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Advanced Modulation Formats and Multiplexing Techniques for Optical Telecommunication Systems

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1. Introduction

Since ancient times, one of the principal needs of people has been to communicate. This need created interest in devising communication systems for sending messages from one place to another. The advent of high performance computer processors brought many advantages for digital communications over that of analog. These benefits include more features, easy storage and faster processing. These caused huge amount of information, which is increasing exponentially every year, to be carried over communication networks.

Various types of communication system appeared over the years. Among the basic motivations behind each type are to improve the transmission fidelity, increase the data rate, and increase the transmission distance between stations. All these facilities are achievable utilizing optical fiber communications. Optical fiber offers several advantages over the traditional media (e.g., twisted wire pair and coaxial cable). Its decisive advantages are huge bandwidth and very low attenuation and noise (Arumugam, 2001). The first, results in higher bit rate, and the second, results in longer transmission distance. These potentials can be further pushed by utilizing multiplexing techniques and/or advanced modulation formats.

The invention of wavelength division multiplexing (WDM) (G. E. Keiser, 1999) contributes great benefit to the optical fiber communication systems especially after the introduction of Erbium-doped fiber amplifier (EDFA). Using WDM, about forty channels can be accommodated in the C-band at 100 GHz (0.8 nm) channel spacing. Based on this condition, up to 1.6 Tb/s transmission capacity has been reported (Zhu et al., 2001). More channels can be transmitted using ultra-dense WDM technique by considering channel spacing of as close as 12.5 GHz (Ciaramella, 2002; Sang-Yuep, Sang-Hoon, Sang-Soo, & Jae-Seung, 2004). Using such channel spacing, up to 2.5 Tb/s transmission is reported (Gyo-Sun et al., 2007) by multiplexing 256 12.5 Gb/s channels, and transmitted over 2000 km standard single mode fiber (SSMF). Larger transmission capacity can be achieved by utilizing the S- and L-bands (Freund et al., 2005; Seo, Chung, & Ahn, 2005). Using triple bands (S + C + L), 10.92 Tb/s transmission is experimentally reported (Fukuchi et al., 2001) by using 273 WDM channels and 50 GHz spacing.

Higher transmission capacity can be achieved with higher bit rate per WDM channel. Time division multiplexing (TDM) is the most commonly used for multiplexing high number of lower bit rate channels to form a higher bit rate. For example, a 40 Gb/s data stream can be achieved by multiplexing four 10 Gb/s data using electrical TDM (ETDM) (Dong-Soo, Man Seop, Yang Jing, & Nirmalathas, 2003; Krummrich et al., 2002; Lach, Bulow, Kaiser, Veith, & Bouchoule, 1998; Lee, Garthe, Pettitt, & Hadjifotiou, 1997; Miyamoto, Yoneyama, Otsuji, Yonenaga, & Shimizu, 1999; Yoneyama et al., 1999). Using such system, 3.2 Tb/s (80 × 40 Gb/s) bidirectional WDM/ETDM transmission over 40 km SSMF is experimentally reported (Scheerer et al., 1999). The feasibility to realize transmission systems, subsystems, and electronic and optoelectronic components operating at bit rates beyond 40 Gb/s has been demonstrated in numerous papers (Andre, Kauffmann, Desrousseaux, Godin, & Konczykowska, 1999; Derksen, Moller, & Schubert, 2007; Elbers, 2002; Jansen et al., 2007; Kauffmann et al., 2001; Lach & Schuh, 2006; Lach et al., 2007; Schuh et al., 2005). Recently, up to 107 Gb/s full-ETDM transmission is experimented in laboratory and tested over installed fiber in the field (Derksen et al., 2007; Jansen et al., 2007; Lach et al., 2007).

WDM channels capacity can be doubled using polarization division multiplexing (PDM) technique (Hinz, Sandel, Noe, & Wust, 2000; Hinz, Sandel, Wust, & Noe, 2001; Martelli et al., 2007; Sandel, Wust, Mirvoda, & Noe, 2002; Suzuki, Kubota, Kawanishi, Tanaka, & Fujita, 2001; Yan, Zhang, Belisle, Willner, & Yao, 2007). Combining PDM with WDM system, 10.2 Tb/s (256 × 42.7 Gb/s) transmission in C + L bands is experimentally demonstrated, which offers 1.28 b/s/Hz SE (Bigo et al., 2001).

Further improvement in WDM network capacity can be realized by using advanced modulation formats. Amongst different types of available modulation formats, differential quaternary phase-shift keying (DQPSK) transmission is currently under serious consideration for high-speed long-haul optical transmission systems due to its reduced optical bandwidth and high tolerance to chromatic dispersion (CD) relative to traditional binary systems (A. F. Abas, 2006; Cho, Grigoryan, Godin, Salamon, & Achiam, 2003; Christen, Nuccio, Xiaoxia, & Willner, 2007; A. H. Gnauck, Winzer, Dorrer, & Chandrasekhar, 2006; Morita & Yoshikane, 2005; Schubert et al., 2006; Weber et al., 2005; Weber, Ferber et al., 2006; Yoshikane & Morita, 2004). Using the mentioned technique, WDM channel capacity can be doubled with requiring transceivers operating at the same baud rate. This improves the spectral efficiency (SE) of WDM system. Using WDM and carrier-suppressed-return-to-zero (CS-RZ) DQPSK format, 4 Tb/s (50 × 85.4 Gb/s) with 70 GHz spacing has been experimentally tested (Yoshikane & Morita, 2004). Using that configuration, 1.14 b/s/Hz spectral efficiency (SE) was achieved. Elsewhere, using RZ-DQPSK, 5.12 Tb/s (64 × 85.4 Gb/s) with 50 GHz channel interval and 1.6 b/s/Hz SE was experimentally demonstrated (Morita & Yoshikane, 2005).

Combining DQPSK with PDM, quadruples WDM channel capacity (Ahmad Fauzi Abas, Hidayat, Sandel, Milivojevic, & Noe, 2007; Charlet et al., 2008; Pardo et al., 2008a; Renaudier et al., 2008; Savory, Gavioli, Killey, & Bayvel, 2007; Wree et al., 2003). With this configuration, Gnauck et al. (Alan H. Gnauck et al., 2007; A. H. Gnauck et al., 2008), demonstrated a record of 25.6 Tb/s transmission over 240 km using 160 WDM channels with 50 GHz grid in the C + L bands. In their experiment, they employed 85.4 Gb/s RZ-DQPSK modulation and polarization multiplexing to attain 160 Gb/s in each WDM channel, resulting in a SE of 3.2 b/s/Hz in each band (Alan H. Gnauck et al., 2007; A. H. Gnauck et al., 2008). This was the record in optical communication systems in 2008.

Recently, Zhou et al. (Zhou et al., 22-26 March 2009) has reported 320 × 114 Gb/s PDM-RZ-8 quadrature amplitude modulation (QAM)dense WDM transmission with channel spacing of 25 GHz over 580 km ultra-low-loss SMF-28. This is a record capacity of 32 Tb/s till 2009.

Duty cycle division multiplexing (DCDM) is another newly reported multiplexing technique that can support multiple users per WDM channel (Mahdiraji et al., (In Press)). In this technique, the multiplexed signals have a rising edge transition at the beginning of the multiplexed symbol. This unique property has never been reported in other multiplexing techniques and modulation formats. Considering that property, the technique allows aggregate bit rate to be recovered at symbol/baud rate. Based on our knowledge, this is the latest multiplexing technique reported to date.

In the following sections, details on principles, operation and implementation of various modulation format and multiplexing techniques are presented.

2. Modulation Formats

Modulation is a process to form the baseband signal using high frequency carrier signal to become more suitable for transmission over long communication link. Advanced modulation formats improves the channel utilization and capacity. There are various types of multiplexing techniques and modulation formats commonly used in optical fiber communication system, which will be further discussed in the following Subsections.

2.1 Amplitude Shift Keying

In optical fiber communication systems, the baseband signals are modulated onto high frequency optical carriers. Various types of modulation can be used for that purpose. Amplitude modulation (AM) or amplitude-shift keying (ASK) or on-off keying (OOK) is the simplest and commonly used technique in optical fiber communication systems, where AM is referred to analog signals, and ASK and OOK referred to digital signals. In this technique, the baseband signal is multiplied by a carrier frequency, thus (assuming binary signaling), the binary 0 is transmitted with 0 W and binary 1 with A W. At the receiver, the demodulation can be easily performed using a photodetector, which converts the optical signal to the electrical signal, resulting in the original transmitted pattern. Figure 1 shows example of a ASK modulation format.
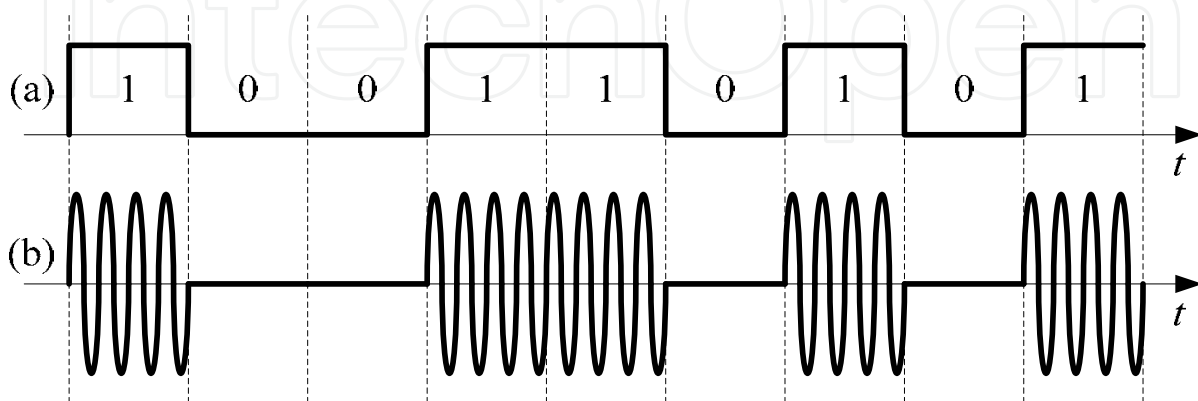

