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 deployments of optical fiber are 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.

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 (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 around 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 fiber can also partition into many bands for multichannel wavelength-division-multiplexed (WDM) systems. Adding noise into the signal, EDFA amplifies all WDM channels without crosstalk and distortion. A fiber link can be constructed without electronic regeneration for trans-oceanic distances (Bergano and Davidson, 1996, Cai et al., 2003, 2002, Golovchenko et al., 2000, Suzuki and Edagawa, 2003).

Currently, only the intensity of optical signal is used to encode information for transmission. Neither the phase nor frequency of an optical carrier is used. In order to transmit more information in an optical carrier, the phase of an optical carrier must be explored to encode more data. 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 encode more information in an optical carrier.

1.1 Intensity Modulation/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-modulation/direct-detection (IM/DD) system. Most textbooks of optical communications

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

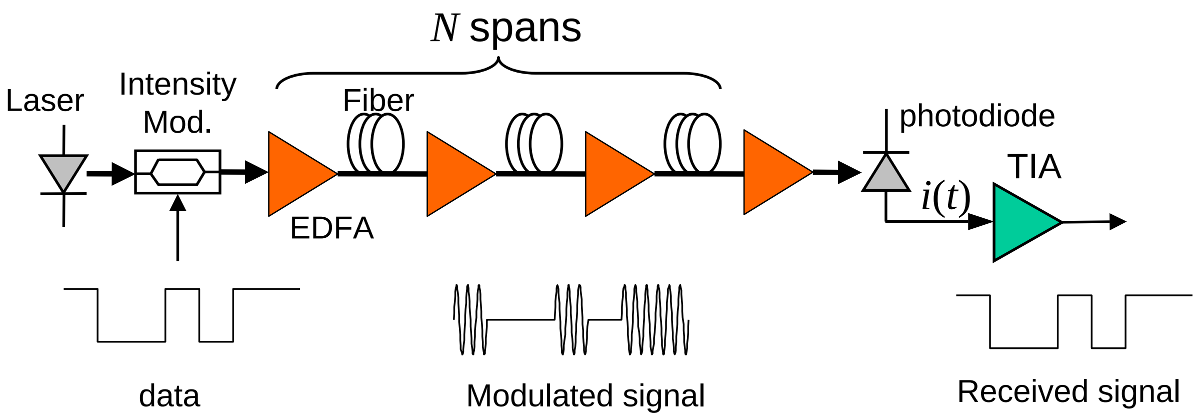


Figure 1.1: Typical configurations of an intensity-modulated/direct-detection (IM/DD) systems.

focus mainly on IM/DD 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 IM/DD system. The transmitted information is modulated into the optical carrier using an external intensity modulator that is basically a very fast switch to turn-on and -off the light to encode either “zero” or “one”. After the modulator, the optical signal passes an EDFA to boost up the power and then launched into the optical fiber. In Fig. 1.1, EDFA is assumed to be used periodically to compensate for fiber loss span after span.

After many spans of optical fiber, the optical signal is 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 into an electron, i.e., the optical intensity into electrical current. All the information in the phase or frequency of the optical carrier is lost in the photodiode. The photodiode is followed by an amplifier, usually a trans-impedance amplifier (TIA) to convert photocurrent into voltage. The received signal after the TIA is the same as the transmitted signal but with noise from optical amplification and the receiver circuitry.

The IM/DD system illustrated schematically in Fig. 1.1 is a very simple system. The receiver decides whether the transmitted bits are “zero” or ”one” 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 IM/DD systems to transmit either digital or analog modulated frequency-division multiplexed (FDM) channels in the intensity of the optical signal.

1.2 Coherent Optical Communications

The low-loss window of optical fiber transmits optical signal with a carrier frequency of about 190 THz at the wavelength of about 1.55 μm. As an oscillator, laser for communication purpose is highly coherent with very pure spectrum. In digital communication systems (Proakis, 2000), 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 IM/DD system, when phase or frequency of an optical carrier is used to transmit information, the transmitted laser must be highly coherence. The phase or frequency noise of the transmit laser adds directly into the phase and frequency of the optical carrier that are used to carry information.

