Chapter 1
Distortions and Their Effect on Signal Transmission in Coherent-OFDM Systems

Gábor Fekete and Tibor Berceli

Abstract The next generation optical systems will use OFDM modulation. It requires highly linear transmitter or the signal will be distorted. However, the commonly used optical Mach-Zehnder Modulator characteristic is not linear. In this paper we examined the modulator caused signal distortions and its possible driving methods to minimize the signal degradation. We will show that the distortions can be eliminated with proper driving technique and it is not necessary to use a dedicate hardware to compensate the effect of nonlinearity. The dispersions and the non-linearities of the optical fibers (e.g. polarization mode dispersion, four wave mixing) are investigated too. A simple method is presented which can reduce the polarization mode dispersion. The transmitter and the channel caused distortions are compared to each other. The results show that some distortions from the transmitter and some from the channel are not only in the same range, but their effect to the signal is also similar.

1.1 Introduction

The demand for faster and larger amount data transmission is continuously increasing, therefore the same higher modulation formats have been started to use in optics as ones are used in the electrical domain. The next generation optical systems will use the Orthogonal Frequency Division Multiplexing (OFDM) modulation [1–3], because of its flexibility. The main benefit of the OFDM is the easy distortions compensation methods. Many compensation techniques use post-compensation techniques, which is

G. Fekete (✉) · T. Berceli
Department of Broadband Infocommunications and Electromagnetic Theory, Budapest University of Technology and Economics, Egry József utca 18, Budapest 1111, Hungary
e-mail: gfekete@hvt.bme.hu; gabor.fekete@omt-lab.hu

T. Berceli
e-mail: berceli@mht.bme.hu

done by DSP (Digital Signal Processing). It is a more compact methode than using a long dispersion compensation fiber. OFDM is a big success in the electrical domain because it is a spectrally efficient modulation form. This spectral efficiency will be also important in the future optical networks. However OFDM has drawbacks such as complex detection method, high sensitivity to nonlinearity and high PAPR (Peak to Average Power Ratio). OFDM transmitter has to be linear to avoid signal distortion, however, the commonly used optical Mach-Zehnder Modulator (MZM) is highly nonlinear [2]. Therefore, it is important to know the MZM caused distortion, then it can be compensated without a DSP. At the transmitter side not only the modulator but the laser noise also degrades the quality of transmission. In this paper these two distortion effects are examined in Sects. 1.3.1 and 1.3.2.

The distortions can come from the transmission channel too. The chromatic dispersion (CD) and the polarization mode dispersion (PMD) are the major limiting factors in the channel. CD is compensated traditionally by Dispersion Compensation Fiber (DCF) but it is not the same for each wavelength and always remains a small CD on the signal. OFDM modulation provides the facility to use DSP for CD compensation, if its effects are well known. The PMD comes from the different propagation speed of the two polarization planes in a fiber [4–6]. PMD is the mean value of the differential group delay of the polarization planes. To develop a PMD compensation method is not easy, because of the statistical nature of the PMD. For a long time its effect was neglected because other nonlinearities (e.g. chromatic dispersion) had much stronger distortion. The older optical fibers have 2 ps/km$^{1/2}$ PMD coefficient while the new fibers PMD coefficient is only 0.1 ps/km$^{1/2}$ [4]. That is due to the new manufacturing technologies which reduce the value of the PMD coefficient. PMD distortion could be decreased by replacing the old fibers having a higher PMD coefficient. However, that method cannot be applied, because it would cost thousand millions of US dollars. Another method would be the selection of the modulation format, which is less sensitive for the PMD or provides easy post-compensation method. OFDM modulation has this benefit because the DSP, which is used for CD compensation, can be used to eliminate the effect of PMD too. CD and PMD effects to the transmission are investigated in Sect. 1.3.3. The fiber nonlinearity caused signal distortion has to be taken into account, if the power density in the fiber is higher than 1 W. High PAPR can cause this kind of distortion. However, the MZM also will distort the signal if the PAPR is too high. VPI TransmissionMaker (VPI) software was used for our simulation examination. We investigate whether the modulator or the fiber caused distortion effect has stronger influence on the transmitted signal or they are in the same range.

1.2 Principle of OFDM

OFDM is a special class of multi carrier modulation. Using more than one carrier frequency for data transmission was the idea [7], [3]. The carrier frequencies are orthogonal to each other because it guarantees the smallest bandwidth for the modulated signal. The mathematical form of the OFDM signal is the following [1]:

$$s(t) = \sum_{i=-\infty}^{\infty} \sum_{k=1}^{N_{sc}} c_{ki} s_k(t - iT_s), \quad s_k(t) = \exp(j2\pi f_k t) \quad \text{if } 0 \le t \le T_s \qquad (1.1)$$

