \pi)$ and a phase difference of an integer multiple of 2π represents the same phase. The drive signal for the phase modulator can be the cumulative parity of the data and calculates by an exclusive-OR gate with a symbol time T of feedback as shown in Fig. 1.4(a). In Boolean variable, if $b_k \in \{0, 1\}$ is the binary data and $d_k \in \{0, 1\}$ is the drive signal, their relationship is $d_k = d_{k-1} \oplus b_k$, where $\oplus$ denotes exclusive-OR logic operation and the index k is for the data at the kth time interval. With the precoder, a DPSK receiver does not require special decoding circuitry.

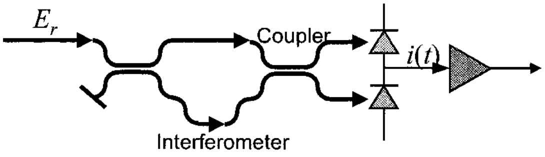
Figures 1.4 show two types of DPSK receiver. A heterodyne receiver uses an electrical delay-and-multiplier circuit to find the differential phase. While frequency locking may be necessary, phase locking



(a) DPSK transmitter



(b) Heterodyne DPSK receiver



(c) Direct-Detection DPSK receiver

Figure 1.4. Transmitter and receivers for optical DPSK signal.

is not required for DPSK signal. The delay-and-multiplier based receiver is functionally the same as DPSK receiver for RF communications.

The direct-detection DPSK receiver of Fig. 1.4(c) is the same as a heterodyne receiver in principle. An asymmetric Mach-Zehnder interferometer splits the signal to two paths and recombines these two signals after a path difference corresponding to the symbol time of T. A balanced receiver follows the interferometer as a multiplier to replace the electrical mixer. With optical amplifier to boost the signal before the receiver, the performance of heterodyne and direct-detection DPSK receiver is approximately the same (Tonguz and Wagner, 1991).

Heterodyne DPSK receivers were demonstrated in various configurations (Chikama et al., 1990a, Creaner et al., 1988, Gnauck et al., 1990). Recently, there is renewed interested of direct-detected DPSK signaling (Cai et al., 2004, Gnauck et al., 2002, 2003c, Rasmussen et al., 2003, Zhu et al., 2003) for long-haul transmission systems, mostly DPSK signal with RZ pulses. Differential quadrature phase-shift keying (DQPSK)

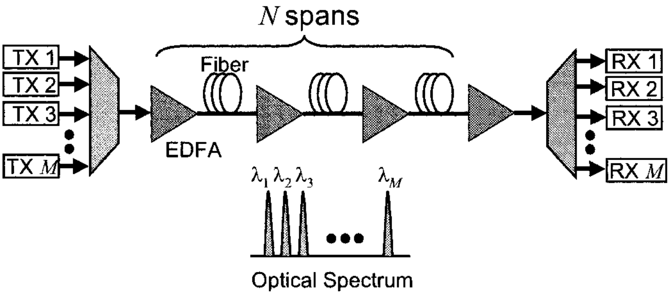


Figure 1.5. Many channels are multiplexed in a single fiber in a WDM system.

signal also improves the spectral efficiency of the systems (Cho et al., 2003, 2004a,b, Griffin et al., 2002, Kim and Essiambre, 2003, Tokle et al., 2004, Wree et al., 2003b, Yoshikane and Morita, 2004a,b, 2005). Using an interferometer to detect phase-modulated signal, direct-detection DPSK receiver is more complicated than the receiver for IMDD systems but far simpler than coherent receiver with a LO laser. Direct-detection DPSK signal is a very active research area right now. Later chapters of this book give more attention to DPSK signal than other modulation formats.

3. WDM Systems

The EDFA of Figs. 1.1 and 1.2 have a very wide gain bandwidth. Instead of just for a single channel, many channels can be amplified together. Figure 1.5 shows a schematic of a WDM system in which many WDM channels are multiplexed in a single fiber and amplified together using the same EDFA chain. Transparent to signal format, the EDFA chain can amplify either IMDD or phase-modulated signal. In principle, a mixed WDM system can be implemented in which some of the channels can be IMDD and others can be phase modulated.