Fig. 1. Example of ASK modulation foramt, (a) binary signal, and (b) ASK modulated signal

In advanced communication systems, instead of transmitting single bit per symbol, using two level binary signals, more than one bit per symbol can be achieved, which it results in higher transmission capacity. This technique is called multilevel signaling. The number of signal level M, follows the rule of $M = 2^b$ where the b is the number of bits per symbol, thus called M-ary signaling. In ASK, the value of M = 4 (4-ary ASK) is mostly used to double the transmission capacity while maintaining the spectral width (Avlonitis, Yeatman, Jones, & Hadjifotiou, 2006; Cimini & Foschini, 1993; Muoi & Hullett, 1975; Walklin & Conradi, 1999). The 8-ary ASK is also studied over fiber optic communication for tripling the transmission capacity (Walklin & Conradi, 1999). The improvement in channel capacity was obtained at the cost of power penalty in the OSNR and system receiver sensitivity. For example, receiver sensitivity of 4-ary ASK coded with NRZ and RZ signaling experienced around 3.8 dB and 6.6 dB penalty in comparison to binary NRZ and RZ respectively (Avlonitis et al., 2006). This is due to the fragmentation of the main eye to the several smaller eyes for the 4-ary ASK.

2.2 Phase Shift keying

In phase modulation, binary data are modulated onto the optical carrier referring to the phase difference between binary 0 and 1. This technique is called phase-shift keying (PSK) or BPSK for binary PSK. Example of BPSK modulation is shown in Figure 2. In this example, binary 1 is signed as $\sin(\omega t)$ and binary 0 is signed as $\sin(\omega t + \pi)$ or $-\sin(\omega t)$.
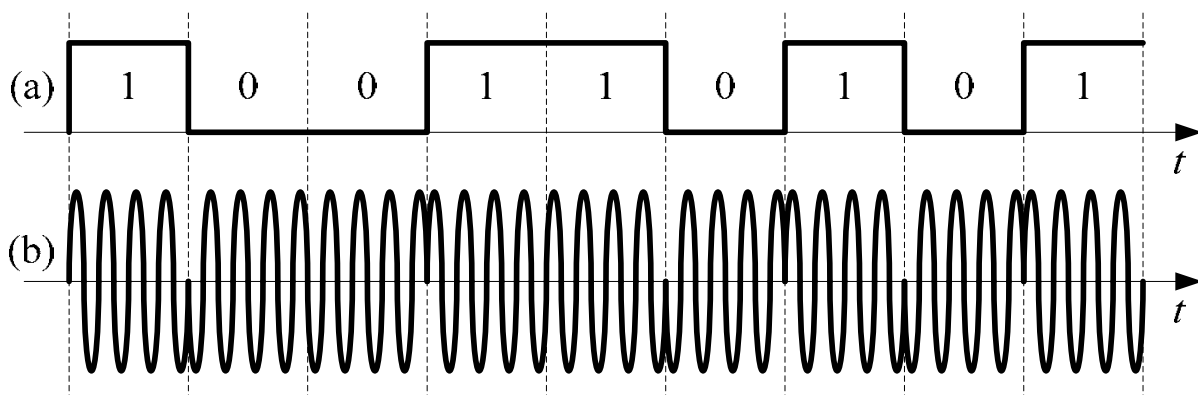

Fig. 2. Example of BPSK modulation format, (a) binary signal, and (b) BPSK modulated signal

In the early days, PSK did not receive much interest due to its demodulator's complexity. Instead, differential PSK (DPSK) had received more interests (Ho, 2005). In DPSK, the data are first encoded differentially as the differential encoder shown in Figure 3(a). The encoded data are then modulated onto optical carrier using a phase modulator (PM) or Mach-Zehnder modulator (MZM), which externally changes the optical phase from its original phase to a relatively π phase shift. In response to the driving baseband signal (Ho, 2005), MZM is preferable to PM due to better chromatic dispersion tolerance. Figure 4 shows example of DPSK, which Figure 4(a) shows the binary signal, and 4(b) is the DPSK modulated signal.
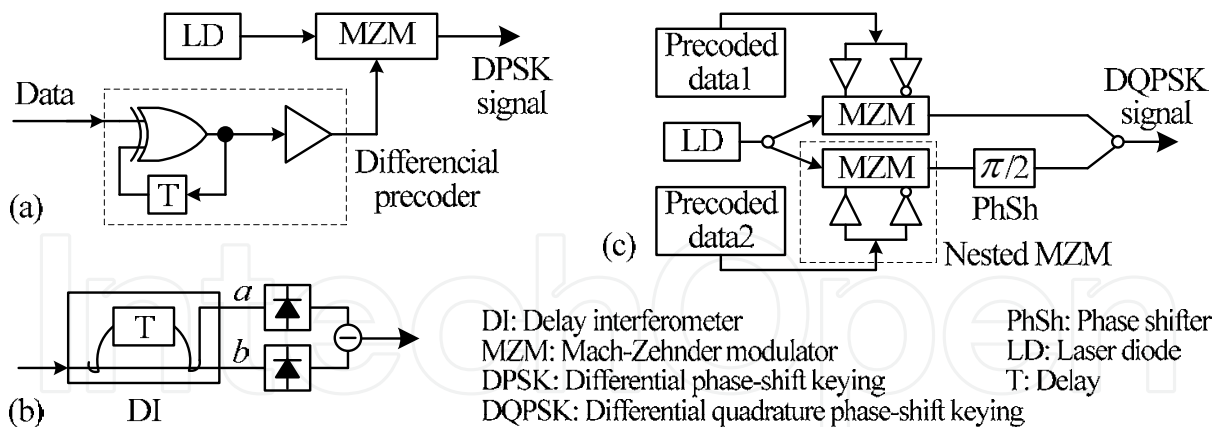
Fig. 3. DPSK transceiver, (a) DPSK transmitter, (b) DPSK balanced receiver, and (c) DQPSK transmitter
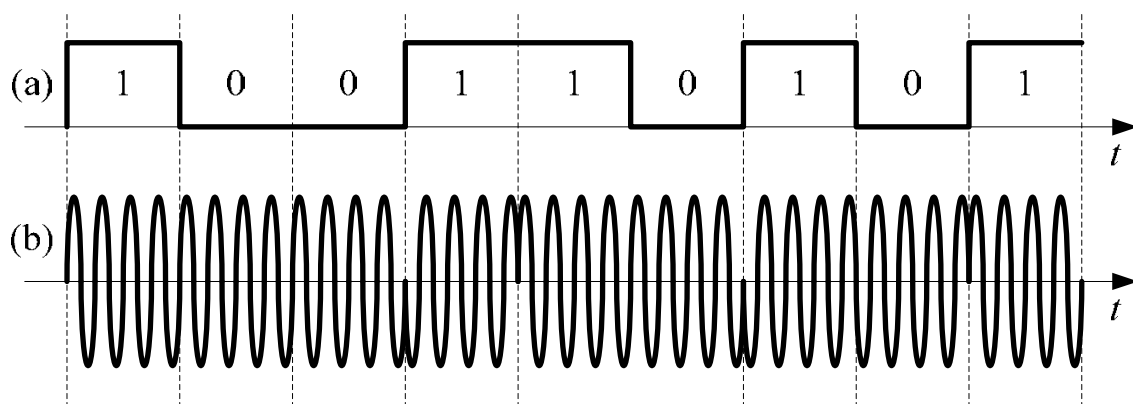

Fig. 4. Example of DPSK modulation format, (a) binary signal, and (b) DPSK modulated signal

At the receiver, since DPSK can not directly be demodulated, a delay interferometer (DI) is inserted in the optical path at the receiver to convert the differential phase modulation into intensity modulation. As shown in Figure 3(b), a DI splits the received signals into two paths, which experience one-bit delay to let two neighboring bits interfere at the DI output. At port *a* (the destructive port), the two optical fields interfere destructively whenever there is no phase change, and constructively whenever there is a phase change between subsequent bits, thus converting phase modulation into intensity modulation (Winzer & Essiambre, 2006).

Maintaining good interference is the most critical aspect in the design of DPSK receivers (Ho, 2005; Winzer & Essiambre, 2006; Winzer & Hoon, 2003). Due to energy conservation within the DI, the second DI output port *b* (the constructive port) yields the logically inverted data pattern. In principle, one of the two DI output ports is sufficient to detect the DPSK signal (single-ended detection). However, the 3-dB sensitivity advantage of DPSK is only seen for balanced detections (Ho, 2005; Winzer & Essiambre, 2006). A balanced detection (as shown in Figure 3(b) made with two photodetectors) considers the difference between ports *a* and *b* signal providing a larger signal than that of a single-branch receiver (Ho, 2005).