N_{sc} is the number of the subcarriers, c_{ki} is the ith information symbol at the kth subcarrier, s_k is the waveform of the kth subcarrier, T_s is the symbol period, f_k is the frequency of the subcarrier. The optimum detector can be a matched filter or a correlator. The subchannels are orthogonal to each other if:

$$f_k - f_i = m \frac{1}{T_s}; \quad m = \in 1, 2, 3, \ldots \qquad (1.2)$$

In any other cases, there will be interference between the subchannels, which decreases the quality of the transmission. The theoretical OFDM modulator and demodulator contain a lot of oscillators and filters. Each subcarrier has its own oscillator which transpose the signal to the proper frequency for transmission then a pass band filter is used to minimize the disturbance. At the end the modulated subcarriers are add together and the OFDM signal is ready. In practice it cannot work because of the frequency faults of the oscillators. Precise oscillators have to be used to minimize the interference, but these oscillators are extremely expensive. Therefore Inverse Discrete Fourier Transformation (IDFT) is used to create the OFDM signal in practice and Discrete Fourier Transformation (DFT) is used for OFDM demodulation. Figure 1.1 shows a typical OFDM transmitter. Data stream is split up N_{sc} parts by a serial-to-parallel converter, and the next block creates the transmitted symbols of the subcarrier from the bit sequence. OFDM modulation is made by the IDFT block. If the subcarriers are not orthogonal to each other (e.g. there is synchronization failure), ISI (Inter Symbol Interference) and ICI (Inter Carrier Interference) will appear in the demodulated signal. This can be avoided if Guard Interval (GI) is applied. It is also called as Cyclic Prefix (CP). A small time period from the end of symbol is copied down. This is the CP and it is placed at the beginning of the symbol. Until the time difference between the subcarriers is smaller than the GI there will not be ISI and ICI in the demodulated signal. After GI is added to the signal, its digital samples are converted into an analogue signal. The optical carrier is modulated by it. After the IDFT block the complex digital signal is separated into two parts: a real (or In phase) and an imaginary (or Quadrature phase) part. These are the I and Q arms of the QAM modulator. The structure of an OFDM demodulator is similar to Fig. 1.1 but the signal flow is reversed so there is a
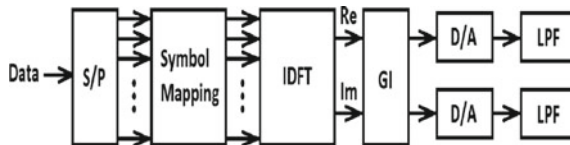

**Fig. 1.1** Baseband OFDM transmitter. OFDM modulation is created by IDFT

DFT block instead of the IDFT and it is extended with a clock restore or synchronization block.

Transmitters and receivers have to have huge dynamic range if the PAPR is high. It is not possible to create a device which has large and linear dynamic range. Therefore the value of PAPR must be decreased by coding technique or clipping. The clipping method is usually used, which cuts off the level of the signal above a given value. However, this increases the noise level outside of the signal spectrum.

1.3   Simulation

Block diagram of our transmission is shown in Fig. 1.2 which is based on the proposed system in [8]. Pseudo random bit sequence with 80 Gbps data rate is used in the simulations. OFDM coder use 16-QAM modulation and creates separately the real (I) and imaginary (Q) parts of the OFDM signal. Here is no 90° phase shift between I and Q. The laser signal is modulated separately by I and Q signals. Mach-Zehnder Modulators (MZM) are applied which have sinusoidal transfer characteristic. They are biased at the quadrature point, where the transfer characteristic is linear. I and Q arms are summarized by an optical coupler. Its behaviour is similar to an electrical one. The input signal intensity from both input ports is halved at the output and it creates 90° phase shift between the input ports signals. It means that the necessary 90° phase shift is done by the coupler. So the optical I-Q modulator is built up by two MZMs and an optical coupler. After the coupler a standard Single Mode Fiber (SMF) is placed, when its distortion is examined. In the other cases it is left out from the network. Signal detection is based on the heterodyne detection method. There is a small frequency difference (f) between the laser on the transmitter side and the laser on the receiver side. It causes that the detected signal (at the output of photo diodes) is converted down at f frequency. This signal is demodulated by the OFDM decoder. The analyzer shows the constellation diagram of the detected signal. We supposed that the other elements in the system are ideal or do not make distortion.