EDFA operates more effectively in the conventional band or C-band from about 1.53 to 1.56 μm. International Telecommunication Union (ITU) standardizes WDM channel grid in either fraction or multiple of 100 GHz that corresponds to a wavelength separation of about 0.8 nm[2]. With an overall bandwidth of about 4 THz, the C-band can support fraction or multiple of 40 WDM channels. As shown in the spectrum

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[2] ITU G.692 (1998): Optical interfaces for multichannel systems with optical amplifiers, and ITU G.694.1 (2002): Spectral grids for WDM applications: DWDM frequency grid.

of Fig. 1.5, a WDM system generally has uniform frequency spacing between channels. The wavelength spacing of each channel is also the same.

In addition to the C-band from 1.53 to 1.56 μm, WDM channels can extend to longer wavelength using L-band EDFA with a wavelength up to about 1.62 μm (Massicott et al., 1990, 1992, Ono et al., 1997, Sun et al., 1997). EDFA also has gain at wavelength shorter than 1.53 μm to support S-band transmission (Arbore et al., 2003, Ono et al., 2003, Yeh et al., 2004). Raman amplifiers can also be used alone or together with EDFA to further the usable bandwidth of an optical fiber (Bromage, 2004, Islam, 2002).

In the WDM systems of Fig. 1.5, a WDM multiplexer is used to combine all WDM channels. While it is preference to have the WDM multiplexer to reject some of the crosstalk from adjacent channels, the WDM multiplexer can be implemented as a passive combiner with a loss of at least $10 \cdot \log_{10} M$ in decibel, where M is the number of channels. To certain extend, a WDM multiplexer instead of passive combiner is used to multiplex many WDM channels mainly to reduce loss.

An IMDD system depends solely on the WDM demultiplexer to separate all WDM channels in Fig. 1.5. The WDM demultiplexer in IMDD system has the contradictory requirement to reject the crosstalk from adjacent channels without distort the signal channel. Therefore, WDM demultiplexer for IMDD WDM systems must have a good response in the pass band but high roll-off at the rejection band. Depending solely on the demultiplexer to reject crosstalk, IMDD WDM systems have a very restricted requirement on the WDM demultiplexer.

In the coherent systems of Fig. 1.2, the LO laser selects the WDM channel to be demodulated. Only the channel having an optical frequency close to the LO laser frequency gives a beating signal within the bandwidth of the receiver. In principle, using coherent receiver, the WDM demultiplexer can be a passive splitter. However, a WDM demultiplexer should be used to reduce loss. Too many coherent WDM channels may also over-load the photodiode. Because channel selection is mainly facilitated using the LO laser, high crosstalk rejection is preference but not essential for the WDM demultiplexer in homodyne and heterodyne systems.

The homodyne receiver of Fig. 1.3(a) requires the smallest receiver bandwidth and has the best channel selectivity for a WDM system. The heterodyne receivers of Figs. 1.3(b) and 1.4(b) require image-rejection to achieve the same channel selectivity of a homodyne receiver. The direct-detection DPSK receiver of Fig. 1.4(c) matches the frequency of a WDM channel to the path length to select a channel. Because adjacent channels may also have a good frequency match, direct-detection DPSK receiver does not guarantee good channel selection. For conservative system design to anticipate for the worst case, direct-detection DPSK receiver of Fig. 1.4(c) may require similar crosstalk rejection as IMDD signal.

Currently, in research laboratory, IMDD WDM systems can achieve an overall data-rate more than 10 Tb/s the distance of a couple hundreds of kilometers (Bigo, 2004, Bigo et al., 2001, Frignac et al., 2002, Fukuchi, 2002, Fukuchi et al., 2001). RZ-DPSK signals with a data rate of about 6 Tb/s can be transmitted over several thousands of kilometers (Charlet et al., 2004b, 2005, Zhu et al., 2003, 2004a). Commercial WDM systems can have an overall data rate over 1 Tb/s.