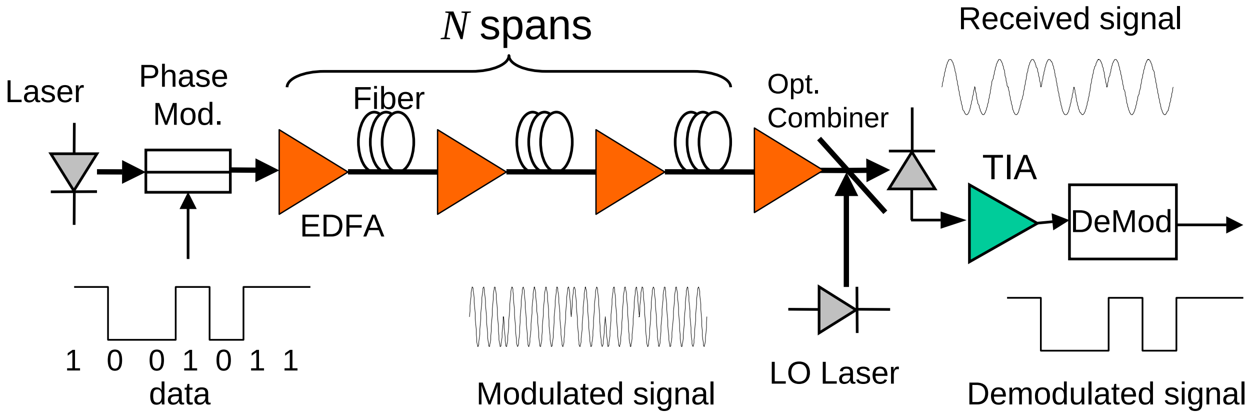


Figure 1.2: Typical schematic of a coherent optical communication system

Figure 1.2 shows a typical schematic of a coherent optical communication system. In the transmitter, digital data are modulated to the amplitude, phase, or frequency of an optical carrier. More complicated system can modulate data into the combinations 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 received signal 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 carrier signal and LO laser, respectively. In homodyne systems, $\omega_{\mathrm{IF}} = 0$.

Compared the IM/DD systems of Fig. 1.1 with the coherent systems of Fig. 1.2, the optical signal in the optical fiber for an IM/DD system looks the same as that of the transmitted or received data but that of a coherent system looks significantly different with the transmitted data. After the mixing of received signal with LO laser at the photodiode, the received data is recovered using a demodulator. The demodulator converts an amplitude, phase or frequency modulated signal back to digital data.

In the 80's to early 90's, there were lots of researches on coherent optical communications to encode 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), Ryu (1995) and reviewed by the papers of Brain et al. (1990), Kazovsky (1989), Linke and Gnauck (1988), Okoshi (1982, 1984, 1987), Saito et al. (1991) and Saito et al. (1991), and the collection by Henry and Personick (1990). In that time, the goal was to achieve better receiver sensitivity and longer unregenerated distance using a coherent receiver, even just to detect 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 on-off keying. In some sense, 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 pre-amplified the received signal. Although coherent optical communication techniques allow more efficient usage of optical bandwidth, fiber based coherent communications had lost its favor 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 into the received signal. In a heterodyne system, carrier recovery is conducted in microwave signal at the IF carrier of ω_{IF}.

Coherent optical communication system has different definition 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 non-coherent or envelop detection, the optical communication is called coherent optical communication systems. For example, differential phase-shift keying (DPSK) system is a non-coherent digital communication system (Proakis, 2000) but a coherent optical communication system (Betti et al., 1995, Hooijmans, 1994, Okoshi and Kikuchi, 1988, Ryu, 1995). Following the tradition terminology of coherent optical communication, 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.

In term of sensitivity, phase-modulated coherent optical communication systems provide the best performance along all types of modulation scheme. Here both phase-shift keying (PSK) and differential DPSK systems are discussed more in details for their excellent sensitivity.

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 may have its advantage as compared with on-off keying (Chan, 1987, 2000, 2003, Rochat et al., 2001), especially for inter-satellite communications. Coherent optical communication is also used for ultra dense radio-on-fiber signal (Kikuchi and Katoh, 2002a,b, Kuri and Kitayama, 2002, 2003).

