Performance Evaluation of Direct-Detection OFDM Optical Receivers with RF Down-Conversion

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Abstract— **A new method based on the moment generating function is proposed to assess the performance of a direct-detection OFDM optical communication system with radio-frequency I/Q demodulation and its accuracy is validated by Monte Carlo simulation.**

I. INTRODUCTION

Nowadays, orthogonal frequency division multiplexing (OFDM) has become an alternative modulation format both for coherent-detection and direct-detection (DD) optical fiber communication systems due to its improved spectral efficiency, enhanced digital signal processing and also due to convergence between radio and optical fiber transmission systems [1], [2].

In [3], an analytical method based on the moment generating function (MGF) has been proposed to assess the performance of DD optical receivers with OFDM baseband signals. However, most DD-OFDM communication systems move the OFDM spectrum from the baseband region where undesirable intermodulation distortion products fall, by performing radio-frequency (RF) up-conversion at the transmitter side, which demands an RF down-conversion at the DD-OFDM optical receiver side.

In this work, the method proposed in [3] is generalized to DD-OFDM optical receivers with intermediate RF down-conversion. The accuracy of the generalized method is assessed by comparison of its bit error probability (BEP) estimates with the estimates obtained from Monte Carlo (MC) simulation.

II. OFDM OPTICAL RECEIVER MODEL AND THEORY

Fig. 1 shows the model of the optically preamplified direct-detection receiver followed by the OFDM electrical receiver with I/Q demodulation at the RF frequency f_{RF}. This model is a generalization of the baseband OFDM optical receiver described in [3]. The optical receiver model includes an optical amplifier, an optical filter, a PIN photodetector and an electrical filter [4]. The OFDM signal is assumed to have been generated electrically using an I/Q RF modulator, with subsequent conversion to the optical domain. Hence, at the optical receiver input, the OFDM signal spectrum is centered f_{RF} above the main optical carrier. The optical amplifier adds amplified spontaneous emission (ASE) noise to the signal. The ASE noise is modeled as completely unpolarized additive white Gaussian noise. The PIN photodetector is modeled as a square-law device with unit responsivity and its frequency limitations are modeled by an electrical filter.

The current at the optical receiver output is splitted between the two branches of the I/Q demodulator, mixed with the signals from the local oscillators and electrically filtered by a lowpass filter with transfer function $H(f)$. The analog-to-digital converter (ADC) samples the current at the I/Q demodulator output at the time instants $t_k^{(\gamma)} = t_o^{(\gamma)} + (k-1)T_c$, with $k = 1,\ldots,N$ and N defining the Fast Fourier Transform (FFT) size; where $t_o^{(\gamma)}$ is the first sampling instant of the γ-th received OFDM symbol defined by $t_o^{(\gamma)} = t_o + (\gamma-1)T$; T_c is the time interval between two successive samples taken by the ADC; T is the total duration of the OFDM symbol; and t_o is the first sampling time instant of the OFDM symbol corresponding to $\gamma = 1$ [3]. The ADC samples are applied to the FFT block and the equalization is performed by multiplying the symbols at the FFT output in each n-th subcarrier by the coefficients $H_{eq}(n) = \rho_n \cdot \exp(j\theta_n)$.

The theory developed to evaluate the performance of optical DD baseband OFDM optical receivers from the MGF is derived in [3]. The main contribution of this work is to include the I/Q RF demodulator influence on that development. The key achievement is the derivation of the equivalent filters, for the real (R) and imaginary (I) parts of the received symbol $Z_\gamma(n)$ in the n-th subcarrier of the γ-th OFDM symbol, respectively, as

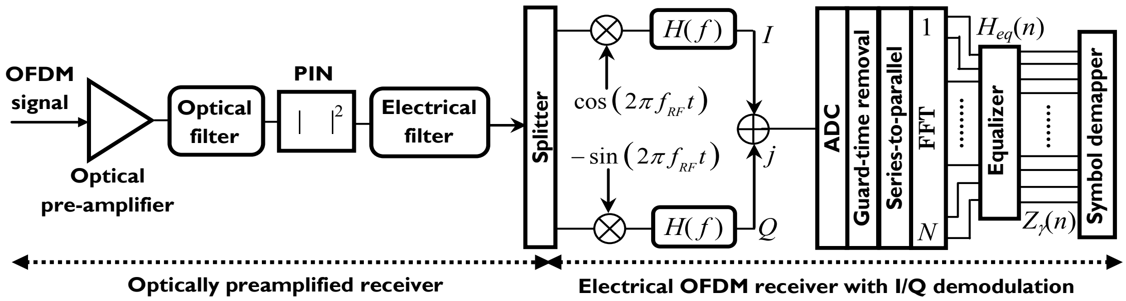

Figure 1. Block diagram of the optically preamplified receiver followed by the OFDM electrical receiver with I/Q demodulation.

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$$H_{R,\gamma,n}(f)=\frac{\rho_n}{4}\cdot\sum_{k=1}^{N}\Big[e^{j\varphi_{n,k}}\cdot e^{j2\pi(f+f_{RF})t_k^{\gamma}}H(f+f_{RF})+ e^{-j\varphi_{n,k}}\cdot e^{j2\pi(f-f_{RF})t_k^{\gamma}}H(f-f_{RF})\Big] \quad (1)$$

$$H_{I,\gamma,n}(f)=j\frac{\rho_n}{4}\cdot\sum_{k=1}^{N}\Big[e^{j\varphi_{n,k}}\cdot e^{j2\pi(f+f_{RF})t_k^{\gamma}}H(f+f_{RF})- e^{-j\varphi_{n,k}}\cdot e^{j2\pi(f-f_{RF})t_k^{\gamma}}H(f-f_{RF})\Big] \quad (2)$$

with $\varphi_{n,k}=2\pi(k-1)(n-1)/N-\theta_n$. Then, to obtain the MGF of the real part of the received symbol $Z_\gamma(n)$, eq. (1) is substituted in eq. (17) of [3], and a similar reasoning to the one described in [3] is followed. In the same way, the MGF of the imaginary part of $Z_\gamma(n)$ can be obtained.

