Design Considerations and Performance
Comparison of High-Order Modulation Formats
using OFDM

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Abstract— This paper addresses OFDM transmission over optical links with high spectral efficiency, i.e. by using high-order QAM-modulation schemes as a mapping method prior to the OFDM multicarrier representation. Low and moderate cost optics which is mandatory in access and in metro applications is assumed. Here we address especially direct detection receivers using photo detectors without the need for local lasers at the transmitter side. In addition, we show 32x10.7 Gb/s optical WDM-OFDM over 3200km SSMF with direct detection.

Index Terms— optical communications, modulation, QAM, OFDM, direct detection, WDM.

I. INTRODUCTION

Orthogonal Frequency Division Multiplexing (OFDM) is currently considered as an interesting alternative transmission scheme in optical communications [1-4]. This holds not only for long haul high-capacity networks, but also for the metro and even the access network. There are two strategies for transmitting the quasi-analogue OFDM signal over optical fiber. One solution is given by optical I-Q-modulation in conjunction with coherent detection (CO-OFDM) [2, 3]. A second method restricts to a real-valued OFDM signal transmitted with intensity modulation and direct detection and is called optical DD-OFDM [1]. The latter requires substantially less complexity in the optical domain and in this paper the focus is thus put on this scheme. OFDM offers a simple possibility to adapt the modulation format to various channel conditions as both transmitter and receiver are basically software defined, i.e. digital signal processing is employed. A high-order modulation format, as e.g. 64-QAM, would result in a high spectral efficiency and is thus efficient in terms of bandwidth. However the noise performance is poor. Vice versa, we achieve high noise resistance if we allow for more bandwidth as e.g. with binary PSK-modulation. Therefore the well known principle in communications, namely the possibility to exchange noise performance against bandwidth is nicely implemented in a practical system.

The paper investigates square QAM modulation constellations from 4-QAM up to 64-QAM. We start with a description of the DD-OFDM system setup. Results are given for the Peak-to-Average Power Ratio (PAPR) and for the impact of the drive conditions of the Mach-Zehnder modulator (MZM) on the system performance. A complete investigation on the sensitivity for the various number of modulation levels is given. Also, we investigate the system in a dispersive transmission scenario based on an optimized system design. As an extension to our previous work [5], the fiber nonlinearity effect on the system performance has been investigated for a specific modulation format, 4-QAM, in Wavelength-Division-Multiplexing (WDM) optical OFDM transmission and experimental results are presented for 4 and 16-QAM modulation formats.

II. OPTICAL-OFDM SYSTEM

Optical-OFDM is based on electronic signal processing before the optical modulator and after the photo-detector. The modulation and demodulation processes are performed in the electrical domain, and the optical components are used just for converting the electrical OFDM signal into an optical signal at the transmitter for transmission through an optical fiber and for converting the received optical signal back into the electrical domain at the receiver. This has a big advantage because the microwave devices are much more mature than their optical counterparts. The schematic diagram of an optical-OFDM is shown in Fig. 1.

Figure 1. Schematic diagram of optical-OFDM system.

In this paper, direct detection optical-OFDM (DD-OFDM) is considered. The main requirements for a DD-OFDM system are:
• **Bias**: to generate the carrier (DC) required for DD, because an electrical OFDM time signal is quasi-analog with zero mean.

• **Frequency gap** ($W_f$): the OFDM signal spectrum ($B_{ofdm}$) is displaced by a frequency gap from the optical carrier to ensure that the second order inter-modulation distortion (IMD), due to the photo-detector, fall outside the signal spectrum.

• **SSB transmission**: to avoid the power null fading due to the chromatic dispersion and to enable a powerful and simple equalization method.

### III. Simulation Results

The general DD-OFDM system setup is shown in Fig. 2. The real valued, up-converted to $f_{RF}$ OFDM signal is generated by using a complex conjugate extension and appropriate zero padding for the input to IFFT [6]. This can also be achieved by using an electrical I-Q modulator. The resulting signal has to be biased for driving an external optical MZM in order to achieve sufficient carrier power for direct detection. A Single-Side-Band (SSB) optical filter is used to transmit only one sideband together with the optical carrier. The optical transmission line consists of spans of 80 km of Standard Single-Mode Fiber (SSMF) without Dispersion Compensating Fiber (DCF). Span loss is compensated for by means of inline optical amplifiers. For the receiver, a variable optical attenuator (VOA) in front of the optical preamplifier, (Erbium Doped Fiber Amplifier, EDFA), allows for OSNR tuning. OFDM demodulation is performed including removing of cyclic prefix (CP$^4$), Serial-to-Parallel (S/P) conversion, FFT, post detection OFDM equalization, symbol de-mapping and parallel-to-serial conversion (P/S) (see Fig. 1).