Fig. 1.2   Block scheme of the simulated CO-OFDM system in VPI
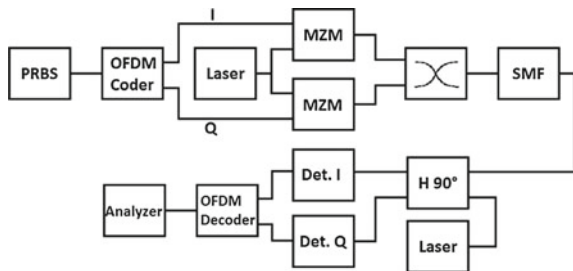
1.3.1 Distortion of Mach-Zehnder Modulator

Two arms of the MZMs can be driven independently from each other in VPI. The relation between the arms can be positive or negative. If it is positive then the sign of phase change is the same in both arms. In the other case the sign of the phase change is opposite. Figure 1.3 shows those cases when MZMs upper arm are driven. MZMs are biased with 0.5 V, which causes 90° phase shift (optimum point) in the controlled arm. Both MZM bias points are similarly changed. If the phase delay is less than 90°, the constellation is rotated clockwise (Fig. 1.3b). It is rotated the opposite way (Fig. 1.3a), when the phase shift is more than 90°. This rotation can be compensated by DSP after detection. Another way to eliminate this rotation is the differential driving of MZMs. In this case only the distance between constellation points will decrease when the bias changes (Fig. 1.4a). However, the standard deviation of constellation points is growing linearly (Table 1.1).

There is another MZM driving method when one MZM is driven in the upper arm and the other is driven in the lower arm with negative sign of phase changes. It does not cause any difference in the output light intensity but the electrical field is different. Between the electrical fields there is a 90° phase difference. The optical coupler which summarizes the I and Q signals (Fig. 1.2) also makes 90° phase shift between them. Its result is that if MZMs are biased at the optimum point, there will be no carrier in the transmitted spectrum. In this case we need an outside clock signal to demodulate the received signal which highly complicates the receiver. It can be avoided, if MZMs are not driven in the optimum point. Slightly shifted from the optimum the carrier will appear in the spectrum but the symbols will be closer to each other as Fig. 1.3 shows it. Figure 1.4b shows the received constellation when MZMs are driven asymmetrically (same bias point but the sign of the bias change is the opposite). This driving method minimizes the rotation of the constellation. The standard deviation of symbols does not increase outside from the optimum point of operation.
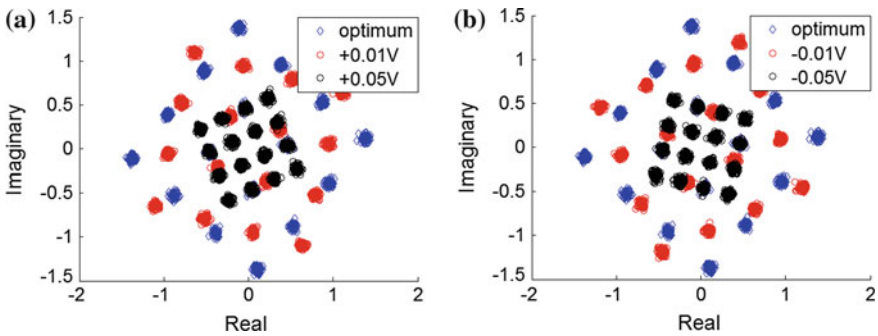

Fig. 1.3 **a** Constellation turns right, if the bias error is positive and it turns left, **b** when the bias changes negatively
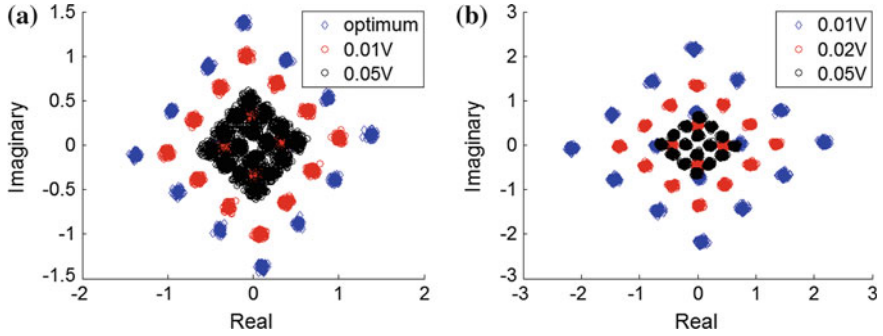
Fig. 1.4 Asymmetrically biased MZMs. **a** Both MZMs are biased at the same arm. **b** MZMs are biased at different arms and the phase change has opposite sign

Table 1.1 Rotation of the constellation

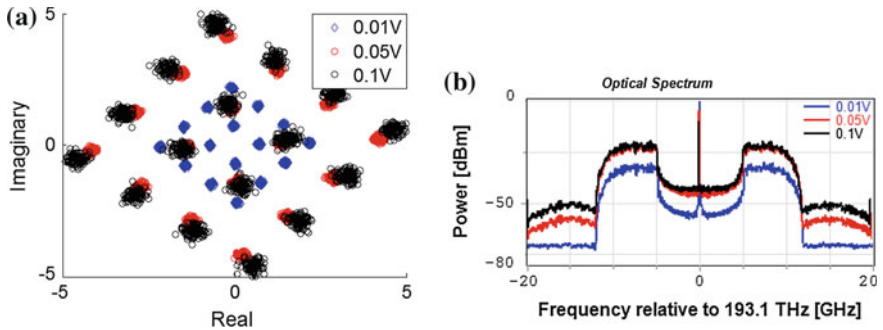| MZM's driving method	Bias (V)	Angle (°)	Deviation
At the same	Optimum	0	0.024
	+0.01	25	0.024
	+0.05	−26	0.024
	−0.01	−25	0.023
	−0.05	26	0.024
Differential	0.01	0.2	0.028
	0.05	1	0.048
Differential, phase change in the MZM's arm is opposite	0.01	0	0.037
	0.02	0.9	0.029
	0.05	3.6	0.025

