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Phase And Amplitude Modulated Ofdm For Dispersion Managed Wdm Systems

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PHASE AND AMPLITUDE MODULATED OFDM
FOR DISPERSION MANAGED WDM SYSTEMS

by

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ABSTRACT

Amplitude and phase modulated optical OFDM (Orthogonal Frequency Division Multiplexing) are analyzed in a 50GBit/s single channel and 40GBit/s 5 channel 512 subcarrier non-ideal dispersion-compensated fiber optic communication systems. PM-OFDM is investigated as an alternative to AM-OFDM to alleviate the problem associated with amplitude-modulated signals in a nonlinear medium.

The inherent dispersion compensation capability in OFDM (using a cyclic prefix) allows transmission over a link whose dispersion map is not exactly known. OFDM also mitigates the effects of dispersion slope in wavelength-division multiplexed (WDM) systems. Moreover, the overall dispersion throughout the transmission link may vary due to environmental effects and aging. OFDM is inherently tolerant to over- or under-compensation and dispersion slope mismatch.

OFDM transmission over dispersive, non-dispersion managed fiber links using OFDM requires an overhead in excess of the maximum accumulated dispersion. Existing WDM systems usually employ periodic dispersion management. OFDM in these systems requires a smaller overhead. It is, however, more susceptible to nonlinearity due to the coherent beating of subcarriers after each dispersion-compensated span.

The large variation in intensity associated with amplitude-modulated OFDM makes this modulation format more susceptible to nonlinear effects in fiber compared to phase-

modulated signals. This holds true unless dispersion and EDFA noise lead to amplitude variations strong enough for PM-OFDM to be degraded by nonlinear effects as well.

In conclusion OFDM is beneficial for non-ideal dispersion managed systems. PM-OFDM can further improve the performance.

ACKNOWLEDGMENTS

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LIST OF ACRONYMS/ABBREVIATIONS

ADC , A/D	Analog to Digital Converter
ASE	Amplified Spontaneous Emission
DAC, D/A	Digital to Analog Converter
DCF	Dispersion Compensating Fiber
DD	Direct Detection
DFT	Discrete Fourier Transform
DI	Delay Interferometer
DSF	Dispersion Shifted Fiber
DSL	Digital Subscriber Line
DSP	Digital Signal Processor
EDFA	Erbium Doped Fiber Amplifier
FFT	Fast Fourier Transform
FM	Frequency Modulation
FWM	Four Wave Mixing
ICI	Inter Carrier Interference

IFFT	Inverse Fast Fourier Transform
ISI	Inter Symbol Interference
NZ-DSF	Non-Zero Dispersion Shifted Fiber
OOK	On-Off-Keying
OFDM	Orthogonal Frequency Division Multiplexing
PAPR	Peak-to-Average-Power-Ratio
PM	Phase Modulation
PMD	Polarization Mode Dispersion
PRBS	Pseudo-Random Bit Sequence
QAM	Quadrature Amplitude Modulation
QPSK	Quaternary Phase Shift Keying
RF	Radio Frequency
SNR	Signal to Noise Ratio
SPM	Self Phase Modulation
SSB	Single Side Band

SSMF	Standard Single Mode Fiber
VPI	Simulation Software VPItransmissionMaker 7.6
WDM	Wavelength Division Multiplexing
XPM	Cross Phase Modulation

CHAPTER ONE: INTRODUCTION

Orthogonal Frequency Division Multiplexing has been largely employed in the radio frequency domain. In wireless networks (e.g. Wifi 802.11a/g, WiMAX 802.16), digital audio and video broadcasting (DAB, DVB-T) as well as wired communications (DSL), OFDM has been widely adopted [1, 2]. It is robust against impairments such as multi-path and frequency selective fading under changing conditions as is the case in wireless communication systems.

Over the past couple of years there has been increased interest in using the benefits OFDM offers for optical communication systems [3, 4].

1.1 Motivation

Coming from wireless communications, OFDM has the capability to compensate for unknown or fluctuating dispersion in optical fiber. The maximum amount of dispersion that can be compensated for is determined by the cyclic prefix. Any amount of dispersion lower than the maximum can be compensated without feedback or adjustment. This presents an advantage with respect to current technology and may allow for development of commercial off-the-shelf components to be deployed in a variety of fiber optic communication links.

Because WDM systems occupy a broad spectrum the dispersion may be different for distant channels due to the dispersion slope. OFDM inherently compensates for dispersion slope mismatch. Employing OFDM the design requirements in an optical communications link can be relaxed, resulting in a reduction of cost.

OFDM is a multicarrier modulation technique. The superposition of many amplitude modulated carriers results in high peak-to-average power variations. PM-OFDM is investigated as an alternative to AM-OFDM to alleviate the problem associated with amplitude-modulated signals in fiber as a nonlinear medium.

1.2 Organization of thesis

Chapter two gives an overview of the theoretical background of fiber-optic communication. Basic modulation formats are explained including their spectral representation. Dispersion and nonlinearity, mayor impairments in fiber optic communication systems, are described as (PM-) OFDM alleviates some of the problems they cause.

Chapter three covers various theoretical aspects of OFDM. The basics of OFDM are explained in detail.

Chapter four describes the experimental setup. The technical feasibility of phase modulated OFDM is demonstrated experimentally.

Chapter five presents simulations of phase- and amplitude-modulated OFDM for both single channel and WDM transmission at higher bitrates.

Chapter six concludes this thesis with a summery and an outlook to prospective future research.

CHAPTER TWO: THEORETICAL BACKGROUND

Information is transmitted via electromagnetic waves in a variety of applications such as TV broadcasting, DSL, wireless LAN or fiber optic communication networks. An electromagnetic wave can be described as

$$E_c(t) = A_c\, cos(2\Pi f_c t + \varphi_c) = A_c\, cos(\omega_c t + \varphi_c), \qquad (1)$$

where A_c is the carrier amplitude, f_c the frequency and φ_c the phase. The state of polarization is not considered in this thesis. In order to transmit information one single or a combination of these parameters can be manipulated at the transmitter. The manipulation is detected at the receiver to restore the information. This chapter briefly shows the effect of those manipulations and gives a short overview about impairments in optical fiber transmission.

2.1 Amplitude Modulation

In amplitude modulation the amplitude is changed according to the information signal m(t). In the case of binary modulation with signal levels '1' and '0' this is called On-Off-Keying (OOK). Information is encoded on the presence or absence of a carrier wave (Fig. 1 a,b,c).

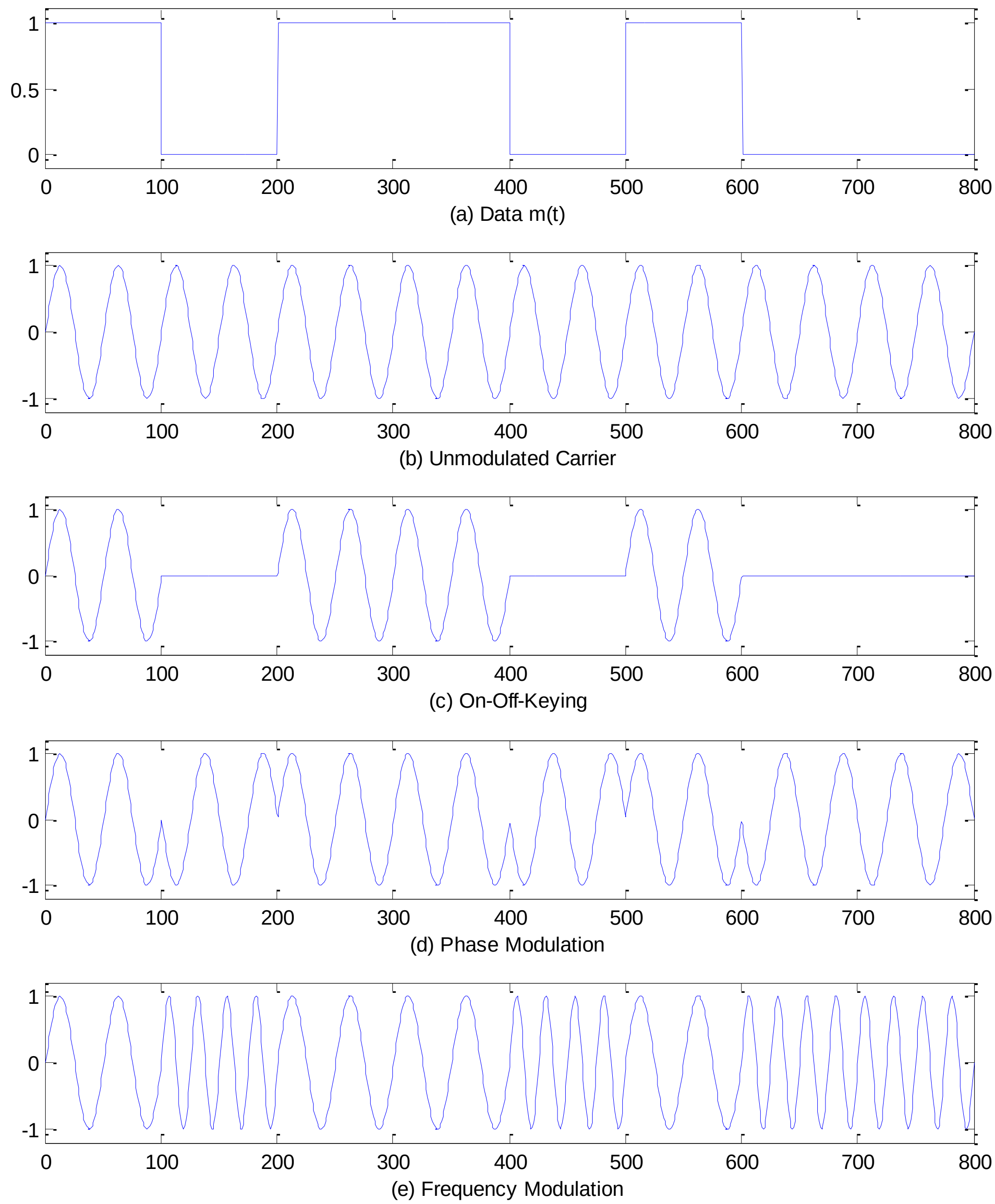

Fig. 1 Overview of basic modulation formats

2.2 Angle Modulation

Manipulation of carrier frequency f_c (FM) or phase φ_c(PM) both change the angle of the cosine in Eq. (1) and are thus referred to as angle modulation. The amplitude and thus the intensity stay constant. Fig. 1 (a) shows a binary information signal m(t) with signal levels ‘0’ and ‘1’ with possible (d) PM and (e) FM signal representation. A more detailed description can be found in [5].

For better spectral efficiency higher order modulation formats can be used that encode more than one bit per information symbol. Fig. 2 depicts the constellation diagram of Quadrature Phase-Shift Keying (QPSK) modulation. Instead of modulating the phase between 0 and π as shown in Fig. 1 (d), four phase states per symbol are used to encode two information bits each. The resulting waveform is shown in Fig. 3. QPSK is used in the following experiments and simulations, however OFDM experiments using higher-order formats like 16-QAM have been demonstrated [3, 6, 7].

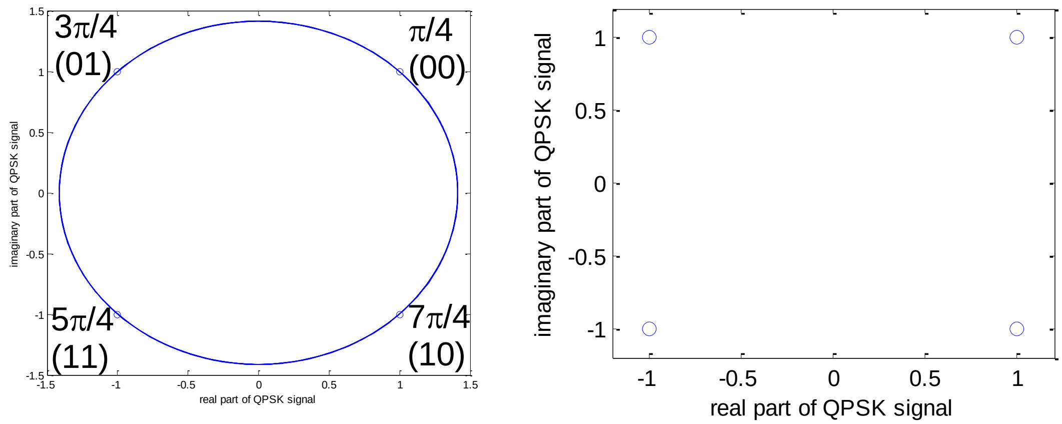

Fig. 2 Constellation Diagram QPSK

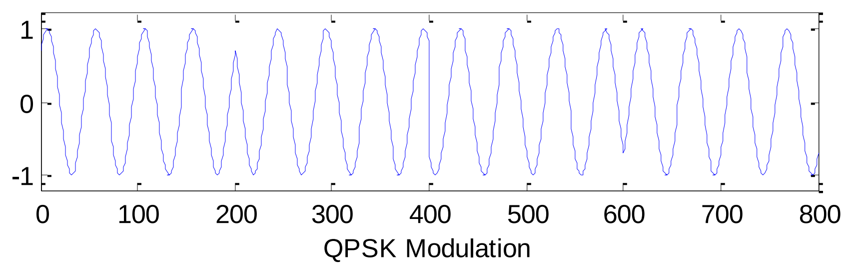

Fig. 3 QPSK Modulation

2.3 Spectra

To describe the spectra of amplitude and phase modulated signals, the spectrum of a sinusoidal information signal $m(t) = \mathrm{A_m} \sin(2\Pi f_m + \varphi_m) = \mathrm{A_m} \sin(\omega_m t + \varphi_m)$ is considered as more complex information signals can be composed of a superposition of sinusoids [8].