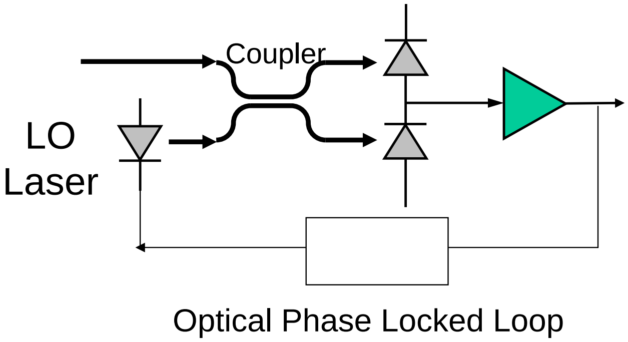
Coherent communication in optical fiber was first proposed in early 80's (Favre et al., 1981, Favre and LeGuen, 1980, Kikuchi et al., 1981, Okoshi and Kikchi, 1980, Saito et al., 1980, 1981, Yamamoto, 1980, Yamamoto and Kimura, 1981). Although coherent optical communication was virtually disappear after the successful introduction of EDFA in early 90's, direct-detection DPSK has received renewed interested since the pioneer work of Gnauck et al. (2002). While early works focused on improving the receiver sensitivity, here, we would like to argue that coherent systems should be considered as an advanced modulation scheme to improve the spectral efficiency. The success of direct-detection DPSK just provides a sensitivity gain of about 3-dB, significantly lower than the early claims of 10 to 20 dB in 80's before the available of optical amplifiers(Okoshi and Kikuchi, 1988).

1.2.1 PSK Systems

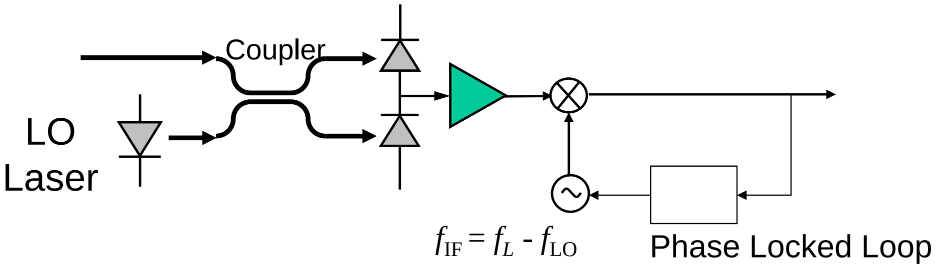
Optical PSK signal carries data in the phase of an optical carrier. Figure 1.2 shows a typical PSK transmitter consists of a phase modulator following a semiconductor laser or other types of light sources. A driver amplifier is used to apply the data into the phase modulator, ideally providing phase shift of 0° and 180°. Figure 1.3 shows 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 two optical signals after a 3-dB coupler. Among many advantages, a balanced receiver can suppress LO noise and provide 3 dB more signal power (Abbas



(a) homodyne PSK receiver



(b) heterodyne PSK receiver

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

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. A radio-frequency (RF) phase-locked loop, 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., 1990, Darcie and Glance, 1986, Glance, 1986). Optical amplified heterodyne receiver has more or less the same performance as homodyne receiver using the same optical amplifiers (Jørgensen et al., 1992, Walker et al., 1990). A heterodyne receiver can also give quadrature components using a quadrature RF 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. Homodyne and heterodyne quadrature receivers in various configurations had also been demonstrated (Derr, 1990, Kahn et al., 1992, Norimatsu et al., 1992).

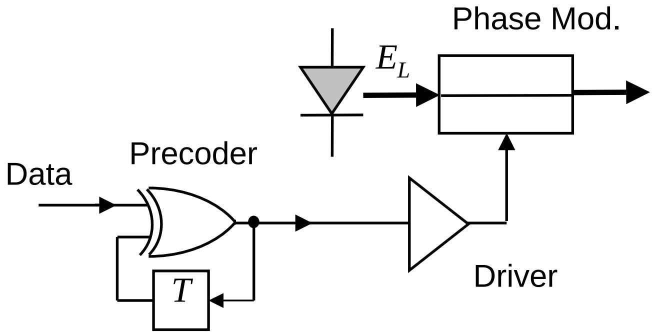
1.2.2 DPSK Systems

Optical DPSK signal carries data in the phase difference between two adjacent symbols of an optical carrier. Figure 1.4 shows the schematic diagram of a DPSK transmitter and receiver. A DPSK transmitter is almost identical to PSK transmitter in Fig. 1.2 other than the requirement of a precoder. In a RZ-DPSK transmitter, the laser is replaced by a pulse source that emits optical RZ pulse synchronized with the data. When the differential phase is used to carry data, mathematically, the precoder should be the accumulative phase shift corresponding to the data stream. Because the phase of a signal is always confined to $[-\pi, \pi)$ and a phase difference of multiple 2π represents the same phase. The signal applies to the phase modulation 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. Logically, 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. With the precoder, a DPSK receiver does not require any decoding function.