Fig. 1.5 **a** Larger drive amplitude increases the distance between symbols but, **b** outside of the OFDM spectrum the noise level also increases

Larger drive amplitude increases the distance between the symbols of the constellation (Fig. 1.5a) but it does not grow linearly. It has saturation because of the MZM sinusoidal characteristic. Large drive amplitude causes bigger standard

deviation of the symbols too. The 0.05 and 0.1 V driving amplitudes are near to the saturation point because the distance between the symbols changed minimally but the standard deviation of the symbols is twice as big. Between the two constellations there is a 3.8° angle. The noise level also increases outside of the signal spectrum (Fig. 1.5b). It comes from the clipping and nonlinearities. This growing noise is harmful in WDM systems, because the channels have to be placed far from each other.

1.3.2 Phase Noise of the Lasers

The linewidth of the lasers is another important factor in the signal quality of optical OFDM systems. To examine the phase noise caused signal distortion the fiber is left out so the transmitter and the receiver are connected directly like in the MZM distortion examination. Linewidth of the lasers changes between 10 kHz and 0.1 GHz. Table 1.2 contains the calculated standard deviations of the constellation diagram. Data in the table have a special symmetry. The standard deviation is not depending on the side where a laser with large linewidth is used. The constellation has the same standard deviation if the transmitter laser linewidth is 10 kHz and the linewidth of the receiver side laser is 100 kHz or the laser linewidths are interchanged. This similarity is shown by Fig. 1.6. The benefit of this symmetry should be utilized. At the transmitter side it is beneficial to use a narrow linewidth laser while a cheaper laser with wider linewidth can be used in the receiver.This method offers a reduction in the price of the system which is good enough to tolerate the signal degradation level using this method. The linewidth of the lasers cannot be larger than 1 MHz if the goal is to reach the best signal transmission quality and the lowest system price. Although the standard deviation of the constellation does not change significantly, the larger laser linewidth increases the noise level. The noise increases with 7 dB when the laser linewidth is changed from 10 kHz to 1 MHz. This noise increase results in a larger standard deviation of the constellation.

If the linewidth of the lasers are larger than 10 MHz the points of the constellation cannot be separated. They will compose one point with huge deviation as

Table 1.2 Laser phase noise caused standard deviation of the constellation diagram

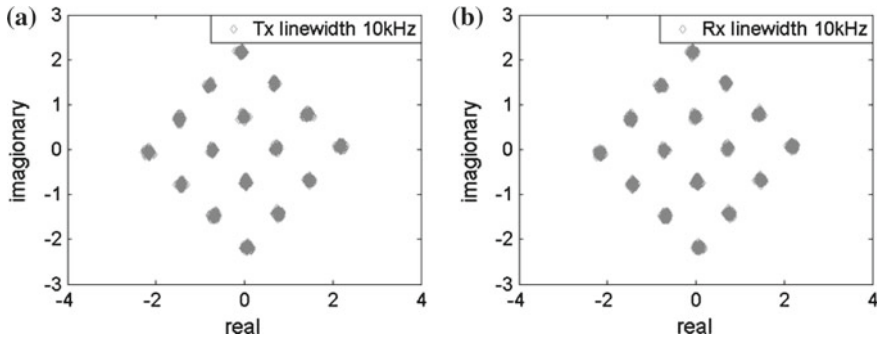| Tx laser linewidth	Rx laser linewidth				
	10 kHz	100 kHz	1 MHz	10 MHz	100 MHz
10 kHz	0.0367	0.039	0.0574	0.1444	0.3247
100 kHz	0.0391	0.0413	0.0589	0.1451	0.3232
1 MHz	0.0573	0.0589	0.0724	0.1513	0.3245
10 MHz	0.1442	0.1449	0.151	0.1993	0.3294
100 MHz	0.3207	0.3213	0.3192	0.329	0.3608

