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

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***Abstract*—We investigate the lower sensitivity bound, in terms of optical signal-to-noise ratio (OSNR), for direct-detected orthogonal frequency-division-multiplexing (DD-OFDM) systems in the presence of optically preamplified receivers. Using the spectrally matched optical filter, which is composed of two parallel filters for the carrier and sideband and has a passband matching to the signal spectrum, the ultimate sensitivity of DD-OFDM is found theoretically to approach that of coherent optical OFDM. We also investigate the effects of the filter's orders and bandwidths to the improved OSNR, and found that these effects could be effectively mitigated via the use of an optical amplifier for the carrier.**

***Index Terms*—Optical fiber communication, optical modulation, orthogonal frequency-division multiplexing (OFDM).**

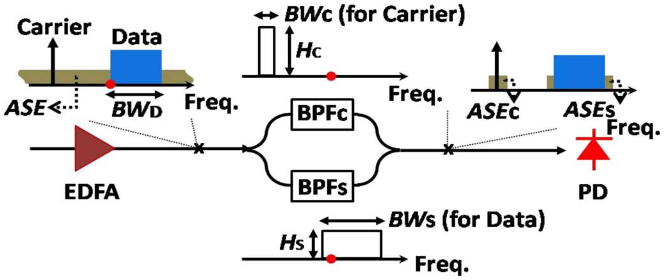

Fig. 1. DD-OFDM signal receiving using SMOF. ASE: amplified spontaneous emission; EDFA: erbium-doped fiber amplifier; BPF: optical bandpass filter; PD: photodiode.

I. 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]–[3]. Compared with the coherent optical orthogonal frequency-division multiplexing (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 [4], [5], depending on the optical filter's bandwidth. However, the conclusions in [4] and [5] 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 amplified spontaneous emission (ASE) noise within the frequency gap to beat with the data sideband and result in an enhanced noise level after the photodiode. In addition, the carrier-to-sideband power ratio (CSPR) [4], [5] is fixed at ~0 dB which would result in an inherent ~3-dB OSNR penalty relative to the coherent approach.

In this letter, we explore the sensitivity bound for the DD-OFDM system using a spectrally matched optical filter (SMOF), 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 could improve the receiving sensitivity. We theoretically analyze the receiving performance with SMOF, and find that the ultimate sensitivity of DD-OFDM, validated by the numerical results, can approach that of CO-OFDM by continuously narrowing the bandwidth of the carrier's filter. We also investigate the impacts of filter's orders and bandwidths on the improved sensitivity, and show that these impacts can be effectively mitigated via the use of an optical amplifier in the carrier path.

II. SPECTRALLY MATCHED OPTICAL FILTERS (SMOF)

The proposed SMOF architecture for DD-OFDM detection is shown in Fig. 1. The SMOF uses the first optical coupler to equally split the received signal and ASE, and has two optical bandpass filters (BPFs) on each branch for filtering out the carrier and the data sideband, respectively, and then combines the carrier and data sideband through the second optical coupler. The benefit of adopting such a filtering mechanism is that the ASE noise within the frequency gap will be discarded and will not deteriorate the received signal. The filter bandwidths and amplitude gains are denoted as BWc and Hc for the carrier's filter (BPFc), and are denoted as BWs and Hs for the sideband's filter (BPFs). The filtered ASE noise after the carrier's and sideband's filters are labeled as ASEc and ASEs, respectively, and the sideband bandwidth is denoted as $\mathrm{BW_D}$ and the total bandwidth of the OFDM signal including the frequency gap is $2\mathrm{BW_D}$. In this letter, the gap width is set to be equal to the sideband bandwidth since this is the minimum