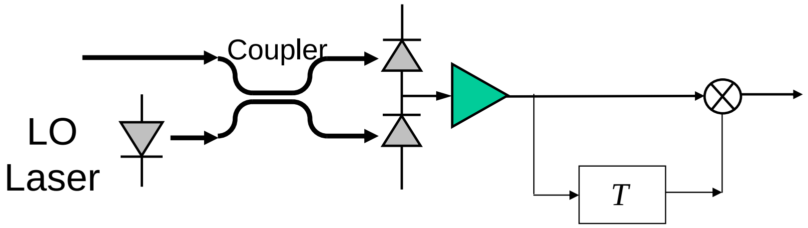
Figure 1.4 shows two types of DPSK receiver. A heterodyne receiver uses a radio frequency (RF) delay-and-multiplier to find the differential phase. While frequency locking may be necessary, phase locking is not necessary for DPSK signal. The delay-and-multiplier based receiver is the same as DPSK signal for RF communications.

The direct-detection receiver of Fig. 1.4 is the same as a heterodyne receiver in principle. An asymmetric Mach-Zehnder interferometer splits the signal into 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 RF 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).

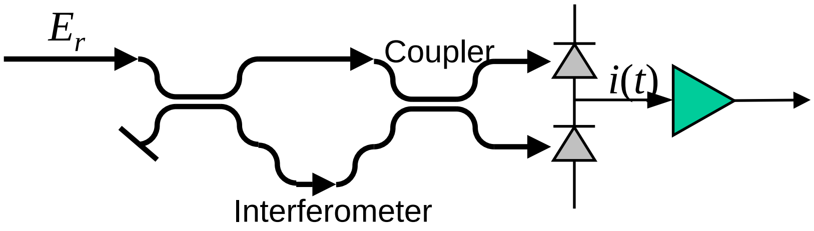
Heterodyne DPSK receivers were demonstrated with different configuration (Chikama et al., 1990, Creaner et al., 1988, Gnauck et al., 1990). Recently, there is renewed interested of direct-detected DPSK signaling (Cai et al., 2003, Cho et al., 2003, Gnauck et al., 2002, 2003, Rasmussen et al., 2003, Zhu et al., 2003) for long-haul transmission systems, mostly DPSK signal with RZ pulses or differential quadrature phase-shift keying (DQPSK) signal (Cho et al., 2003, Griffin et al., 2003, Griffin and Carter, 2002, Griffin et al., 2002, Kim and Essiambre, 2003, Wree et al., 2003b), to improve spectral efficiency systems. Using an interferometer to detect phase-modulated signal, direct-detection DPSK receiver is more complicated



(a) DPSK transmitter



(b) Heterodyne DPSK receiver



(c) Direct-Detection DPSK receiver

Figure 1.4: Transmitter and receivers for optical DPSK signal.

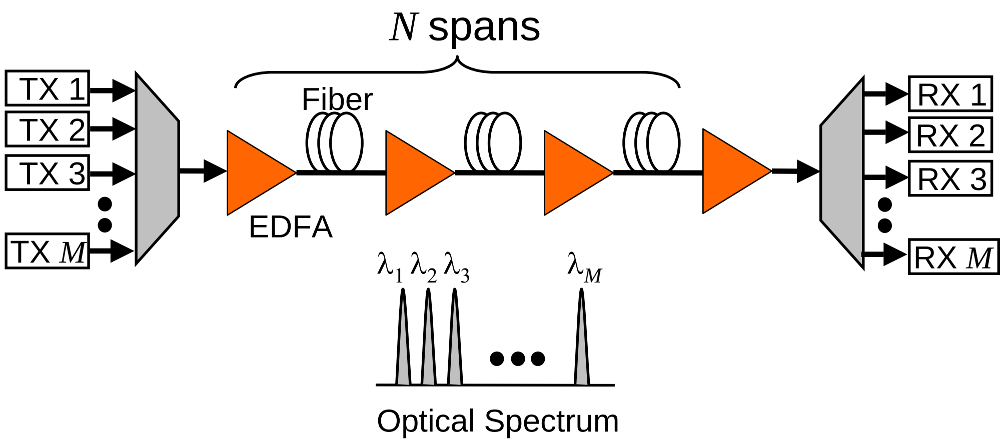


Figure 1.5: Many channels are multiplexed in a single fiber in a wavelength-division-multiplexed (WDM) system.

than the receiver for IM/DD but far simpler than coherent receivers with a local oscillator (LO).