Fig. 1.6 Received constellations if **a** the transmitter laser linewidth is 10 kHz and the receiver side laser linewidth is 100 kHz. **b** The transmitter laser linewidth is 100 kHz and the receiver side laser linewidth is 10 kHz
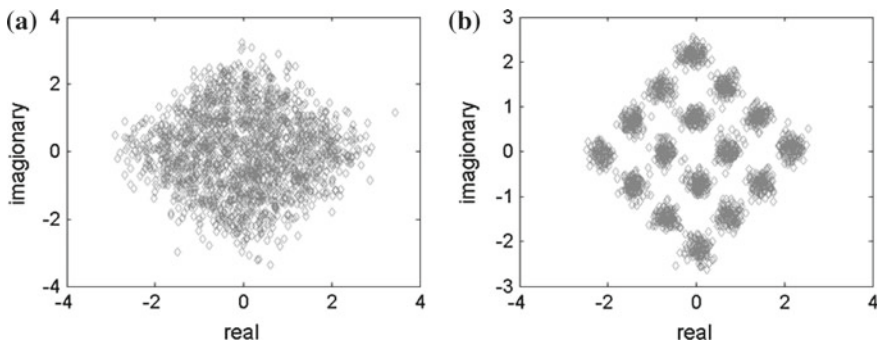

Fig. 1.7 a Received constellations if the lasers have larger linewidth than 10 MHz. **b** The constellation diagram if the transmitter laser linewidth is 10 kHz and the receiver side laser linewidth is 10 MHz

Fig. 1.7a shows. The critical laser linewidth is 10 MHz. It highly increases the deviation as it can be observed in Fig. 1.7b. The transmitter laser linewidth is only 10 kHz, but the large (10 MHz) linewidth of the down converting laser spreads the constellation points. If both lasers have 10 MHz linewidth the detected constellation is similar to the Fig. 1.10b. The simulation results show that the laser phase noise spreads the points of the constellation.

1.3.3 Dispersions of the Fiber

Signal shape mainly degrades by the fiber dispersion. Chromatic dispersion is the significant effect in SMF. It rotates the constellation and spreads the symbols (Fig. 1.8a). Constellation of the received signal will be a circle because of the
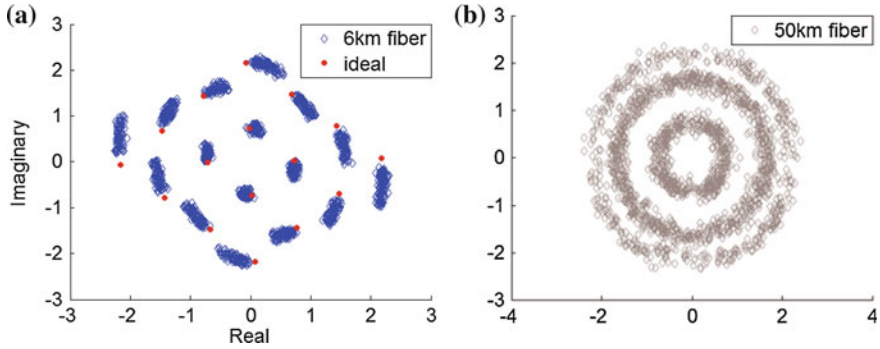
Fig. 1.8 **a** Dispersion spreads the symbols and rotates the constellation. **b** Constellation diagram after 50 km fiber, if dispersion is not compensated

dispersion (Fig. 1.8b). CD has much stronger effect on the transmitted signal than the MZM. 6 km fiber rotates the constellation with angle of 8°. It is twice larger than the rotation caused by differential driving of the MZM. Chromatic dispersion can be compensated by DSP or DCF. Doing it by DSP is much more comfortable because it can be done electronically besides doing other signal processing steps. Using of pilot tones this rotation can be calculated and the correction also can be done.

Polarization mode dispersion becomes critical at high speed. To show its effect the CD has to be negligible because CD has much stronger effect than PMD. Therefore in the simulation any other fiber nonlinearity was turn out except the PMD. Polarization mode dispersion comes from the different propagation time between the two polarization states. Because of it, we examined the PMD effect as the function of the polarization of the laser beams (transmitter and receiver). The usual lasers emit unpolarized beams so the emitted light contains both polarization components. In the simulations the unpolarized laser beams contained the same energy in the two polarization states. If the laser is polarized e.g. at 0° then only the X polarization plane contains energy in the laser beam. The unpolarized laser beam is the worst case in the aspect of the PMD. To simulate this case the degree of the laser polarization was set to 45°. Different fiber lengths (from 1 to 10,000 km) are investigated in the simulations. The PMD coefficient of the fiber is set to 2 and 0.1 ps/km$^{1/2}$ because these are the typical coefficient value for an old and a new fiber, respectively. The received constellation does not change significantly for 500 km as Fig. 1.9a shows. The size of the constellation does not change, however its standard deviation is increased (Table 1.3). The points of the constellation go to the centre and they rotate inverse clockwise as the fiber length was increased up to 10,000 km. Therefore some decision ranges overlap each other (Fig. 1.9).