In advanced communication systems, similar to the *M*-ary ASK, *M*-ary DPSK are used instead of binary DPSK. The most reports are on *M* = 4, which called 4-ary DPSK or differential quadrature PSK (DQPSK). DQPSK is the only true multilevel modulation format (more than one bit per symbol) that has received appreciable attention in optical communications so far (A. F. Abas, 2006; Cho et al., 2003; Christen et al., 2007; A. H. Gnauck et al., 2006; Kawanishi et al., 2007; Morita & Yoshikane, 2005; Nasu et al., 2008; Schubert et al., 2006; van den Borne et al., 2008; Weber et al., 2005; Weber, Ferber et al., 2006; Yoshikane & Morita, 2004). It experiences four phase shifts, 0, $+\pi/2$, $-\pi/2$, and π ($\sin(\omega t)$, $\sin(\omega t + \pi/2)$, $\sin(\omega t - \pi/2)$, and $\sin(\omega t + \pi)$), for data modulation, and operates at a symbol rate of half the aggregate bit rate. Figure 3(c) shows a schematic of DQPSK based on (Winzer & Essiambre, 2006), consisting of a continuously operating laser source, a splitter to divide the light into two paths of equal intensity, two nested MZMs operated as PMs, an optical $\pi/2$ phase shifter in one of the paths, and a combiner to produce a single-output signal. Figure 5 shows example of a QPSK/DQPSK modulated signal. In this example, the binaries 00, 01, 10, and 11 are signed with 0°, 90°, 270°, and 180° respectively. The QPSK and DQPSK modulated signal are the same. The different is referred to the encoder before the modulator. If the encoder is a differential encoder, then the modulated signal is DQPSK, otherwise it is QPSK.
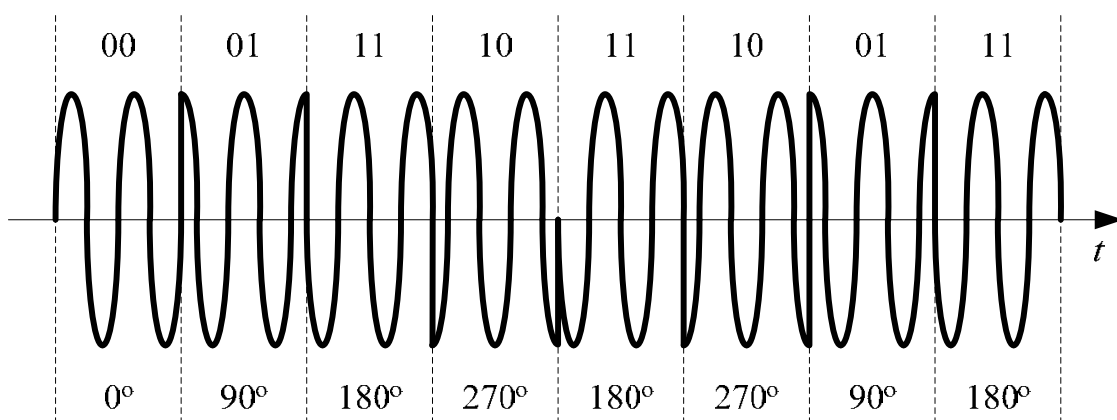

Fig. 5. Example of QPSK/DQPSK modulated signal

At the receiver, DQPSK signal first splits into two equal parts, and detected by two balanced receivers of the form depicted in Figure 3(b). The two balanced receivers are used in parallel to simultaneously demodulate the two binary data streams contained in the DQPSK signal. Note that, the delay produced by DI has to be equal to the symbol duration for DQPSK demodulation, which is twice the bit duration. In general, feedback-controlled DI tuning within the receiver is needed for both DPSK and DQPSK (Winzer & Essiambre, 2006). In DQPSK, the reduction of bandwidth is beneficial for achieving high SE in WDM systems, as well as for increasing tolerance to CD.

The higher bandwidth reduction or higher channel capacity can be achieved by increasing the value of *M*. This is achieved by combination of the amplitude and phase modulation which is called *M*-ary-quadrature amplitude modulation (QAM). In fact, the QAM (or 4-ary QAM) is produced by two PSK/DPSK signals, thus, it is the same as QPSK/DQPSK. Higher value of *M*, for example *M* = 16, which means 4 bits per symbol, is produced by utilizing 4 different amplitude levels combined with 8 different phase levels. In theory, this will lead to

32 states, allowing us to encode 5 bits per symbols ($2^5 = 32$). However, only 16 of these states are used to encode 4 bits ($\log_2(16) = 4$) per symbol (Lathi, 1998; Zahedi, 2002). Using QAM technique, 20-Msymbol/s using 128-QAM with coherent transmission over 500 km (Nakazawa, Yoshida, Kasai, & Hongou, 2006), and 1-Gsymbol/s using 64-QAM coherent transmission over 150 km optical fiber has been reported (Jumpei, Kasai, Yoshida, & Nakazawa, 2007; Yoshida, Goto, Kasai, & Nakazawa, 2008). In M-ary signaling, since there is b number of bit information per symbol, therefore, one symbol error produced b number of errors. This is called error propagation, which is more serious at higher value of b and M.

2.3 Duobinary

Optical duobinary (DB) has attracted great attention in recent years. The two main advantages attributed to this modulation format are increased tolerance to the effects of CD and improved SE (Ibrahim, Bhandare, & Noe, 2006; Lender, 1964; Said, Sitch, & Elmasry, 2005; Wei et al., 2002; Yonenaga & Kuwano, 1997; Yonenaga, Kuwano, Norimatsu, & Shibata, 1995). The fundamental idea of DB modulation (electrical or optical) that were first described by Lender (Lender, 1964) is to deliberately introduce intersymbol interference (ISI) by overlapping data from adjacent bits. This correlation between successive bits in a binary signal leads the signal spectrum to be more concentrated around the optical carrier (Said et al., 2005). This is accomplished by adding a data sequence to a 1-bit delayed version of itself, which can be obtained by passing the binary signal through the delay-and-add filter as shown in Figure 6(a) (Said et al., 2005). For example, if the (input) data sequence is $x(nT) = (0, 0, 1, 0, 1, 0, 0, 1, 1, 0)$, we would instead transmit the (output) data sequence $y(nT) = (0, 0, 1, 0, 1, 0, 0, 1, 1, 0) + (*, 0, 0, 1, 0, 1, 0, 0, 1, 1) = (0, 0, 1, 1, 1, 1, 0, 1, 2, 1)$. Here the sign * denotes the initial value ($z(nT)$) of the input sequence, which is assumed to be zero. Note that while the input sequence is binary and consists of 0s and 1s, the output sequence is a ternary sequence consisting of 0s, 1s, and 2s. Mathematically, DB results in $y(nT) = x(nT) + x(nT - T)$, where T is the bit period and n in the number of bit sequences (in above example n is 10). At the receiver, the input sequence $x(nT)$ can be recovered from the received $y(nT)$ based on $z(nT) = y(nT) - z(nT - T)$ (detail refer to (Ramaswami & Sivarajan, 2002)).

There is one problem with this scheme, however; a single transmission error will cause all further bits to be in error, until another transmission error occurs to correct the first one! This phenomenon is known as error propagation (Ramaswami & Sivarajan, 2002). The solution to the error propagation problem is to encode the actual data to be transmitted in a differential form. For example, the $x(nT)$ is encoded into $d(nT) = (0, 0, 1, 1, 1, 1, 0, 1, 0, 1)$. To see how differential encoding solves the problem, observe that if sequences of consecutive bits are all in error, their differences will still be correct. However, such an approach would eliminate the bandwidth advantage of DB signaling (Ramaswami & Sivarajan, 2002). The bandwidth advantage of DB signaling can only be exploited by using a ternary signaling scheme.
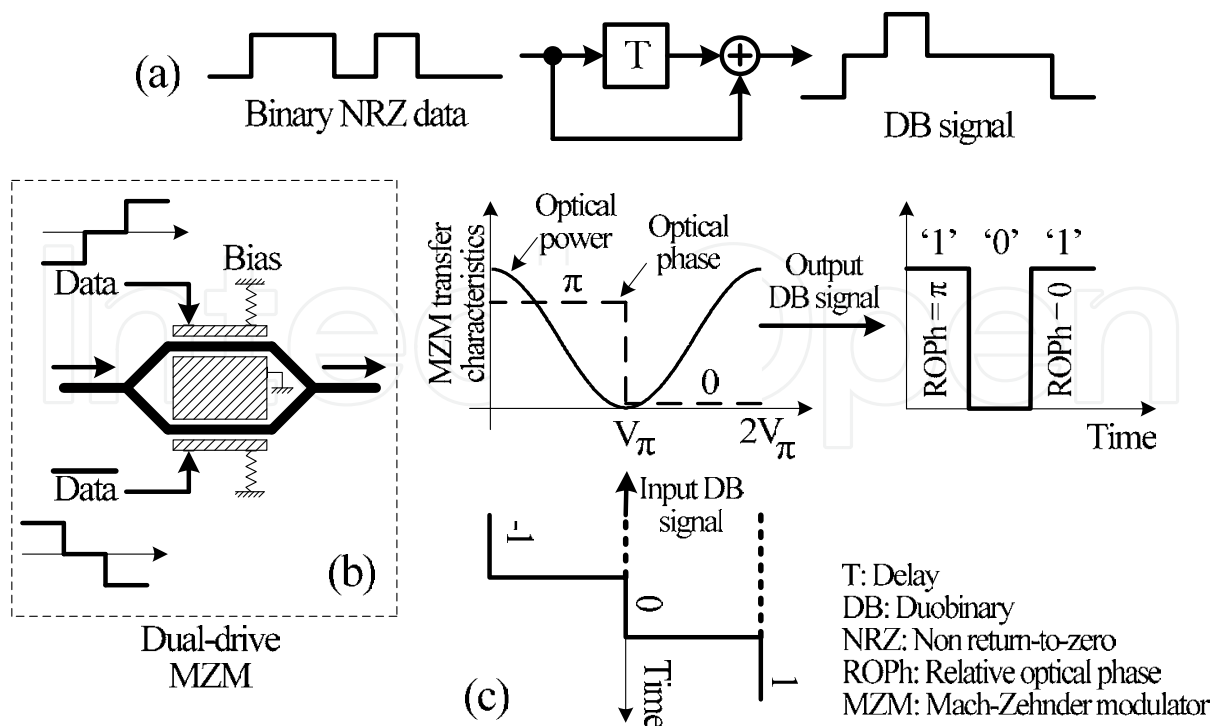
Fig. 6. Generating DB signal, (a) digital filter for electrical DB signal, (b) dual-derive MZM and (c) MZM bias and derive conditions for optical DB signal

