Sensitivity Bound for Optically-Preamplified Direct-Detected OFDM Systems Using Spectrally Matched Filters

Wei-Ren Peng[1], Kai-Ming Feng[2], Alan E. Willner[3], and Sien Chi[1]
1 . Department of Photonics & Institute of Electro-Optical Engineering, National Chiao Tung University, Hsinchu, Taiwan 300, R.O.C.
Tel: +886-3-5712121- 52992, E-mail: pwr.eo92g@nctu.edu.tw
2. Institute of Communications Engineering, National Tsing Hua University, Hsinchu, Taiwan 300, R.O.C.
3. Department of Electrical Engineering, University of Southern California, Los Angeles, CA 90089, USA

Abstract: We investigate the sensitivity bound, in terms of OSNR, for direct-detected OFDM systems in presence of optically-preamplified receivers, and show that OSNR requirement for DD-OFDM could theoretically reach that of CO-OFDM using the spectrally matched filters.

OCIS codes: (060.2330) Fiber optics communications; (060.4080) Modulation

1. Introduction

Optical orthogonal-frequency-division-multiplexing (OFDM) has attracted much attention since the fiber chromatic dispersion (CD) and polarization mode dispersion (PMD) can be electronically equalized through the receiver-end digital signal processing (DSP) [1-2]. Compared with the coherent optical OFDM (CO-OFDM), the direct-detected OFDM (DD-OFDM) uses simpler receiver architectures and thus is an alternative candidate for next generation metropolitan and long-haul transmission.

In spite of its simpler and cost-effective implementations, the DD-OFDM approach has a much poorer sensitivity (~5-9 dB) in terms of optical signal to noise ratio (OSNR) compared with CO-OFDM [3-4], depending on the filter's optical bandwidth. However, the conclusions in [3-4] are obtained with the use of one broadband optical filter, covering the frequency range from the carrier to the whole data sideband, which would allow the ASE noise within the frequency gap to beat with the data sideband and result in an enhanced noise level after photodiode. In addition, the carrier to sideband power ratio (CSPR) is fixed at ~0 dB which would result in an inherent ~3-dB OSNR penalty relative to the coherent approach.

In this paper, we explore the sensitivity bound for DD-OFDM system using a spectrally matched filter, which is composed of two parallel optical filters having passbands for the carrier and sideband, respectively. This matched filter can reject the ASE noise within the frequency gap and naturally can improve the receiving sensitivity. We, theoretically and numerically, analyze the receiving performance with the matched filter, and found that, surprisingly, the ultimate sensitivity of DD-OFDM can approach that of CO-OFDM by continuously narrowing the bandwidth of the carrier's filter. We also investigate the impacts of some practical filter shapes on the improved sensitivity, and show that these impacts can be effectively mitigated via a use of optical amplifier in the carrier path.

2. Spectrally Matched Filter

The spectrally matched filter for DD-OFDM detection is shown in Fig. 1, which consists of two parallel optical filters for extracting the carrier and the data sideband, respectively. The filter bandwidths and amplitude gains are denoted as BWc and Hc for carrier extraction, and are denoted as BWs and Hs for the sideband. The sideband bandwidth is denoted as BW_D. With the assumptions of both BWc and $(BWs–BW_D) \ll BW_D$, and the use of

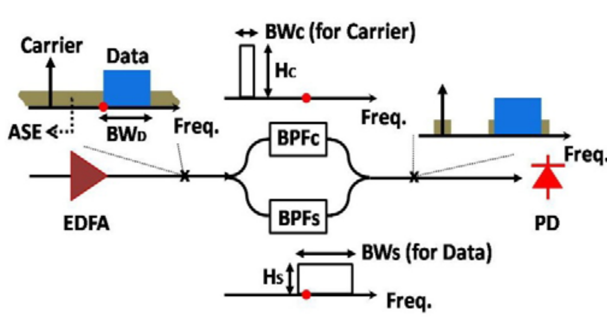

Fig. 1. DD-OFDM signal receiving using spectrally-matched optical filter. ASE: amplified spontaneous emission, EDFA: Erbium doped fiber amplifier, BPF: optical band-pass filter, PD: photodiode.

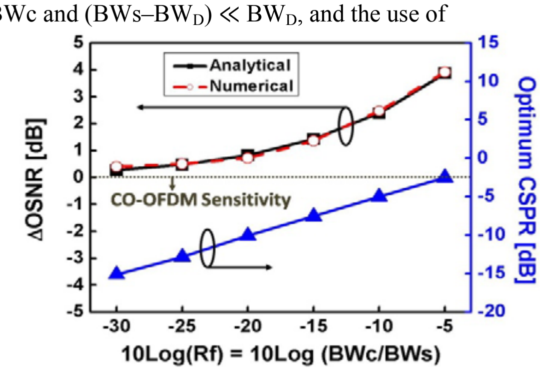

Fig. 2. OSNR penalty (relative to CO-OFDM) and the optimum CSPR vs. the bandwidth ratio Rf. Assumptions of BWs ≈ BW_D, rectangular filters, and $|H_C| = |H_S|$ are used in simulation.

rectangular filters to simplify the analysis, the converted ESNR for each subcarrier can be written as: ESNR = [OSNR*$\log_2$(M)]*[CSPR/ [(1+CSPR)*(CSPR+Rf)], where OSNR is defined with its noise bandwidth equal to the bit rate, M is the QAM size for each subcarrier, and Rf = (BWc / BWs) ≈ (BWc / BW_D) is the bandwidth ratio between the carrier and sideband filters' bandwidths. Interestingly, the gains of the filters, H_C and Hs, are cancelled out in this derived ESNR model. Since for CO-OFDM the ESNR is equal to [OSNR*$\log_2$(M)], the OSNR penalty of DD-OFDM relative to CO-OFDM is obtained as ΔOSNR [dB] = -10*log[CSPR/ [(1+CSPR)*(CSPR+Rf)], which is a function of CSPR and Rf. Using CSPR = 1, as has been broadly applied in many researches [3-4], the OSNR penalty is larger than ~3 dB based on the ΔOSNR model.