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gap width that thoroughly prevents the signal from suffering the signal–signal beat interference (SSBI) [4], [5]. After photodiode, the beat noise can be mainly categorized as 1) cross-beating noise: (carrier × ASEs) and (sideband × ASEc), and 2) self-beating noise: (carrier × ASEc) and (sideband × ASEs). With the assumptions of both BWc and $(\mathrm{BWs} - \mathrm{BW_D}) \ll \mathrm{BW_D}$, the self-beating noise will fall on within the frequency gap and take no effect on the desired signal. Thus, the electrical signal-to-noise power ratio (ESNR) for each subcarrier only needs to consider the cross-beating noise, and can be written as follows:

$$\mathrm{ESNR} = \frac{|A|^2|H_C|^2|d|^2|H_S|^2}{N_o\left\{|A|^2|H_C|^2|H_S|^2\Delta f + |d|^2|H_C|^2|H_S|^2\mathrm{BW}_C\right\}} \tag{1}$$

where A and d are the amplitudes of the optical carrier [6], or the inserted RF-tone [3], [5], and modulated symbol on each subcarrier, respectively, for which we assume the optical power on each data subcarrier are equal. N_o represents the power spectral density (PSD) of ASE per polarization, and Δf is the subcarrier frequency spacing. After some manipulations with the relations of $|A|^2 = P_T * \mathrm{CSPR}/(1+\mathrm{CSPR})$ and $|d|^2 = P_T/[N_d * (1+\mathrm{CSPR})]$, where P_T is the total received optical power and N_d is the number of data subcarriers [5], the ESNR can be further simplified as

$$\mathrm{ESNR} = 2\mathrm{OSNR}\left[\frac{\mathrm{CSPR}}{(1+\mathrm{CSPR})(R_f+\mathrm{CSPR})}\right] \tag{2}$$

where $\mathrm{OSNR} = P_T/(2N_o * \mathrm{BW_D})$ is defined considering both polarizations with its noise bandwidth equal to $\mathrm{BW_D}$, and $R_f = (\mathrm{BWc}/\mathrm{BW_D})$ is the ratio between the carrier filter's bandwidth and the sideband's bandwidth. Interestingly, the gains of the filters, $\mathrm{H_C}$ and Hs, are cancelled out in (2). Contrary to the colored ESNR distribution with the previous one-broadband-filtering approach [4], [5], the ESNR with SMOF is derived independently to the subcarrier index, meaning that the ESNR is whitely distributed over the signal band. The bit-error rate (BER) associated with this analytically obtained ESNR can be easily evaluated via (12) in [7]. Since for CO-OFDM the ESNR is equal to 2OSNR, the OSNR penalty of DD-OFDM relative to CO-OFDM can be directly derived as

$$\Delta\mathrm{OSNR[dB]} = -10\log_{10}\left[\frac{\mathrm{CSPR}}{(1+\mathrm{CSPR})(R_f+\mathrm{CSPR})}\right] \tag{3}$$

which is a function of both CSPR and R_f. Using the Cauchy–Schwarz's inequality, the minimum $\Delta\mathrm{OSNR}$ [dB] of $20\log_{10}(1+\sqrt{R_f})$ can be obtained with the optimum $\mathrm{CSPR} = \sqrt{R_f}$. Thus, with infinitely small values of R_f and CSPR, the penalty $\Delta\mathrm{OSNR}$ could be theoretically reduced to zero, meaning that the DD-OFDM, theoretically, could have a comparable receiving sensitivity with CO-OFDM when the carrier's filter has an infinitely narrow bandwidth. However, in the conventional DD-OFDM systems with $\mathrm{CSPR} = 1$, as has been broadly applied in many studies [4], [5], the OSNR penalty is larger than ~3 dB based on (3).

III. Results and Discussion

Shown in Fig. 2 are the theoretical results for the OSNR penalties with different bandwidth ratios R_f. Numerical simulations of OSNR penalty with 10-Gb/s and 4-QAM DD-OFDM using rectangular optical filters are also presented to validate our theoretical results. The number of data subcarrier and total fast Fourier transform (FFT) size are 64 and 512 with an oversampling ratio of 8 which should be high enough for modeling a real system. The bandwidths of the reserved frequency gap and the sideband's filter are both set equal to the bandwidth of the data sideband $\mathrm{BW_D}$ so that the self-beating noise will not take any effect on the receiving performance. The OSNR penalty, which is evaluated relative to the cyclic-prefix free 10-Gb/s, 4-QAM CO-OFDM system throughout this letter, is found to be ~6.9 dB (noise bandwidth $= \mathrm{BW_D}$) at $\mathrm{BER} = 10^{-3}$ with the consideration of both polarizations. The analytical results of OSNR penalty in Fig. 2 are drawn with (3) and the optimum CSPR is obtained by simply taking the square root of R_f. With steadily reducing the carrier filter's bandwidth and the corresponding optimum CSPR, the OSNR penalty, both analytically and supported numerically, is found to be continuously mitigated and becomes even smaller than ~0.3 dB with a bandwidth ratio of $R_f \approx 0.001$. The relative penalty of ~5.3 dB for the conventional DD-OFDM system, which uses a rectangular passband filter with a bandwidth of $\sim 2\mathrm{BW_D}$ covering the frequency range from the carrier to the whole sideband, is also presented in Fig. 2 for comparisons.

