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.

Keywords: optical communications, modulation, QAM, OFDM, direct detection.

1. 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. Finally we investigate the system in a dispersive transmission scenario based on an optimized system design.

2. 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.

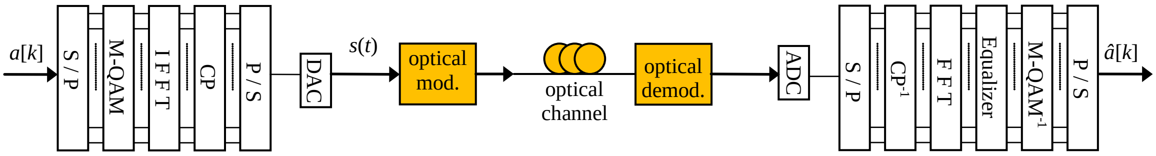

Figure 1.Schematic diagram of Optical-OFDM System.

In this paper, direct detection optical-OFDM (DD-OFDM) is considered. The mean 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_g)*: 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.

- *Single-sideband (SSB) transmission*: to avoid the power null fading due to the chromatic dispersion and to enable a powerful and simple equalization method.

3. 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 [5]. 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, serial-to-parallel conversion, FFT, post detection OFDM equalization, symbol de-mapping and parallel-to-serial conversion (see Fig. 1).

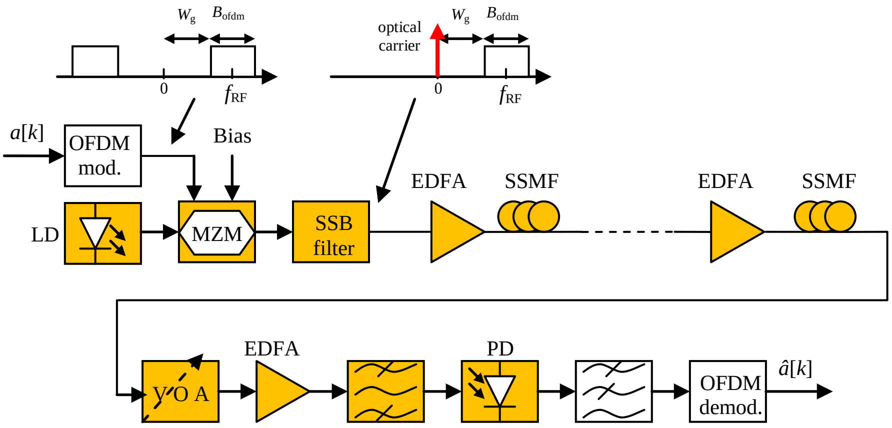

Figure 2.DD-OFDM System setup.

Baud rate of 5.35GBaud including 7% overhead for forward error correction (FEC) are used as this is compatible with existing component technology. The received raw Baud rates after FEC decoding and removing of cyclic prefix are 5 Gbit/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).

3.1 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 [6]. 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.

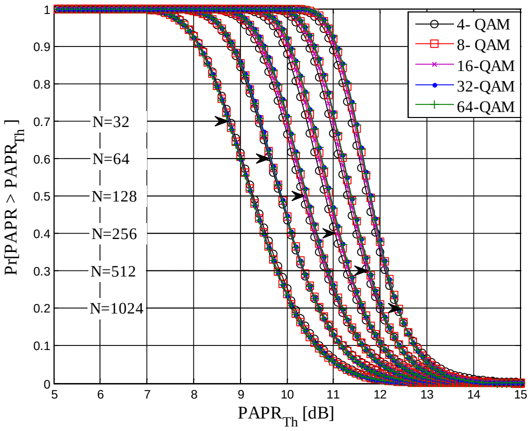

Figure 3.PAPR distribution for different modulation formats and different number of subcarriers.

The PAPR of the transmitted signal is obtained 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 $PAPR_{TH}$ 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 .

3.2 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, carrier to single sideband power ratio (PR)=1 for each modulation format to achieve optimum receiver sensitivity [7]. 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 σ_s divided by the switching voltage V_π.