4. Comparison of Phase- and Intensity-Modulated Signals

In early day, coherent optical communications were investigated for better receiver sensitivity and channel selectivity. Before the advances of optical amplifiers in general and EDFA in particular, the mixing with LO laser served a function similar to a noiseless optical amplifier. A sensitivity gain of up to 20 dB was usually quoted in early literatures (Okoshi and Kikuchi, 1988). With optical amplifiers, coherent system has limited sensitivity gain. As shown later, PSK signal has around 3.5-dB sensitivity gain compared with on-off keying. DPSK signal has about 3.0-dB gain compared with on-off keying. The 3-dB gain may not worth the additional complexity of either a homodyne or heterodyne receiver.

For WDM systems, homodyne or heterodyne system with image-rejection provides good channel selectivity regardless of the quality of the WDM demultiplexer. Coherent optical receivers allow two WDM channels located very close to each other. To reduce the loss at channel demultiplexing, a WDM demultiplexer is desirable though not essential. For coherent WDM systems, crosstalk rejection is not a critical issue as compared with that in IMDD WDM systems.

With optical amplifiers, the biggest advantage of coherent system is to improve spectral efficiency using multilevel modulation. Figure 1.6 shows the signal constellation of binary and quaternary on-off keying signal (4-OOK), and quarter- and 64-ary quadrature-amplitude modulated (QAM) signal. The constellation or signal space is commonly used to study digital modulations (Proakis, 2000, Wozencraft and Jacobs, 1965). Although the optical carrier has both in- and quadrature-phase that was represented as a two-dimensional constellation in Fig. 1.6, on-off keying uses only the positive axis of a single dimension to carry information. In

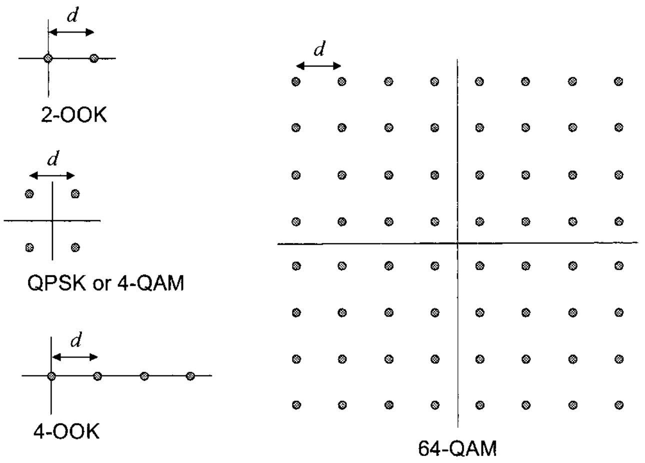

Figure 1.6. The signal space representation of 2- and 4-ary on-off keying (OOK), and 4- and 64-ary quadrature-amplitude modulation (QAM).

QAM scheme, positive and negative sides of both dimensions are used to carry information.

Table 1.1 summarizes the average energy per symbol, bits per symbol, and energy per bit of the constellations of Fig. 1.6. From Table 1.1, 4-OOK and 64-QAM has the same energy per bit of $1.75d^2$, where d is the Euclidean distance between two closest constellation points. The error probability of a signal is mainly determined by the minimum Euclidean distance of d (Proakis, 2000). From Table 1.1, coherent optical modulation using both in- and quadrature-phase can provide better spectral efficiency. Required the same energy per bit as 4-OOK, 64-QAM can transmit three times the data rate. Having 3-dB better energy per bit as binary on-off keying, 4-QAM or quadrature phase-shift keying (QPSK) can double the data rate.

In an alternative interpretation of Table 1.1, if the same data rate is transmitted, 64-QAM requires three times less bandwidth than 4-OOK but the same power. QPSK requires half the bandwidth of binary on-off keying and also half the power. The spectral efficiency of phase-modulated optical communications is rarely discussed in previous literatures for coherent optical communications. Although the spectral efficiency is also related to the better receiver sensitivity, the superior spectral efficiency may be the future driving force for coherent optical communications (Kahn and Ho, 2004).

Table 1.1. Comparison of the Signal in Fig. 1.6.