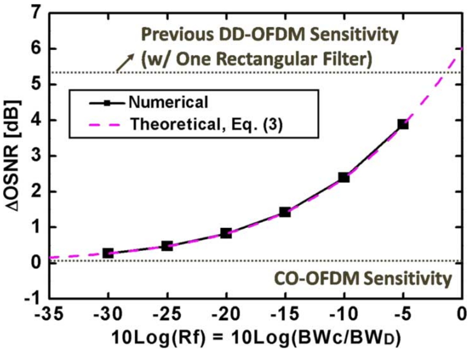

Fig. 2. OSNR penalty (relative to CO-OFDM) versus the bandwidth ratio R_f. Assumptions of $\mathrm{BWs} \approx \mathrm{BW_D}$, rectangular filters, and $|\mathrm{H_C}| = |\mathrm{H_S}|$ are used in simulation.

In Fig. 3(a), the rectangular filters used for Fig. 2 are both replaced by Gaussian-type optical filters for the purpose of a more practical system consideration. In simulations, the amplitude gains of the carrier and sideband filters are set to equal, that is, $|\mathrm{Hc}| = |\mathrm{Hs}|$. The OSNR penalties, as well as the optimum CSPR, are obtained with different Gaussian orders of $m = 1, 2,$ and 4, and the 3-dB bandwidths of the sideband filters are set to $\mathrm{BW_D}$. The CSPR results for Fig. 3 are numerically obtained for the minimum BER with an resolution of 0.5 dB. We found in Fig. 3(a) that both the optimum CSPR and $\Delta\mathrm{OSNR}$ follow the theoretical results, which are represented by the dashed curves, only for larger R_f values, and eventually will deviate the theoretical predictions and have the improvement limitations for smaller R_f values. The origins of these limitations can be explained as follows. Due to the inherent frequency roll-off, the sideband filter will involve the self-beating noise of (sideband × ASEs) into the converted signal band. Since the power of cross-beating noise, considered in deriving (3), will eventually become insignificant with continuously decreasing R_f values, the self-beating noise instead will dominant the system performance for small R_f values and will break

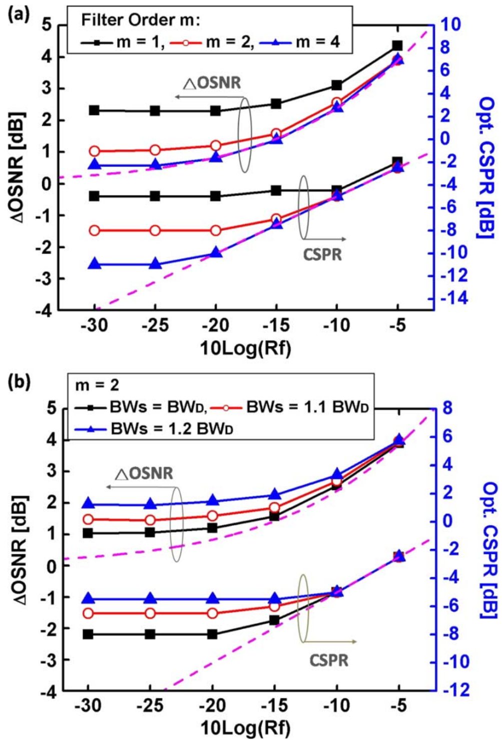

Fig. 3. OSNR penalty (relative to CO-OFDM) and the optimum CSPR as a function of the bandwidth ratio R_f with $|H_{\mathrm{C}}| = |H_{\mathrm{S}}|$ for Gaussian-type optical filters. (a) Different Gaussian orders of $m = 1, 2,$ and 4 with fixed bandwidth $\mathrm{BWs} = \mathrm{BW_D}$, and (b) different sideband bandwidths of $\mathrm{BWs} = 1, 1.1,$ and $1.2\ \mathrm{BW_D}$ with fixed filter order $m = 2$. The dashed lines are the theoretical results.