A Baud rate of 5.35GBaud/s including 7% overhead for Forward Error Correction (FEC) is used as this is compatible with existing component technology. The received raw Baud rate after FEC decoding and removing of cyclic prefix is 5 GBaud/s. In our investigation we examine the system performance with different modulation formats but with the same Baud rate, i.e. bitrates vary between 10 Gbit/s (4-QAM) and 30 Gbit/s (64-QAM).

#### A. Peak-to-Average Power Ratio (PAPR)

An OFDM signal consists of a number of independently modulated subcarriers, which can give a large PAPR when added up coherently [7]. As a result, the DAC, ADC, amplifiers and optical modulators like MZM need to have large dynamic range, which leads to an inefficiency of power and cost.

The PAPR of the transmitted signal can be calculated by interpolating the IFFT output at least by a factor of 4 (i.e oversampling factor=4). It also is advantageous to examine the PAPR behavior for different modulation formats. Simulation is carried out for different modulation formats and number of subcarriers ($N$). Fig. 3 shows the PAPR distribution results for 100,000 OFDM symbols with 8-times oversampling, where the probability that PAPR exceeds a specific threshold value $P_{\text{APR} > P_{\text{Th}}}$ is plotted. Obviously, for a given number of subcarriers, the PAPR behavior is the same for different modulation formats, however is strongly dependent on $N$.

#### B. MZM Nonlinearity (B2B Transmission)

The sensitivity of an OFDM signal to MZM nonlinearity for different modulation levels is examined next. The simulation parameters are: $N=512$, relative CP=1/8 of OFDM symbol duration, Baud rate of 5.35GBaud/s, carrier to single sideband power ratio (PR)=1 for each modulation format to achieve optimum receiver sensitivity [8].

Fig. 4(a) shows the simulation results, where the required OSNR at BER=$10^{-3}$ is plotted for different modulation formats and different Optical Modulation Indexes (OMI), which is defined as the standard deviation of the OFDM driving signal $\sigma$ divided by the switching voltage $V_{g}$. From Fig. 4(a) we can see that the effect of the nonlinearity of the MZM is very severe for higher levels $M$ of modulation formats. This could be attributed to the increased influence of the neighbor symbols. Therefore, in order to avoid these nonlinear distortions, suitable driving amplitude has to be chosen for each
modulation format. Fig. 4(b) shows the received constellations for different modulation formats and different OSNR at BER≈10⁻³.

![Figure 4](image)

**Figure 4.** Impact of MZM nonlinearity (a). Received constellations for different OSNR and modulation formats at BER≈10⁻³ (b).

### C. Receiver Sensitivity (B2B Transmission)

The noise performance of the system in terms of receiver sensitivity is investigated for different modulation formats. The simulation parameters are the same as in sec. 3.2, except that an OMI is set to 0.1 to avoid the MZM nonlinearity.

The sensitivity penalties for different modulation formats compared to 4-QAM are calculated to make a comparison with the simulation results. For example, doubling the bandwidth efficiency by doubling the digital modulation format from 4-QAM to 16-QAM results in a mean power of 5d²/2 per symbol compared to d²/2 for 4-QAM, where d is equal to the minimum Euclidian distance between two symbols. Using the approximation that the BER only depends on d when comparing several formats, a factor of 5 (≈7dB) higher signal-to-noise ratio is required to achieve the same BER compared to 3 dB increase in data throughput [9]. Fig. 5(a) shows approximate penalties compared to 4-QAM for several modulation formats. Fig. 5(b) shows the simulation results for the receiver sensitivity. For the same BER (e.g. BER=10⁻³), doubling the constellation size from 4-QAM to 16-QAM requires 7dB higher OSNR, 3dB for doubling the data throughput and 4dB sensitivity penalty which confirms the calculation results in Fig. 5(a).

![Figure 5](image)

**Figure 5.** Sensitivity penalty for different modulation formats (a). Receiver sensitivity for different modulation formats (b).