3. Results and Discussions

Shown in Fig. 2 are the theoretical results for the optimum CSPR values and OSNR penalties with different bandwidth ratio, Rf. Numerical simulations of OSNR penalty with 10-Gbps and 4-QAM DD-OFDM using rectangular optical filters are also presented to validate our theoretical results. With steadily reducing the carrier filter's bandwidth and the corresponding optimum CSPR, the OSNR penalty is found to be continuously mitigated and becomes even smaller than ~0.3 dB with a bandwidth ratio of Rf ≤ 0.001. Notably, the optimum CSPR, according to the results in Fig. 2, is found to be related to the bandwidth ratio Rf as CSPR [dB] ≈ 5*log(Rf).

In Fig. 3 the rectangular filters are both replaced by Gaussian-type optical filters. The OSNR penalties are obtained with different Gaussian orders of m = 1, 2 and 4, and the 3-dB bandwidths of the sideband filters are set to BW_D. The sensitivity for conventional DD-OFDM using one broadband filter, which has a rectangular passband with a bandwidth of ~2BW_D, is ~5.3 dB worse than CO-OFDM and is also presented in Fig. 3 for comparisons. Due to the slow frequency roll-off, the sideband filter with lower orders would involve more (data sideband x sideband filter's ASE) beating noise into the system, and will strongly limit the OSNR improvement when both Rf and CSPR are small. Thus, lower-order filters (m ≤ 4) actually put a limit on the OSNR improvement while higher-order filters (m = 4) can relax this limit and have similar OSNR improvements to those of using rectangular filters.

If the filters have different amplitude gains of $|H_C|^2$ = 100$|Hs|^2$, which could be equavilently achieved by boosting the carrier power (gain = 20 dB) as in [5], the results in Fig. 4 are shown with the rest parameters set to be equal to those in Fig. 3. Since the relatively high gain of H_C could help enhance the data sideband after PD and the (data sideband x sideband filter's ASE) noise could be ignored, the OSNR penalties behave similar to those with the rectangular filters and are independent of the filter orders. Note that, compared with the results in Fig. 2, the high gain of H_C will not directly improve the receiving sensitivity, but only relax the requirement for the filter parameters, such as the filters' orders and the sideband filter's bandwidths.

In summary, we explore the ultimate sensitivity, in terms of OSNR, of DD-OFDM with the spectrally matched filter and show that the sensitivity can continuously approach that of CO-OFDM, theoretically. Considering a practical 100-Gbps DD-OFDM (50 Gbps per polarization) system with a sideband bandwidth of ~16 GHz [2], the required carrier filter's bandwidth, with a filter's order ≥ 2, for a < 3-dB ΔOSNR is ~1-2 GHz, which has been commercially available with current fabrication technology. Although a relatively high gain of the carrier filter will not directly help improve the receiving sensitivity, it can effectively relax the requirements for filter's parameters and promise that the theoretical model presented in this paper is still true even with practical filters.

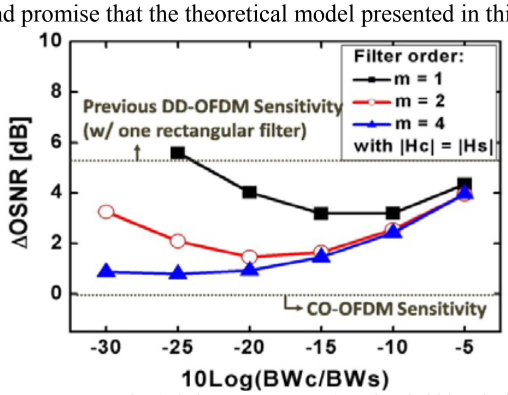

Fig. 3. OSNR penalty (relative to CO-OFDM) vs. bandwidth ratio for Gaussian-type optical filters with different orders of m = 1, 2, and 4. The filter gains of $|H_C| = |H_S|$ are used in simulation.

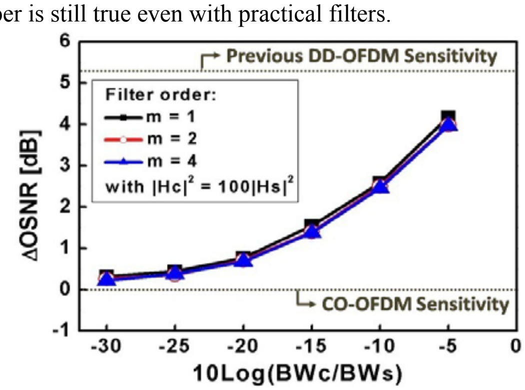

Fig. 4. Fig. 3. OSNR penalty (relative to CO-OFDM) vs. bandwidth ratio for different filter orders of m = 1, 2, and 4 with $|H_C|^2$ = 100 $|H_S|^2$.

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