PMD caused distortion should be smaller if polarized lasers are used, because in that case there is only one polarization in the fiber. However, the polarization state of the fiber changes randomly, so at the end of the fiber both polarizations will contain some signal components. The PMD caused polarization changes can result in 90°
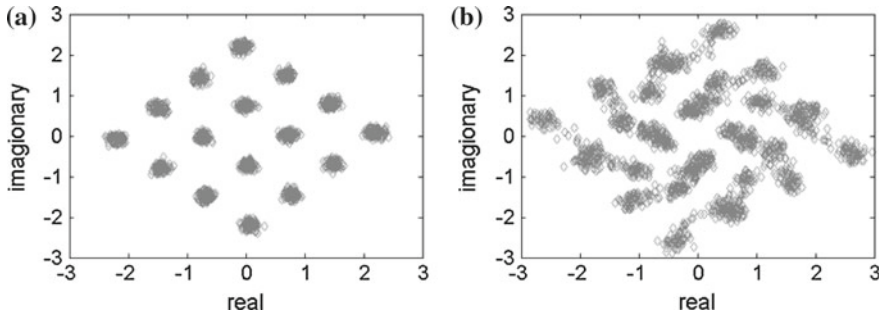
Fig. 1.9 Received constellations if the PMD coefficient is 0.1 ps/km$^{1/2}$. The lasers are unpolarized and the fiber length is **a** 500 km, and **b** 10,000 km

Table 1.3 Standard deviation of the constellation if the fiber PMD coefficient is 0.1 ps/km$^{1/2}$

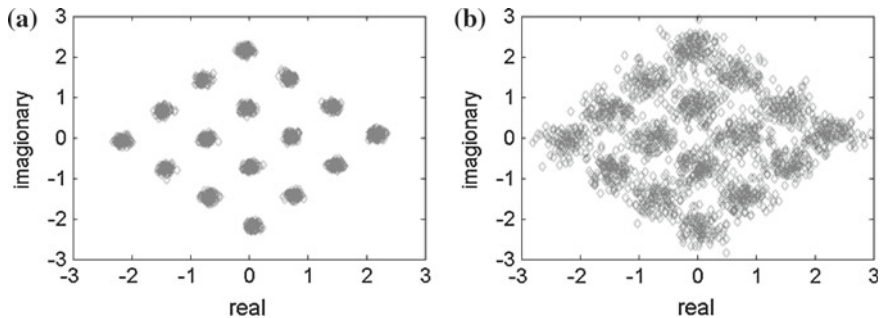| Fiber length (km)	Transmitter/receiver laser polarization (°)			
	45/45	0/0	0/45	45/0
1	0.068	0.065	0.0521	0.1166
5	0.0566	0.0611	0.0539	0.1356
10	0.0671	0.2229	0.0765	0.0679
50	0.0551	0.0674	0.0542	0.716
100	0.0641	0.1085	0.1177	0.0778
500	0.0696	0.0782	0.1987	0.165
1000	0.1191	0.1059	0.3999	0.0708
5000	0.0951	0.1099	0.0793	0.0757

Fig. 1.10 Received constellations if the PMD coefficient is 0.1 ps/km$^{1/2}$. The lasers are polarized (0°) and the fiber length is **a** 5 km and **b** 10 km

polarization differences between the transmitter and the receiver signals. In that case the two signals are orthogonal to each other and the receiver cannot demodulate the received signal. Figure 1.10 shows the PMD caused signal distortion if the lasers are polarized at 0°. The detected constellation does not have any significant distortion

(Fig. 1.10a) if the fiber length is 5 km or 50 km. But the points spread largely if the distance is 10 km (Fig. 1.10b), because the polarization state of the received signal and the receiver laser is near to 90°. At this length the uncertainty of the decision is very high. The centre of the constellation points can be determined but the large spread increases the probability of wrong decision. The standard deviation of the constellations is not better than the deviation of the unpolarized system (Table 1.3). It is due to the polarization sensitivity of the detection method. At the receiver another laser is used to demodulate the signal which converted it down it to a lower frequency. If the polarization of the signals is orthogonal to each other only noise is detected by the analyzer. This polarization sensitivity is higher than in the case when the PMD caused smaller distortion on a polarized light.

In the previous simulations the PMD coefficient was set to 0.1 ps/km$^{1/2}$, which is close to the coefficient of the new fibers. However, most telecommunication fibers are older than 10 years, so their PMD coefficient is about 2 ps/km$^{1/2}$. Because of that, the simulations are repeated and this higher PMD value is set in the fiber parameters. Distortion can be observed on the constellation in case of a 5 km fiber length. Figure 1.11 shows the distorted constellation at 50 km fiber length. The points are spread and it looks like they are on a circle. This behavior is similar to the chromatic dispersion caused distortion. However, most of the constellation points split into two distinct parts. Chromatic dispersion caused distortion does not make this separation. It spreads the points into a circle (Fig. 1.8b). PMD caused distortion for longer fibers are similar to the case of the low PMD coefficient fiber. The points of the constellation move to the centre and are rotated. Using polarized (0°) light the effect of the PMD is similar to the case of the lower PMD coefficient. The polarization mismatch at the receiver increases the deviation of the constellation (Table 1.4).

