OFDM Spectral Efficiency Limits from Fiber and System Non-Linearities

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Abstract: Coherent optical OFDM systems offer a straight-forward approach to address high spectral efficiency. Non-linear impairments set limits to the maximum spectral efficiency. The limiting effects are explored by simulations, calibrated from published experimental results.

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1. Introduction

In recent years enormous progress has been achieved in optical transmission by applying coherent detection with electronic signal processing at the receiver. The ability to utilize polarization multiplexing (PDM) has allowed to double data rates on standard fibers. Similarly orthogonal frequency division multiplexing (OFDM) has been identified as a candidate technique to explore fiber capacity, i.e. the maximum data rate, which can be achieved [1]. PDM-CO-OFDM has gained much interest as this scheme allows efficient equalization of chromatic dispersion (CD) and polarization mode dispersion (PMD). The receiver delivers estimates of the channel model and the signal-to-noise ratio (SNR). The latter one is especially important, as it allows to estimate the achievable data rate. For the investigation of fiber limiting effects occurring from Kerr non-linearity we start with a single channel with optical bandwidth of 10GHz to explore the spectral efficiency (SE). As a cross-check simulation results were calibrated with the experimental outcomes presented in [1]. In a second setup a larger bandwidth was selected to fill up the same spectral range. The total optical power is kept constant. These results are then compared with [2], where an approach is described how to explore the maximum achievable data rate on single mode fiber.

2. OFDM system

Fig. 1 depicts the principal OFDM transmission system setup. Two independent baseband signals modulate the orthogonally polarized parts of the TX laser signal. At the receiver, polarization diverse coherent detection is applied. Channel estimation is based on pilot tones as described in [3]. The simulation parameters have been chosen close to the experiments reported in [1] with slight adaptation to a 10 GHz WDM grid (see Table 1). The simulation model of the DAC and ADC devices assume equidistant quantization levels and 8 bit resolution. As OFDM signals have a high peak-to-average power ratio, distortion due to clipping has to be taken into consideration.

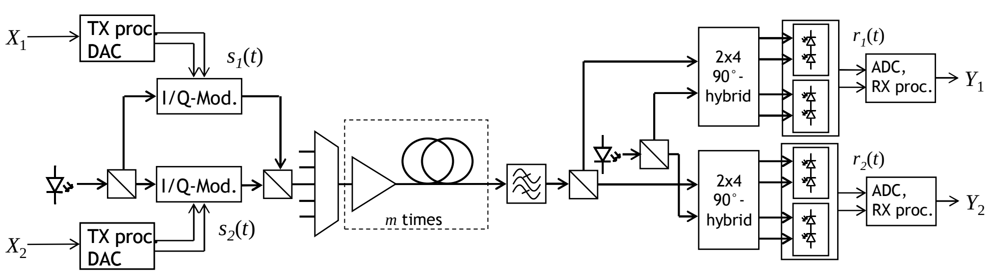

Fig. 1: Investigated OFDM system.

The "clipping ratio" is defined as the maximum allowable signal amplitude over the root mean square of the signal. This parameter is set to 10 dB in the following. The I/Q-modulators are modeled as linear devices assuming that a memory-less non-linearity can be compensated for by appropriate pre-distortion, similar to the concepts used in RF power amplifiers of wireless base stations. Simulations have been carried out for multiple span transmissions. The optical link consisted of 2 to 12 spans of 80 km SSMF. Optical amplifiers compensate the attenuation of 16 dB per span with a noise figure NF = 4 dB. The resulting OSNR value (defined in a reference bandwidth B_{ref} of 12.5 GHz (0.1 nm)) depends on the launch power P_{Tx} per channel and the number of spans m.

$$\mathrm{OSNR}_{dB} = 58 - \mathrm{NF} - \mathrm{G} + \mathrm{P}_{Tx} + 10\log_{10}(\mathrm{m}) = 58 - 4 - 16 + \mathrm{P}_{Tx} + 10\log_{10}(\mathrm{m}) = 38 + \mathrm{P}_{Tx} - 10\log_{10}(\mathrm{m}) \quad (1)$$

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Gross bit-rate	70 Gb/s
Number of sub-carriers	192
Symbol duration	20.3 ns
Symbol constellation	16QAM
Cyclic prefix length	1/12 of OFDM symbol duration
ADC/DAC resolution	8 bit
Clipping ratio	10 dB
LO laser line-width	100 kHz
WDM channels	20
WDM channel grid	10 GHz
Dispersion coefficient	D = 17 ps/nm/km
Span length	80 km

Table 1: System parameters.