Modulation	Average Energy	bits per symbol	Energy per bit	Gain (dB)
2-OOK	$0.5d^2$	1	$0.5d^2$	0.00
4-OOK	$3.5d^2$	2	$1.75d^2$	-5.44
4-QAM (QPSK)	$0.5d^2$	2	$0.25d^2$	3.00
64-QAM	$10.5d^2$	6	$1.75d^2$	-5.44

5. Recent Advances in Direct-Detection DPSK Systems

Recently, direct-detection DPSK signaling has received great attention for long-haul transmission or high spectral efficiency systems. Table 1.2 summarizes recent experimental demonstrations of DPSK transmission with an overall capacity approaching 41 Peta-bits/s·km (Cai et al., 2003b). For DQPSK experiments in Table 1.3, the focus is to improve the spectral efficiency to 1.6 b/s/Hz or higher (Cho et al., 2004a,b). Other than Gnauck et al. (2003b), there are also activities to increase the data rate per channel up to 640 Gb/s (Beling et al., 2003, Kieckbusch et al., 2005, Marembert et al., 2004, Milivojevic et al., 2005, Möller et al., 2004).

Direct-detection DPSK signals had been around for years by directly modulated a semiconductor laser (Shirasaki et al., 1988, Vodhanel, 1989, Vodhanel et al., 1990). The main propose of those early works was to generate low-chirp optical signal to overcome fiber chromatic dispersion. Most recent DPSK systems use RZ pulses for better nonlinearity tolerance, adapted for long-haul transmission with optical amplifiers to boost the optical power. Before the wide usage of optical amplifiers, fiber nonlinearities usually did not have a major system impact. When optical signal is periodically amplified by a chain of optical amplifiers, a high power optical signal is maintained for high signal-to-noise ratio (SNR) before the signal is limited by fiber nonlinearities.

In phase-modulated optical systems, due to fiber Kerr effect, amplitude noise is converted to phase noise, generating nonlinear phase noise. The beating of the signal itself with amplifier noise gives the Gordon-Mollenauer effect (Gordon and Mollenauer, 1990), or more precisely, self-phase modulation (SPM) induced nonlinear phase noise. The beating of another WDM channel with amplifier noise gives cross-phase modulation (XPM) induced nonlinear phase noise. Added directly to

Table 1.2. Selected Recent DPSK Experimental Demonstrations.

Year	Data Rate (Gb/s)	Channel Number	Total Rate (Tb/s)	Distance (km)	Capacity (Tb/s·km)	Channel Space (GHz)	Reference	Comments
2002	42.7	64	2.5	4,000	10,000	100	Gnauck et al. (2002)	All-Raman
2002	42.7	80	3.2	5,200	16,600	100	Zhu et al. (2002)	
2002	43.0	40	1.6	400	640	100	Miyamoto et al. (2002)	S-band
2003	40.0	40	1.6	300	480	100	Bissessur et al. (2003)	
2003	40.0	25	1.0	1,200	1,200	50	Gnauck et al. (2003c)	co-pol.
2003	10.0	100	1.0	10,000	10,000	45	Ishida et al. (2003)	
2003	42.8	40	1.6	10,000	16,000	100	Rasmussen et al. (2003, 2004)	All-Raman
2003	42.7	160	6.4	3,200	20,800	50	Zhu et al. (2003, 2004a)	
2003	10.7	185	1.9	8370	15,485	25	Vareille et al. (2003)	22 dB span
2003	10.0	373	3.7	11,000	41,300	25	Cai et al. (2003b)	
2003	42.7	40	1.6	8,700	13,920	70	Tsuritani et al. (2003, 2004)	
2003	42.7	64	2.6	8,200	20,992	70	Morita and Edagawa (2003)	
2003	10.7	301	3.0	10,270	30,912	15.4	Becouarn et al. (2003)	
2003	43.0	100	4.0	6,240	24,960	62.5/100	Charlet et al. (2003)	
2003	170.6	6	1.0	2,000	2,000	200	Gnauck et al. (2003b)	
2004	10.0	96	0.96	13,000	12,480	33	Cai et al. (2004, 2005)	Field trial
2004	42.7	6	0.24	1,600	384	100	Gnauck et al. (2004a)	200-km span, EDFA only
2004	42.7	149	6.0	6,120	36,720	50	Charlet et al. (2004a, 2005)	
2004	42.7	42	1.68	4,820	8,098	100	Becouarn et al. (2004)	EDFA only
2004	10	64	0.64	6,000	3,840	50	Vaa et al. (2004)	No dispersion management
2004	42.7	40	1.60	9,180	14,688	100	Charlet et al. (2004b)	Alternating Polarization

Note: Total date-rate and capacity are calculated by discounting the redundancy due to forward-error-correction code.

