Impact of Nonlinearities on Optical OFDM with Direct Detection

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Abstract *The impact of Kerr effect and modulator nonlinearity on optical OFDM transmission is studied for an uncompensated link of 8x80km of SSMF. Especially, the dependency on the number of OFDM subcarriers considered.*

Introduction

Optical orthogonal frequency-division multiplexing (OOFDM) is another example of the current tendency in optical communications to consider technologies that are originally known from classical digital communications. Several aspects of OOFDM have been studied before, such as modulator nonlinearity and single side band filtering [1], dispersion tolerance [2], and PMD tolerance [3]. Experimental results have been reported also very recently [4,5].

From theory and mobile communications, nonlinear environments such as amplifier clipping are known to be very critical for OFDM [6]. For optical fiber transmission, nonlinear effects are mainly introduced by modulator characteristic and Kerr effect. In this contribution, we investigate, if these effects turn out to be as critical as in mobile communications.

While the majority of the current publications on OOFDM assume a certain fixed value for the number N of OFDM subcarriers, in mobile communications it is known to be a central parameter as a large value for N increases the sensitivity towards Doppler spread. Therefore, the dependency of nonlinearity on N is a central issue in this contribution.

OOFDM Setup

In the following setup, the bandwidth of the generated OOFDM signal is set to B_{OFDM}=21.4 GHz. This is equal to the minimum bandwidth required for 40 Gb/s (D)QPSK with 7% overhead for FEC.

Figure 1 shows the block diagram. First, the serial high speed data channel is separated into N low speed parallel data sub-channels. Each data path is mapped using 4-QAM (=QPSK) and presented to the input of an IFFT processor. A real-valued waveform and up-conversion to an intermediate frequency of f_{IF}=1.5·B_{OFDM}=32.1 GHz are generated by appropriate zero-padding and complex conjugate extension. Finally, the Guard interval is added. The resulting signal is modulated onto an optical carrier by a Mach-Zehnder-modulator (MZM), which is biased at the quadrature point. A Single-Side-Band (SSB) optical filter of B_{oSSB}=70 GHz bandwidth is used to transmit only one side of the two-sided OFDM spectrum and the optical carrier. The optical transmission line consists of 8 spans of 80 km of standard single-mode fiber. Span loss is compensated for by means of inline amplifiers. For the receiver, an optical attenuator in front of the optical preamplifier allows for OSNR tuning. ASE-noise is reduced by means of an optical filter with bandwidth B_{oSSB}. An electrical post-detection filter having a bandwidth of B_e=60 GHz models the bandwidth of the electrical circuit. OFDM demodulation is performed including the removing of Guard interval, serial-to-parallel conversion, FFT, post detection OFDM equalization, symbol de-mapping and parallel-to-serial conversion.

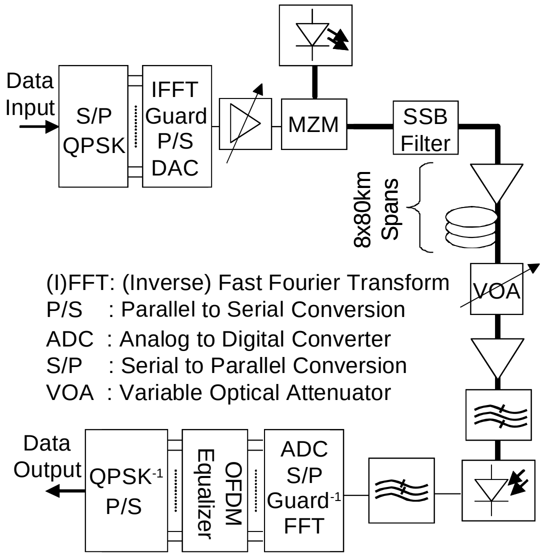

Figure 1: OOFDM Setup

Guard Interval and Raw Data Rate

An advantage of OFDM is its equalization technique which is a simple complex multiplication in frequency domain (=cyclic convolution). The Guard interval has to be of sufficient length, i.e. at least equal to the channel impulse response. However, the length of the impulse response of dispersive fiber theoretically is infinite. The actually observable length depends on signal bandwidth [7]. To use a Guard interval of constant length for all N, the bandwidth is fixed to B_{OFDM}=21.4 GHz resulting in OFDM symbol length of T_s=N/B_{OFDM} (e.g. T_s=96 ns for N=2048). In order to concentrate on nonlinear impairments, the length of the Guard interval is chosen long enough such that there is no dispersion-induced interference from one OFDM symbol to the next one. By simulation, a value of T_G=12 ns is found. A raw data rate (after FEC decoding) of 20 Gb/s, 26.7 Gb/s, 30 Gb/s and 32 Gb/s is obtained for N=256, 512, 1024 and 2048, respectively. However, accepting slight interference between the OFDM symbols will allow for decreasing the length of Guard interval and the raw data rate will approach 40 Gb/s without significant degradation.