2.3.1 Amplitude Modulation Spectrum

Using Eq. (1) and a phase offset of $\varphi_c = -\frac{\Pi}{2}$ the amplitude modulated carrier is

$$E(t) = m(t)\, E_c(t) = \mathrm{A_m} \sin(\omega_m t + \varphi_m)\, A_c sin(\omega_c t) \tag{2}$$

Setting $A_m = A_c = 1$, $\varphi_m = 0$ and using $\sin(a+b) = \frac{1}{2}\cos(a+b) - \frac{1}{2}\cos(a-b)$ gives:

$$E(t) = \frac{1}{2}\cos([\omega_c + \omega_m]t) - \frac{1}{2}\cos([\omega_c - \omega_m]t) \tag{3}$$

Taking the Fourier transform results in two discrete Dirac pulses symmetrically spaced at $\pm\omega_m$ from ω_c, shown in Fig. 4.

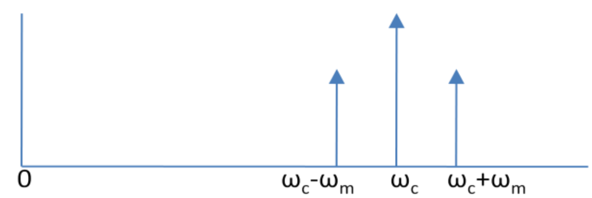

Fig. 4 Spectrum of Amplitude Modulation

The bandwidth B of a sinusoidal AM signal is twice the highest modulation frequency f_m. However the information in both sidebands is redundant. For higher spectral efficiency the signal can be band-pass filtered so that, e.g., only the upper sideband is transmitted [9].

2.3.2 Phase Modulation Spectrum

The spectrum of angle modulated signals is more complex; “even for simple signals […] mathematically intractable” as Proakis and Salehi describe it in [5]. In fact even for a sinusoidal modulation signal the bandwidth of the modulated signal is infinite as shown below [5].

Using Eq. (1) and a phase offset of $\varphi_c(t) = m(t)$, $\varphi_m = 0$ the angle modulated carrier is

$$E(t) = \mathrm{A_c}\cos\left(2\Pi f_c t + A_m sin(2\Pi f_m t)\right) = Re(\mathrm{A_c}\mathrm{e}^{\mathrm{j}2\Pi f_c t}\, e^{j\,A_m sin\,(2\Pi f_m\, t)}) \qquad (4)$$

The term $e^{j\,A_m sin\,(2\Pi f_m\, t)}$ can be expanded in a Fourier series described with Bessel functions and Eq. (4) becomes

$$E(t) = \sum_{n=-\infty}^{\infty} A_c\, J_n(A_m)\cos(2\Pi(f_c + nf_m)t) \qquad (5)$$

The n-dependent cosine terms shows that the signal bandwidth is infinite. However most of the signal energy is contained in the first few harmonics. Therefore the signal may be band-pass filtered especially in WDM systems to prevent spectral overlap and to allow for multiplexing.

2.4 Dispersion and Dispersion Compensation

The speed of light in optical fiber is wavelength dependent. The dispersion parameter D of the fiber is the derivative of the group delay with respect to wavelength, whereas the group delay is the time for a pulse of energy to travel a unit distance [10].

$$D = \frac{d}{d\lambda}\frac{1}{v_g} = \frac{d^2\beta}{d\lambda\; d\omega} \approx -\frac{2\Pi c}{\lambda^2}\beta_2, \qquad (6)$$

where β is the propagation constant, c the speed of light and β_2 the chromatic dispersion parameter. A typical value for Standard Single Mode Fiber (SSMF) is $D \approx 16\frac{ps}{nm\;km}$ which will be employed in the simulations in chapter 5. The high frequency components, the ‘blue part’, of a pulse travel faster than the low frequency, ‘red part’, leading to broadening of a pulse.

Dispersion itself is wavelength dependent, described by the dispersion slope $\frac{dD}{d\lambda} \approx 0.08 \frac{ps}{nm^2\ km}$ for SSMF. This becomes important for broadband communication systems i.e. WDM systems (chapter 5.2).

Dispersion can limit transmission distance and/or bit rate because broadened neighboring pulses start leaking into one another. Among others, there are the following methods to compensate dispersion.

2.4.1 Fiber with low dispersion parameter

Dispersion Shifted Fiber (DSF) and Non-Zero Dispersion Shifted Fiber (NZ-DSF) have a dispersion parameter of $D \approx 0 \frac{ps}{nm\ km}$ and $D \approx 4 \frac{ps}{nm\ km}$ respectively. However a certain amount of dispersion is beneficial in terms of nonlinearity (see chapter 2.5) as will be shown in simulation (chapter 5, Fig. 45).

2.4.2 Dispersion managed links

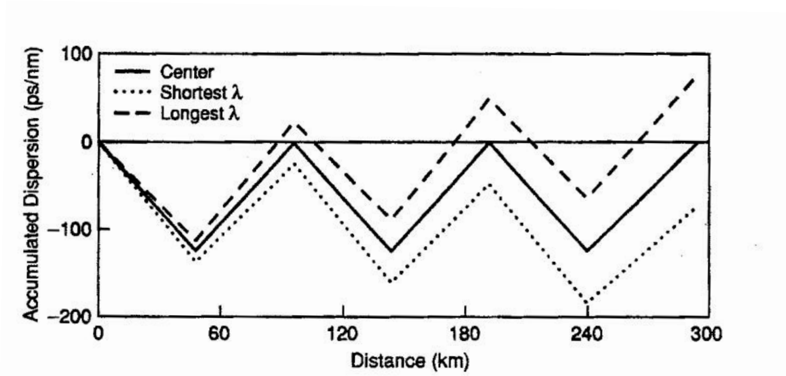

Fig. 5 Dispersion managed link with non-perfect compensation besides center frequency [11]

As shown in Fig. 5 (solid line) each section of fiber is followed by fiber with a total dispersion of equal magnitude but opposite sign. The length of the fiber sections is adjusted such that the net effect of dispersion cancels out. E.g. SSMF is followed by Dispersion Compensating Fiber (DCF) having a roughly five times higher dispersion parameter of opposite sign.

Note that dispersion slope comes into play for WDM systems. The net dispersion is zero for one specific wavelength. However the dispersion slope may not match perfectly. As a result WDM channels suffer from residual dispersion that has to be compensated for as shown with the dotted and dashed lines for shorter or longer wavelengths respectively. OFDM is a solution as will be shown later on.

2.4.3 Electronic dispersion compensation [4]

a) Electronic Pre-Distortion (EPD)

   The pulses to be transmitted are manipulated at the transmitter to a pulse-shape they would have had after propagating in dispersion compensating fiber. This requires a more complex transmitter that can introduce a frequency chirp [10]. To compensate for fluctuations in the transmission path feedback is needed.

b) Electronic Post-Compensation (EPC)

   The entire distorted field is detected at the receiver and processed in a digital signal processor (DSP). The DSP does a virtual back propagation with impairments of opposite sign. This method is not limited to dispersion but can also take nonlinear effects [chapter 2.5] into account. It can be realized e.g. using the split-step Fourier method [12] and demonstrated both with simulations and experimentally [13].

c) Coding / Modulation Format

   The signal is transmitted with symbols that are not affected by dispersion or to be more exact the part of the symbol affected by dispersion is redundant. OFDM falls into this category and will be described in more detail in chapter 3.

The effect of polarization-mode dispersions (PMD), a polarization dependent dispersive effect due to random imperfections in fiber, is not considered in this thesis.

2.5 Nonlinearity

Light propagating long distances in optical fiber is influenced by the nonlinear properties of the fiber. Scattering effects manifest simplified an intensity dependent gain or loss [10]. Effects caused by the intensity dependent refractive index are briefly described below.

$$n(I) = n_0 + n_2 \cdot I \tag{7}$$

, where $n_0$is the constant part of the refractive index and $n_2(I)$ the intensity dependent part because of third order susceptibility of the material [14].

Impairments due to mixing of (sub-)carriers are present in the system in chapter 5 and will further degrade performance but are not analyzed theoretically in depth.

2.5.1 Self Phase Modulation (SPM)

The variation of the refractive index with intensity (Equ. 7) produces a phase shift of the optical pulses, which in turn changes the spectrum. A modulation format of constant intensity should not suffer from this effect.

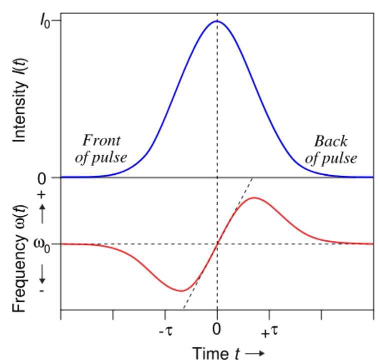

Fig. 6 Self frequency shift due to SPM in nonlinear medium [15]

SPM interacts with dispersion. In the regime of anomalous dispersion, the leading edge of the pulse is blue-shifted. Fig. 6 shows that the leading edge for a Gaussian pulse is red-shifted. SPM can in fact be beneficial as the result when those two effects balance is a soliton, a pulse that does not change shape or broaden during transmission.

In multichannel or wavelength division multiplexed (WDM) systems the interaction between different channels is described by Cross Phase Modulation (2.5.2) and Four Wave Mixing (2.5.3).

2.5.2 Cross Phase Modulation (XPM)

In the case of a WDM systems the intensity is a superposition of all channels propagating in the respective fiber. Thus the refractive index is influenced by all WDM channels.

2.5.3 Four Wave Mixing (FWM)

The interaction of WDM channels can generate a new wave at a difference frequency of the incident waves. If the channels are equally spaced, some of the mixing products coincide with an information carrying WDM channel. The resulting crosstalk between channels deteriorates the respective SNR. A more detailed description can be found in [10, 11]

The effect is strongest when there is no dispersion, as the WDM channels beat coherently. A certain amount of dispersion can thus be beneficial for system performance (Fig. 45).

CHAPTER THREE: INTRODUCTION TO OFDM

This chapter explains why OFDM is inherently capable of compensating for dispersion including dispersion fluctuations and dispersion slope mismatch. It creates the basis for analyzing amplitude- and phase-modulated OFDM.

OFDM has been extensively used in radio frequency systems in both wired (e.g. DSL) and wireless network standards such as 802.11 a/g Wifi, WiMAX, digital audio and video broadcasting (DAB, DVB-T) [2]. Coming from and RF background, this chapter discusses the theory of OFDM and its implementation in optical communication systems.

3.1 General idea

Wireless communication channels suffer from frequency selective fading and effects due to multipath propagation [16]. To combat frequency selective fading, a transmission system should be able to choose only those channels with better transmission characteristics or transmit more information where the channel characteristics are better. Multipath issues can be dealt with a long symbol length. OFDM presents a solution.

Orthogonal Frequency division multiplexing is a multi-carrier modulation scheme. The idea is to divide the spectrum from one channel into many narrow parallel sub channels. Instead of modulating one carrier at a high symbol rate with symbols of short duration that occupy a broad frequency spectrum (Fig. 7, left), the frequency spectrum is divided into sub channels each of which carries information at a lower symbol rate with longer symbol duration (Fig. 7, right). If the bandwidth B_{total} is divided into n OFDM subchannels the bandwidth per subchannel is $B_{subc\,hannel} = \Delta f = \frac{B_{total}}{n}$, the symbol length $t_{OFDM\ symbol} = t_{symbol} * n$.

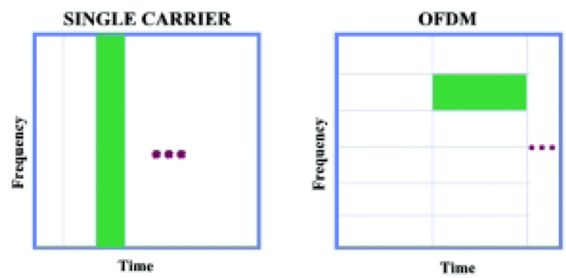

Fig. 7 Comparison of single carrier versus OFDM spectrum [1]

The subcarriers can be adapted to channel characteristics, e.g. using a higher order modulation format on subchannels with a good SNR.

In optical fiber transmission chromatic dispersion and polarization-mode dispersion (PMD) can be compensated using OFDM [2]. A broad spectrum signal is severely affected by dispersion, however dispersion for each narrow-band subchannel is negligible.

3.2 Orthogonality

For high spectral efficiency, the narrow band OFDM subchannels must be closely spaced but must not interfere. This is achieved by orthogonal subchannels. Any two subchannels at a symbol rate $\frac{1}{T} = \Delta f$ with carrier

$$E_{c,k}(t) = \ cos\left(2\Pi f_{c,k} t + \varphi_{c,k}\right) \tag{8}$$

$$k = 0, \dots, n-1, f_{c,k} - f_{c,k-1} = \Delta f$$

must satisfy the condition for mathematical orthognality:

$$\int_0^T cos\left(2\Pi f_{c,k} t + \varphi_{c,k}\right) cos\left(2\Pi f_{c,j} t + \varphi_{c,j}\right) dt = 0 \tag{9}$$

Fig. 8 illustrates orthogonality between subchannels as the peak of any one subcarrier coincides with the zero crossing of any other subcarrier.

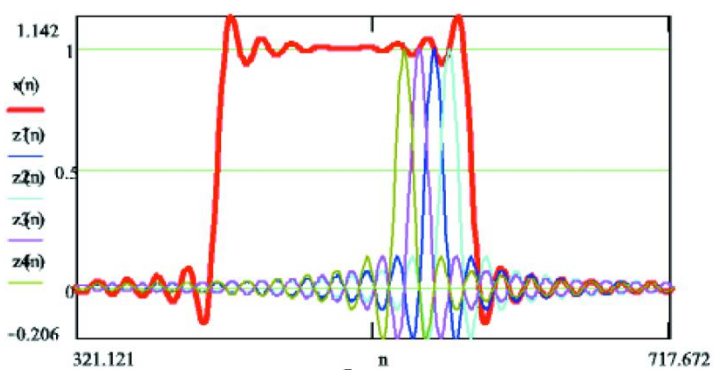

Fig. 8 "Overall spectrum of the simple OFDM signal shown with four subcarriers within. Note that the zero crossings all correspond to peaks of adjacent subcarriers." [1]

Note that the phase offset $\varphi_{c,k/j}$ in (9) does not break orthogonality.

