ON THE BER ESTIMATION OF EXPERIMENTAL DIRECT DETECTION OFDM SYSTEMS

Tiago Alves and Adolfo Cartaxo
Group of Research on Optical Fibre Telecommunication Systems, Instituto de Telecomunicações, DEEC
Instituto Superior Técnico, Avenida Rovisco Pais 1, 1049-001, Lisboa, Portugal

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Abstract: We propose to extend the exhaustive Gaussian approach (EGA) to assess the bit error ratio (BER) of experimental direct detection optical orthogonal frequency division multiplexing setups. Excellent agreement between the actual probability density function (PDF) of each subcarrier and the Gaussian PDF estimated from a set of experimental runs is shown. The proposed EGA allows evaluate quickly the BER as only a few hundreds of runs are required to reach stabilized BER estimates. The BER estimated by EGA has shown an excellent agreement with the BER estimates provided by direct error counting.

1 INTRODUCTION

Orthogonal frequency division multiplexing (OFDM) has been proposed in the past few years as a promising technology to be used in different range optical networks (Llorente et al., 2008; Lin et al., 2008; Schmidt et al., 2009). The main impairments of OFDM-based networks have been extensively analyzed experimentally and through numerical simulation (Schmidt et al., 2009; Schuster et al., 2008; Alves and Cartaxo, 2009; Lowery, 2008; Jansen et al., 2009; Peng et al., 2008). The performance assessment has been accomplished by using three main figures of merit: direct error counting (DEC), error vector magnitude (EVM) and Q factor. DEC provides rigorous bit error ratio (BER) estimates but the amount of transmitted data required to achieve low BER levels may lead to unacceptable measurement time. The assessment of the system performance from EVM and Q factor approaches allows overcome this limitation. However, these approaches may lead to unreliable estimates of the system performance as the statistical distribution of the subcarriers distortion may not be rigorously taken into account due to the assumptions of the analytical formulation each approach relies on. Furthermore, the different signal-to-noise ratio (SNR) of each subcarrier is not considered by these approaches. Further information regarding the validity range of these figure of merits to evaluate the performance of DD OFDM systems can be found in (Alves and Cartaxo, 2010), where the BER was assessed for two types of DD-OFDM systems through numerical simulation.

In a previous work, a novel approach to evaluate the BER of each subcarrier of a direct detection (DD) optical OFDM system through numerical simulation has been proposed (Alves and Cartaxo, 2009). In that case, the mean and the standard deviation (STD) of each subcarrier of each OFDM symbol are obtained through numerical simulation and analytically, respectively, and an exhaustive Gaussian approach (EGA) is used to evaluate the BER of each subcarrier. The main advantage of the EGA is the possibility to take into account separately the noise and interference effects. In this work, we propose to extend that approach to experimental DD-OFDM systems by evaluating the statistical properties of each subcarrier required by the EGA from a set of experimental runs.

2 EXHAUSTIVE GAUSSIAN APPROACH DESCRIPTION

The EGA considers that the received components (I and Q) of each OFDM subcarrier are well described by a Gaussian distribution (confirmed numerically in (Alves and Cartaxo, 2009)). The extension of the EGA to experimental setups is based on the estimation of the mean and STD of each subcarrier over a set of experimental runs. In this case, the BER of the I or Q component of the k-th subcarrier is given by:

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$$BER_{(I,Q)}[k] = \frac{1}{N_s} \sum_{\substack{i=1 \\ a^{(i)}_{(I,Q)}[k]=0}}^{N_s} Q\left(\frac{F_{(I,Q)}[k] - m^{(i)}_{(I,Q)}[k]}{\sigma^{(i)}_{(I,Q)}[k]}\right)$$
$$+ \frac{1}{N_s} \sum_{\substack{i=1 \\ a^{(i)}_{(I,Q)}[k]=1}}^{N_s} Q\left(\frac{m^{(i)}_{(I,Q)}[k] - F_{(I,Q)}[k]}{\sigma^{(i)}_{(I,Q)}[k]}\right) . \quad (1)$$

where $m^{(i)}_{(I,Q)}[k]$ is the mean and $\sigma^{(i)}_{(I,Q)}[k]$ is the STD of the k-th subcarrier of the i-th OFDM symbol at the output of the system setup, given by:

$$m^{(i)}_{(I,Q)}[k] = \frac{1}{N_r} \sum_{n=1}^{N_r} y^{(i)}_{(I,Q),n}[k]$$
$$\sigma^{(i)}_{(I,Q)}[k] = \left[\frac{1}{N_r} \sum_{n=1}^{N_r} \left(y^{(i)}_{(I,Q),n}[k] - m^{(i)}_{(I,Q)}[k]\right)^2\right]^{\frac{1}{2}} \quad (2)$$