### D. Chromatic Dispersion

The benefit of the cyclic prefix (CP) in OFDM, to minimize the chromatic dispersion induced inter-symbol-interference (ISI), is examined here. Linear fiber model is considered with chromatic dispersion of 17 ps/nm/km. The number of subcarriers used here is N=512, the SSB and ASE optical filters are Gaussian filters of 5th order and each of 15 GHz FWHM bandwidth. The electrical filter after the photodiode is a 5th order Butterworth filter with 3dB cutoff frequency of 15GHz. The net Baud rate for each modulation format after extracting the CP and FEC overhead is 5GBaud/s (i.e. 10, 15, 20, 25 and 30Gb/s for 4, 8, 16, 32 and 64-QAM respectively).
Fig. 6 shows the results for the maximum reach that can be obtained for all $M$-QAM when the relative CP=1/8. It is obvious from Fig. 6 that transmission is possible up to 12000km for all cases. This is an optimized result, after optimization of the synchronization, compared to the results of our previous work [5]. Longer transmission reach can be obtained by increasing the cyclic prefix.

D. Fiber Nonlinearity

Simulation was carried out also to investigate the effect of fiber nonlinearity, impact of input optical power and number of WDM channels are treated here. In a single channel transmission, the main nonlinear effect is Self-Phase-Modulation (SPM) while in WDM transmission, the main additional limiting factors are Cross-Phase-Modulation (XPM) and Four-Wave-Mixing (FWM).

In out setup according to Fig. 2, up to 32 channels (each of 10.7Gb/s and 512 QPSK-modulated subcarriers) are combined using optical multiplexer (OPTMUX) to generate a WDM-SSB-OFDM comb with a channel spacing of 20GHz. The OMI is set to 0.1 to minimize the effect of MZM nonlinearity and the PR is set to one for optimum receiver sensitivity.

The fiber link consists of 80-km spans of 17 ps/nm/km dispersion fiber with 0.2 dB/km loss, a nonlinear refractive index of $3.2\times10^{-20}$ m$^2$/W and $A_{eff}$ of $8\times10^{-13}$ m$^{-2}$. The loss of each span is compensated with an optical amplifier with a noise figure of 5 dB. The Amplified Spontaneous Emission (ASE) noise is included also in the inline optical amplifiers to consider the mixing of the noise with the signals due to fiber nonlinearity. The WDM channels were demultiplexed using a 15-GHz FWM bandwidth Gaussian optical filter. The performance of a transmission system is specified in terms of the $Q$-value. The $q$-factor was calculated as $q^2 = |\mu|^2/\sigma^2$, where $\mu$ and $\sigma^2$ are the mean-value and variance of a particular cluster with $\mu = \mu_h + j\mu_v$ and $Q$ is defined as $Q_{(dB)} = 20\log_{10}(q)$. The bit error ratio (BER) [10] can be estimated using $0.5\text{erfc}(q/\sqrt{2})$.

multiple WDM channels, $q$ was averaged in a linear scale over all channels.

The simulation result for a single channel is shown in Fig. 7 where the system $Q$-value is plotted versus the input power. It can be seen that, for low optical power the system is limited by ASE noise, while for high input power the system is limited by nonlinear effects. In the noise limit regime, The $Q$-value increases by 1dB as the input power increased by 1dBm, while in the nonlinear limit regime, the $Q$-value decreases by 2dB as the input power increases by 1dBm. Also, for each system length, there is an optimum input power (for which a maximum system $Q$-value is achieved) which decreases slightly with the system length. Therefore, for a given system setup, transmission performance is optimized by realizing a compromise between noise limit and nonlinear limit given by the optimal input power.

![Figure 6. Required OSNR at BER=10^{-3} vs. fiber length for relative CP=1/8.](image)

![Figure 7. System $Q$-value versus optical input power for single channel and different fiber lengths.](image)

![Figure 8. Receiver sensitivity at maximum $Q$-value for different fiber lengths.](image)
dispersion after exhaustion of the cyclic prefix. Transmission is possible up to 5600 km at which the required OSNR at BER=10^{-3} is ≈ 16 dB.

Simulation for WDM-OFDM was already carried out in [11] with an assumption of linearized optical modulator (MZM). In our simulation the MZM nonlinearity is also included to make our system more realistic. The plot of the system $Q$-value versus the optical input power per channel for 8-WDM channels is shown in Fig. 9. The optimal input power (for maximum $Q$-value) is decreased in 8-WDM system compared with the optimum input power in a single channel.

The influence of the number of WDM channels has been investigated, too. Fig. 11 plots the maximum $Q$-value (for an optimum input power) versus number of WDM channels for each fiber length. For small number of channels, the impact of nonlinearity is strong and the $Q$ falls rapidly, while when increasing the number of channels, the decrement of the $Q$-value is less rapid, because the impact of nonlinearity is reduced for the outer channels.