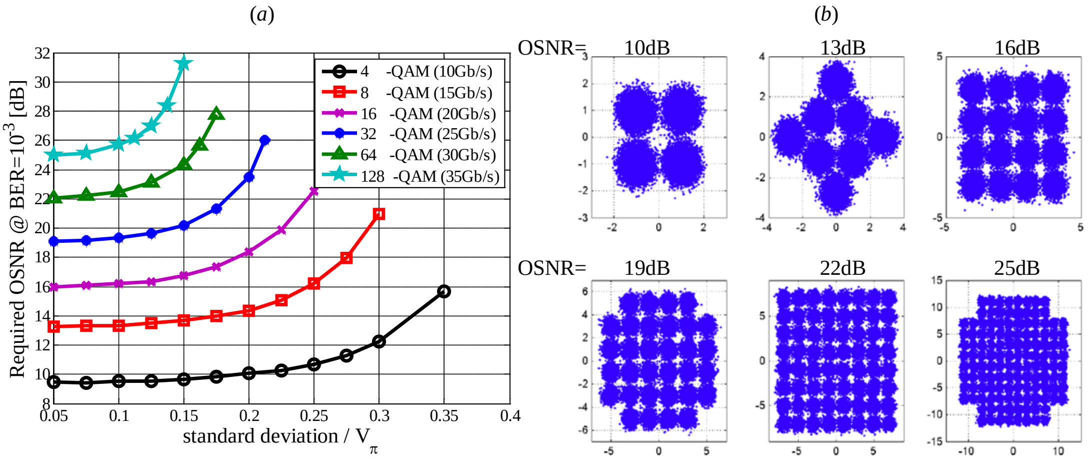

Figure 4.Impact of MZM nonlinearity (a). Received constellations for different OSNR and modulation formats at BER≈10^{-3}(b).

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}.

3.3 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.

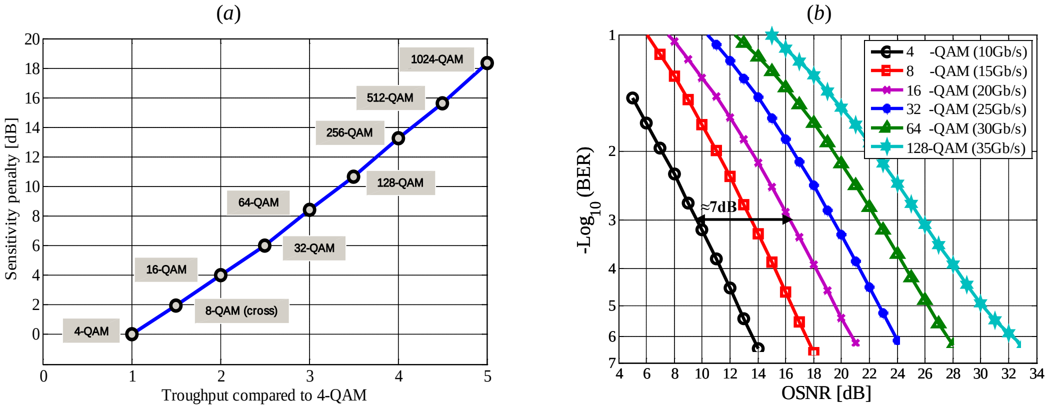

Figure 5.Sensitivity penalty for different modulation formats (a). Receiver sensitivity for different modulation formats (b).

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 from4-QAM to 16-QAM results in a mean power of $5d^2/2$ per symbol compared to $d^2/2$ 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 ratios is required to achieve the same BER compared to 3 dB increase in data throughput [8]. 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*).

3.4 Simulation Results with Fiber Channel

The benefit of the cyclic prefix (CP) in OFDM, to minimize the chromatic dispersion induced ISI, is examined here. Linear fiber model is considered and the number of subcarriers used here is *N*=256. Fig. 6(*a*) 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 the Fig. 6(*a*) that transmission is possible above 2000km for all cases. Longer transmission reach can be obtained by increasing the cyclic prefix. Fig. 6(*b*) shows the maximum transmission distance achieved when the relative cyclic prefix was increased to CP= 1/4. In all the *M*-QAM constellations considered, a transmission distance of over 3000km was reached.

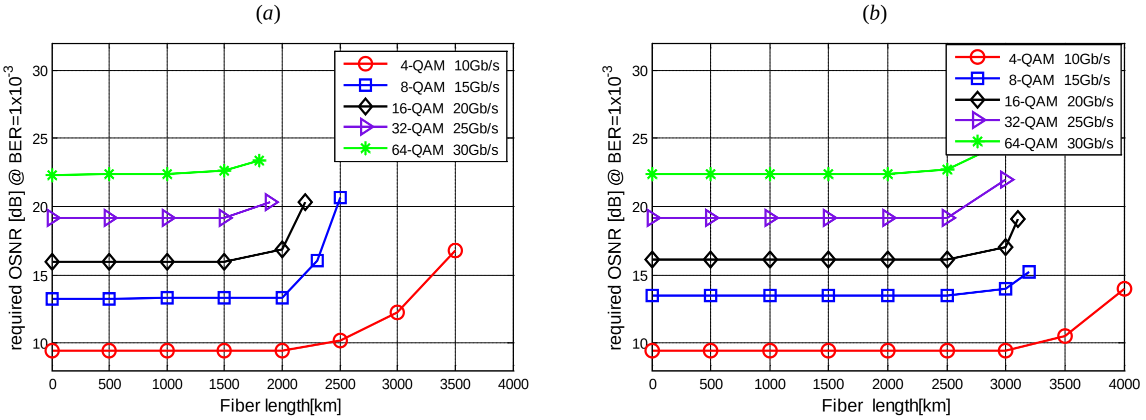

Figure 6.Required OSNR vs. number of spans (a). Required OSNR vs. fiber length (b).

4. 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.

ACKNOWLEDGEMENT

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