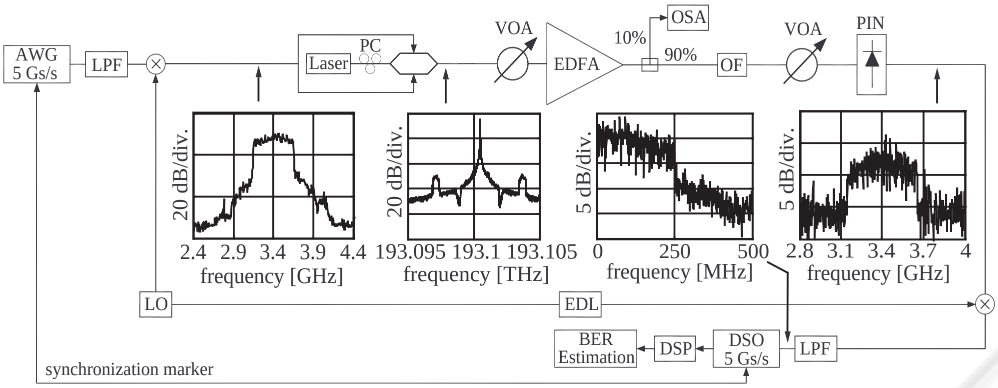
where $y^{(i)}_{(I,Q),n}[k]$ is the received I or Q component of the subcarrier transmitted in the n-th run and N_r is the number of runs. In eq. (1), $a^{(i)}_{(I,Q)}[k]$ identifies the bit transmitted in the (I,Q) component of the k-th subcarrier of the i-th OFDM symbol and $F_{(I,Q)}[k]$ is the decision threshold level of the k-th subcarrier. N_s is the number of transmitted OFDM symbols per run and $Q(x) = 0.5\mathrm{erfc}\left(\frac{x}{\sqrt{2}}\right)$. Eq. (1) considers that binary phase shift keying (BPSK) or quadrature phase shift keying (QPSK) symbol mapping is used. Nevertheless, the estimation of the BER using the EGA for other more efficient mappings can still be accomplished by developing a generalized version of eq. (1) and using the same procedure to evaluate the means and the standard deviations of each subcarrier as the one described in this work. If BPSK symbol mapping is used (with symbols j and $-j$), the means and the standard deviations of eq. (1) are relative to the Q component only. Instead, if QPSK is used and assuming that the I and Q signal components at the equalizer output are uncorrelated and that Gray mapping is used, the BER of each OFDM subcarrier is given by $BER[k] = \frac{1}{2}\left[1-(1-BER_I[k])\,(1-BER_Q[k])\right]$, where $BER_I[k]$ and $BER_Q[k]$ are the BER of the I and Q components of each subcarrier at the equalizer output given by eq. (1). The overall BER is evaluated averaging the BER over all information subcarriers.

It should be stressed that the EGA described by eq. (1) to evaluate the BER of each subcarrier considers a Gaussian distribution for noise and allows characterizing correctly the statistical distribution of the distortion rather than using a Gaussian distribution to characterize the distortion induced on all subcarriers, as assumed when the BER is calculated from the EVM or the Q factor. This indicates that distortion-induced degradation due to, for instance, electro-optic modulator nonlinearity, non-ideal frequency response of the different devices, I/Q imbalance or phase offset, should be correctly accounted by eq. (1). The distortions effects that are not addressed in this work will be investigated in future work.

3 EXPERIMENTAL SETUP

OFDM ultra-wideband (UWB) signals are used in this work to demonstrate the accuracy of the extended EGA to estimate the BER in experimental setups. The results presented in (Alves and Cartaxo, 2009) suggest that the proposed method can also be used to estimate experimentally the BER of other DD-OFDM signals, as the ones proposed for long-haul systems. The OFDM-UWB radio signal is composed by 128 subcarriers from which 100 are used as information subcarriers, the spectrum occupies 528 MHz of bandwidth and the time interval of each OFDM symbol is 312.5 ns. Further details on the OFDM-UWB signal generation can be found in (Alves and Cartaxo, 2009), (ECMA-368, 2007).