Orthogonality is crucial for the subchannels not to interfere. However orthogonality can easily be broken if the intensity fluctuates during the OFDM symbol period, or if subcarriers are delayed and start leaking into one another. Without countermeasure (chapter 3.3) dispersion can destroy orthogonality as it introduces a delay between OFDM subcarriers.

3.3 Cyclic prefix

Dispersion in optical OFDM is mitigated by introducing a cyclic prefix. The concept is described in more detail in [16] and summarized in [2] from where Fig. 9 is taken.

Fig. 9 a) shows two subsequent OFDM symbols perfectly lined up at the transmitter. DFT window denotes the part of the signal that is used for demodulation in this case by a Discrete Fourier Transform (DFT) method as will be described in section 3.4. For simplicity only two subchannels are considered.

In Fig. 9 b), due to dispersion, the subcarriers reach the receiver with a relative delay t_d. This leads to two major impairments. Firstly Inter Symbol Interference (ISI) because the first symbol is leaking into the observation window of the second by t_d. Thus the symbol frequency content necessary to retrieve information is impaired. Furthermore the system suffers from Inter Channel Interference (ICI) because the subchannels in the observation window are not orthogonal anymore as

$$\int_0^{T_s} cos(2\Pi f_{c,k} t + \varphi_{c,k}) cos(2\Pi f_{c,j} t + \varphi_{c,j}) dt \neq 0. \qquad (10)$$

In the frequency domain this results in frequency components from the ‘slow subcarrier’ overlapping with the ‘fast subcarrier’.

Fig. 9 c) shows two subsequent OFDM symbols with cyclic prefix at the transmitter. The cyclic prefix is an identical, periodic copy of the tail of the OFDM symbol. The length of the observation period is unchanged, thus covers only part of symbol + prefix.

In Fig. 9 d), after transmission, the slow subcarrier is received with a time delay t_d which does leak into the next OFDM symbol with cyclic prefix but does not leak into the observation window. As a result there are no ISI or ICI. Orthogonality is restored as the frequency content in the observation window is unchanged. Note that dispersion introduces a phase shift that does not affect orthogonality (see above Eq. (9)). However tracking this phase shift is important to restore the information i.e. for phase modulated coding schemes such as QPSK. Phase tracking and equalization can be done using pilot symbols [4] .

The shorter the cyclic prefix, the less redundancy is added but it must be at least as long as the maximum delay between the fastest and slowest subchannel.

In conclusion dispersion (including ISI and ICI) is compensated for at the cost of additional overhead.

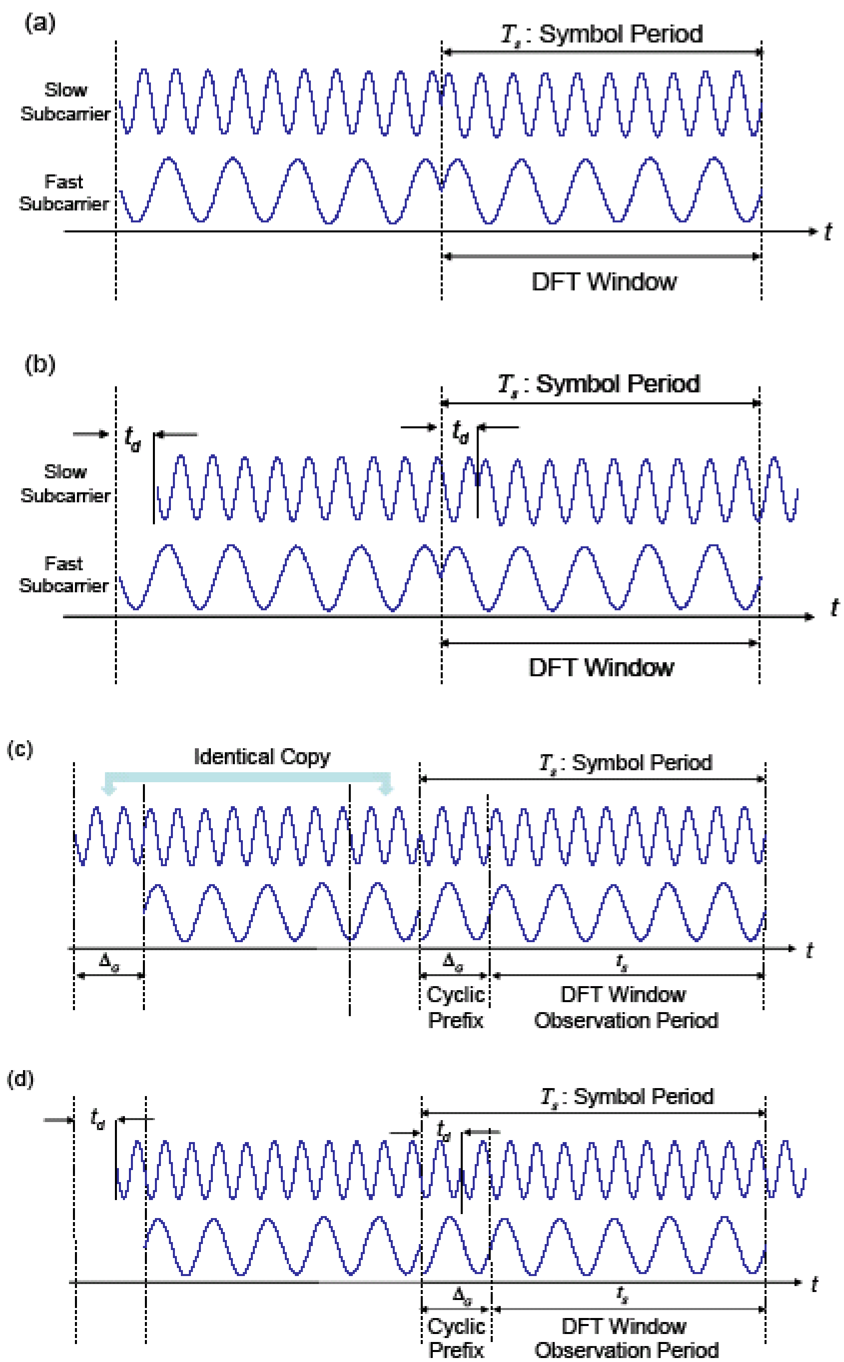

Fig. 9 "The OFDM signals (a) without cyclic prefix at the transmitter, (b) without cyclic prefix at the receiver, (c) with cyclic prefix at the transmitter, and (d) with cyclic prefix at the receiver." [2]

3.4 Transmitter / FFT Implementation

3.4.1 FFT implementation

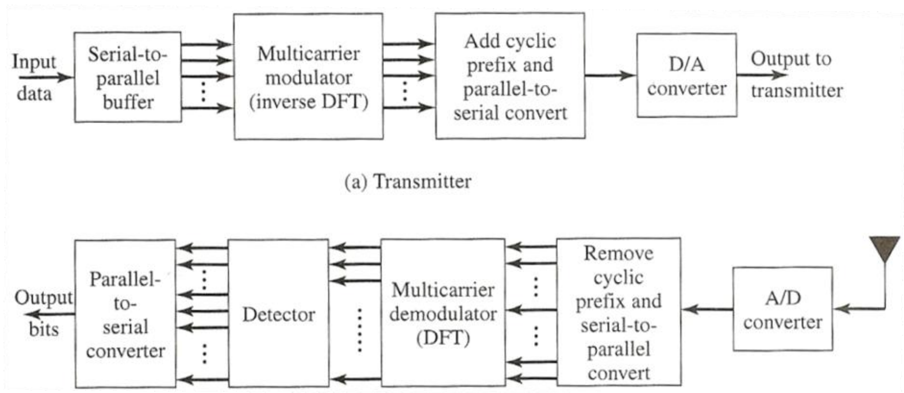

Fig. 10 "Block diagram of a multicarrier OFDM digital communications system" [5]

The OFDM transmitter, see Fig. 10, first converts a serial stream of input data into n parallel bit streams of lower bitrates that will be modulated onto n information carrying OFDM subcarriers. Each of the parallel bit streams is mapped onto subchannel symbols independently, allowing for different modulation formats depending on the subchannel characteristics. For example one subchannel may use 64-QAM and thus have a higher subchannel bit rate than a QPSK modulated subchannel of equal symbol rate. An inverse Fourier transform (IFFT) of this complex frequency-domain representation of the subchannels is applied for transformation into a time domain signal.

The IFFT can be implemented efficiently as a discrete inverse Fourier transform for DSP. Note that current commercially available DSP are not yet fast enough to process bit rates of 40Gbit/s or 100Gbit/s in real time for this application. Therefore signal processing in the experiment (chapter 4) and simulation (chapter 5) is done using offline processing in Matlab. Nevertheless according to [17] current silicon speed can support 40GBit/s OFDM .

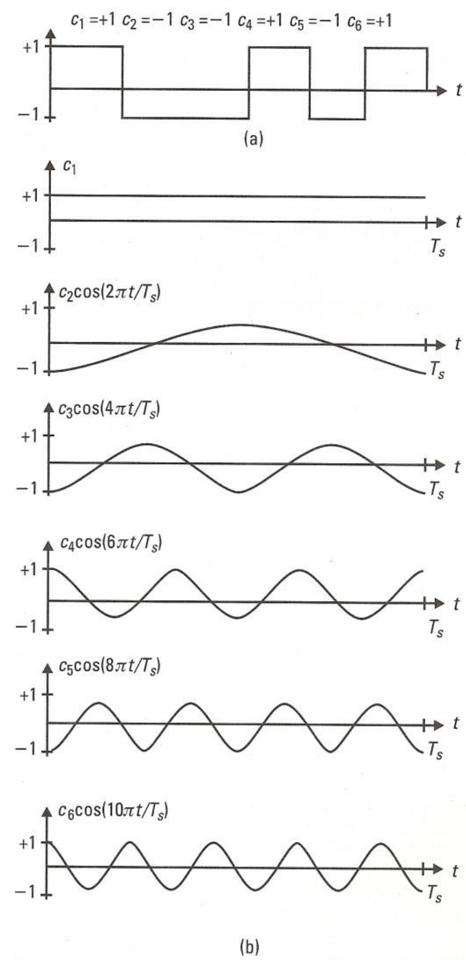

Fig. 11 (a) Binary serial bit stream (b) parallel OFDM subcarrier representation [16]

Fig. 11 shows how a binary serial bit stream is represented on the OFDM subcarriers. The superposition of the subcarriers in Fig. 11 (b) is the OFDM symbol to be transmitted.

After the inverse DFT (Fig. 10), the cyclic prefix (chapter 3.3) is added and the parallel subchannels superimposed. All of the previous signal processing can be done in the digital domain. The resulting signal is fed into a digital to analog converter to generate the analog signal to be transmitted.

Note that the system requirements for the D/A converter are challenging, as it has to satisfy both a broad spectrum and a wide dynamic range. The latter results from the high peak-to-average ratio of the superposition of multiple waves. This issue will be addressed below (3.6) with respect to nonlinear performance.

3.4.2 Single sideband OFDM

In general, the transmitter output is a complex signal requiring detection of both amplitude and phase at the receiver to reconstruct the entire information transmitted.

To allow for a much simpler and thus cheaper receiver that detects either amplitude or phase, a real valued single sideband signal is used. Three approaches are described and analyzed in detail by Schmidt et al. [3] and depicted in Fig. 12.

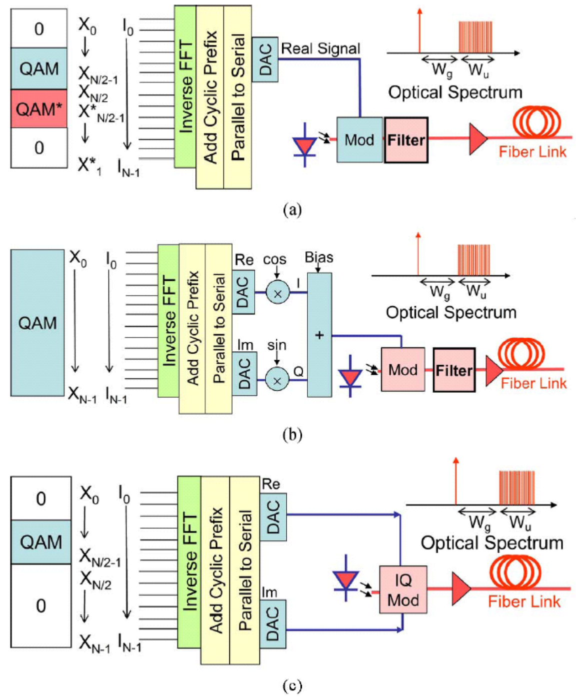

Fig. 12 "OFDM transmitters: (a) using Hermitian symmetry and an optical filter;

(b) using upconversion and an optical filter; (c) using a frequency domain Hilbert transform"

The method of choice in this thesis for both experiment and simulation is a variation of method (b). A baseband OFDM signal is generated in the digital domain. Instead of digital-to-analog converting the signal before it is upconverted with an external RF-source, the frequency shift is done in the digital domain. Undesired additional effects such as additional noise from the RF source are eliminated. Zero padding is another alternative to digital domain RF upconversion [18]. Note that the bandwidth requirements for the Digital-to-analog converters increase and will ultimately limit transmission bandwidth (chapter 4.1).

The real-valued output signal is fed either on an amplitude or phase modulator.