The primary version of DB, which used three levels signal, increases the sensitivity penalty (Said et al., 2005). To avoid the penalty, the three level DB signals need to be encoded in both the amplitude and the phase of the optical carrier (Yonenaga & Kuwano, 1997; Yonenaga et al., 1995). Such a scheme is called optical AM-PSK (Ramaswami & Sivarajan, 2002) and most studies of optical DB signaling today are based on AM-PSK. If the data is differentially encoded before the DB filter, the carrier phase information becomes redundant, and hence, the received data can be decoded using a conventional binary direct-detection receiver (Yonenaga & Kuwano, 1997; Yonenaga et al., 1995). This DB signal can be generated by applying a baseband, three-level electrical DB signal to a dual-drive MZM (Figure 6 (c)) that is biased at maximum extinction ratio, as shown in Figure 6(b) (Yonenaga & Kuwano, 1997; Yonenaga et al., 1995). Conceptually, the carrier is a continuous wave signal, a sinusoid denoted by $a \cos(\omega t)$. The three levels of the ternary signal correspond to $-a \cos(\omega t) = a \cos(\omega t + \pi)$, $0 = 0 \cos(\omega t)$, and $\cos(\omega t)$, which is denoted by –1, 0, and +1, respectively. These are the three signal levels corresponding to 0, 1, and 2, respectively, in $y(nT)$. The AM-PSK signal retains the bandwidth advantage of DB signaling.

3. Multiplexing Techniques

Multipleixng is an essential part in a communcation system where multiple users transmit data simultaneously through a single link, whether the link is a coaxial cable, a fiber, radio or satellite. Multiplexing is widely employed in communication systems due to its capability to increase the channel utilization or the transmission capacity and decrease system costs. Figure 7 depicts the multipleixng function in its simplest form. There are n inputs to a multiplexer. The multiplexer multiplex or combine these inputs in a way so that they are

separable. The demultiplexer performs opposite process as multiplexer to separate the multiplexed data, and delivers them to the appropriate output lines. If each input to the multiplexer carrying k bps digital data, the total data rate or the aggregate rate of the link is nk. There are various types of multiplexing techniques commonly used in optical fiber communication system, which working principles are discussed in the following Subsections.
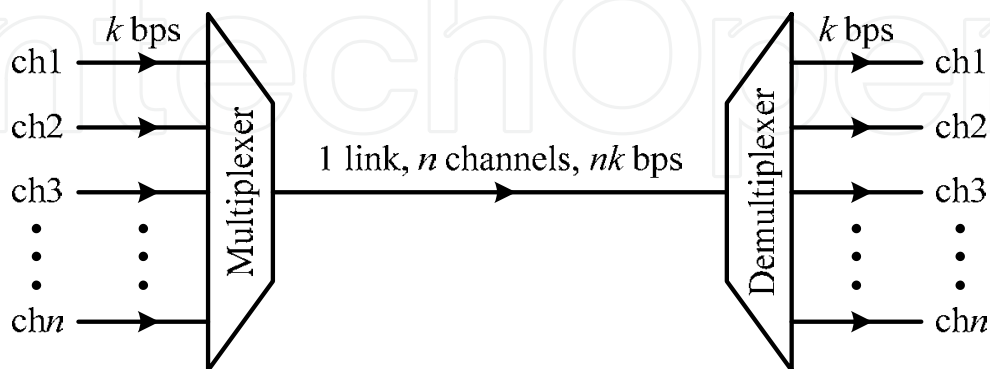

Fig. 7. Multiplexing

3.1 Time Division Multiplexing

Several low bit rate signals can be multiplexed, or combined to form a high bit rate signal by sharing the time. Because the medium is time shared by various incoming signals, this technique is generally called time division multiplexing (TDM). For those implemented in electrical domain, they are called electrical TDM (ETDM). Example of TDM system for multiplexing two channels is shown in Figure 8. In TDM systems, if n number of users with the same pulse width of T s (seconds) is multiplexed, the pulse width of the multiplexed signals is T/n. In TDM, the multiplexer and demultiplexer needs to operate at frequency equal to the total aggregate bitrate, which is n times faster than the bit rate of a single user.
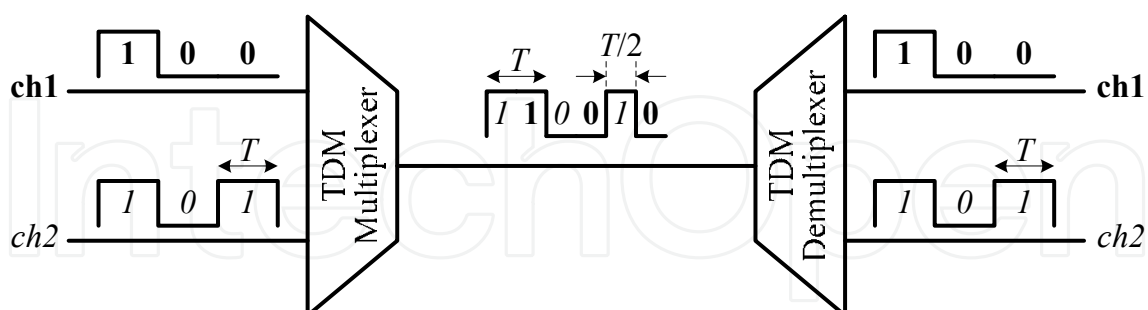

Fig. 8. Example of a TDM system for multipleing two channels

The multiplexer typically interleaves the lower speed streams to obtain the higher speed stream. The interleaving can be performed on a bit-by-bit (Figure 8) or packet-by-packet basis. Framing is required for both cases because at the receiving terminal, the incoming digital streams must be divided and distributed to the appropriate output channels. For this purpose, the receiving terminal must be able to identify the timing of each bit correctly. This requires the receiving system to uniquely synchronize in time with the beginning of each frame, with each slot in a frame, and each bit within a slot. This is accomplished by adding

framing and synchronization bits to the data bits. These bits are part of the so-called overhead bits.

Optical time division multiplexing (OTDM) has a similar concept to electrical TDM, only that it is implemented in optical domain. Figure 9 illustrates the basic concept of point-to-point transmission system using bit-interleaved OTDM. In this system, access nodes share different channels that operate at a fraction of the media rate. For example, the channel rates could vary from 100 Mb/s to 10 Gb/s, whereas the time-multiplexed media rate is around 100 Gb/s. In Figure 9, a laser source produces a regular stream of very narrow RZ optical pulses at a repetition rate R. This rate typically ranges from 2.5 Gb/s to 10 Gb/s, which corresponds to the bit rate of the electronic data tributaries feeding the system. An optical splitter divides the pulse train into n separate streams. In Figure 9, the pulse stream is 10 Gb/s and $n = 4$. Each of these channels is then individually modulated by an electrical tributary data source at a bit rate R. The modulated outputs are delayed individually by different fractions of the clock period, and interleaved through an optical combiner to produce an aggregate bit rate of nR. At the receiving end, the aggregate pulse stream is demultiplexed into the original n independent data channels for further signal processing. In this technique, a clock-recovery mechanism operating at the base bit rate R is required at the receiver to drive and synchronize the demultiplexer (G. Keiser, 2000).