PMD has smaller effect on the signal if the light is polarized, but our detection method cannot profit from this benefit if both lasers have the same polarization. There is a chance to improve the PMD insensitivity if polarization requirement of the fiber and the receiver is used at the same time. Therefore, the transmitter laser was polarized at 0° because PMD has smaller effect to a polarized light. To avoid the signal degradation from the polarization mismatch an unpolarized laser is used in the receiver. In the simulation the lower PMD coefficient is applied. This mixed polarization offers a better signal quality for short (less than 10 km) fiber length

Fig. 1.11 Received constellations if the PMD coefficient is 2 ps/km$^{1/2}$, the lasers are unpolarized and the fiber length is 50 km
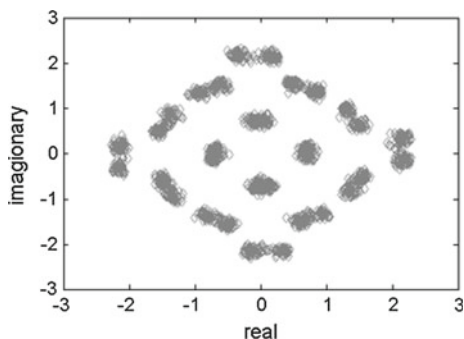
Table 1.4 Standard deviation of the constellation if the fiber PMD coefficient is 2 ps/km$^{1/2}$

Fiber length (km)	Transmitter/receiver laser polarization (°)			
	45/45	0/0	0/45	45/0
1	0.0771	0.0822	0.0652	0.1573
5	0.1046	0.15	0.0665	0.231
10	0.1362	0.3212	0.1675	0.1463
50	0.1289	0.1649	0.0603	0.1663
100	0.1829	0.2627	0.2837	0.209
500	0.2556	0.2544	0.4753	0.4274

than the unpolarized lasers (Table 1.3). Between 10 and 100 km the constellation is quite similar to the results of the unpolarized lasers (Fig. 1.12). However, the standard deviation of the constellation is increased significantly if the fiber length is longer than 500 km. The mixed polarization can reduce the PMD effect at short ranges. The laser polarization can be reversed but it will result in a worse signal transmission. Because the transmitter is unpolarized the PMD has higher effect on the signal which results in a larger standard deviation (Table 1.3). The unpolarized signal transmission provides better signal transmission at all examined fiber lengths than the mixed polarization. Although the standard deviation of the constellation is increased but moving of the constellation is eliminated. Similar results can be observed if the higher PMD coefficient fiber is used in the simulations. Only the length of the transmission is shortened. The maximum fiber length is 50 km then the points of the constellation are overlapped.

1.3.4 Fiber Nonlinearity

Four wave mixing (FWM) and self-phase modulation (SPM) make smaller signal degradation than CD or PMD. They appear, if the power density in the fiber is
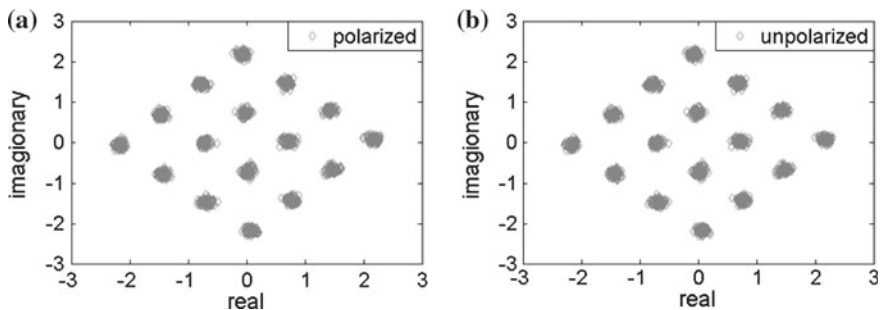

Fig. 1.12 Received constellations if the PMD coefficient is 0.1 ps/km$^{1/2}$, and the fiber length is 50 km. **a** Transmitter laser is polarized and the laser at the receiver side is unpolarized. **b** Both lasers are unpolarized
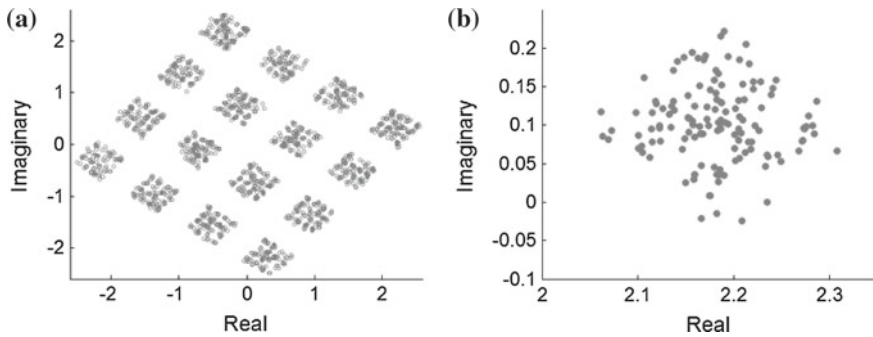
Fig. 1.13 a Symbol deviation caused by SPM and FWM. **b** Only FWM caused symbol spread at one point of the constellation