3.5 Receiver

The bottom part of Fig. 10 depicts the structure of an OFDM receiver once the signal is extracted from the optical carrier. The signal is analog-to-digital converted before the cyclic prefix is removed. The resulting serial signal is a superposition of the information carrying OFDM subcarriers. Unlike shown in Fig. 10, the serial-to-parallel conversion and Fourier transform are basically one step as the result of the Fourier transform is the time domain signal represented by its comprising (complex) frequencies. The (QAM) demodulator converts the received subchannel symbols into bits. The parallel bit streams are then fed into a parallel-to-serial converter. Note that the receiver also has to equalize the subchannels as they are affected differently by transmission. For the case of subcarrier dependent attenuation and a dispersion introduced phase shift, only one simple complex multiplication per subchannel is needed for equalization of both phase and amplitude. This is described as “single-tap equalizer” in Fig. 13.

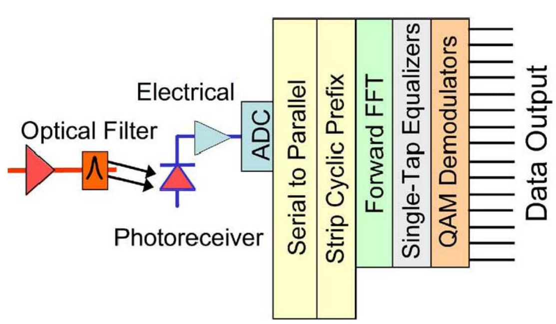

Fig. 13 Direct detection OFDM receiver [3]

a) Direct detection AM receiver

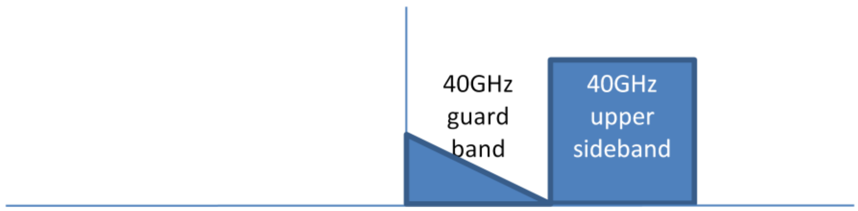

Fig. 14 Schematic of spectrum after direct detection

The direct detection receiver shown in Fig. 13 consists of preamplifier, optical filter and photodiode. The preamplifier assures sufficient power is received that the system is not thermal noise limited but rather ASE noise limited. An optical bandpass filter prevents out-of-band noise to degrade the SNR. The photoreceiver is a photodiode that detects the difference frequency of carrier and signal in baseband. The difference frequencies of the subcarriers are also detected. They are sketched schematically as a triangle in Fig. 14. Therefore a guard interval has to be inserted at the transmitter (Optical spectrum Fig. 12) for these frequencies not to degrade the SNR of the information signal. Note that the transmitted signal can already be filtered at the transmitter for single sideband transmission.

b) Direct detection PM receiver

Fig. 15 Schematic of PM spectrum before detection

Transmitting both sidebands of a PM modulated signal maintains constant amplitude. After filtering, one sideband is suppressed which converts phase modulation into amplitude modulation that can be detected as shown above. The concept is down-converting the signal by beating one sideband with the carrier.

c) Delay interferometer PM receiver

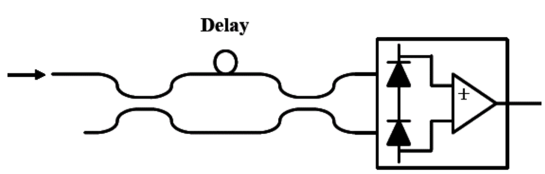

Fig. 16 Schematic of Delay Interferometer and Balanced Receiver

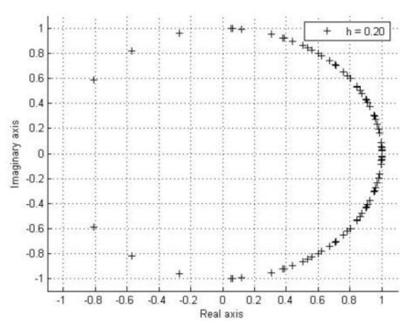

Fig. 17 Phase modulator signal on unit circle [19]

The phase modulated OFDM signal is fed into a delay interferometer for differential detection as shown in Fig. 16. The signal is split into two by a 3dB-coupler. One arm is delayed by Δt before the signals are recombined. The transfer function of a delay interferometer is described by

$$E(t) = A(t)\cos(\Delta\varphi), \tag{11}$$

where $A(t)$ is the amplitude and $\Delta\phi$ the phase difference. Note that the cosine of the phase difference is detected by the receiver. Mathematical post-processing is used to reconstruct the phase difference.

$$\arccos\left[\cos\left(\varphi(t) - \varphi(t + \Delta t)\right)\right] = \Delta\varphi(t) \tag{12}$$

Integrating the differential signal gives the original phase of the OFDM signal.

$$\int \Delta\varphi(\tau)dt = \varphi(t) \tag{13}$$

Note that the detector cannot distinguish whether the output signal is due to a phase difference $\Delta\varphi$ or amplitude fluctuation $A(t)$. In a perfect theoretical system, the amplitude remains constant during transmission. Unfortunately impairments such as EDFA noise also affect the amplitude which is mistaken as a modulation in phase by the receiver.

Fig. 17 shows the distribution of sampling points on a phase diagram of a phase-modulated OFDM channel.

This detection scheme does not require beating with the carrier, thus increasing power efficiency.

d) Coherent detection

Coherent detection and coherent OFDM is an entire field of research and shall only be mentioned here as a side note for completeness. In coherent detection the optical signal is mixed with a local oscillator and both phase and amplitude of a complexly modulated signal can be restored. Besides a local oscillator, this approach requires polarization stabilization and phase estimation at the receiver[17]. Most recent developments relax the immense hardware requirements as "the use of DSP alleviates the need for hardware phase-locking and polarization tracking, which can now be achieved in the digital domain." [20].

3.6 Nonlinear influence on AM- and PM- OFDM

As shown in chapter 2.5 the impact of third order nonlinearities depends on the varying intensity of the signal.

AM- OFDM, as an amplitude-modulated format, inherently exhibits varying intensity.

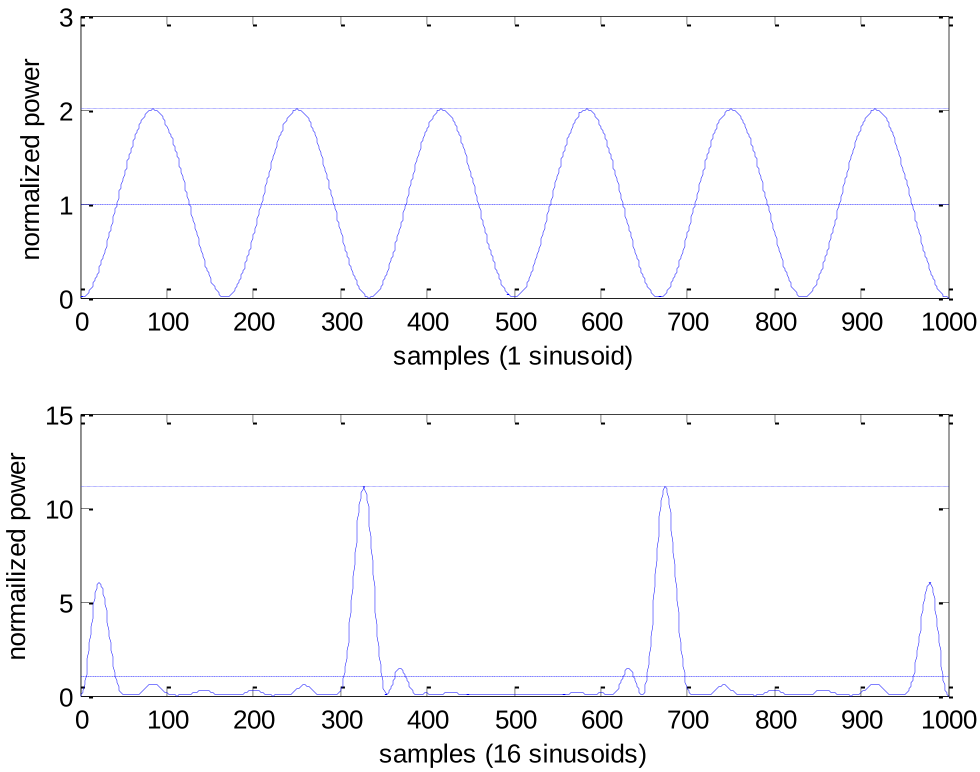

Fig. 18 Peak-to-Average-Power-Ratio in OFDM

Fig. 18 illustrates the superposition of orthogonal sinusoids leading to a high PAPR (Peak-to-Average-Power-Ratio). Both graphs are normalized to unity average signal power. The PAPR is defined as

$$PAPR = \frac{P_{peak}}{P_{avg}} = \frac{|A_{max}\ (t)|^2}{\overline{|A(t)|^2}}, \tag{14}$$

where P_{peak} is the peak power (dotted line) and P_{avg} is the average power (dashed line) of the signal. Note that the PAPR using 16 sinusoids exceeds the PAPR of one sinusoid by a factor of

5.57. In a system with 256 OFDM subcarriers, the PAPR is 6-10dB higher compared to conventional modulation formats [21]. The strong power fluctuations on a short timescale translate into strong nonlinear impairments.

Various methods have been applied to reduce the PAPR. For example clipping [22] at the expense of a distorted signal or distortionless implementations at the expense of an increased system complexity that is not feasible for practical application [23]. Note that none of these approaches achieves constant intensity to eliminate nonlinear influence.

PM-OFDM as an angle modulated format features constant intensity. As a consequence a phase modulated signal should not suffer from intensity dependent nonlinearity at all.

Extensive simulations were run to prove this expected advantage of PM over AM systems in chapter 5 and discussed in chapter 6.

CHAPTER FOUR: EXPERIMENTAL PHASE MODULATED OFDM SYSTEM

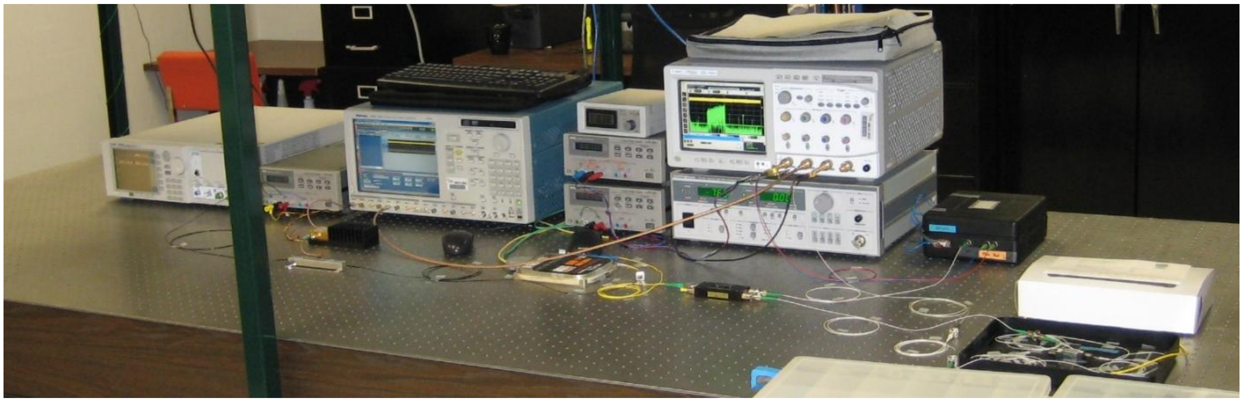

Fig. 19 Photography of experimental setup

This chapter provides an experimental realization of phase modulated OFDM. The experiment does not aim for long-haul transmission but is a proof of concept for the two different PM receiver architectures proposed above. A 5GBit/s data stream is transmitted. Higher data rate transmission, WDM and an analysis of nonlinear impairments in both AM and PM are done in simulation.

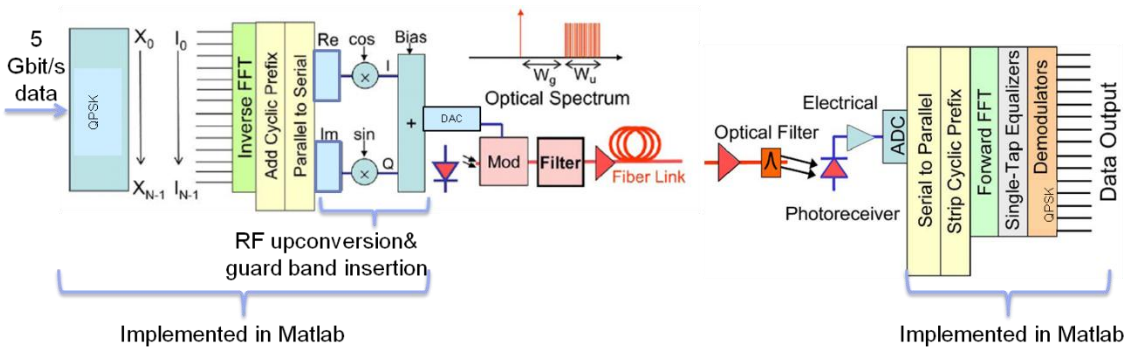

Fig. 20 Schematic of experimental setup: PM-OFDM system; modified from [3]

Fig. 19 shows a photograph of the experimental setup. Fig. 20 shows a schematic of a PM-OFDM system and denotes which functions are performed in Matlab in the digital domain. The schematic depicts filter with direct detection receiver. Note that the recirculating loop has to be inserted for transmission experiments, as done in simulation. Experimental transmitter and receiver are connected back-to-back.