OTDM requires very narrow RZ pulses to be able to interleave data of different users within a bit interval. These narrow pulses require higher spectral width. In addition, this system becomes vulnerable to CD and polarization mode dispersion (PMD) as well as creating the need for a higher optical signal-to-noise ratio (OSNR) in the wavelength channels due to the very short pulses. A higher OSNR is obtained by employing a higher signal power and will make the system more sensitive to fiber nonlinearity (Weber, Ludwig et al., 2006).
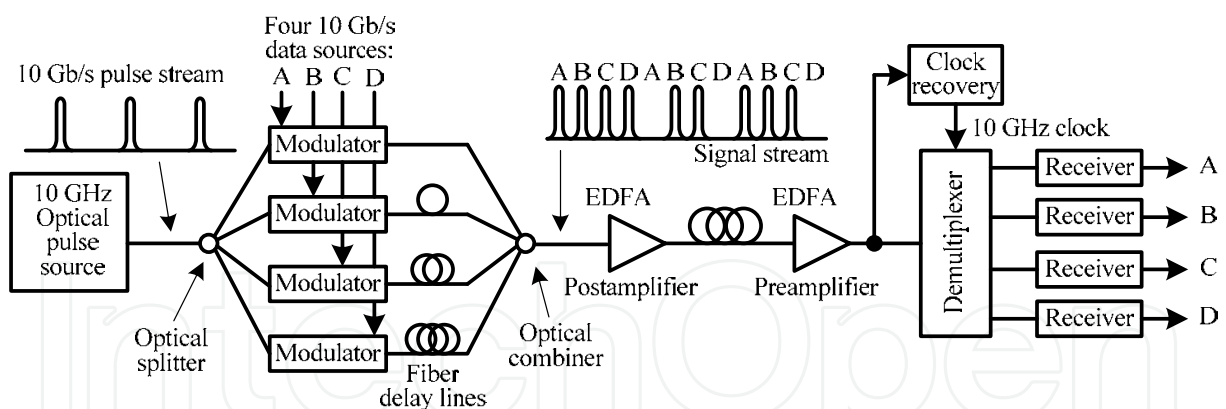

Fig. 9. Example of an ultrafast point-to-point transmission system using OTDM technique (G. Keiser, 2000)

3.2 Wavelength Division Multiplexing

In wavelength-division multiplexing (WDM) systems, different independent users transmit data over a single fiber using different wavelengths (G. E. Keiser, 1999; Palais, 2005). Conceptually, WDM scheme, which is illustrated in Figure 10, is similar to frequency division multiplexing (FDM) used in microwave radio and satellite systems. At the transmitter side, n independent users' data are modulated onto n high frequency carriers, each with a unique wavelength (λ). These wavelengths can be spaced based on ITU-T

standards. A wavelength multiplexer combines these optical signals and couples them into a single fiber. At the receiving end, a demultiplexer is required to separate the optical signals into appropriate channels. This is done with n optical filters, whereby their cut-off frequency is set based on the transmitted light source frequency. The total capacity of a WDM link depends on how close the channels can be spaced in the available transmission window. In late 1980s, with the advent of tunable lasers that have extremely narrow linewidth, one then can have very closely spaced signal bands. This is the basis of dense WDM (DWDM) (G. Keiser, 2000; G. E. Keiser, 1999). Figure 10 shows a typical WDM network containing various types of optical filter such as post-amplifier or booster, in-line amplifier and preamplifier.
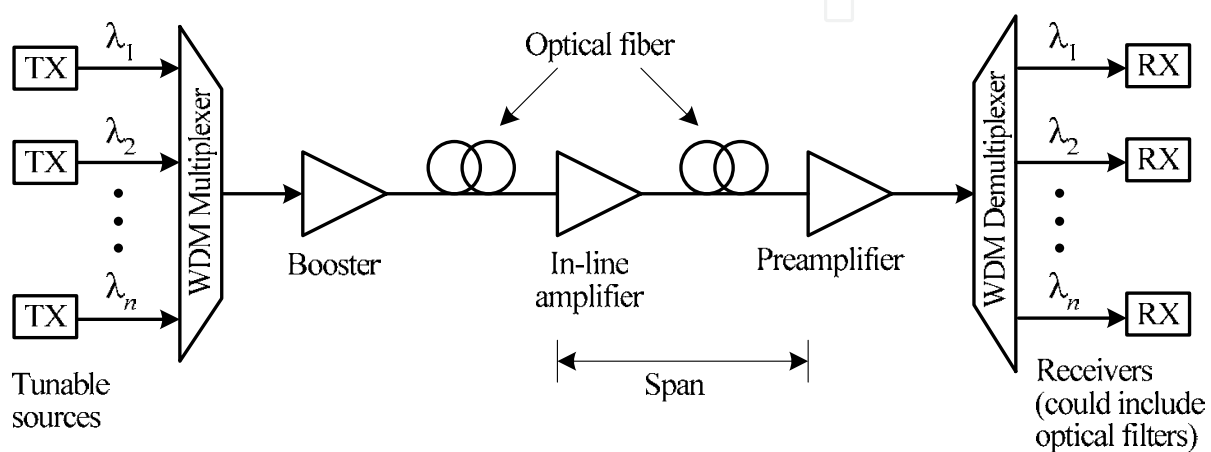

Fig. 10. Implementation of a typical WDM network

The major disadvantage of WDM is the low channel utilization and spectral efficiency because one wavelength is required per user. Therefore, for multiplexing n users, n wavelengths or light sources with n filters are required, which increase the cost of the system. The goal of all other multiplexing techniques and modulation formats are to increase channel utilization and/or channel capacity of the WDM systems.

3.3 Orthogonal Frequency Division Multiplexing

Orthogonal frequency division multiplexing (OFDM) is a special form of a multi-carrier modulation (MCM) or subcarrier multiplexing (SCM). In MCM, information of different users is modulated with different waveforms, which are called subcarriers. The channel spacing between subcarriers has to be multiple of symbol rate, which reduces the spectral efficiency (Shieh, Bao, & Tang, 2008). A novel approach which overlaps between subcarriers by reducing the channel spacing employing orthogonal signal set is called OFDM. A fundamental challenge of OFDM is on the number of subcarriers, where a large number of them are needed so that other channel treats sub-channels as a flat channel. This leads to an extremely complex architecture involving many oscillators and filters at both transmitting and receiving ends (Shieh, Bao et al., 2008). A family of OFDM was first proposed by Weinsten and Ebert (Weinsten & Ebert, 1971), in which OFDM modulation/ demodulation was implemented by using inverse discrete Fourier transform (IDFT)/discrete Fourier transform (DFT) (Weinsten & Ebert, 1971). This made OFDM attractive to be investigated for

applications in the optical domain because of its resilience to the channel dispersion (Shieh & Athaudage, 2006; Shieh, Bao et al., 2008). The most critical assumption for OFDM is the linearity in modulation, transmission, and demodulation. Consequently, a linear transformation is the key goal for the OFDM implementation. This is realized in coherent optical OFDM (CO-OFDM) with challenges in designing a linear modulator (RF-to-optical up-converter) and demodulator (optical-to-RF down-converter) (Shieh, Bao et al., 2008; Shieh, Yi, Ma, & Yang, 2008). A generic CO-OFDM system can be divided into five functional blocks including (Shieh, Bao et al., 2008; Shieh, Yi et al., 2008) (i) the RF OFDM transmitter, (ii) the RF-to-optical (RTO) up-converter, (iii) the optical channel, (iv) the optical-to-RF (OTR) down-converter, and (v) the RF OFDM receiver as shown in Figure 11.