above 1 W. The dispersion of the fiber is set to zero to examine only the effect of nonlinearity. Laser power is 20 W and fiber length is 50 km. Increasing the laser power will not improve the quality of transmission. Noise level increases outside of the OFDM spectrum because of FWM. Constellation symbols highly spread and it seems they contain the full constellation diagram in small size (Fig. 1.13a). This kind of modulation mainly comes from the SPM and in smaller extent from the FWM. Decreasing the laser power the SPM effect will be negligible and FWM will be dominant. FWM causes ICI and it spreads the symbols along both axes (Fig. 1.13b). It is similar to the effect of white noise. Standard deviation is 0.0472 which is twice as much as that one caused by the MZM.

1.4   Conclusions

In this paper we showed the major distortion effect on the transmitted signal. Chromatic dispersion has the strongest signal degradation effect among the investigated distortions. However, it can be compensated, the easiest way is using DCF. A more compact CD compensation solution is made by DSP. CD caused distortion will not play an important role in optical OFDM systems because its value can be fully controlled.

Distortion of the MZM is similar to the CD caused one. It rotates the constellation and the symbol distances depend on the bias point of the MZM. The rotation caused by MZM can be easily eliminated by differential driving. It minimizes the rotation but the standard deviation of symbols is increased slightly. If the electrical field of MZM provides opposite rotation this effect does not exist and the rotation stays small. The nonlinearity of the modulator also can be compensated by DSP, but this solution requires plus equipment, which increases the price. Laser phase noise increases the standard deviation of the constellation diagram. In our system two lasers are applied and they show symmetry in the phase noise investigation.

The standard deviation of the constellation diagram is independent from the place of the narrow linewidth laser. It is the same if the narrow linewidth laser is put into the transmitter or it is placed at the receiver side. Using a narrow linewidth laser at either side of the system the phase noise caused distortion can be significantly decreased.

PMD not only spreads the constellation points but it rotates them and in some cases it splits the points into two pieces. The use of low PMD coefficient fiber is the most efficient way to decrease the PMD effect. However, to replace all fibers with a new low PMD coefficient one is extremely expensive. Using polarized light smaller PMD caused signal distortion can be achieved, but the applied detection method is sensitive for the polarization state. It is pointed out that using polarized light a higher distortion is obtained because of the polarization sensitivity of the detecting method. The golden way between the polarization sensitivity and the PMD effect is the mixed polarization. Transmitter laser is polarized to decrease the PMD effect while at the receiver side an unpolarized laser is used to minimize the polarization sensitivity of the receiver. This gives better results compared to the case when both lasers are unpolarized. However, using only polarized lasers a major drawback is encountered. If the polarization of the transmitter laser is orthogonal to the laser polarization at the receiver, no signal detection will occur. Only the noise will be detected. The chance of this orthogonality is small but we showed it can cause high signal degradation independently of the fiber length. As both polarizations are used to decrease the PMD it will make difficulties in the future when the signal transmission is multiplexed in polarization too.

Other nonlinearities of SMF (e.g. four wave mixing, self phase modulation) cause smaller distortion and they are covered by the distortion effect of MZM nonlinearity, CD or PMD. We usually use low laser power so only FWM will influence the transmission.

Most of the examined distortion can be compensated without any plus equipment. CD is one of the exceptions which needs plus hardware to eliminate its distortion. It is beneficial to do post CD compensation by DSP, because then DSP can be used to compensate the other distortions effect. There is a question; is it worth to do everything with a DSP or it is better to apply proper MZM driving technique (e.g. differential driving) or using small linewidth lasers.

References

1. W. Shieh, OFDM for flexible high-speed optical networks, J. Lightwave Technol., **29**(10) (2011)
2. W. Shieh, H. Bao, Y. Tang, Coherent optical OFDM: theory and design, Opt. Exp. **16**(2) (2008)
3. W. Shieh, I. Djordjevic, *Orthogonal frequency division multiplexing for optical communication* (Academic Press, London, 2010)
4. B. Collings, F. Heismann, G. Lietaert, *Reference guide to fiber optic testing*, **2**, JDSU (2010)
5. S. Ten, M. Edwards, *An introduction to the fundamentals of PMD in fibers*, WP5051, Corning Incorporated (2006)

6. F. Heismann, *Polarization mode dispersion: fundamentals and impact on optical communi-cation systems*, ECOC (1998)
7. J. Armstrong, OFDM for optical communications, J. Lightwave Technol. **27**(3) (2009)
8. H. Louchet, A. Richter, *Novel scheme for high bit-rate coherent OFDM transmission without PLL*, ECOC (2007)