the conditions for obtaining (3). To combat with the extra self-beating noise, a finite carrier power to maintain the electrical signal power [5] is necessary and thus yields the improvement limitations in Fig. 3(a). Because of the slow frequency roll-off, the lower order filter $(m = 1)$ will need more carrier power for combating the self-beating noise and will eventually have a worse OSNR improvement when compared with the higher-order filters. Fortunately, with higher order filters $(m = 2, 4)$, the extra OSNR penalties compared with the theoretical results are found to be <1 dB for $R_f \geq 0.001$.

In Fig. 3(b), we change the bandwidth of the sideband filter of $m = 2$ with its 3-dB bandwidth of $\mathrm{BWs} = 1, 1.1,$ and $1.2\ \mathrm{BW_D}$. Similar the case with different filter orders, the impact of utilizing a broader bandwidth for the sideband filter is the involvement of the self-beating noise to the signal band. Thus, the optimum CSPR and the OSNR improvement would still have their limits when R_f is small. However, the minimum $\Delta\mathrm{OSNR}$ for all the three considered bandwidths can still reach as low as ≤~2 dB.

If the filters have different amplitude gains with $|\mathrm{H_C}|^2 = 100|\mathrm{Hs}|^2$, which could be equivalently achieved by boosting the carrier power $(\mathrm{gain} = 20\ \mathrm{dB})$ as in [6], the results in Fig. 4 are simulated with the rest parameters equal to those in Fig. 3. Since the relatively high gain of $\mathrm{H_C}$ will enhance both the electrical power of the data sideband and the cross-beating noise, the self-beating noise will become insignificant which will keep the theoretical predictions of (3) still be true even involving the filter's finite order and broader sideband bandwidths. In Fig. 4, we consider three different bandwidths of $\mathrm{BWs} = 1, 1.2,$ and $1.5\ \mathrm{BW_D}$ with $m = 1$, which should introduce the most self-beating noise power, and use the optimum $\mathrm{CSPR} = \sqrt{R_f}$ for $\Delta\mathrm{OSNR}$ evaluations. With the extra gain for the carrier, we found all the considered filters have removed the improvement limitations and basically follow the theoretical predictions of (3).

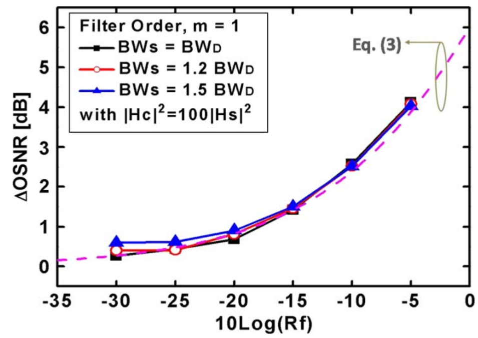

Fig. 4. OSNR penalty (relative to CO-OFDM) versus bandwidth ratio R_f with $|H_{\mathrm{C}}|^2 = 100|H_{\mathrm{S}}|^2$. Different bandwidths of $\mathrm{BWs} = 1, 1.2,$ and $1.5\ \mathrm{BW_D}$ with filter order of $m = 1$ are considered.

In summary, we explore the ultimate sensitivity, in terms of OSNR, of DD-OFDM with SMOF and show that the sensitivity could theoretically approach that of CO-OFDM. We further investigate the impacts of the filters' order and the sideband's bandwidth and show that the carrier filter's gain can effectively mitigate these practical effects. However, although we have demonstrated that $\Delta\mathrm{OSNR}$ could be less than 1 dB with very small values of R_f, the current technologies would limit the minimum achievable R_f in the range of $R_f > 0.1$, which will in turn yield a minimum OSNR penalty of $\Delta\mathrm{OSNR} =\sim 2.4$ dB with a filter order of ≥2. The penalty could be further reduced with the consideration of the laser linewidth because of its greater impact on CO-OFDM system.

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