In the RF OFDM transmitter, the input digital data is converted from serial to parallel into a block of bits consisting of information symbols. This information symbol will be mapped into a two-dimensional complex signal. The subscripts of the mapped complex information symbol correspond to the sequence of the subcarriers and OFDM blocks. The time-domain OFDM signal is obtained through IDFT and a guard interval is inserted to avoid the channel dispersion. The digital signal is then converted into analog form through a digital-to-analog converter (DAC) and filtered with a low-pass filter (LPF) to remove the alias sideband signal. The subsequent RTO up-converter transforms the baseband signal into the optical domain using an optical in-phase/quadrature (I/Q) modulator comprising a pair of Mach-Zehnder modulators (MZMs) with a 90° phase offset. The baseband OFDM signal is directly up-converted to the optical domain and propagates inside the optical medium. At the receiver, the optical OFDM signal is then fed into the OTR down-converter where it is converted to a RF OFDM signal. In the RF OFDM receiver, the down-converted signal is first sampled with an analog-to-digital converter (ADC). Then the signal needs to go through sophisticated three-level synchronization before the symbol decision can be made. The three levels of synchronization are (i) DFT window synchronization where the OFDM symbol is properly delineated to avoid intersymbol interference; (ii) frequency synchronization, namely, frequency offset needs to be estimated, compensated, and preferably, adjusted to a small value at the start; (iii) the subcarrier recovery, where each subcarrier channel is estimated and recovered (Shieh, Yi et al., 2008). Assuming successful completion of DFT window synchronization and frequency synchronization, the sampled value of RF OFDM signal passed through the DFT. The third synchronization of the subcarrier recovery involves estimation of the OFDM symbol phase (OSP), and the channel transfer function. Once they are known, an estimated value, which is calculated by the zero-forcing method is used for symbol decision or to recover the transmitted value, which is subsequently mapped back to the original transmitted digital bits (Shieh, Bao et al., 2008; Shieh, Yi et al., 2008).
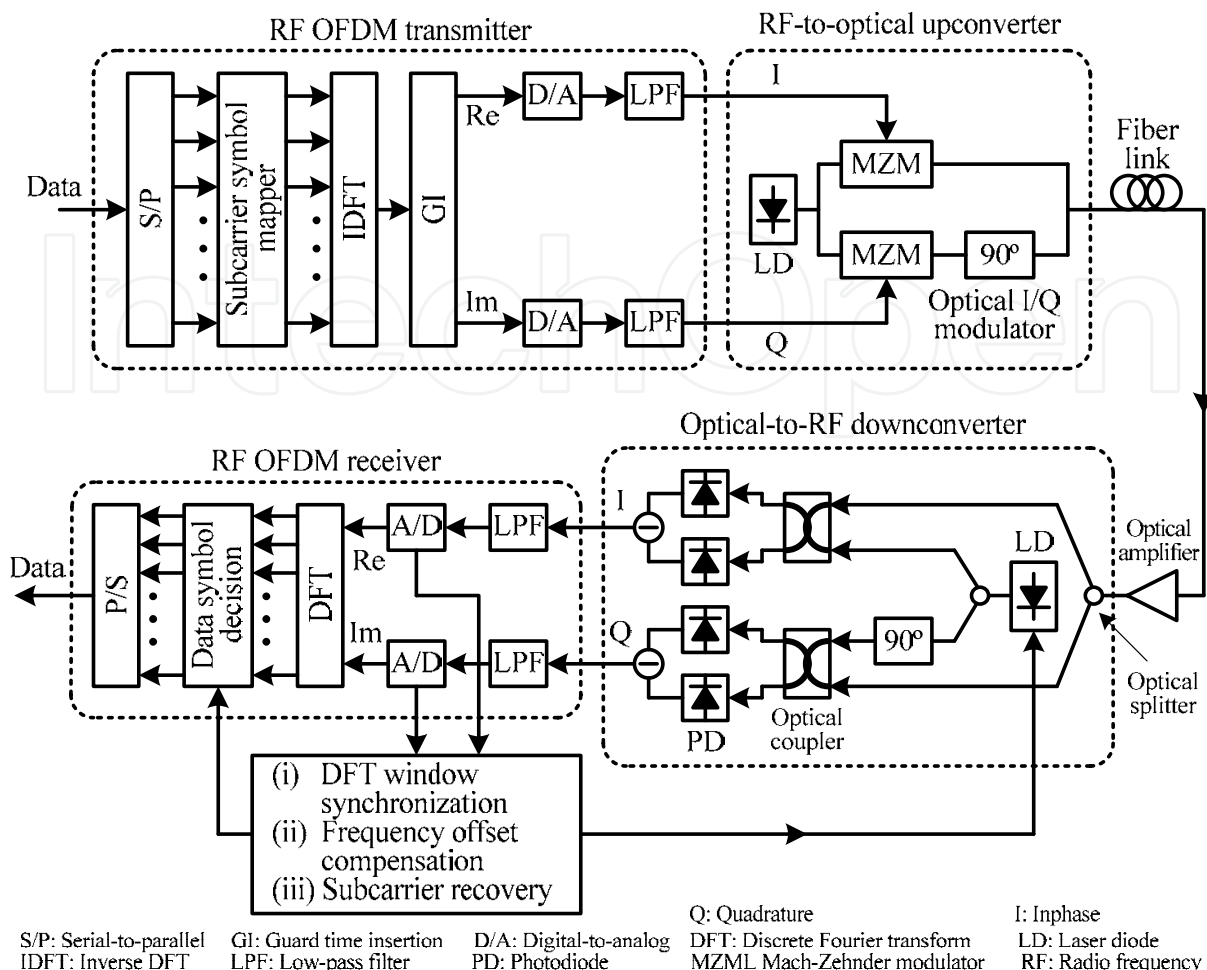
Fig. 11. Conceptual diagram for a generic CO-OFDM system with direct up-down conversion architecture (Shieh, Yi et al., 2008)

CO-OFDM has advantages in mitigating CD effects (Shieh & Athaudage, 2006; Shieh, Yi et al., 2008), as it transmits a high data rate divided into several low subcarrier channels resulting in longer signal pulse width. Also, the spectra of OFDM subcarriers are partially overlapped, resulting in high optical spectral efficiency. On the other hand, CO-OFDM requires very accurate synchronizations (Shieh, Bao et al., 2008; Shieh, Yi et al., 2008), very sensitive to nonlinear effects (Shieh, Bao et al., 2008), very complex and costly.

3.4 Polarization Division Multiplexing

Polarization division multiplexing (PDM) is a method for doubling the system capacity or spectral efficiency, in which two independently modulated data channels with the same wavelength, but orthogonal polarization states are simultaneously transmitted in a single fiber (Hayee, Cardakli, Sahin, & Willner, 2001; Martelli et al., 2008; Nelson & Kogelnik, 2000; Nelson, Nielsen, & Kogelnik, 2001; Yao, Yan, Zhang, Willner, & Jiang, 2007). At the receiver end, the two polarization channels are separated and detected independently. Figure 12 shows a simple sketch of a polarization multiplexed system. As shown in this figure, the multiplexer requires a polarization beam combiner (PBC) to combine two channels with orthogonal polarizations. State of polarization is controlled accurately with very high speed

optical polarization controller (PC). At the receiver, the polarization demultiplexer operates opposite of the multiplexer, in which a dynamic PC controls the polarization state before the polarization beam splitter (PBS) separates the two data streams.

The main advantage of PDM is that, it can be applied on existing fiber system without having to change any part of transmission hardware or software (Yao et al., 2007). It can also be used together with modulation format like DQPSK (Alan H. Gnauck et al., 2007; A. H. Gnauck et al., 2008) or QPSK (Charlet et al., 2008; Pardo et al., 2008a, 2008b) to quadruple system capacity and increase SE. Even though polarization multiplexing is straightforward, separating the two channels with acceptable crosstalk at the receiving end is not trivial because the polarization state of the multiplexed channels changes rapidly with time. Therefore, coherent crosstalk due to misaligned signal in reference to the input state of polarization in the polarizers or polarization beam splitters arises. In addition to that, PMD is another impairment for PDM (Nelson & Kogelnik, 2000; Nelson et al., 2001). Different techniques have been proposed to mitigate this impairment such as monitoring of clock tone or pilot tones (Chraplyvy et al., 1996; Hill, Olshansky, & Burns, 1992), multi-level electronic detection (Han & Li, 2006; Hayee et al., 2001), cross-correlation detection of the two demultiplexed channels (Noe, Hinz, Sandel, & Wust, 2001), and coherent detection (Charlet et al., 2008; Jansen, Morita, Schenk, & Tanaka, 2008; Pardo et al., 2008a), but they add to the system complexity and cost (Yao et al., 2007).
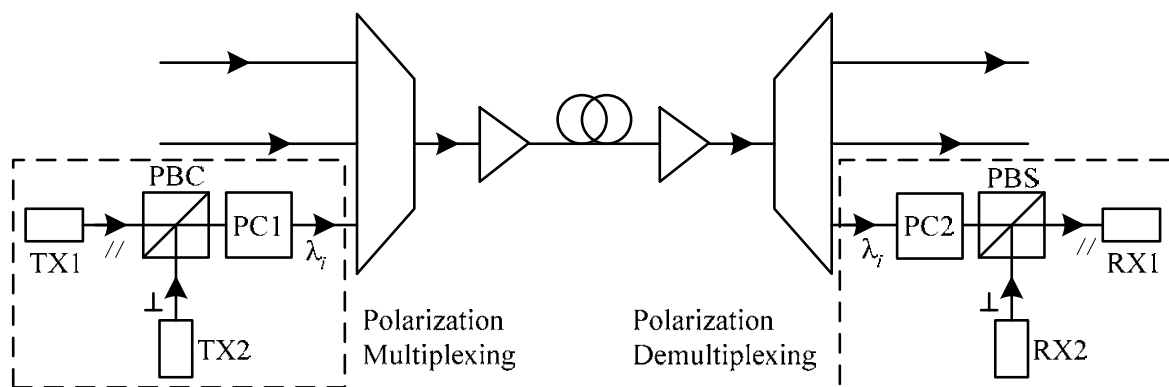

Fig. 12. Schematic of a simple polarization division multiplexing system (Nelson & Kogelnik, 2000; Yao et al., 2007)

3.5 Duty-Cycle Division Multiplexing

Duty cycle division multiplexing (DCDM) is a new multiplexing technique introduced recently by (Abdullah, Abdalla, F.Abas, & Mahdiraji, 2007). In this technique, different users sign with different RZ duty cycles and then combine together synchronously to form a multilevel step shape signal. The multiplexing process can be Performed either in electrical domain (E-DCDM) or optical domain (O-DCDM). Figure 13(a) shows example of an E-DCDM system for multiplexing three users. Data of the User 1 to 3 (U1, U2, and U3), each with let say 10 Gb/s pulse at pseudo random binary signal (PRBS) 2^{10}–1, are curved with three RZ modulators (RZ1, RZ2, and RZ3), which produces different duty cycles (DCs). The three RZ modulators operate synchronously based on a central clock. The ith RZ modulator has a DC of $T_i = (i \times T_s)/(n + 1)$, where T_s represents the symbol duration and n is the number of user. Thus, data of U1 is curved with RZ1 which is set at 25% DC (U25); data of U2 is curved with RZ2 set at 50% DC (U50); and finally, data of U3 is curved at 75% DC