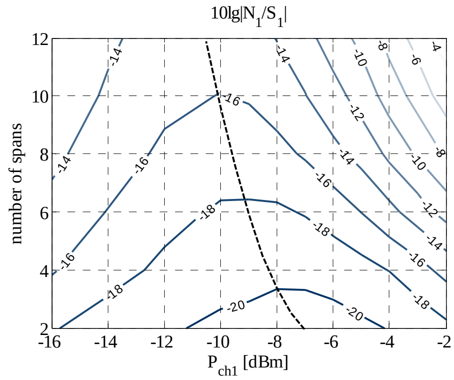

Fig. 2: Estimated inverse SNR for 2 up to 12 spans. Dashed line indicates optimum launch power P_{Tx}.

In the presence of non-linearities, the procedure described in [4, 5] is used to estimate an equivalent noise power representing the signal distortions as additional noise contribution. Results for the inverse SNR in a single polarization are shown in Fig. 2, which have been obtained from averaging over 50 OFDM symbols. For longer distances the optimum launch power (dashed line) decreases as expected.

3. Estimates for Spectral Efficiency

Assuming a band-limited channel of bandwidth B and additive white Gaussian noise (AWGN) the maximum information-rate which can be transmitted according to Shannon is given by (p is the number of polarizations):

$$C = B \cdot \log_2\left(1+\left(\frac{S}{N}\right)_{pol}\right), \qquad \text{with} \qquad \left(\frac{S}{N}\right)_{pol} = \frac{2 \cdot B_{ref}}{p \cdot B} \cdot \text{OSNR} \tag{2}$$

An ideal transmission scheme using forward error correction allows for error-free transmission at the Shannon limit. Dividing (2) by the signal bandwidth B results in the maximum achievable spectral efficiency Γ. As both orthogonal polarizations use the same frequency band we add up their contributions for the capacity and obtain

$$\Gamma = \eta \cdot \left(\log_2\left(1+\frac{S_1}{N_1}\right)+\log_2\left(1+\frac{S_2}{N_2}\right)\right), \tag{3}$$

where η describes the ratio between channel bandwidth and channel spacing in frequency division multiplex systems. The ratio shall be close 1 to achieve high spectral efficiency.

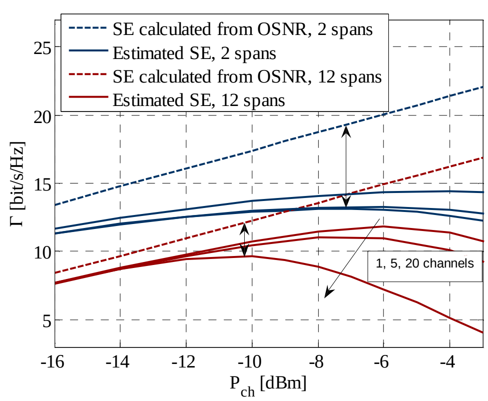

Fig. 3: Estimated spectral efficiency versus optical input power for 10 GHz channel bandwidth.

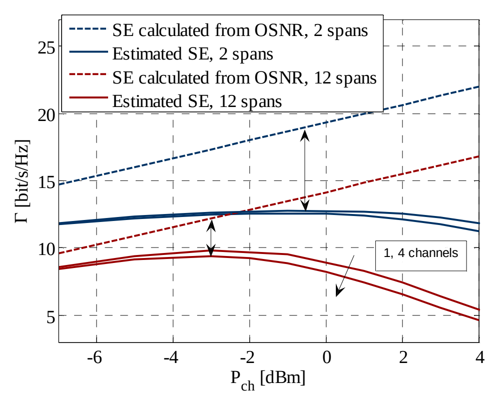

Fig. 4: Estimated spectral efficiency versus optical input power for 50 GHz channel bandwidth.