Figure 1 shows the experimental setup used to assess the accuracy of the proposed EGA. The measured spectra of the OFDM-UWB signal along the setup are also shown as insets in Figure 1. The OFDM-UWB baseband signal is generated off-line and converted to the electrical domain by a Tektronix AWG7052 operating in continuous mode. The OFDM-UWB signal is composed by 32 symbols and BPSK mapping is employed. The baseband OFDM-UWB signal is up-converted to the first UWB subband with carrier frequency of 3.4 GHz and is then applied to a Sumitomo single-electrode 10 Gbit/s intensity modulator biased at the quadrature point. Due to the lack of electrical amplifiers with adequate bandwidth, only a 4% modulation index (defined as the ratio between the root mean square voltage of the OFDM signal applied to the modulator arms and the modulator bias point) is reached and, as a consequence, a high optical signal-to-noise ratio (OSNR) has to be used to achieve acceptable BER levels. A variable optical attenuator (VOA) and an optical amplifier (noise figure of 4.5 dB) are used to adjust the OSNR (defined in a reference optical bandwidth of 0.1 nm). At the optical receiver, the signal is optically filtered by a Kylia demultiplexer with 50 GHz of channel spacing and 32 GHz of bandwidth, and photodetected by a Discovery Semiconductors PIN with 0.7 A/W and 9 GHz of bandwidth. The detected OFDM-UWB signal is down converted and low-pass filtered to reduce the



AWG: arbitrary waveform generator	EDL: electrical delay line	PC: polarization controller
BER: bit error ratio	LO: local oscillator	PIN: positive-intrinsic-negative
DSO: digital signal oscilloscope	LPF: low-pass filter	TF: transmission fiber
DSP: digital signal processing	OF: optical filter	VOA: variable optical attenuator
EDFA: erbium doped fiber amplifier	OSA: optical spectrum analyzer	

Figure 1: DD optical OFDM system used to assess the accuracy of the EGA in experimental setups. Measured spectra of the signals at different points of the system setup (insets).

noise and the out-of-band distortion. Two different Mini-Circuits low pass filters (LPF) are used in the experiments in order to analyze different distortion situations: the VLFX-225 (-3 dB bandwidth of 345 MHz) and the VLFX-300 (-3 dB bandwidth of 450 MHz). Finally, the OFDM signal is acquired by a real time oscilloscope Agilent DSO81204A that is connected to a PC to perform the OFDM demodulation and equalization by digital signal processing (DSP), and BER measurement.

4 EXPERIMENTAL RESULTS

In this study, the accuracy of the proposed approach is assessed considering only noise and distortion induced by the frequency response of the devices. The number of experimental runs required to get stabilized BER estimates is also analyzed while fibre transmission and nonlinear system effects will be addressed in future work.

The validity of the Gaussian distribution considered for each OFDM subcarrier in the EGA is analyzed by comparison with the actual probability density functions (PDF) obtained experimentally. 4×10^5 runs have been used to evaluate the PDFs.

Figure 2 shows the actual PDFs of the Q component of four OFDM subcarriers at the equalizer output and the PDFs obtained when the Gaussian distribution is considered. Figure 2 shows that the Gaussian distribution fits very well the actual PDF of the subcarriers and that the subcarriers located at the edges of the spectrum present high variance leading to different SNRs between the subcarriers, as mentioned before. As the tail region is also adequately described by a Gaussian distribution, Figure 2(a) indicates that a very good accuracy of the BER estimates obtained from the EGA is expected. The main advantages of

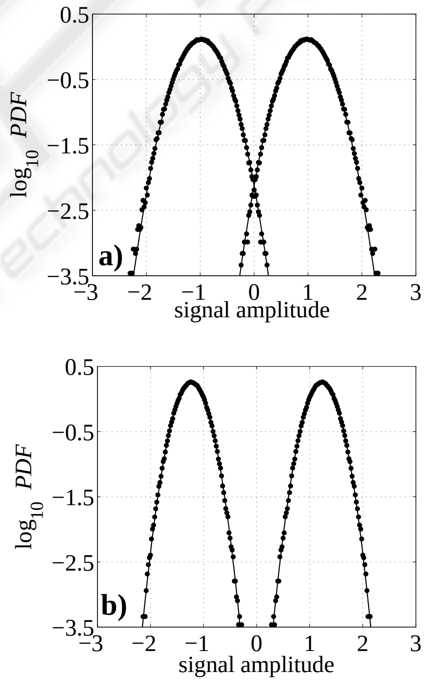


Figure 2: PDF of the subcarriers at the system output for *OSNR*=27.3 dB and considering the subcarriers located in a) the edges and b) the middle of the OFDM-UWB spectrum. Gaussian PDF (lines) and actual PDF (marks). LPF: VLFX-225.