(U75). The signals with different DCs are then multiplexed synchronously using an electrical adder and then modulated with a laser diode (LD) signal, using an intensity modulator (IM). Figure 13(b) shows the eye diagram of the modulated signal obtained from the receiver.
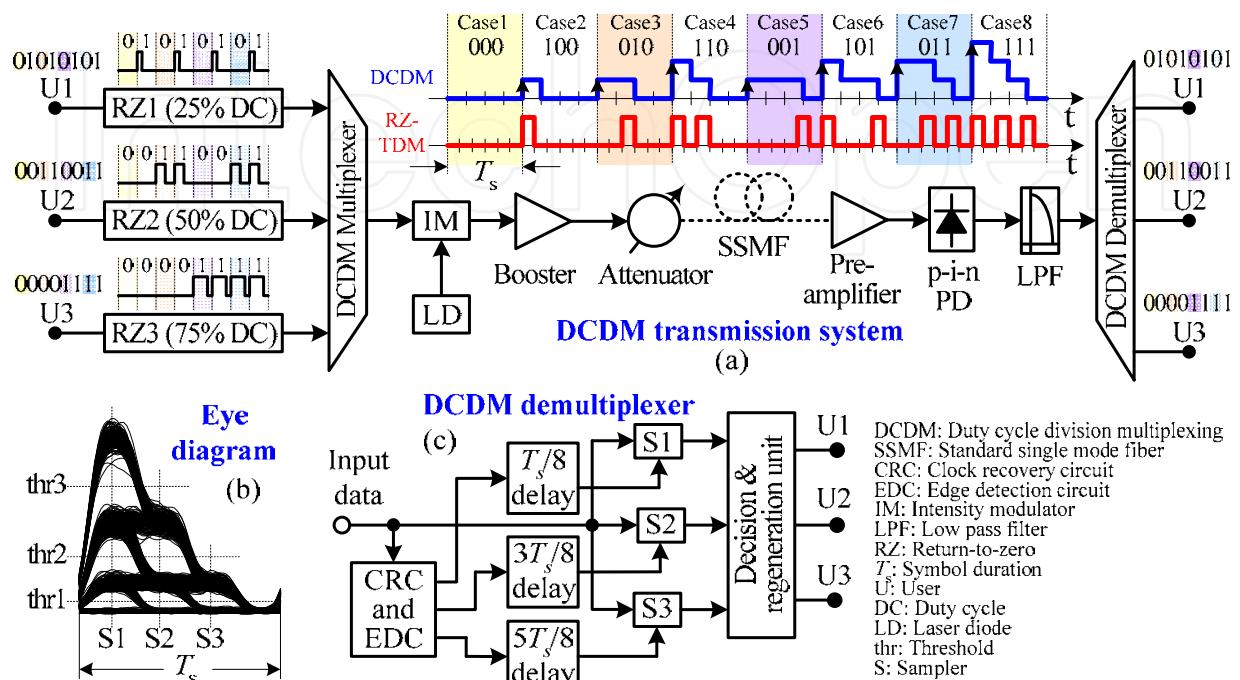

Fig. 13. (a) Schematic of E-DCDM system, (b) eye diagram, and (c) demultiplexer

The main advantage of DCDM is the inherent self-symbol synchronized system. As highlighted in Figure 13(a), there is one and only one rising edge transition in each multiplexed symbol (except the case that all user send bit 0), which located at the beginning of the symbol. Comparing these properties with RZ-TDM, they can only support the bit synchronization and required external symbol synchronization scheme. For comparison purpose, three-user RZ-TDM signal is shown in Figure 13(a). Another unique advantage of DCDM is the impulse transitions in the multiplexed signal spectrum. Figure 14(a) shows modulated spectra of 3 × 10 Gb/s DCDM, where the modulation is performed using a LD operated at 1550 nm. It can be seen that DCDM has multiple impulse transitions in its spectra. In general, the number of impulses are equal to the number of multiplexing users with spacing equal to the single user bit rate or the symbol rate, which in Figure 14(a) the transitions repeated every 10 GHz. Comparing this against RZ-TDM shows that it has only one impulse transition , which is located at frequency equal to the channel aggregate bit rate, which it is 30 GHz away from the carrier frequency (Figure 14(b)). DCDM provides smaller spectra width in comparison to RZ-TDM.
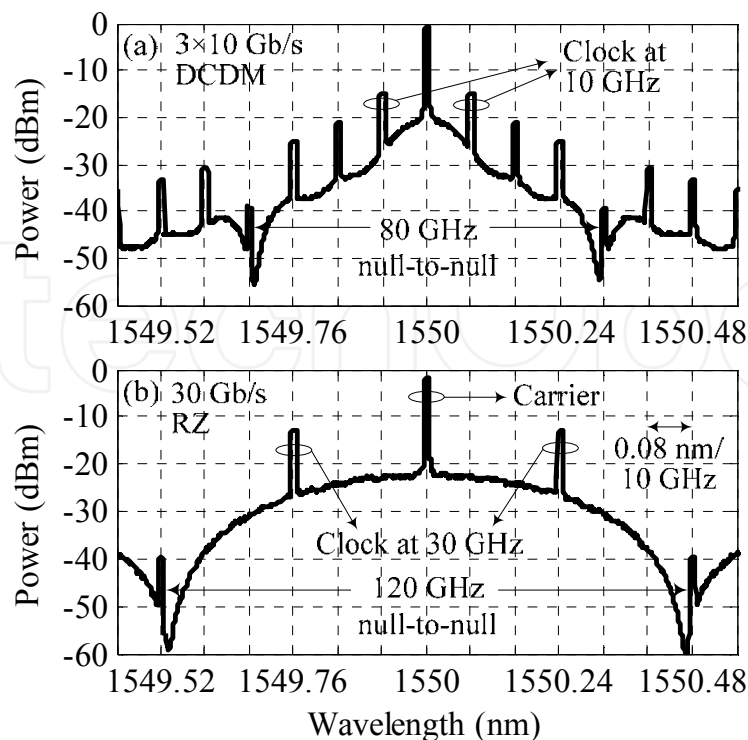
Fig. 14. Modulation spectra of 3 × 10 Gb/s DCDM and 30 Gb/s RZ-TDM

DCDM demultiplexer operates in electrical domain. Considering Figure 13(a), at the receiver side, the optical signal is first detected by a P-i-N photodiode (PD) and passed through a low-pass filter (LPF) followed by the demultiplexer. In the demultiplexer (Figure 13(b)), a clock recovery circuit (CRC) and edge detection circuit (EDC) is used to recover the clock and detect the beginning of each multiplexed symbol. A 10 GHz clock is recovered referring to the impulse transition available in the signal spectra (Figure 14(a)). On the other hand, considering the 10 GHz recovered clock, the beginning of ach multiplexing symbol can be detected using the EDC. Three sampling circuits are synchronized with the recovered clock or the detected edges. By putting appropriate delay lines for each sampler as shown in Figure 13(b), the first, second, and third sampler ($S1$, $S2$, $S3$) take samples at $T_s/8$, $3T_s/8$, and $5T_s/8$ s per symbol respectively. The frequency of all samplers is equal to the symbol rate (10 GHz). Outputs of the samplers are fed into the decision and regeneration unit. In this unit, the sampled values are compared against three threshold values thr_1, thr_2, and thr_3, and the decision is performed based on the operations shown in Table 1. Regarding to the rules in that table, for U25, the decision is made based on the information taken from the two consecutive sampling points, $S1$ and $S2$. If amplitudes of those two adjacent sampling points are equal, bit 0 is regenerated (rules 1 to 3 from Table 1 and cases 1, 3, 5, and 7 from Figure 13(a)). On the other hand, when the amplitude at $S1$ is one level greater than $S2$, bit 1 is regenerated (rules 4 to 6 from Table 1 and cases 2, 4, 6, and 8 from Figure 13(a)). The same method is used for U50, which utilizes information extracted from $S2$ and $S3$. Finally, U75 is recovered from only $S3$ by comparing amplitude of $S3$ against thr_1.

Rules for U1								Cases
1	if	$(S1 < thr_1)$	&	$(S2 < thr_1)$,	then	$U1 = 0$		1
2	if	$(thr_1 \leq S1 < thr_2)$	&	$(thr_1 \leq S2 < thr_2)$,	then	$U1 = 0$		3, 5
3	if	$(thr_2 \leq S1 < thr_3)$	&	$(S2 \geq thr_2)$,	then	$U1 = 0$		7
4	if	$(thr_1 \leq S1 < thr_2)$	&	$(S2 < thr_1)$,	then	$U1 = 1$		2
5	if	$(thr_2 \leq S1 < thr_3)$	&	$(thr_1 \leq S2 < thr_2)$,	then	$U1 = 1$		4, 6
6	if	$(S1 \geq thr_3)$	&	$(S2 \geq thr_2)$,	then	$U1 = 1$		8
Rules for U2								Cases
1	if	$(S2 < thr_1)$	&	$(S3 < thr_1)$,	then	$U2 = 0$		1, 2
2	if	$(thr_1 \leq S2 < thr_2)$	&	$(S3 \geq thr_1)$,	then	$U2 = 0$		5, 6
3	if	$(thr_1 \leq S2 < thr_2)$	&	$(S3 < thr_1)$,	then	$U2 = 1$		3, 4
4	if	$(S2 \geq thr_2)$	&	$(S3 \geq thr_1)$,	then	$U2 = 1$		7, 8
Rules for U3							Cases	
1	if	$(S3 < thr_1)$,	then	$U3 = 0$			1, 2, 3, 4	
2	if	$(S3 \geq thr_1)$,	then	$U3 = 1$			5, 6, 7, 8	

Table 1. Data recovery rules for three-DCDM users

The main disadvantage of DCDM system is that it required high OSNR in comparison to the binary signalling such as RZ or NRZ. This is due to the fragmentation of the main eye to several smaller eyes (Figure 13(b)) similar to the multilevel amplitude signalling. Performance of DCDM is improved using optical multiplexer by adding the cost in multiplexer, which required one modulator for each multiplexing user. In terms of transmitter and receiver complexity, DCDM has simple transmitter and receiver. At the same time, DCDM allows high speed aggregate bit rate to be recovered at symbol or baud rate, which made DCDM receiver very economic. Furthermore, this technique allow more users to be allocated in a WDM channel, which contributes towards improvement in SE.