4.1 Transmitter

The OFDM signal is generated in the digital domain using Matlab. A pseudorandom bit sequence (PRBS) is serial-to-parallel converted and mapped onto QPSK symbols on 2^{10} OFDM subcarriers. The baseband OFDM signal is implemented using the FFT-method described above (3.4.1). The baseband signal is up-converted in the digital domain in Matlab to obtain a guard band of equal width as the signal content.

The Matlab waveform to be transmitted is loaded into a Tektronix AWG7102 arbitrary waveform generator as the digital-to-analog converter (DAC). The data rate in this experiment is limited by the bandwidth of the DAC. Using the interleaved output of the AWG, the maximum bandwidth is 5.8GHz at 20GS/s sampling rate.

The 5GBit/s signal mapped onto QPSK has a bandwidth of 2.5GHz. It is spaced 2.5GHz guard band (see 3.5) from the carrier. Note that the effective bit rate for a 2.5 GHz QPSK mapped OFDM signal is lower than the nominal bit rate because of the insertion of the cyclic prefix.

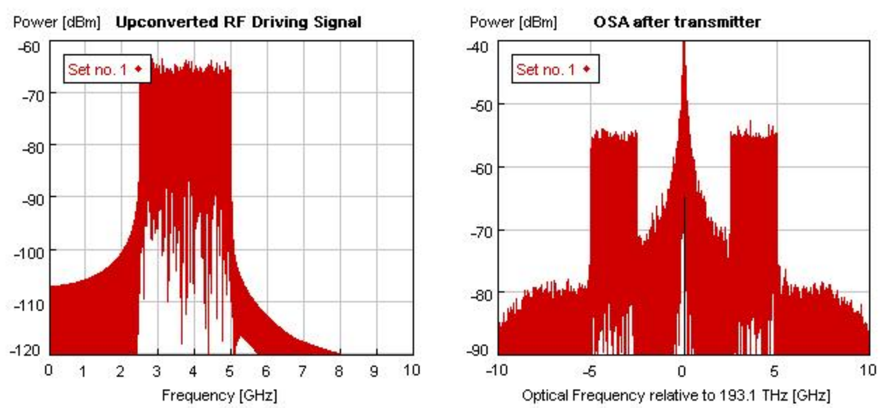

Fig. 21 (a) Electrical RF Spectrum of Modulater Driving Signal and (b) Optical Spectrum after Transmitter

The optical carrier laser is a 1550nm Agilent 8164A. The RF output from the AWG is amplified by a SHF 100CP that drives a Sumitomo phase modulator. The modulator is followed by a Nortel EDFA to provide sufficient power for detection at optimum sensitivity of the receivers. Fig. 21 shows a VPI simulation of the spectrum of the electrical and the modulated optical signal.

4.2 Receiver

The transmitter design is the same for both detectors. Note that the integration for differential detection using the delay interferometer can be done in the digital domain at the transmitter. Before transmission in the optical domain, a 1GBit all-electrical back-to-back test of Matlab+AWG at the transmitter and DSO+Matlab at the receiver produced an almost perfect QPSK constellation diagram (Fig. 22).

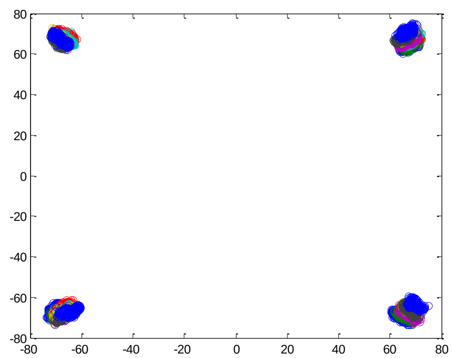

Fig. 22 QPSK constellation diagram of all-electrical back-to-back test

4.2.1 Direct detection

A simple photodiode can only detect the intensity of a signal. Filtering out one sideband converts the double sided PM signal into an amplitude modulated signal (3.5 b). The difference frequencies of carrier and subcarriers are used to down-convert the signal and detected by the photodiode.

As shown in Fig. 21 (b), the sidebands are spaced 5GHz apart. The carrier and the sideband are spaced 2.5GHz apart. Filtering out the lower sideband while still having enough power in the carrier and upper sideband is challenging. Various filters were tested. Fig. 23 (a) shows the transfer function of the first filter tested (black squares) and the filter chosen for the experiment (blue triangles). The bandwidth of the filter must include carrier and one side band but attenuate the lower sideband sufficiently (Fig. 23 b). Any additional bandwidth above the upper sideband increases the amount of noise.

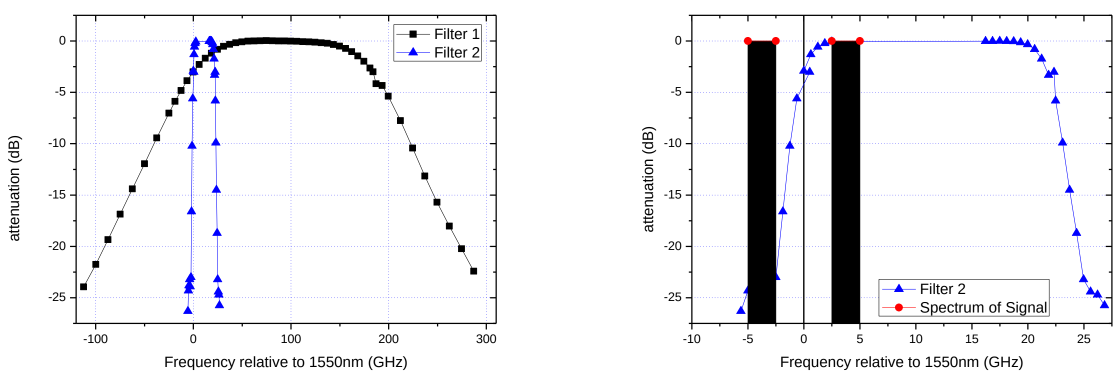

Fig. 23 Transfer Function of (a) Direct Detection Filters (b) Employed Filter 2 and Signal Spectrum

Table 1 Comparison of filters for direct detection PM receiver

	Filter 1	**Filter 2**
Product	DiCon 1565-0.8	Redfern FBG 25GHz DWDM and circulator
Technology	Thin film interference filter	Reflection from FBG band-stop and circulator
3dB bandwidth	184 GHz	21.8 GHz
Attenuation slope	0.2 dB/GHz	7.3 dB/GHz

The filter chosen for the experiment consists of a fiber Bragg grating (FBG) band-stop filter and a circulator (Fig. 24). The filter output is the reflection from the band-stop thus a narrow band band-pass with the desired steep attenuation slope. The filter has to be adjusted carefully to suppress only the lower sideband. Instead of tuning the filter, in this experiment the signal spectrum is shifted in frequency, changing the carrier frequency of the Agilent laser.

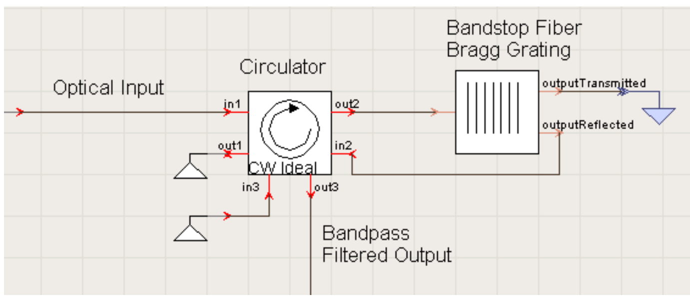

Fig. 24 Bandpass Filter with Circulator and FBG Bandstop

After filtering, the signal is captured with a u^{2}t XPDV3020R photodetector and an Agilent DSO81204A real-time sampling scope at 40GSA/s. The necessity of the guard band becomes apparent looking at the direct detection RF spectrum after the photodiode in Fig. 25. The digitized signal is processed in Matlab. The constellation diagram of the received QPSK symbols is shown in Fig. 26.

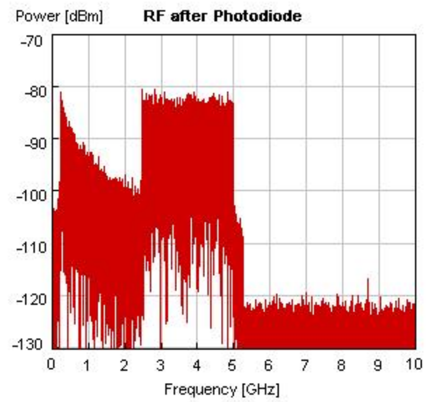

Fig. 25 RF Spectrum after DD Photodiode

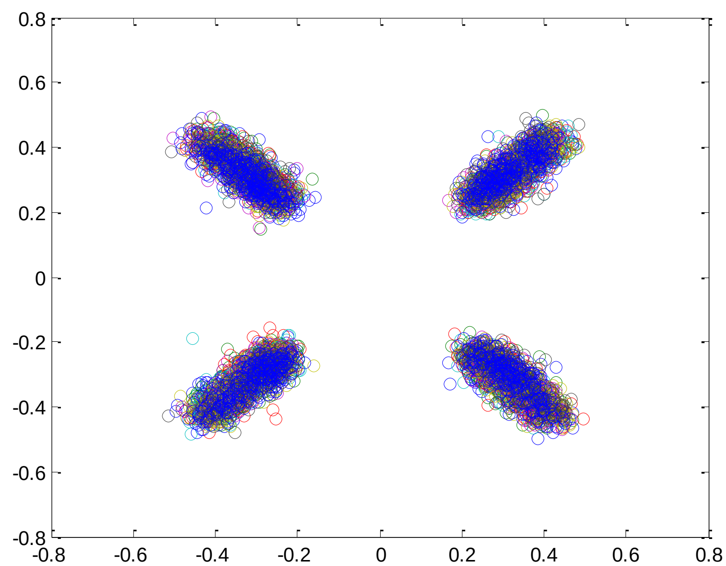

Fig. 26 QPSK constellation diagramm using PM filtered direct detection

Note that the constellation points are elongated, i.e. the symbols do not have the same amplitude. Besides some variation because of noise, this is due to the fact that the filter transfer function has some residual attenuation for the lower subcarriers of the upper sideband. A single tap equalizer could compensate this with one multiplication per subcarrier.

4.2.2 Delay Interferometer

The delay interferometer detector does not need a filter for detection. However in long-haul transmissions system with multiple EDFAs a band-pass covering both sidebands would be used to suppress ASE noise.

A custom build delay interferometer from a 10GSymbol/s communication system introduces a $\frac{1}{10GHz} = 100ps$ delay between the two interferometer arms. The phase difference between the actual phase and the 100ps delayed signal is detected by a u[2]t BPDV2020R balanced detector followed by an Agilent DSO81204A real-time sampling scope (Fig. 27).

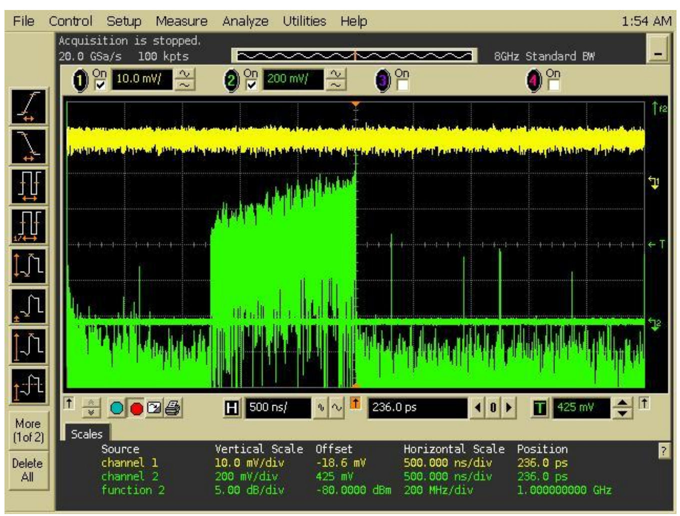

Fig. 27 Spectrum of PM OFDM with Delay Interferometer Detection

Analogous to filter + direct detection the digitized signal is processed in Matlab. The constellation diagram of the received QPSK symbols is shown in Fig. 28.

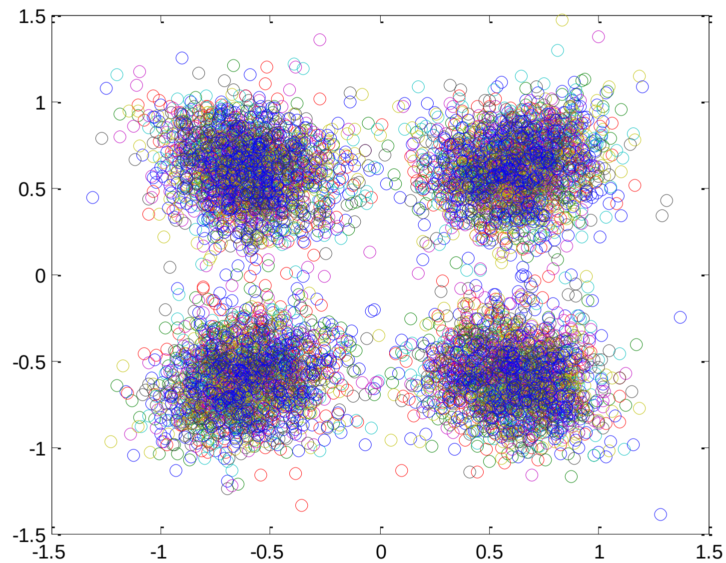

Fig. 28 QPSK constellation diagram using PM delay interferometer detection

4.3 Discussion

Detection with a delay interferometer (DI) seems be advantageous over filter and direct detection (DD) in various respects. DD requires a strong carrier that basically does not carry any information. For DI on the other hand the carrier could be suppressed, leaving all signal power for information on subcarriers. Furthermore both sidebands are used to extract information which may lead to better sensitivity.