III. Numerical Results

In this section, the symbol error probability is computed for the n-th subcarrier of the γ-th OFDM symbol from the MGF using the saddlepoint approximation [4]. After, the BEP of the received OFDM signal is obtained as in [3]. The parameters μ and η necessary to obtain the MGF and that are defined in [4], are determined iteratively until a stabilized value of the BEP is attained. The accuracy of the BEP obtained from the MGF is assessed by comparison with the BEP obtained using MC simulation, considering that the error counting is stopped when 100 errors occur in the worst performing subcarrier [5].

In the numerical results, the electrical baseband OFDM signal is generated with 32 OFDM symbols, 4-QAM mapping and bandwidth of B = 2.5 GHz. The OFDM I/Q modulator is the reciprocal of the I/Q demodulator presented in Fig. 1. The electro-optical conversion is performed by a Mach-Zehnder modulator with a modulation index of 0.1. At the optical receiver, the optical filter is a 2^{nd} order super Gaussian optical filter with a –3 dB bandwidth of 30 GHz; a polarizer is assumed after the optical filter; the optical signal-to-noise ratio is 26 dB measured in the reference bandwidth of 0.1 nm; and the electrical filtering at the optical receiver is neglected. The equalizer coefficients are obtained through the averaging of the coefficients estimated for each individual OFDM symbol.

Fig. 2 shows the BEP as a function of the radio-frequency f_{RF}, considering a 6^{th} order Butterworth electrical filter at the I/Q demodulator with –3 dB bandwidth of 1.5B and different number of OFDM subcarriers: N = 32, N = 64 and N = 128. The BEP is obtained from the MGF with μ = 1.1 and η = 0.6, and from MC simulation. Fig. 3 shows the BEP as a function of the –3 dB bandwidth of the electrical filter of the I/Q demodulator for 5^{th} order Bessel and 6^{th} order Butterworth filters; different number of OFDM subcarriers (N = 32 and N = 64), and f_{RF} = 7.5 GHz are considered. The BEP is obtained from the MGF with μ = 1.1 and η = 0.6, and from MC simulation.

Figs. 2 and 3 show a very good agreement between the BEP estimates obtained using MC simulation and using the MGF, and validate the MGF-based method for DD-OFDM optical receivers with I/Q demodulation. Additionally, Figs. 2 and 3 demonstrate also that the MGF formulation provides good estimates of the BEP for a different number of OFDM subcarriers. The performance of the DD-OFDM receiver remains very similar to the subcarriers number, since the OFDM signal bandwidth is kept the same for different N.

The MGF has been also validated for different optical filters with varying -3 dB bandwidths.

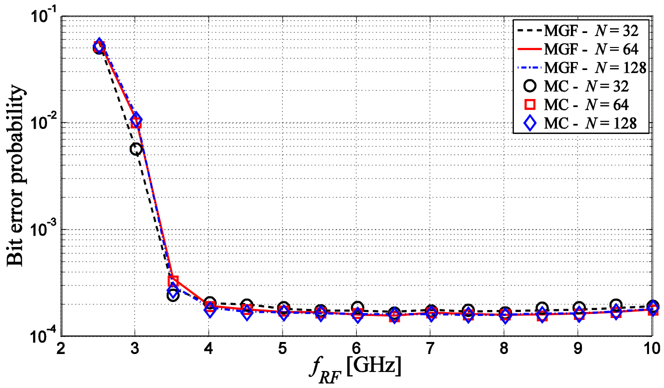

Figure 2. BEP as a function of the radio-frequency f_{RF} for a 6^{th} order Butterworth electrical filter with –3 dB bandwidth of 1.5B, for N = 32, N = 64 and N = 128. Marks: MC; lines: MGF.

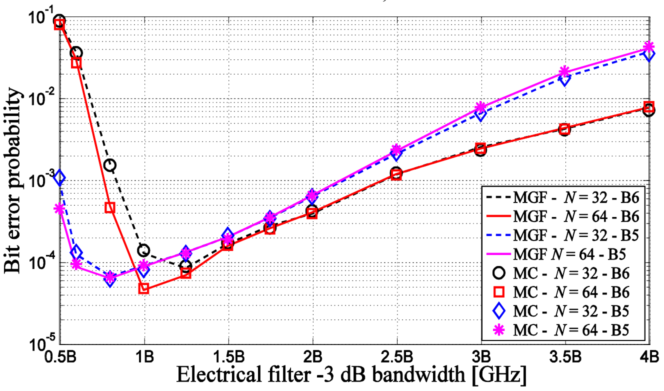

Figure 3. BEP as a function of the –3 dB bandwidth of the electrical filter (with B = 2.5 GHz), for 5^{th} order Bessel (B5) and 6^{th} order Butterworth (B6) filters, for N = 32 and N = 64 and f_{RF} = 7.5 GHz. Marks: MC; lines: MGF.

IV. Conclusions

In this work, a new method to assess the performance of DD-OFDM optical receivers with RF I/Q demodulation using the MGF has been proposed and validated by MC simulation. The validation has been performed for different electrical filter types at the I/Q demodulator (and varying –3 dB bandwidth), different radio-frequencies, different number of OFDM subcarriers, and different optical filter types.

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