MZM Nonlinearity

The MZM is biased at quadrature point where the power transfer characteristic is linearizable. By means of low modulation depth, the nonlinear distortions due to the MZM can be made arbitrarily small. This results in low ratio of useful power to carrier power, i.e. the sensitivity is low. Hence, modulation depth is a compromise between these constraints.

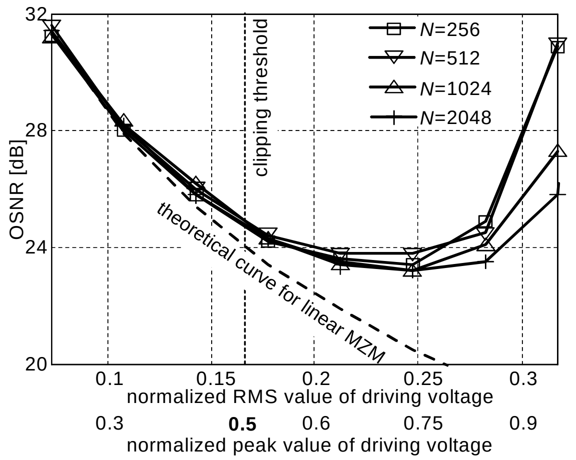

Figure 2: Required OSNR for BER=10^{-3} as function of driving voltage swing.

Figure 2 shows results for back-to-back transmission obtained by Monte-Carlo simulation. The OSNR for BER=10^{-3} is plotted vs. normalized driving voltage. The normalization is performed such that minimum and maximum optical output power are obtained for instantaneous input voltages of -0.5 and 0.5, respectively. Beyond these values, clipping occurs due to MZM characteristic. The OFDM signal is an analog signal having nearly Gaussian amplitude distribution [6]. In good approximation, the peak voltage is within an interval from plus to minus the triple of the RMS voltage. This relation is used to create the lower from the upper of the two horizontal axes. The clipping threshold obtained for a peak voltage of ±0.5 is given in the figure, too. Finally, the impact of MZM nonlinearity, which within the range of acceptable sensitivity obviously does not depend significantly on *N*, is identified by means of the dashed line.

Fiber Nonlinearity

Figure 3 depicts the nonlinear performance of the fiber link. To investigate only one impairment at a time, the MZM is driven in the quasi-linear range with a normalized effective voltage swing of ≈0.15 resulting in a back-to-back sensitivity of ≈25.5 dB. This value is significantly above those reported e.g. in [5], which is due to incoherent detection and higher bandwidth. For low values of launch power, figure 3 shows the robustness of OOFDM towards fiber dispersion, as the OSNR penalty achieved with ≈11000 ps/nm accumulated dispersion is negligible. In the nonlinear regime, however, penalty increases rapidly. Beyond 8 dBm fiber launch power, the BER does not fall below 10^{-3} due to strong signal distortion. The optical power consists of a strong DC component and a weaker AC component carrying the OFDM-signal. Since only the AC component results in signal distortion [8], the acceptable launch power found in this contribution is higher than for coherent detection.

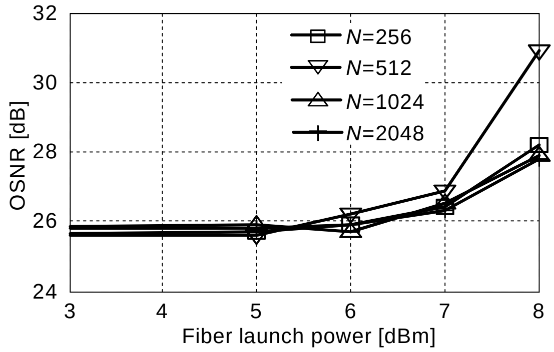

Figure 3: *Required OSNR for BER=10^{-3} as function of fiber launch power.*

Except for the value for *N*=512 at *P*=8 dBm, attributed to limited simulation accuracy, the result does not depend on *N*. Increasing *N* decreases the separation between the subchannels, and fiber nonlinearity is expected to cause strong Cross-Phase Modulation and Four-Wave-Mixing. However, with increasing *N* the power per subchannel is decreased. Apparently, both aspects cancel out each other to result in equal performance for all *N*.

Conclusions and Perspective

The impact of nonlinear modulator characteristic and Kerr effect is studied for an uncompensated OOFDM 8x80 km fiber link with a varying number *N* of subcarriers. Both impairments are independent of *N*. Obviously, OOFDM is quite robust towards the specific nonlinear impairments in fiber-optic transmission systems and therefore it seems as if in contrast to mobile communications there is no upper limit for *N* from point of view of system performance.

References

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