1.3 WDM Systems

The EDFA of Figs. 1.1 and 1.2 have a very wide bandwidth. Instead of just amplifies 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. In general, the EDFA chain can amplify either IM/DD or coherent modulated signals. In principle, a mixed WDM system can be implemented in which some of the channels can be IM/DD and others can be coherent modulated and detected.

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[2]. With an overall bandwidth of about 4 THz in C-band, fraction or multiple of 40 channels can be transmitted. As shown in the spectrum of Fig. 1.5, a WDM system generally has uniform frequency spacing between channels.

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 IM/DD system depends solely on a WDM demultiplexer to separate all WDM channel in Fig. 1.5. For IM/DD systems, the WDM demultiplexer has the contradictory requirement to the reject crosstalk from adjacent channels without distort the signal channel. Therefore, WDM demultiplexer for IM/DD WDM systems must have a good response in the pass band but high roll-off at the rejection band. IM/DD WDM system 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 frequency within

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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.

the bandwidth of the receiver. In principle, for coherent signal, 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.

The homodyne receiver of Fig. 1.3(a) requires the smallest receiver bandwidth and has the best WDM channel selectivity. The heterodyne receivers of Fig. 1.3(b) and Fig. 1.4(b) require image-rejection to achieve the same channel selectivity of a homodyne receiver. The direct-detection 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, the direct-detection receiver of Fig. 1.4 does not guarantee good channel selection.

1.4 Comparison of Coherent and IM/DD Optical Communications

Coherent optical communications were investigated for better sensitivity and channel selectivity. Before the advances of optical amplifiers in general and EDFA in particular, the mixing with LO laser serves a function similar to an optical amplifier. A sensitivity gain of up to 20 dBm was usually quoted in early literature (Okoshi and Kikuchi, 1988). With optical amplifiers, coherent system has limited sensitivity gain. As shown later, PSK signal has only 3-dB sensitivity gain compared with on-off keying signal. DPSK signal has about 2.8 dB gain compared with on-off keying. The about 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 us to bring two WDM channels very close to each other. To reduce the loss at channel demultiplexing, a WDM demultiplexer is desirable though not essential. However, for coherent WDM system, crosstalk rejection is not a critical factor as compared with that in IM/DD WDM systems.

With optical amplifiers, we think that 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, and quarter- and 64-ary quadrature-amplitude modulation (QAM). The constellation is commonly used in digital communications (Proakis, 2000). Although the optical carrier has both in- and quadrature-phase and represents as a two-dimensional constellation in Fig. 1.6, on-off keying uses only the positive axis of a single dimensional to carry information. In QAM scheme, positive and negative sides of both dimensional are used to carry information.

Table 1.1 summarizes the average energy per symbol, bits per symbol, and energy per bit of the constellation of Fig. 1.6. From Table 1.1, quaternary on-off keying and 64-ary QAM has the same energy per bits 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 bits as quaternary on-off keying, 64-QAM can transmit three times larger data rate. Having 3-dB better energy per bits as binary on-off keying, 4-QAM or quadrature phase-shift keying (QPSK) can double the data rate.

In an alternative implementation of Table 1.1, if the same data rate is transmitted, 64-QAM requires three times less bandwidth than quaternary on-off keying but the same power. QPSK requires half the bandwidth than binary on-off keying and also half the power. The spectral efficiency of coherent optical communication is rarely discussed in previous literatures (Betti et al., 1995, Cvijetic, 1996, Hooijmans, 1994, Okoshi and Kikuchi, 1988, Ryu, 1995). Although the spectral efficiency is also related to the better receiver sensitivity, we believe that superior spectral efficiency will be the future driving force for coherent optical communications.