The filter in the DD setup was very sensitive and had to be adjusted every time the system was started. A DI receiver does not have a filter, however a delay interferometer is needed that may be more expensive than a filter. However the DI may not have to be as precise because it does not compare subsequent symbols but merely tracks the phase within one long OFDM symbol.

The delay time has to be optimized for the system. The sampling theorem suggests that the maximum delay must be short enough to track the highest frequency component that occurs in the OFDM signal. A shorter delay allows following the phase more closely but small changes are harder to detect. As an example an OOK coded OFDM signal without guard band may have very low frequency components in the order of several Hertz. The change in phase at the DI over 100ps for this signal is very small if not intractable. A minimum frequency large enough to be detected may be needed at the expense of lower spectral efficiency.

As the DI compares the phase at two different instants in time, time variant impairments are likely to have strong impact on system performance. Especially random phase and amplitude noise such as ASE noise by EDFAs or laser line width deteriorate the signal. This may be the reason for the worse constellation in DI comparing Fig. 26 and Fig. 28. Note that the detector cannot distinguish whether the output signal is due to a phase difference $\Delta\varphi$ or amplitude fluctuations $A(t)$.

From this proof-of-concept experiment it is hard if not impossible to draw reliable conclusion about the performance and superiority of one design. Starting from the different receiver sensitivities over to the optimization of the DD filter and equalization and noise characteristics, the parameters have to be investigated in detail. The optimization of the DI delay time may be worth investigating as preliminary simulations indicate an optimum delay for a given signal frequency content.

Instead of evaluating PM receiver architectures in detail, the focus of interest was shifted towards the behavior of phase and amplitude modulated OFDM in WDM systems in the next chapter.

CHAPTER FIVE: SIMULATIONS

This chapter presents the simulations for both single channel and WDM phase and amplitude modulated OFDM systems with direct detection. The results are discussed in the next chapter. Periodic inline dispersion-compensated fiber links are widely employed in current WDM systems. Transmission over such a link is a likely scenario for upgrading current systems to 40GB/s or 100GB/s without changing the fiber [24].

The software VPItransmissionMaker 7.6 is used for simulation of optical components and transmission, Matlab for digital signal processing.

5.1 Single channel system

5.1.1 Single Channel Simulation Setup

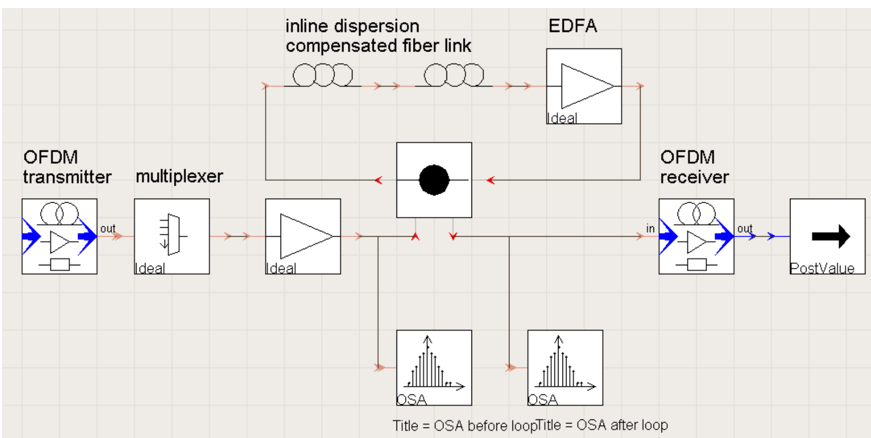

Fig. 29 VPI block diagramm of single channel OFDM system

The transmission link is simulated by a recirculating loop of 80km SSMF (Standard Single Mode Fiber) followed by 16km of DCF (Dispersion Compensating Fiber) with a five times higher dispersion parameter of opposite sign. Note that the DCF used in this simulation employs the same fiber parameters as SSMF (e.g. core area, nonlinear index, …) but only differs in length and dispersion parameter. The fiber parameters are listed in Table 2. To compensate for power losses during transmission, the signal is amplified 19.2dB after each span consisting of both SSMF and DCF with 5dB EDFA noise. Other than this simulation, the use of two EDFAs per span, one after SSMF and a second EDFA after DCF, is a very common amplifier distribution along the dispersion managed fiber link.

Table 2 Fiber parameters

Parameter	**SSMF / DCF**
Length	$80\ km$ / $16\ km$
Attenuation	$0.2\ \frac{dB}{km}$
Dispersion	$16\ \frac{ps}{nm\ km}$ / $-80\ \frac{ps}{nm\ km}$
Dispersion slope	$0.08\ \frac{ps}{nm^2\ km}$
Nonlinear index	$2.6\ 10^{-16}\ \frac{cm^2}{W}$

The multiplexer after the transmitter is employed later on in the WDM system (5.2). A subsequent EDFA controls that the same average power is launched into the fiber for AM and PM modulation. Note that this EFDA is ideal without any noise.

A 50GBit/s data stream is transmitted in this simulation. 512 subcarriers are used as in previous work by Lowery et al. [4, 25].

AM and PM have a slightly different transmitter design shown in Fig. 30 and Fig. 33, respectively. The baseband real-valued OFDM signal is generated in Matlab (CoSim Interface). Other than in the experimental setup, up-conversion to obtain a guard band between carrier and signal content is realized with external RF-up-conversion (see Fig. 12 b). External upconversion relaxes the requirement on the Digital-to-Analog conversion that may be one limiting factor in hardware implemented systems.

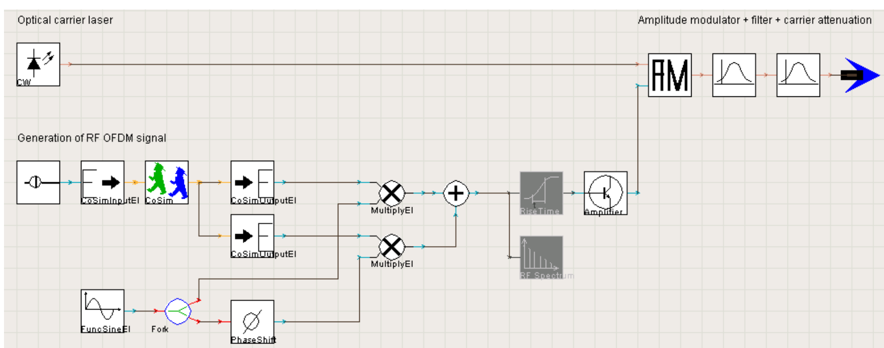

Fig. 30 VPI block diagramm of AM transmitter

For the AM case, the driver amplifier before the modulator adds a bias to and normalizes the signal. The driver output is the OFDM signal peak to peak modulated between 0% and 100%. As the lower sideband in an AM systems contains redundant information, it can be filtered for better spectral efficiency (Fig. 31). Furthermore there is relatively more power in the upper sideband as the power is set with an ideal EDFA after filtering.

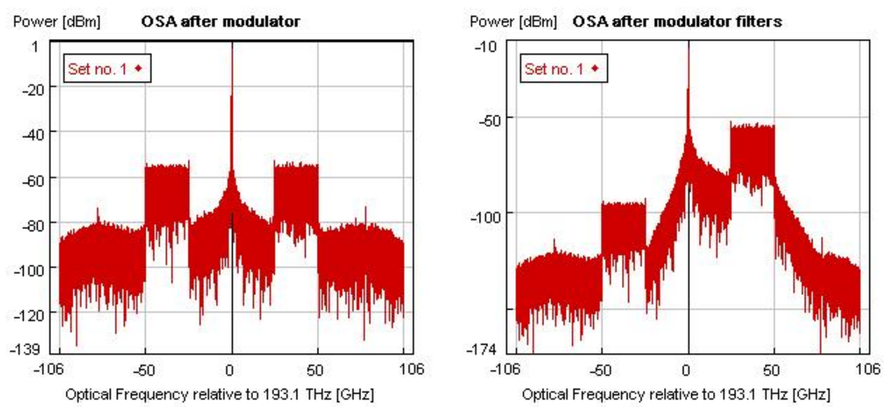

Fig. 31 Spectrum of QPSK AM-OFDM channel, 40GBit/s, 100GHz spacing (a) before and (b) after filtering at transmitter

The second filter is a narrow bandstop to attenuate the carrier for optimum carrier to sideband power ratio as proposed in [4].

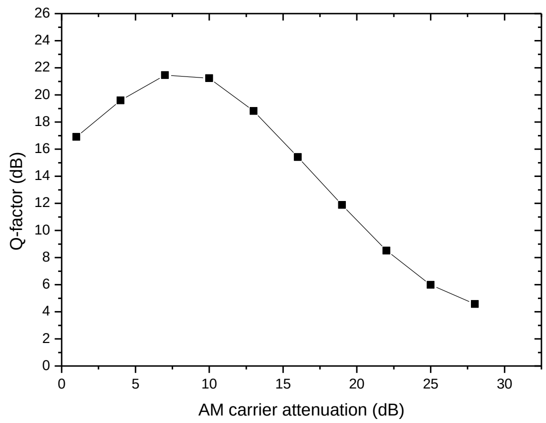

Fig. 32 Optimization of carrier attenuation for AM

Sweeping the carrier attenuation factor 1 to 28 dB as shown in Fig. 32 gives the optimum carrier to sideband power at maximum Q-factor.

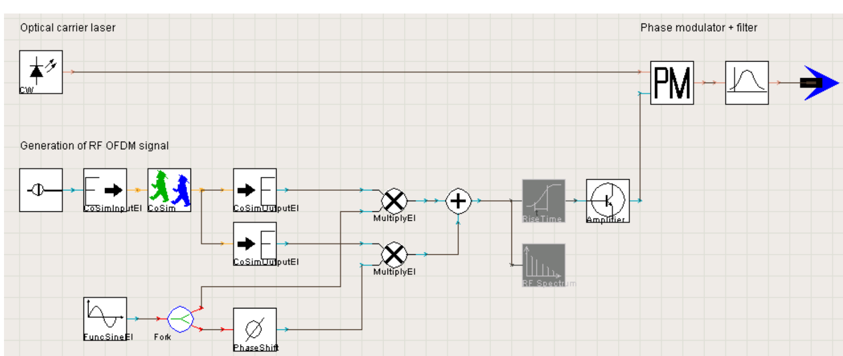

Fig. 33 VPI block diagramm of PM transmitter

For the PM case no bias is added at the modulator driver. Instead the OFDM signal with both positive and negative values is used to drive the signal.

The spectrum for the PM signal contains both sidebands (Fig. 34). Filtering out one sideband is used for detection at the receiver. However both sidebands are needed for constant amplitude and to exploit the associated benefits. Because of the infinite spectrum shown before in 2.3.2 (Phase Modulation Spectrum), a modulator output filter is needed to limit the bandwidth especially in WDM systems.

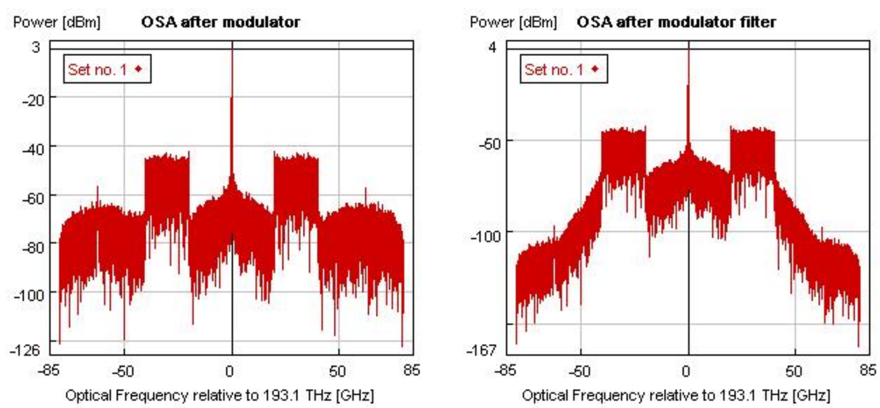

Fig. 34 Spectrum of QPSK PM-OFDM channel, 40GBit/s, 100GHz spacing (a) before and (b) after filtering at transmitter

The PM system is optimized for maximum Q-factor sweeping the modulator driver gain as shown in Fig. 35. Additional carrier attenuation did not improve the Q-factor significantly.

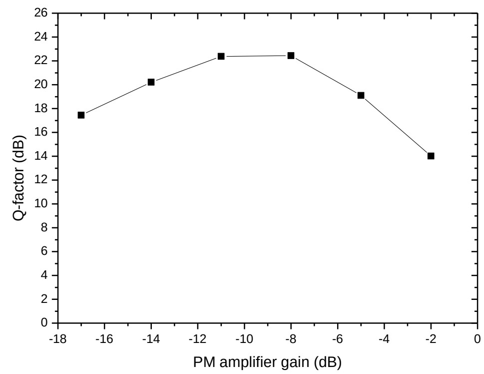

Fig. 35 Optimization of modulator driver gain for PM

After transmission in the recirculating loop, the signal is fed into an OFDM receiver (Fig. 36).

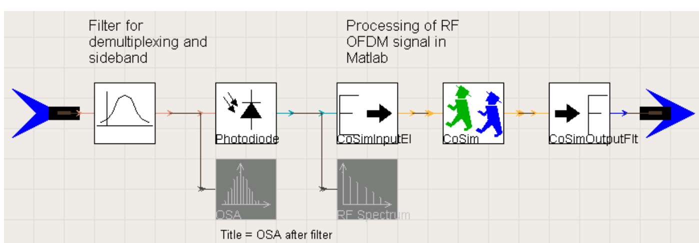

Fig. 36 VPI block diagram of direct detection receiver

Filtering with a bandpass, only the carrier and the upper sideband are passed on to the photodiode for both AM and PM. For a more realistic system, the RF signal is further impaired by diode noise. Other publications focus on the transmission and assume ideal detection (e.g.

