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On the use of the Gaussian approach for the performance evaluation of direct-detection OFDM receivers impaired by in-band crosstalk

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Abstract — **The Gaussian approach (GA) is used to assess the impact of in-band crosstalk on the performance of direct-detection orthogonal frequency division multiplexing (OFDM) optical communication systems. The GA accuracy is compared with estimates of the bit error probability (BEP) and crosstalk penalty obtained using Monte Carlo (MC) simulation. The GA revealed a reduced accuracy when estimating the BEP. However, when estimating the 1 dB crosstalk penalty, the GA exhibited a good accuracy (less than 0.5 dB in comparison with the crosstalk level estimated using MC simulation), for 16-quadrature amplitude modulation (QAM) and 64-QAM mappings in the OFDM subcarriers. The GA leads to very discrepant estimates of the crosstalk penalty for high crosstalk levels.**

Keywords— Direct-detection, Gaussian approach, in-band crosstalk, Monte-Carlo simulation, optical communication systems, orthogonal frequency division multiplexing.

I. INTRODUCTION

Recently, orthogonal frequency division multiplexing (OFDM) with direct-detection (DD) optical communication systems, has gained research attention as a solution technique for lower capacity and shorter reach optical networks, such as metropolitan and access networks [1]-[3].

In such networks, due to imperfections of optical devices, such as reconfigurable optical add-drop multiplexers, in-band crosstalk coming from interfering signals at the same nominal wavelength as the original signal may occur and degrade the network performance [4]-[6]. However, when considering DD OFDM optical networks, only a small number of works has investigated the impact of in-band crosstalk on the system performance [7]-[9].

It is well-known that, in optical communication systems with DD and on-off keying and differential phase-shift keying modulation formats [5], [10], the decision variable in the presence of in-band crosstalk and amplified spontaneous emission (ASE) noise does not follow a Gaussian statistics. However, even with DD, the statistics of the decision variable of an OFDM optical communication system impaired only by ASE noise is well described by a Gaussian distribution [11], [12]. Recently, although for coherent detection [6], the addition of in-band crosstalk to a Gaussian noise model has provided a good agreement between simulation and experimental results. Due to all these reasons, it makes sense to study the statistics of the decision variable in DD OFDM optical communication systems impaired by both in-band crosstalk and ASE noise.

Hence, in this work, the statistics of DD OFDM optical receivers impaired by in-band crosstalk and ASE noise are studied by estimating the bit error probability (BEP) and the crosstalk penalty using a Gaussian approach (GA), with mean and variance of the decision variable obtained using Monte Carlo (MC) simulation. The accuracy of the GA estimates is studied by comparison with estimates obtained using direct-error counting (DEC) in the MC simulation [11], [13].

The remainder of this paper is structured as follows. Section II describes the developed model and the assumptions made to obtain the BEP and the crosstalk penalty of the DD OFDM optical system in presence of in-band crosstalk. The accuracy of the BEP and crosstalk penalty estimates obtained with the GA is studied and discussed in Section III. The concluding remarks are presented in Section IV.

II. SIMULATION MODEL

In this section, the optical communication system model, the MC simulator and the BEP estimation are described.

A. Optical communication system model

In order to study the impact of in-band crosstalk on the performance of DD OFDM optical networks, we consider the system model depicted in Figure 1. An electrical OFDM transmitter generates the "classical" gapped OFDM signal used in DD [14], where the frequency gap between the optical carrier and the OFDM signal spectrum is equal to the OFDM signal bandwidth. The radio-frequency (RF) to perform the up-conversion at the electrical transmitter is denoted as f_{RF}. An optical single sideband (SSB) OFDM signal is obtained using an optical filter after the optical modulator [14]. As the main focus of our work is to evaluate the impact of in-band crosstalk on the DD OFDM communication system performance, transmission impairments are neglected and a back-to-back configuration is assumed.