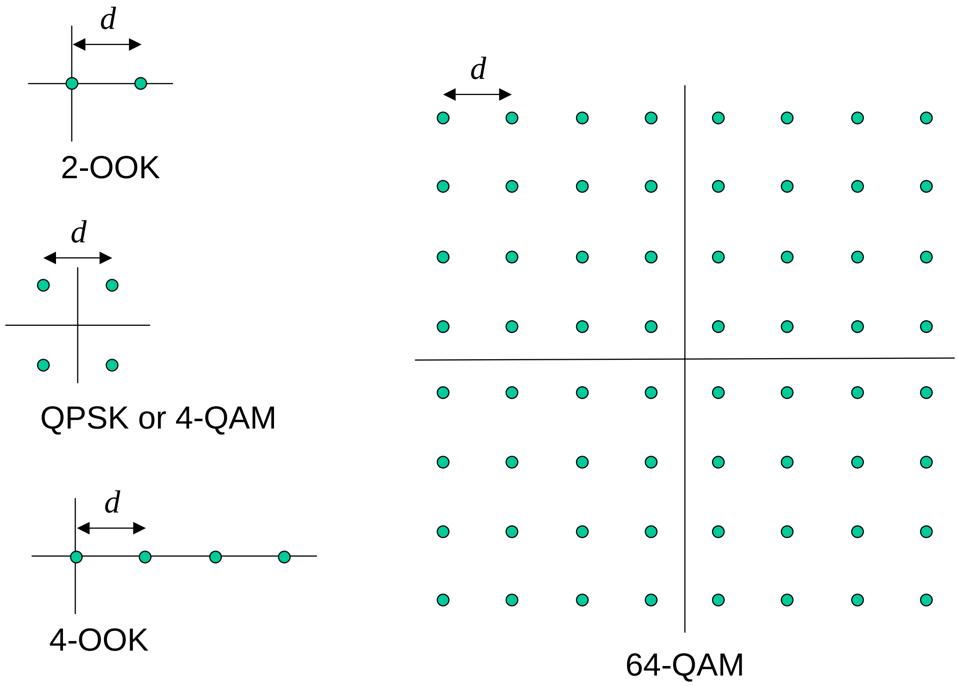

Figure 1.6: The signal space representation of 2- and 4-ary on-off keying (OOK), and 4- and 64-ary quadrature-amplitude modulation (QAM).

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
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

1.5 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., 2003). For DQPSK experiments in Table 1.3, the focus is to improve the spectral efficiency to 1.6 b/s/Hz (Wree et al., 2003a).

Direct-detected DPSK signals had been around for years by directly modulated a 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 dispersion. Most recent DPSK systems use RZ pulses for better nonlinearity tolerance, adapted for long-haul transmission with optical amplifier to boost the optical power. Before the wide usage of optical amplifier, fiber nonlinearities usually do not have a major system impact. When optical signal is periodically amplified by optical amplifier, a high power optical signal is desirable to achieve a 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, often called the Gordon-Mollenauer effect (Gordon and Mollenauer, 1990). Nonlinear phase noise becomes a major limitation of phase-modulated systems (Ho, 2003a,b,c, Ho and Kahn, 2004, Kim, 2003, Kim and Gnauck, 2003, Mecozzi, 1994, Ryu, 1992, Saito et al., 1993).

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. (2003)	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)	All-Raman
2003	42.7	160	6.4	3,200	20,800	50	Zhu et al. (2003)	
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. (2003)	
2003	42.7	40	1.6	8,700	13,920	70	Tsuritani et al. (2003)	

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

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

1.6 Overview

There are already many books in coherent optical communication (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 focus on coherent optical communication limited by shot noise when optical amplifiers were not yet invented. Coherent optical communication requires a re-visit for the following reasons:

- For binary systems, sensitivity improvement is limited to about 3 dB.
- With optical amplifier, the system is more likely to be limited by nonlinear phase noise induced by the interaction of fiber Kerr effect and amplifier noise (Gordon and Mollenauer, 1990), in contrast of laser phase noise in early systems.
- 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.
- Frequency-shift keying (FSK) system provides no performance gain compared with on-off keying.
- Coherent WDM systems usually do not give closer channel spacing than IM/DD WDM systems as long a well-design WDM demultiplexer is used.
- Coherent WDM systems may mainly provide superior spectral efficiency as compared with on-off keying.

Nonlinear phase noise affects mainly phase-modulated signals, including PSK and DPSK signals discussed in earlier parts of this chapter. Conventionally, phase-modulated signal is mostly analyzed for additive Gaussian noise channel with laser phase noise (Henry, 1982, Kazovsky, 1986, 1989, Nicholson, 1984).

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