[4]). The processing of the RF domain OFDM signal is realized in Matlab. It performs removal of the cyclic prefix, phase estimation and QPSK mapping from which the Q-factor is derived.

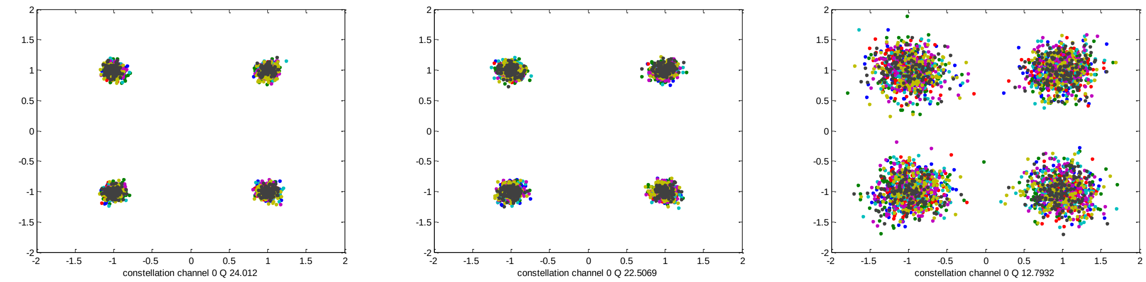

Fig. 37 Constellation Diagram of single channel QPSK PM-OFDM at 9dBm launch power (a) 1 span (b) 2 spans (c) 20 spans

The Q-factor is calculated from the QPSK constellation diagram Fig. 37 using

$$Q_{dB} = 20\log(\frac{\mu}{\sigma}), \tag{15}$$

where μ is the mean distance of a symbol cloud from the center of the constellation diagram and σ is the standard deviation of the clouds.

5.1.2 Single Channel Simulation Results & Discussion

Fig. 38 (a) shows the bell-shaped simulation result of Q-factor versus launch power for a single channel amplitude modulated system of 20 spans (1920km). For low launch powers the signal-to-noise ratio is low because EDFA noise. A simulation without EDFA noise is shown in Fig. 38 (b) (blue triangles) where the Q-factor is significantly higher for low launch powers. Note that the Q-factor without EDFA noise decreases slightly for very low launch powers. Reason being that thermal noise at the receiver degrades the SNR.

Fiber nonlinearity is the dominating impairment for high launch powers. Without nonlinearity (Fig. 38 (b), red circles) the Q-factor increases with power as the SNR improves. The optimum launch power balances EDFA noise and nonlinearity.

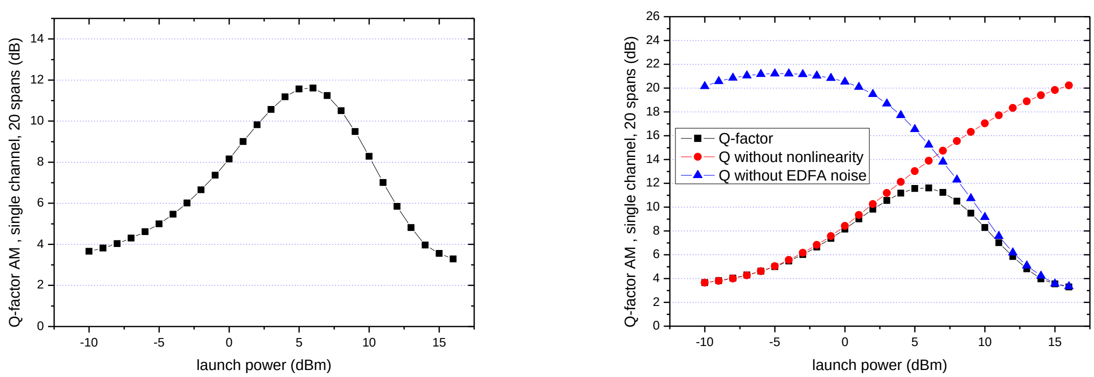

Fig. 38 (a) Q-factor vs. launch power diagram; AM; single channel; 20 spans (b) Influence of nonlinearity and EDFA noise on Q-factor vs. launch power

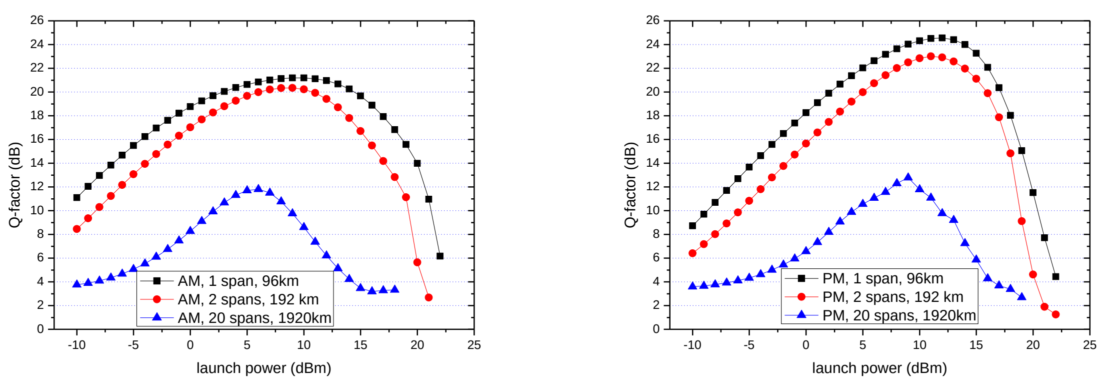

Fig. 39 Q-factor vs. launch power at various distances for single channel (a) AM- and (b) PM-OFDM

Various distances simulated are depicted in Fig. 39 for both amplitude (a) and phase modulated (b) transmission.

Comparing the maximum Q-factor for both amplitude and phase modulation in Fig. 40 results in a 3dB advantage of PM over AM for 192 km transmission.

For longer distances the advantage of PM over AM is reduced <1dB. EDFA of random phase is introduced each span that appears to influence PM more severely. Those newly introduced intensity fluctuations in PM are affected by nonlinearity further degrading the performance.

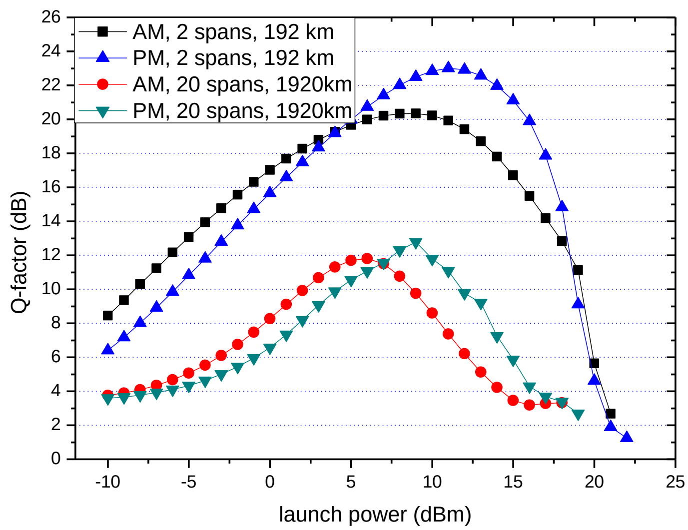

Fig. 40 Comparison of single channel AM- and PM- OFDM

Note that the maximum Q-factor for PM occurs at higher power levels than for AM. One reason is that the peak power for AM signals is much higher and thus more severely impaired by nonlinearity than PM systems of same average launch power. Another reason is that in am PM system both sidebands are launched into the fiber. One of them is filtered at receiver requiring for a higher PM launch power to obtain the same SNR as AM at the receiver.

5.2 WDM system

In Wavelength Division Multiplexing (WDM) various information channels modulated onto different optical carriers are sent over the same fiber. The concepts are the same as for the single channel system. Instead of only intra-channel effects, the channels now influence each other with inter-channel effects such as XPM and FWM.

5.2.1 WDM Simulation Setup

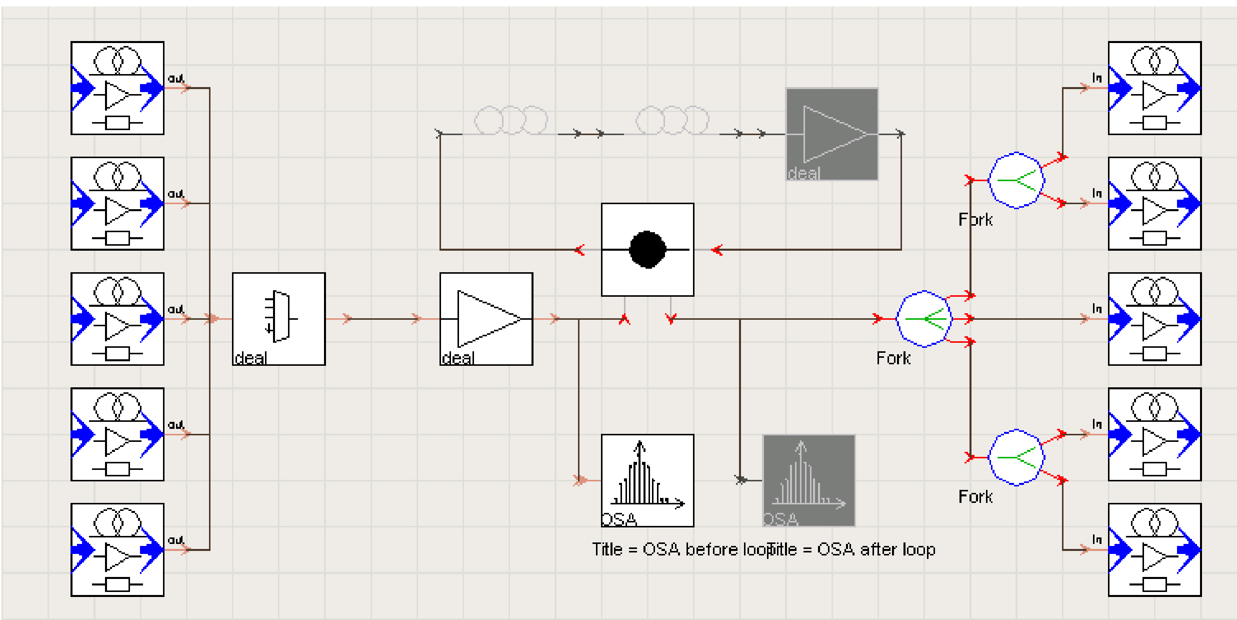

Fig. 41 VPI block diagramm of WDM OFDM system

The multi-channel WDM system employs the transmission system and optimization as described above. Five channels spaced 100GHz apart are multiplexed onto the fiber. 100GHz spacing is predefined by current WDM systems that may be upgraded. The data rate in the WDM simulation had to be reduced from 50GBit/s QPSK (covering the entire 100GHz bandwidth including guard band for PM) to 40GBit/s QPSK to allow for reasonable filter design.

Demultiplexing is done in the OFDM receivers discarding the adjacent channels and performing the bandpass filtering for detection in one step.

Transmitter and receiver design are the same as for the single channel system with modified filters for the adjusted data rate.

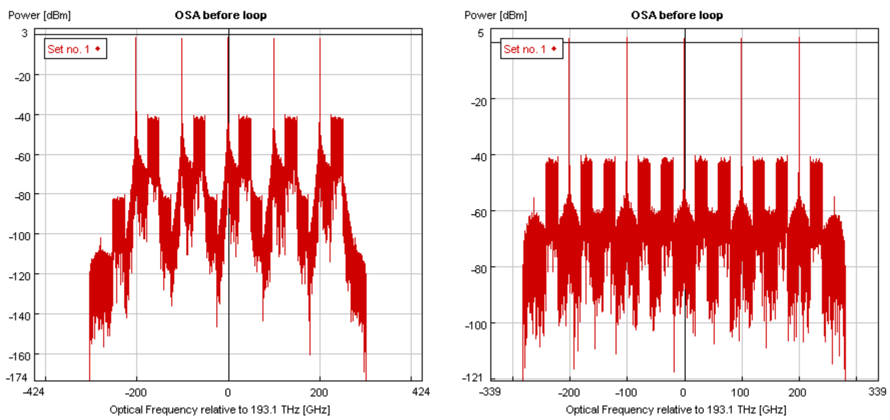

Fig. 42 Spectrum of 5 WDM QPSK channels, 40GBit/s/channel, 100GHz spacing for (a) AM- and (b) PM- OFDM

Fig. 42 (a) shows the spectrum of the amplitude modulated five channel WDM system. The lower sideband is filtered for SSB transmission leaving bandwidth e.g. to increase the symbol rate to use the bandwidth more efficiently. In order to compare AM and PM, the symbol rates are kept the same in both systems.

Fig. 42 (b) shows the spectrum of the phase modulated five channel WDM system. Note that both sidebands are transmitted.

5.2.2 WDM Simulation Results & Discussion

The Q-values in the following graphs represents the WDM center channel.

Various distances simulated are depicted in Fig. 43 for both amplitude (a) and phase modulated (b) transmission.

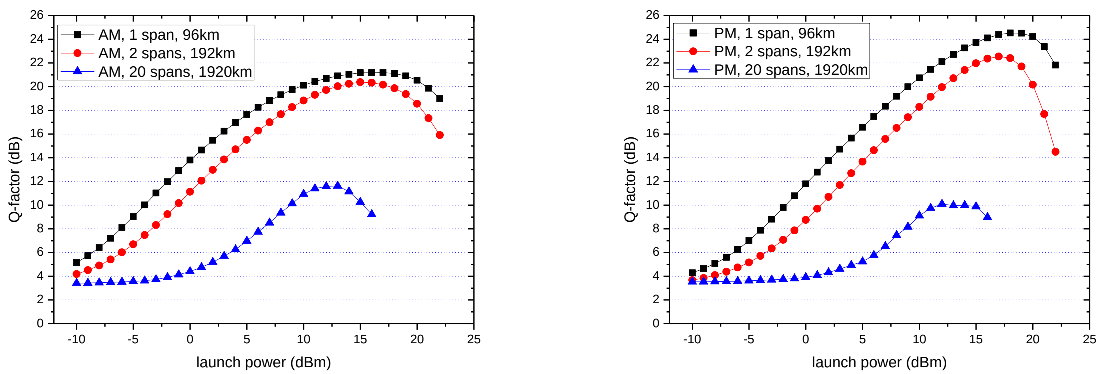

Fig. 43 Q-factor vs. launch power at various distances for WDM (a) AM- and (b) PM-OFDM

Comparing the maximum Q-factor for both amplitude and phase modulation in Fig. 44 results in a 2.5 dB advantage of PM over AM for 2 spans (192 km) transmission.