To determine the Non-Linear Threshold (NLT) of our system, the maximum power (nonlinear limit) and minimum power (noise limit) per channel that gave $Q$=11.4 dB (which corresponds to BER=10^{-4}) are plotted against the system length for different numbers of WDM channels in Fig. 10.

In the noise limit regime, it is obvious that increasing the number of WDM channels has no effect on the noise limit, except when the NLT is approached, while in the nonlinear limit regime, the nonlinear limit decreases with increasing the number of WDM channels and reduces approximately 2 dB with each doubling of the system length. For system length of 4000 km with 32 WDM channels $Q$=11.4 dB could not be achieved.

The experimental system setup is the same as Fig. 2. The real valued OFDM signal is generated offline in MATLAB with the following parameters: number of subcarriers $N$=256, FFT size is 2048 and CP=1/8 of the useful OFDM symbol duration. The OFDM signal, which occupies the frequency range from 2.5 to 5 GHz, is displaced by frequency gap $W_c$=2.5 GHz for the reason mentioned previously. The signal is then downloaded to an arbitrary waveform generator (AWG7102) which is used in an interleaved mode to give a sampling rate of 20 GS/s. The resolution of the digital-to-analog converter (AWG7102) is 8 bits. The nominal baud rate is then 2.5GBaud/s. The output signal from the AWG is then amplified to drive the single drive MZM. For SSB transmission, a tunable optical filter (0.2 nm) is used to suppress one sideband and the signal is then boosted with an optical amplifier.

At the receiver, the signal is preamplified, a fiber Bragg Grating (0.2 nm FWHM) is used as an ASE filter and the optical signal is detected by 12 GHz photoreceiver. The received data is captured using digital sampling oscilloscope (Tektronix DPO72004) of 50 GS/s. A post processing is performed offline in MATLAB including up/down sampling, synchronization and OFDM demodulation and equalization.

### IV. EXPERIMENTAL RESULTS

The experimental system setup is the same as Fig. 2. The real valued OFDM signal is generated offline in MATLAB with the following parameters: number of subcarriers $N$=256, FFT size is 2048 and CP=1/8 of the useful OFDM symbol duration. The OFDM signal, which occupies the frequency range from 2.5 to 5 GHz, is displaced by frequency gap $W_c$=2.5 GHz for the reason mentioned previously. The signal is then downloaded to an arbitrary waveform generator (AWG7102) which is used in an interleaved mode to give a sampling rate of 20 GS/s. The resolution of the digital-to-analog converter (AWG7102) is 8 bits. The nominal baud rate is then 2.5GBaud/s. The output signal from the AWG is then amplified to drive the single drive MZM. For SSB transmission, a tunable optical filter (0.2 nm) is used to suppress one sideband and the signal is then boosted with an optical amplifier.

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1000 OFDM symbols were transmitted. 4 and 16-QAM modulation formats were considered here. The OSNR was measured within 0.1 nm resolution bandwidth.

Fig. 12 shows the results for B2B transmission where the BER curves are plots versus OSNR. It can be seen from Fig. 12 that at BER=10^{-3}, the required OSNRs are ~9.5dB and 19.5dB for 4-QAM and 16-QAM respectively, that is the OSNR penalty is ~10dB when we move from 4 to 16-QAM, which is 3dB more compared to the simulation results (see Fig. 5). This can be attributed to the impacts of DAC filtering (suppression of high frequency subcarriers) and MZM nonlinearity. These impacts become high as the modulation level increases, and as a result more 3dB OSNR is required. Fig. 13 shows the results after 100km transmission. It is obvious that no OSNR penalty is obtained compared with B2B transmission.

VI. CONCLUSIONS

We demonstrate and investigate the behavior of DD-OFDM with different high-order modulation formats, ranging from 4-QAM up to 64-QAM. The investigations are based on the assumption that the optical and electronic devices are all 10 Gbit/s equipment irrespective of the modulation level. Thus we automatically increase the bitrate up to a factor of three without requesting more bandwidth or higher speed components. From the given results one can estimate the OSNR-requirements for all those constellations. We observe roughly a 3-dB degradation per doubling of the constellation size. Moreover, we investigate the impact of fiber nonlinearity for 4-QAM modulation format in long-haul WDM-OFDM transmission with direct detection. Transmission of 32×10.7 Gb/s over 3200km SSMF is possible. Finally, experimental results for 4-QAM and 16-QAM are demonstrated.

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REFERENCES

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