4. Comparison between Multiplexing Techniques and Modulation Formats

Table 2 shows a comparison between different modulation formats and multiplexing techniques at 40 Gb/s. The comparison is made based on transmitter (Tx) and receiver (Rx) complexity, optical signal-to-noise ratio (OSNR), chromatic dispersion (CD), null-to-null modulated bandwidth (MBW) and clock recovery frequency (CRF).
Multiplexing techniques improve transmission capacity of optical networks. TDM with a simple transmitter and receiver can improve channel utilization by expending spectral bands or bandwidth. This technique is limited by the electronics technology (for example, based on today technology, the maximum aggregated bit rate per single channel reported is 114 Gb/s). PDM can double the channel capacity with the same spectral band as required by TDM systems. However, it suffers from channel crosstalk due to PMD and requiring very high speed polarization controllers, which increase the system complexity and the cost. OFDM improves channels capacity by allowing hundreds of low speed channels to form a single channel with very complex transmitter and receiver and requiring 3 stages of precise synchronizations. DCDM with simple transceivers can support multiple channels per WDM channel with requiring smaller spectral bandwidth in comparison to the RZ-TDM. It also facilitates symbol synchronization and allows high speed transmission to be recovered at low speed clock. However, it suffers from the high OSNR requirement.

40Gb/s Modulation & multiplexing techniques	Tx complexity	Rx complexity	OSNR (dBm)	CD (ps/nm)	MBW (GHz)	CRF (GHz)
NRZ-TDM	1 M	1 PD	Sim: 16.5 (E-3),19.8 (E-9) Exp: ~23.3 (E-9)	54	80	40
50% RZ-TDM	2 Ms	1 PD	Sim: 14.4 (E-3), 18.3 (E-9) Exp: ~21 (E-9)	48	160	40
67% CS-RZ-TDM	2 Ms	1 PD	Sim: 14.9 (E-3), 15.1 (E-3), 18.8 (E-9)	42	120	40
DB			Sim: 22.4 (E-9)			40
NRZ-DPSK	1 M	1 DI + 2 PDs	Sim: 11.7 (E-3),13.5 (E-3), 18.5 (E-9) Exp: ~20 (E-9)	74	80	40
50% RZ-DPSK	2 Ms	1 DI + 2 PDs	Sim: 11.1 (E-3), 15.6 (E-9) Exp: ~18 (E-9)	50	160	40
NRZ-DQPSK	2 Ms	2 DIs + 4 PDs	Sim: 13.2 (E-3), 15 (E-3), 13.4 (E-3), 20.5 (E-9) Exp: ~24.5 (E-9)	168	40	20
50% RZ-DQPSK	2 Ms	2 DIs + 4 PDs	Sim: 12.2 (E-3), 15 (E-3), 17.7 (E-9), 20.2 (E-9) Exp: ~23.3 (E-9)	161	80	20
RZ-DQPSK-PDM	3PCs, 2 Ms, 1PM, 1RZ-PG, 2PBS,1PBC	PS, PBS, 2DIs, 4PDs, PC	Exp: 13.7 (E-9)		40	10
NRZ-16-QAM	3 PCs, 1 M	2 PDs, 3 PCs, Pol, TFL	Sim: 20.9 (E-9)		20	10
E-DCDM (2 × 20 Gb/s)	1 M	1 PD	Sim: 17.8 (E-3), 21.74 (E-9)	62	120	20
E-DCDM (4 × 10 Gb/s)	1 M	1 PD	Sim: 21.6 (E-3), 26.4 (E-9)	58	100	10
E-DCDM (7 × 5.71 Gb/s)	1 M	1 PD	Sim: 27 (E-3), 31.4 (E-9)	52	91.4	5.71

WDM: Wavelength division multiplexing   NRZ: Non return-to-zero   RZ: Return-to-zero   M: Modulator
DQPSK: Differential quadrature phase shift keying   CD: Chromatic dispersion   DB: Duobinary   Num: Numerical
QAM: Quadrature amplitude modulation   RS: Receiver sensitivity   Tx: Transmitter   Rx: Receiver
PDM: Polarization division multiplexing   PS: Polarization stabilizer   Exp: Experimental   Pol: Polarizer
CRF: Clock recovery frequency   DI: Delay interferometer   PD: Photodetector   OOK: On off keying
PBC: Polarization beam combiner   PC: Polarization controller   PG: Pulse generator
PBS: Polarization beam splitter   TFL: Tunable fiber laser   MBW: Modulated bandwidth

Table 2. Performance and complexity comparison between different multiplexing techniques and modulation formats at 40 Gb/s aggregation bit rate (Daikoku, Yoshikane, & Morita, 2005; Essiambre, Winzer, & Grosz, 2006; Jumpei et al., 2007; Leibrich, Serbay, Baumgart, Rosenkranz, & Schimmler, 24-28 September 2006; Martelli et al., 2008; Ohm & Freckmann, 2004)

Advanced modulation formats such as QASK, QAM, QPSK, QDPSK and DB double channel capacity of optical network with requiring the same spectral band as TDM. However, they have complex and costly transmitter and receiver. Beside all these techniques, WDM allows the use of available spectra in optical domain but only at one channel per wavelength.

Combining WDM with individual or combination of the techniques mentioned above and/or other techniques can increase the transmission capacity tremendously and improve spectral efficiency of the optical fiber communication systems. Overall, the goal of all multiplexing techniques and modulation format are to increase spectral efficiency of WDM networks. To date, PDM and DQPSK and combination of these two techniques achieved the most attention from the communication society. At the same time, DCDM has some attractive and unique properties that have not been discovered in other techniques. This technique has the potential to become an alternative multiplexing technique but it required more investigation on the practical and experimental systems.

5. Conclusion

The main objective in the communication systems is to transmit as much as possible information in as low as possible bandwidth and cost. Different modulation formats such as M-ary ASK, QPSK/DQPSK, QAM and DB are proposed to improve WDM channel capacity. M-ary ASK improves the channel capacity by transmitting more than one bit per signal element utilizing different signal levels or multilevel signals. QPSK/DQPSK utilizes multiple phases for transmit more than one bit per signal element. QAM improve channel capacity by transmitting more than one bit per signal element utilizing different phases and different amplitudes. DB use either three amplitude levels or two amplitudes (like binary signals) and one redundant phase element instead of the third level. All the advanced modulation schemes are limited to double or triple the channel utilization but all of them improve the channel capacity or the spectral efficiency. On the other hand, different multiplexing techniques such as TDM, WDM, OFDM, PDM and DCDM are proposed to improve the channel utilization. In TDM, different users share the same WDM channel by allocating each user different time slot. Using WDM, the available optical spectrum can be to utilize to support multiple numbers of users. In this technique, each user is assigned a wavelength as the carrier signal. In OFDM, utilizing IDFT many different RF signals can be assigned as the carrier for many low bit rate users. PDM allows two users to be carried over two different polarizations, vertical and horizontal polarizations. In DCDM, different users signed with different RZ duty cycles to share the same WDM channel. Except PDM, all other multiplexing techniques can support multiple users. Eventhough multiplexing techniques improve the channel utilization, but all of them except PDM, failed to improve the spectral efficiency of the link. PDM act like modulation schemes that can double the channel capacity or the spectral efficiency. Amongst all these multiplexing techniques and modulation schemes, PDM and QPSK/DQPSK or combinations of them have obtained the most attention in the communication systems. Finally, DCDM can reduce the clock recovery frequency significantly.

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Trends in Telecommunications Technologies

Edited by Christos J Bouras

The main focus of the book is the advances in telecommunications modeling, policy, and technology. In particular, several chapters of the book deal with low-level network layers and present issues in optical communication technology and optical networks, including the deployment of optical hardware devices and the design of optical network architecture. Wireless networking is also covered, with a focus on WiFi and WiMAX technologies. The book also contains chapters that deal with transport issues, and namely protocols and policies for efficient and guaranteed transmission characteristics while transferring demanding data applications such as video. Finally, the book includes chapters that focus on the delivery of applications through common telecommunication channels such as the earth atmosphere. This book is useful for researchers working in the telecommunications field, in order to read a compact gathering of some of the latest efforts in related areas. It is also useful for educators that wish to get an up-to-date glimpse of telecommunications research and present it in an easily understandable and concise way. It is finally suitable for the engineers and other interested people that would benefit from an overview of ideas, experiments, algorithms and techniques that are presented throughout the book.

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