For long-haul transmission of 20 spans (1920 km) the Q-factor of the PM system drops below AM performance. As previously described for the single channel system, EDFA noise of random phase and amplitude is introduced each span. In WDM systems the launch power is divided up between the channels. Thus the launch power per channel is reduced, which in turn degrades the SNR. A higher launch power is required to maintain the single channel SNR which making the system susceptible to nonlinearity.

Comparing the spectrum of AM and PM (Fig. 42) may provide a reason, why PM performance in WDM is reduced compared to single channel. In AM the bandwidth occupied by one channel is 40GHz because the lower sideband is filtered at the transmitter. The spacing between the highest subcarrier to the carrier of a neighboring channel is 60GHz. In PM however the spacing between the highest subcarrier of one and the lowest subcarrier of the lower sideband of the next channel is 20GHz. The closely spaced channels in WDM PM-OFDM give rise to crosstalk that impairs PM worse than AM.

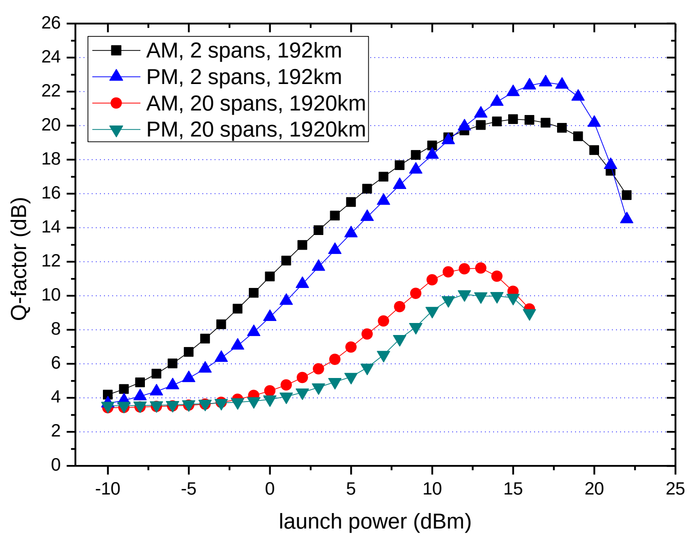

Fig. 44 Comparison of WDM AM- and PM- OFDM

It has been mentioned above (2.5) that a certain amount of dispersion is in fact beneficial for transmission. Fig. 45 shows a Q-factor versus launch power diagram for $D_1 = 16\frac{ps}{nm\ km}$ and $D_2 = 0\frac{ps}{nm\ km}$. The dispersion parameter of DCF is adjusted accordingly. All other DCF parameters such as length, attenuation and nonlinear index remain unchanged in order to keep the systems comparable. A 5 dB advantage in Q-factor is obtained for dispersive fiber. In zero dispersion fiber, the subcarriers remain in the same time relationship with each other. Nonlinearity impairs the very same part of high intensity in the waveform over the entire transmission. In dispersive systems however, the time relationship between the subcarriers changes as they walk of due to dispersion.

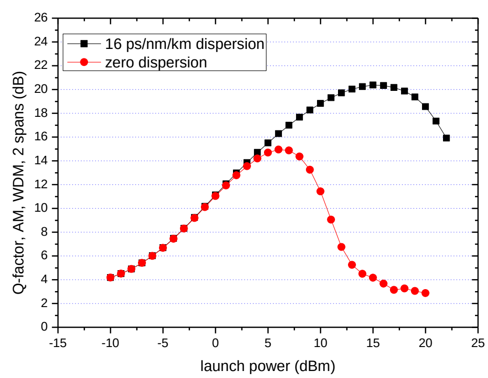

Fig. 45 Q-factor vs. launch power with and without dispersion in AM-OFDM

CHAPTER SIX: CONCLUSION

6.1 Summary

Orthogonal Frequency Division Multiplexing has been studied as a modulation scheme that is inherently capable of compensating for dispersion. Unlike other dispersion compensation schemes that account for a specific amount of dispersion, OFDM compensates for any amount of dispersion up to a maximum determined by the cyclic prefix. This is beneficial as it mitigates the effects of dispersion slope in WDM systems. Moreover, the overall dispersion throughout the transmission link may vary due to environmental effects and aging. OFDM is inherently tolerant to over- or under-compensation.

As each OFDM symbol is composed of a superposition of multiple subcarriers the resulting waveform has a high peak-to-average power ratio. The large variation in intensity associated with amplitude-modulated OFDM makes this modulation format more susceptible to nonlinear effects in fiber compared to phase-modulated signals. Therefore phase-modulated OFDM is studied.

The feasibility of PM-OFDM is verified in a 5 GBit/s QPSK coded back-to-back experiment. A delay interferometer with balanced detector and a filter with direct detection are the two receiver architectures employed in this experiment.

As existing WDM systems usually employ periodic dispersion management, simulations of phase and SSB amplitude-modulated OFDM are performed therein. PM offers a 3dB sensitivity advantage over AM in Q-factor for a single channel 50 GBit/s QPSK coded transmission over 192 km. The advantages of PM hold until dispersion and EDFA noise lead to amplitude and phase variations strong enough to be degraded by nonlinear effects as well.

Also in the WDM simulation, PM excels in Q-factor by 2.5dB for a 5 channel 40 GBit/s/channel transmission system over 192 km. However for long-haul transmission of 1920km the performance of AM is better. Crosstalk affects PM as a double sideband modulation format more severely than single sideband AM due to the wider AM guard band to the next channel.

In conclusion OFDM is highly beneficial for communication links whose dispersion characteristics are not exactly known, different for each channel or fluctuating. Unfortunately the broad bandwidth requirement is not technically feasible yet. From our simulations, PM outperforms AM in short-haul transmission but does not offer benefit for long-haul transmission. It is not likely to find PM- or AM-OFDM systems employed for broadband communications in the near future. However specific applications may emerge.

6.2 Future Research

Analyzing phase and amplitude modulated OFDM systems in this thesis has raised more interesting approaches to optimize the system and further improve performance.

- Higher-order modulation formats may be used, a high Q-factor permitting. Fig. 37 (b) for example shows plenty of 'room' for further symbols in the constellation diagram, e.g. using 16-QAM in medium range applications.
- A high number of subcarriers is needed in a dispersive long-haul transmission system in order to reduce the required overhead. In a periodically dispersion compensated system the number of subcarriers could be reduced. The lower PAPR may be balanced with an increased susceptibility to dispersion for few broader subchannels.
- Modifications to the OFDM signal such as clipping high peaks of the signal may improve performance. "With larger number of subcarriers […] the peak values occur with very probability" [19] Clipping high peaks of low probability, the majority of the OFDM signal is strongly modulated onto the entire dynamic range of the modulator. Without clipping, the modulator is driven softly most of the time reserving the maximum dynamic range for OFDM peaks of low probability. Note that the spectral content of the signal is changed marginally as "the probability of the occurrence of the theoretically highest PAPR becomes negligible." [26]
- Pilot tones may be used to gain more information about the subcarriers in order to optimize the system.

- A subchannel selective coding scheme may be interesting. Especially in WDM applications mixing products may fall onto certain frequencies and impair the Q-factor of specific subcarriers. OFDM permits to reduce bitrates of impaired subcarriers or not to use them at all.
- A closer channel spacing for single sideband AM systems improves spectral efficiency. However mixing may deteriorate the signal.
- The spectral efficiency may be improved using the guard band (partially) for transmission. The impaired subcarriers in the guard band can be modulated at lower bitrates. Approaches that do not require a guard band have been presented [22].
- Carrier-suppressed phase-modulated OFDM with a delay interferometer (DI) receiver. Comparing DI and DD receiver for PM-OFDM is of interest including an optimization of the DI delay time.
- Preliminary simulations showed that linewidth barely affects the phase modulated system whereas the amplitude modulated system Q-factor is degraded.
- Using DCF followed by SSMF may improve system performance as higher dispersion is beneficial terms of nonlinearity.

LIST OF REFERENCES

1 Litwin, L., and Pugel, M.: ‘The principles of OFDM’, RF signal processing, 2001

2 Shieh, W., Bao, H., and Tang, Y.: ‘Coherent optical OFDM: theory and design’, Optics Express, 2008, 16, (2), pp. 841-859

3 Schmidt, B.J.C., Lowery, A.J., and Armstrong, J.: ‘Experimental demonstrations of electronic dispersion compensation for long-haul transmission using direct-detection optical OFDM’, Journal of Lightwave Technology, 2008, 26, (1-4), pp. 196-203

4 Lowery, A.J., Du, L.B., and Armstrong, J.: ‘Performance of optical OFDM in ultralong-haul WDM lightwave systems’, Journal of Lightwave Technology, 2007, 25, (1), pp. 131-138

5 Proakis, J.G., and Salehi, M.: ‘Communication Systems Engineering’ (2002, 2nd edn. 2002)

6 Wei-Ren, P., Xiaoxia, W., Vahid, A., Bishara, S., Louis, C., Jeng-Yuan, Y., Kai-Ming, F., Alan, W., and Sien, C.: ‘Experimental Demonstration of a Coherently Modulated and Directly Detected Optical OFDM System Using an RF-Tone Insertion’. Proc. Optical Fiber Communication Conference and Exposition and The National Fiber Optic Engineers Conference2008 pp. Pages

7 Djordjevic, I.B., and Vasic, B.: ‘100-Gb/s transmission using orthogonal frequency-division multiplexing’, Ieee Photonics Technology Letters, 2006, 18, (13-16), pp. 1576-1578

8 Kiencke, U., and Jäkel, H.: ‘Signale und Systeme’ (Oldenbourg, 2005, 3 edn. 2005)

9 Leuthold, J.: ‘KIT Lecture Notes Optical Communication Systems’, 2007

10 Li, G.: ‘Creol Lecture Notes OSE5143 - Fiber Optics Communication’, 2008

11 Agrawal, G.P.: 'Nonlinear Fiber Optics' (Academic Press, 1995, 2nd. edn. 1995)

12 Li, X., Chen, X., Goldfarb, G., Mateo, E., Kim, I., Yaman, F., and Li, G.: 'Electronic post-compensation of WDM transmission impairments using coherent detection and digital signal processing', Optics Express, 2008, 16, (2), pp. 880-888

13 Goldfarb, G., Li, G.F., and Taylor, M.G.: 'Orthogonal wavelength-division multiplexing using coherent detection', Ieee Photonics Technology Letters, 2007, 19, (21-24), pp. 2015-2017

14 Hagan, D.J., and Kik, P.G.: 'Creol Lecture Notes OSE5312 - Fundamentals of Optical Science', 2007

15 http://en.wikipedia.org/wiki/Self-phase_modulation, accessed 10/07/2008

16 Hara, S., and Prasad, R.: 'Multicarrier Techniques for 4G Mobile Communications' (Artech House, 2003. 2003)

17 Shieh, W., Yi, X.W., Ma, Y., and Yang, Q.: 'Coherent optical OFDM: has its time come? [Invited]', Journal of Optical Networking, 2008, 7, (3), pp. 234-255

18 Louchet, H., and Richter, A.: 'Novel Scheme for High-Bit-Rate Coherent-OFDM Transmission without PLL'. Proc. ECOC2007 pp. Pages

19 Kiviranta, M., Mammela, A., Cabric, D., Sobel, D.A., and Brodersen, R.W.: 'Constant envelope multicarrier modulation: performance evaluation AWGN and fading channels'. Proc. Military Communications Conference, 2005. MILCOM 2005. IEEE2005 pp. Pages

20 Goldfarb, G.: 'Digital Signal Processing Techniques for Coherent Optical Communication', University of Central Florida, 2008

21 Jansen, S.L., Morita, I., Schenk, T.C.W., Takeda, N., and Tanaka, H.: ‘Coherent optical 25.8-Gb/s OFDM transmission over 4160-km SSMAF’, Journal of Lightwave Technology, 2008, 26, (1-4), pp. 6-15

22 Schuster, M., Randel, S., Bunge, C.A., Lee, S.C.J., Breyer, F., Spinnler, B., and Petermann, K.: ‘Spectrally Efficient Compatible Single-Sideband Modulation for OFDM Transmission With Direct Detection’, Photonics Technology Letters, IEEE, 2008, 20, (9), pp. 670-672

23 Lee, S.C.J., Breyer, F., Randel, S., van den Boom, H.P.A., and Koonen, A.M.J.: ‘High-speed transmission over multimode fiber using discrete multitone modulation [Invited]’, Journal of Optical Networking, 2008, 7, (2), pp. 183-196

24 Jansen, S.L.: ‘Optical OFDM, a hype or is if for real?’. Proc. ECOC2008 pp. Pages

25 Lowery, A.J., and Armstrong, J.: ‘Orthogonal-frequency-division multiplexing for dispersion compensation of long-haul optical systems’, Optics Express, 2006, 14, (6), pp. 2079-2084

26 Ochiai, H., and Imai, H.: ‘On the distribution of the peak-to-average power ratio in OFDM signals’, Ieee Transactions on Communications, 2001, 49, (2), pp. 282-289