The estimated relative noise powers presented in Fig. 2 can thus be translated into an estimate for the maximum achievable spectral efficiency. In Fig. 3 and 4 the dashed line gives the values for pure ASE noise contribution, calculated by Eq. (1) while the straight line includes all degrading effects. The difference at very small channel power is due to other impairments than fiber non-linearity, e.g. laser line width, signal clipping and quantization. As can be seen the drop in SE for shorter distances becomes significant. Fig. 4 shows results for increased channel

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bandwidth of 50 GHz (same overall data rate). The per-channel power is increased by a factor of 5 (7 dB), but the principal behavior is similar.

4. Simulation Results and Discussion

Applying the model described in preceding sections the achievable spectral efficiency is estimated based on 4 different conceptual approaches. The results are shown in Fig. 5:

1) The theoretical bound for spectral efficiency on SSMF has been addressed in literature, e.g. [2]. For distances of 500 km, 1000 km and 2000 km maximum values have been extracted from the respective publications (blue stars), where a theoretical constellation in concentrical circles, distributed Raman amplification and pulse pre-distortion for SPM compensation has been assumed.

2) Experimental results for spectrally efficient transmission systems from recent literature [1, 6-10] are given by green circles. These are close to real implementation and include hardware limitations. These values for achieved SE present the upper limit for systems utilizing today's technology. In order to perform trustworthy simulations (red diamonds) different symbol constellations (4QAM to 32QAM) were applied, based on the ODFM parameter set close to [1] as described earlier, assuming a typical FEC code rate of 0.93 with corresponding pre-FEC BER of 10^{-3}.

3) Using a simple SNR approximation based on the noise from accumulated ASE only (i.e. OSNR from eq.(1) together with P_{Tx} from Fig.2) provides the values shown as black crosses. Ignoring non-linear distortion does overestimate the achievable spectral efficiency significantly, as can also be seen by the gap between the straight and the dashed lines in Fig. 3 and 4.

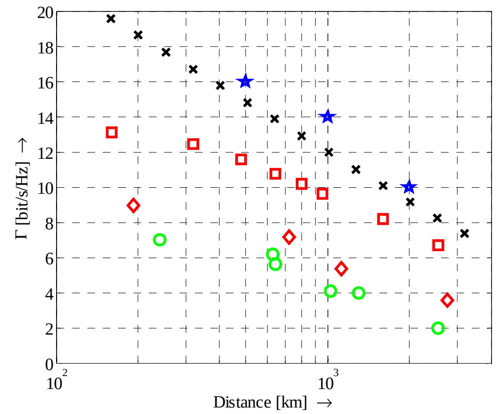

Fig. 5: Comparison of achievable spectral efficiency versus distance (explained in text).

4) Based on the concept of equivalent noise power estimation, a maximum spectral efficiency can be computed, which includes contributions from all degrading effects as equivalent additive noise sources (red squares). Especially the drop due to non-linear distortion is considered. The upper limit for short distances is caused by laser phase noise, quantization noise as well as clipping. This approach shall provide a realistic estimate for the "Shannon limit", however, does not give a constructive procedure to get there. In order to close the gap from today's system performance based on a pre-FEC BER of around 10^{-3} improved coding schemes have to be explored for future optical transmission systems. Since the maximum achievable data rate depends on distance, the proposed method to derive a performance metric can also be utilized for data rate adaptation in future optical networks with dynamic path assignment.

5. Conclusions

In optical OFDM receivers equalization of the linear channel impairments is straight-forward. Separation of noise contributions revealed that in WDM systems spectral efficiency is limited by fiber non-linearity for long distances. On shorter links potential increase in SE is limited by further sources for degradation. Based on these simulation results, increased data rates of optical transmission systems can be expected, when more sophisticated coding schemes are applied to better explore spectral efficiency.

6. References

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