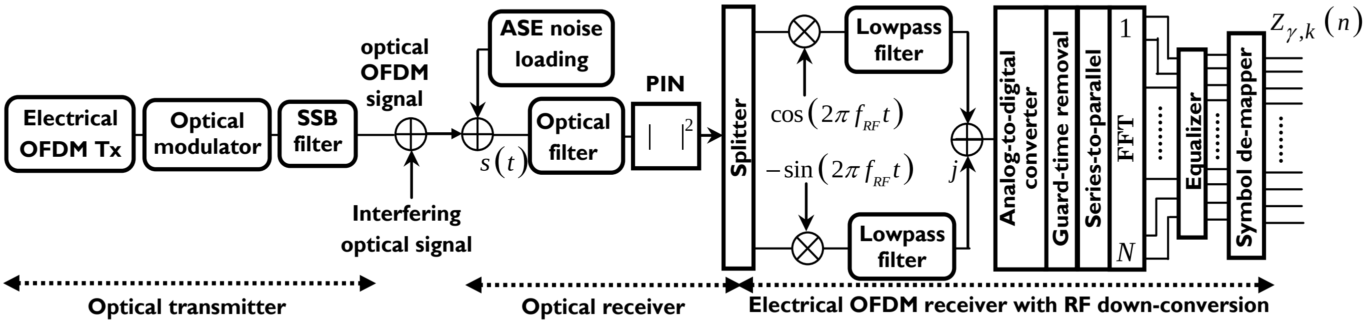

Figure 1. Model of the system used to study the impact of in-band crosstalk on the DD OFDM network performance.

At the optical receiver input, the “original” optical OFDM signal is impaired by the interfering optical signal. This interference can arise from a signal leakage in an add-drop operation inside an optical network node that interferes with the original signal at the same nominal wavelength [4], [5]. Then, ASE noise is added to the original signal plus interfering signal. The resulting signal is optically filtered and converted to the electrical domain by a PIN photodetector. After photodetection, down-conversion to baseband of the electrical signal is performed. The electrical OFDM baseband receiver comprises analog-to-digital conversion, guard time-removal, series-to parallel conversion, Fast-Fourier Transform (FFT), equalization and quadrature amplitude modulation (QAM) symbol de-mapping.

B. *Monte Carlo simulation*

MC simulation is used to study the crosstalk impact on the performance of the DD OFDM optical communication system. At each run of the MC simulator, one sample function of ASE noise and one sample function of the optical OFDM interfering signal are generated. The interfering signal is modeled as in [9], [15]. In Fig. 1, at the input of the optical filter, the resulting sample function of the signal $s(t)$ at each iteration of the MC simulator is given by [9]

$$s(t) = \sqrt{P_s} \cdot s_{OFDM}(t) + \sum_{i=1}^{M} \sqrt{P_{c,i}} \cdot s_{c,i}(t) e^{j\phi_i} + n(t) \qquad (1)$$

where the first term is the original OFDM signal at the optical receiver input with average power P_s; the second term of (1) represents the possible M interferers, with each i-th interfering signal having average power $P_{c,i}$; and $n(t)$ is the ASE noise complex field envelope. The average powers of $s_{OFDM}(t)$ and $s_{c,i}(t)$ are assumed normalized to unit. The crosstalk level of the i-th interferer $X_{c,i}$ is defined as the ratio between the power of the i-th interfering signal, $P_{c,i}$, and the power of the original OFDM signal, P_s [4], [5]. The total crosstalk level is defined by the sum of the crosstalk levels of the M interferers. At each run of the MC simulator, a sample function of each interfering signal composed by a random sequence of bits is generated and converted to the desired QAM modulation format. The random phase shift ϕ_i describes the phase difference between the original and i-th interfering signal and is modeled by an uniform distribution over the interval [0, 2π[[15]. We have ignored a possible temporal misalignment between the original OFDM and interfering signals, as its influence on the system performance is insignificant [9]. We also assume that the interfering optical signal is co-polarized with original optical OFDM signal, which is a worst-case assumption [5]. The sample function of the ASE noise $n(t)$ is modeled as completely unpolarized additive white Gaussian noise [11], [15].

C. *Bit error probability estimation*

By analysis of the received symbol in the n-th subcarrier of the γ-th OFDM symbol, $Z_{\gamma,k}(n)$, in each OFDM subcarrier, symbol errors can be identified by comparison with the transmitted QAM symbols. The BEP is, then, estimated using [16]

$$BEP = \sum_{k=1}^{N_{it}} \sum_{\gamma=1}^{N_s} \sum_{n=1}^{N} \frac{1-\left[1-SEP\left\{\mathrm{Re}\left[Z_{\gamma,k}(n)\right]\right\}\right]\left[1-SEP\left\{\mathrm{Im}\left[Z_{\gamma,k}(n)\right]\right\}\right]}{N_{it} N_s N \log_2 M} \qquad (2)$$