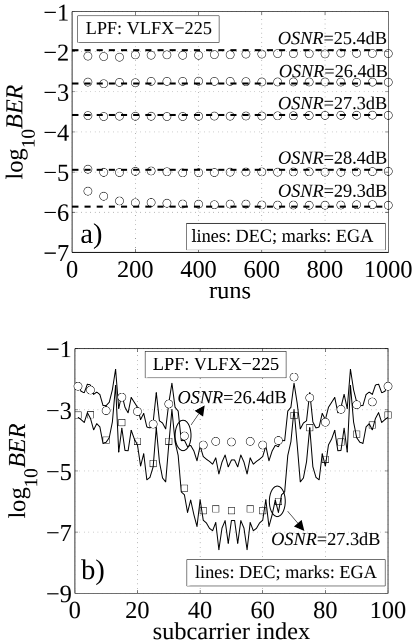


Figure 3: a) BER as a function of the noise runs. b) BER as a function of the subcarriers index.

the proposed EGA are the fast and good estimates of the system performance independently of the BER levels. Hence, one of the key parameters of the EGA is the number of runs needed to achieve good BER estimates.

Figure 3(a) depicts the BER of the OFDM system as a function of the number of runs used in the EGA to estimate the properties of the Gaussian distribution. The BER obtained from the DEC is also shown as a reference. In order to obtain a good confidence on the BER estimates, the BER provided by DEC is evaluated when at least 100 errors occur in the subcarrier with worst performance. Figure 3(a) shows that a few hundreds of noise runs are enough to obtain confident overall BER estimates using the EGA, independently of the OSNR level. Nevertheless, in the following, 1000 noise runs are considered in order to get a reasonable confidence on the estimation of the BER of the subcarriers showing lower BER. Figure 3(b) shows the BER as a function of the subcarrier index (subcarriers with lower indexes correspond to subcarriers transmitted at lower frequencies) for two OSNR levels. The BER obtained with DEC is evaluated over 3.3×10^5 and 4.3×10^5 runs for the case with lower and higher OSNR, respectively. Figure 3(b) shows that the BER of each subcarrier provided by EGA fits well the BER measured by DEC. The discrepancy observed in the estimated BER of the center subcarriers is attributed to rare error events. Figure 3(b) shows also that some subcarriers present high BER peaks.

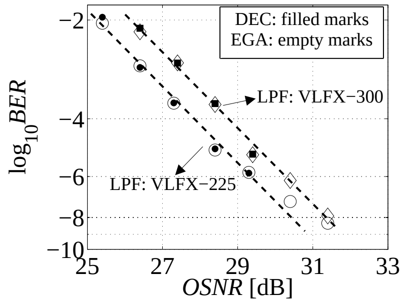


Figure 4: BER as a function of the OSNR.

This is due to the non-ideal frequency response of the devices.

Figure 4 presents the BER of the optical OFDM-UWB system as a function of the OSNR for the two LPFs considered along this work. The BER obtained with DEC is evaluated when at least 100 errors occur on the subcarrier with worst performance. The comparison between the BER estimated by both methods shows that the BER can be estimated using the EGA with a very good agreement with DEC, independently of the OSNR levels, avoiding the high amount of data necessary to estimate the BER from DEC. For instance, for the VLFX-225 LPF and *OSNR*=29.3 dB case, the BER estimated by DEC requires (to get 100 errors in the subcarrier showing worst performance) the transmission of 3.84×10^6 OFDM-UWB symbols whereas the EGA only requires 3.2×10^4 symbols. This difference is still higher when the estimation of lower BER levels is desired as more symbols are required to estimate the BER using DEC.

5 CONCLUSIONS

An extension of the exhaustive Gaussian approach (EGA) to estimate the BER of each subcarrier in experimental direct-detection OFDM setups has been proposed. It has been experimentally shown that the actual statistical distribution of each OFDM subcarrier is well described by a Gaussian distribution whose statistical properties are estimated over a set of few hundreds of noise runs. Additionally, the experimental results have shown that the BER of each OFDM subcarrier estimated by the EGA agrees very well with the actual BER obtained from direct error counting with the advantage of providing fast estimates, independently of the estimated BER levels.

The comparison between the BER estimates provided by the EGA with ones obtained using the EVM or the *Q* factor approaches in DD OFDM experimental setups will be reported elsewhere.

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