Table 1.3. Selected Recent DQPSK Experimental Demonstrations.

Year	Data Rate (Gb/s)	Channel Number	Total Rate (Gb/s)	Distance (km)	Capacity (Tb/s·km)	Channel Space (GHz)	Reference	Comments
2002	20.0	1	20	200	2	nil	Griffin et al. (2002)	
2003	25.0	9	180	1,000	180	25	Cho et al. (2003)	0.8 b/s/Hz
2003	20.0	8	160	310	50	25	Kim and Essiambre (2003)	0.8 b/s/Hz
2003	40.0	8	320	300	96	25	Wree et al. (2003a)	1.6 b/s/Hz
2004	40.0	8	320	320	96	25	Zhu et al. (2004b)	1.6 b/s/Hz
2004	40.0	14	560	400	224	20	Cho et al. (2004b)	2 b/s/Hz
2004	85.4	50	4,000	300	1,200	70	Yoshikane and Morita (2004a, 2005)	1.14 b/s/Hz
2004	12.5	64	800	6,500	5,200	66	Tokle et al. (2004)	
2004	42.7	25	1,000	2,800	2,800	50	Gnauck et al. (2004b)	0.8 b/s/Hz
2004	85.4	64	5,120	320	1,638	50	Yoshikane and Morita (2004b)	1.6 b/s/Hz

Note: Total date-rate and capacity are calculated by discounting the redundancy due to forward-error-correction code.

the phase of a signal, nonlinear phase noise becomes a major limitation for phase-modulated optical communications (Ho, 2003b,e,g, 2004c, Ho and Kahn, 2004a, Kim, 2003, Kim and Gnauck, 2003, Mecozzi, 1994a,b, Ryu, 1992, Saito et al., 1993).

As a constant pulse train, DPSK signal has larger tolerance to interchannel nonlinearities induced mostly by XPM (Leibrich et al., 2002) or similar effects (Cho et al., 2004a, Lu et al., 2004). The periodic intensity of DPSK signal gives the same XPM distortion to adjacent pulses that does not degrade the differential phase.

In dispersive fiber, the optical pulse is broadened by chromatic dispersion with traveling distance. When adjacent pulses overlap with each other, their interaction with Kerr effect also induces phase noise to the pulse itself or other optical pulses. With a phase modulation into a pulse train, DPSK signal also has higher tolerance of intrachannel pulse-to-pulse interaction than on-off keying signal.

Recently, DPSK signal is also used to build a high dynamic range burst receiver (Nizhizawa et al., 1999, Su et al., 2004). For packet switching data, DPSK signal can also be used to label an on-off keying packet (Chi et al., 2003, Hung et al., 2004) or using an ASK signal as a label for DPSK packet (Liu et al., 2004a). To certain extend, the phase and amplitude are used to carry independent data in those applications.

6. Overview

Many books in coherent optical communications have been published, mostly in the 90's (Betti et al., 1995, Cvijetic, 1996, Hooijmans, 1994, Okoshi and Kikuchi, 1988, Ryu, 1995). Standard textbooks in optical communications also have a chapter in coherent optical communications (Agrawal, 2002, Kazovsky et al., 1996, Keiser, 1999, Liu, 1996, Senior, 1992). However, most of those works focused on coherent optical communications limited by shot noise when optical amplifiers were not yet widely deployed. Phase-modulated or coherent optical communication deserves a re-visit for the following reasons:

- For binary signals, sensitivity improvement for typical systems with optical amplification is limited to about 3 dB instead of much higher improvement quoted in early works.
- For system limited by LO-spontaneous beat noise, homodyne and heterodyne system has the same performance instead of 3-dB difference in shot-noise limited systems.
- Binary frequency-shift keying (FSK) system provides no performance improvement compared with on-off keying signal.