where a rectangular M-QAM mapping and Gray coding have been assumed. In Eq. (2) , N_{it} is the number of iterations of the MC simulator, N_s is the number of OFDM symbols generated in each iteration and N is the number of useful subcarriers in each OFDM symbol. The symbol error probabilities of the real and imaginary parts of $Z_{\gamma,k}(n)$ are denoted as $SEP\left\{\mathrm{Re}\left[Z_{\gamma,k}(n)\right]\right\}$ and $SEP\left\{\mathrm{Im}\left[Z_{\gamma,k}(n)\right]\right\}$, respectively. The BEP is estimated using two methods: by DEC of 100 symbol errors in the worst-performing subcarrier [11], [13]; and by the GA. The mean and variance of the received symbols used to calculate the GA are obtained from the sample functions of the MC simulator, as described in [13]. In this case, the MC simulation is stopped after 10^5 iterations, to ensure a good estimation of the mean and variance.

III. NUMERICAL RESULTS

In this section, the numerical estimates of the BEP and the crosstalk penalty of the DD OFDM optical receiver impaired by in-band crosstalk are obtained using the two methods (DEC and GA) for several situations, and the GA accuracy is discussed.

To focus our attention on the in-band crosstalk impact, all system parameters are set to minimize the distortion on the received OFDM symbol, either coming from signal-signal beat interference or from filtering along the transmission system. The electrical baseband OFDM signal is generated with N = 32, a bandwidth of B = 2.5 GHz, with two times oversampling and a guard time duration that lasts 22.5% of the total OFDM symbol duration. 4-QAM, 16-QAM and 64-QAM symbol mappings are considered in the OFDM subcarriers. The number of simulated OFDM symbols per run is N_s = 16. The baseband OFDM signal modulates a RF carrier with frequency $f_{RF} = 15\text{ GHz}$ or $f_{RF} = 7.5\text{ GHz}$, depending on the lowpass filter used. The carrier-to-signal power ratio (CSPR) of the original and interfering signals is set at 3.3 dB, which is near the CSPR that minimizes the BER of DD OFDM signals [14]. A linear model for the optical modulator is assumed. The optical signal-to-noise ratio (OSNR) is measured at the optical filter input in the reference bandwidth of 0.1 nm at λ = 1550 nm. The optical filter is an ideal rectangular filter with a very large bandwidth when compared to the OFDM signal. The electrical lowpass filter at the RF down-converter is considered as an ideal rectangular filter (when $f_{RF} = 15\text{ GHz}$) or a 5th order Bessel filter (when $f_{RF} = 7.5\text{ GHz}$). The equalizer coefficients are obtained using training OFDM symbols.

We assume that the interfering signal is also a “classical” gapped OFDM signal with similar characteristics to the original signal, i.e., same subcarriers number, similar bandwidth and equal radio-frequency, etc. A single interferer scenario is also considered, since it was shown in [9] that the influence of the number of interferers under the worst-polarization case on the performance is negligible.

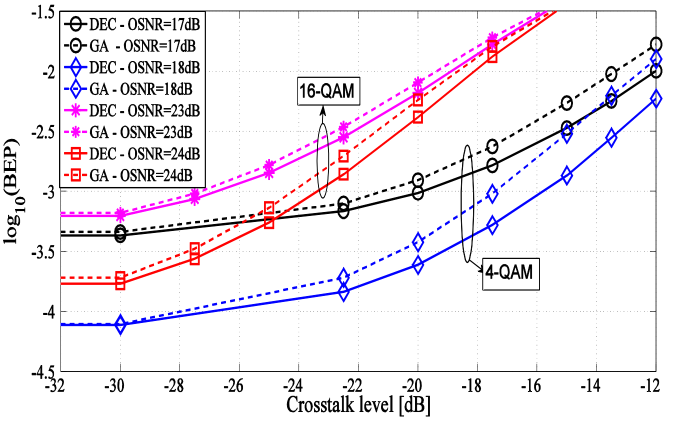

Fig. 2. BEP as a function of the crosstalk level, for 4-QAM mapping in the OFDM subcarriers (OSNR = 17 dB and OSNR = 18 dB) and for 16-QAM mapping in the OFDM subcarriers (OSNR = 23 dB and OSNR = 24 dB). The BEP is estimated using the GA (dashed lines) and DEC (solid lines).

Figure 2 shows the BEP as a function of the crosstalk level, for 4-QAM mapping (OSNR = 17 dB and OSNR = 18 dB); and 16-QAM mapping (OSNR = 23 dB and OSNR = 24 dB). The BEP is estimated using the GA and DEC. The electrical filter at the RF down-converter is the ideal rectangular filter with –3 dB bandwidth of 7.5 GHz, to achieve negligible signal distortion. Figure 2 shows that the GA fails to predict accurately the BEP of DD OFDM receivers impaired by in-band crosstalk, especially for the 4-QAM mapping in the OFDM subcarriers. For the 16-QAM, the BEPs obtained with the GA seem more precise. Figure 2 shows also that the 16-QAM mapping is much more sensitive to in-band crosstalk than the 4-QAM mapping. The decrease of the in-band crosstalk tolerance with the increase of the order of the modulation format has been already observed in [17], for single-carrier coherent detection optical systems.

Figure 3 depicts the crosstalk penalty as a function of the crosstalk level considering 4-QAM mapping in the OFDM subcarriers, for two types of electrical filter: ideal rectangular filter with –3 dB bandwidth of 7.5 GHz and a radio-frequency of $f_{RF} = 15\text{ GHz}$, to achieve negligible signal distortion; and 5th order Bessel filter with –3 dB bandwidth of 3 GHz and a radio-frequency of $f_{RF} = 7.5\text{ GHz}$, to introduce some signal distortion in the DD OFDM optical communication system. The BER is estimated using the DEC and the GA for both electrical lowpass filters. The crosstalk penalty is defined as the difference in dB between the OSNRs required to obtain the BER of 10^{-3}, with and without crosstalk [5], [9].

Figure 3 shows that the GA predicts that a crosstalk level of –19.3 dB leads to a 1 dB crosstalk penalty, while the DEC predicts a crosstalk level of –17.8 dB, for the same penalty. For this crosstalk penalty, the difference between the two methods estimates of the crosstalk level is 1.5 dB. This difference increases for higher crosstalk penalties. The discrepancies between the two methods seem independent of the electrical filter type used in the RF down-converter.

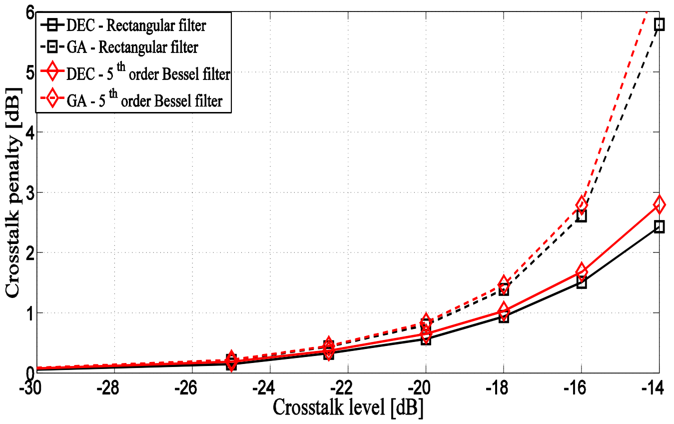

Fig. 3. Crosstalk penalty as a function of the crosstalk level, considering 4-QAM mapping in the OFDM subcarriers, for the electrical lowpass filters: ideal rectangular filter with –3 dB bandwidth of 7.5 GHz and 5th order Bessel filter with –3 dB bandwidth of 3 GHz. The BEP is estimated using DEC (solid lines) and the GA (dashed lines).

Figure 4 depicts the crosstalk penalty as a function of the crosstalk level considering 16-QAM mapping in the OFDM subcarriers, for two types of electrical filter: ideal rectangular filter with –3 dB bandwidth of 7.5 GHz and a radio-frequency of $f_{RF} = 15\text{ GHz}$, and 5th order Bessel filter with –3 dB bandwidth of 3 GHz and a radio-frequency of $f_{RF} = 7.5\text{ GHz}$. The difference between the crosstalk levels estimated using the GA and from DEC, considering the 1 dB crosstalk penalty, is approximately 0.4 dB, which is a very low difference, when compared with the 4-QAM mapping, for both electrical filters used. For higher crosstalk levels, we observe significant discrepancies between the estimates obtained by DEC and from the GA.

Figure 5 depicts the crosstalk penalty as a function of the crosstalk level considering 64-QAM mapping in the OFDM subcarriers, for the ideal rectangular electrical filter bandwidth of 7.5 GHz. For the 64-QAM mapping, the DD OFDM communication system with the 5th order Bessel electrical filter (with the same parameters of Figs. 3 and 4) leads to OSNRs, which are unreasonable in practical systems, and, hence, its corresponding results are not shown. The difference between the crosstalk levels estimated using the GA and from DEC, considering the 1 dB crosstalk penalty, is about 0.5 dB, similar to the difference observed with the 16-QAM mapping in the OFDM subcarriers. For higher crosstalk levels, significant discrepancies between the estimates obtained by DEC and from the GA are again observed.

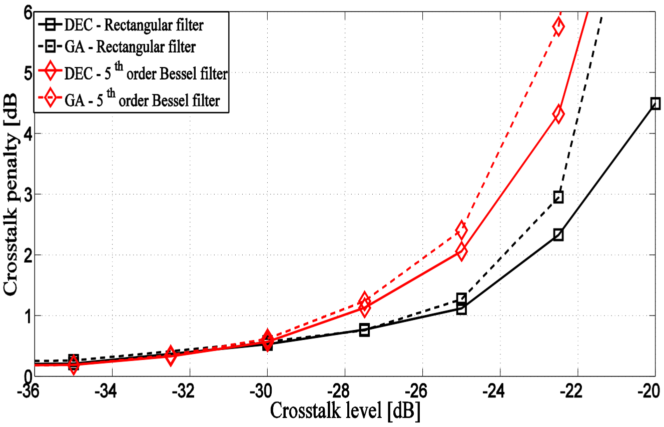

Fig. 4. Crosstalk penalty as a function of the crosstalk level, considering 16-QAM mapping in the OFDM subcarriers, for the electrical lowpass filters: with −3 dB bandwidth of 7.5 GHz and 5th order Bessel filter with −3 dB bandwidth of 3 GHz. The BEP is estimated using DEC (solid lines) and the GA (dashed lines).

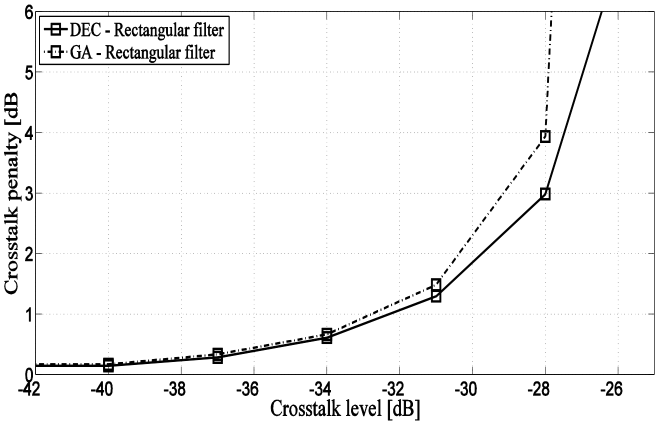

Fig. 5. Crosstalk penalty as a function of the crosstalk level, considering 64-QAM mapping in the OFDM subcarriers, for the ideal rectangular electrical filter with −3 dB bandwidth of 7.5 GHz. The BEP is estimated using DEC (solid lines) and the GA (dashed lines).

We have also studied the accuracy of the GA, for $N = 128$ for 4-QAM and 16-QAM mappings in the OFDM subcarriers. In this case, we have assumed that the bandwidth of the baseband OFDM signal is maintained at 2.5 GHz when considering the different subcarriers number. A much similar behavior of the GA accuracy to those shown in Figs. 3 and 4 has been found.

Figures 2-5 indicate also that the GA provides pessimistic estimates of the BEP and of the crosstalk penalty.

IV. CONCLUSION

In this work, the accuracy of the GA to estimate the impact of in-band crosstalk on the performance of DD OFDM optical communication systems has been assessed, for 4-QAM, 16-QAM and 64-QAM mappings in the OFDM subcarriers, different electrical filters at the RF down-converter and different subcarriers numbers. Although predicting discrepant estimates of the BEP, the GA revealed a good accuracy when estimating the 1 dB crosstalk penalty (less than 0.5 dB in comparison with MC simulation), for 16-QAM and 64-QAM mappings in the OFDM subcarriers. For the 4-QAM mapping, when predicting the crosstalk level that leads to a 1 dB crosstalk penalty, the GA gives a 1.5 dB difference in comparison with the crosstalk level obtained using MC simulation. The GA leads to very discrepant estimates for higher crosstalk penalties. As a summary, our results indicate that the GA is a reasonably accurate tool to estimate the 1 dB crosstalk penalty in DD OFDM optical communication systems, for higher QAM orders (≥ 16) in the OFDM subcarriers. Due to its pessimistic predictions, but faster computational speed than the DEC, the GA can be regarded as a useful conservative tool to estimate the impact of in-band crosstalk on the performance of DD OFDM optical communication systems.

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