# Chapter 3
# Estimation of the OSNR Penalty Due to In-Band Crosstalk on the Performance of Virtual Carrier-Assisted Metropolitan OFDM Systems

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**Abstract.** The impact of the in-band crosstalk on the performance of virtual carrier (VC)-assisted direct detection (DD) multi-band orthogonal frequency division multiplexing (MB-OFDM) systems was numerically assessed via Monte-Carlo simulations, by means of a single interferer and 4-ary, 16-ary and 64-ary quadrature amplitude modulation (QAM) formats in the OFDM subcarriers. It was also investigated the influences of the virtual carrier-to-band power ratio (VBPR) and the virtual carrier-to-band gap (VBG) on the DD in-band crosstalk tolerance of the OFDM receiver. It was shown the modulation format order decrease enhances the tolerance to in-band crosstalk. When the VBG is the same for both interferer and selected signal, the interferer VBPR increase is seen to lead to lower optical signal-to-noise ratio (OSNR) penalties due to in-band crosstalk. Considering that the VCs frequencies of the selected and interferer OFDM signals are equal, the increase of the interferer VBG also gives rise to lower OSNR penalties. When the interferer and selected signals bands central frequencies are the same, the change of interferer VBG can attain 11 dB less tolerance to in-band crosstalk of the VC-assisted DD OFDM system. We also evaluate the error vector magnitude (EVM) accuracy of the in-band crosstalk tolerance of the DD OFDM receiver and our results show that the EVM estimations are inaccurate.

### 3.1 Introduction

Metropolitan networks aggregate different types of traffic and provide links between access and back-bone networks. In addition, these networks need to present a fast traffic exchange as a result of the protocols employed to aggregate different traffic types. Hence, metropolitan networks must present high flexibility, dynamic reconfigurability and transparency, and should enable scalability [4]. Additionally, the lower power consumption and less space occupied by network elements have been important requirements for metro networks planning from operators viewpoint [4]. In order to respond to those requirements, hybrid optical networks, that integrate metro and access networks in the same optical network, have been selected as an attractive alternative. In comparison with conventional metro and access networks, the hybrid networks should comprise less network elements, therefore, the power consumption will be potentially lower [10].

Orthogonal frequency division multiplexing (OFDM) is generaly known for having a high spectral efficiency, allowing to increase the capacity and robustness of optical networks against fibre dispersion. In terms of detection schemes, there are two methods [26] i) coherent detection, in which a local oscillator, hybrid couplers and several photodetectors at the optical receiver are used, and ii) direct-detection where only one photodetector is required at the receiver. The coherent detection presents higher transmission performance in comparison with DD. However, it has a higher system cost and complexity. Hence, DD systems are favored for metro applications.

The OFDM technique also enables flexible bandwidth allocation, which is an important aspect for hybrid optical networks. This OFDM feature can be used to allocate bandwidth for several users with both higher energy and efficiency on the resources management. These features can be accomplished through the multi-band (MB) OFDM technique, in which several OFDM bands are simultaneously transmitted by a single wavelength [6].

The MORFEUS network, which is a virtual carrier (VC)-assisted DD MB-OFDM network [3], has been designated as a system that efficiently meets the requirements for hybrid networks aforementioned [4].

The signal-to-signal beat interference (SSBI) is an important impairment caused by photodetection [26]. The impact of the SSBI on the performance degradation is eliminated by setting a frequency gap, larger than the OFDM signal bandwith, between the OFDM band and the VC, or by using digital signal processing algorithms that mitigate the SSBI term at the OFDM detected signal. In this work, the SSBI mitigation technique presented in [17] is implemented. The use of the SSBI mitigation technique allows to reduce the band gap between the VC and the OFDM band, and consequently, improves the system spectral efficiency [19].

The performance of metro networks can be strongly impaired by in-band crosstalk, which is the interference between signals with the same nominal wavelength. The interfering signals are due to power leakage coming from the deficient isolation of the switching devices inside the optical nodes, as for example in a reconfigurable add-drop multiplexer (ROADM) [28]. The ROADM is a network element that plays an essential role in nowadays transport networks, as they are responsible for the switching of optical signals. The optical switching, inside the ROADM, is performed by wavelength selective switches. Those devices have imperfect isolation, consequently, during the add and drop operation, in-band crosstalk signals are originated from power leakage. Then, the crosstalk signals are transmitted through the optical network, causing a strong degradation on system performance [8]. The tolerance to in-band crosstalk has been investigated in DD OFDM systems [22], where the selected OFDM signal bandwidth is equal to the band gap between the VC and the OFDM band. Nonetheless, the tolerance to in-band crosstalk of a VC-assisted DD OFDM receiver with SSBI mitigation algorithm is still to be assessed.

In this chapter, the impact of the in-band crosstalk on the performance of the VC-assisted DD MB-OFDM receiver with SSBI mitigation algorithm for different $M$-QAM format orders is evaluated through Monte-Carlo (MC) simulation by using direct error counting (DEC) as a bit error rate (BER) estimation method. The error vector magnitude (EVM) is also used as performance estimation method. The effect of the main parameters of the OFDM signal with VC, such as the virtual carrier-to-band power ratio (VBPR) and virtual carrier-to-band gap (VBG), on the performance of the DD OFDM receiver impaired by in-band crosstalk is also assessed using the EVM and DEC methods. The EVM accuracy is studied by comparison with the results obtained from DEC.

This chapter is organized as follows. In section 3.2, some important works referring to in-band crosstalk research are reviewed and the most relevant conclusions of those studies presented. Section 3.3 describes the MORFEUS network and its simulation model. The MORFEUS network is presented in section 3.3.1 and, in section 3.3.2, the MC simulation is described. Numerical results are presented and discussed in Section 3.4. Conclusions are outlined in section 3.5.

### 3.2 Literature Review

The study of the impact of in-band crosstalk on the performance of optical systems has been an important subject of optical communication research in the past years. In the first works related to this subject, for example [15, 16, 5], the imperfect isolation of the devices that comprise the optical nodes is identified as the origin of the crosstalk signals, and also that the in-band crosstalk is the most detrimental type of crosstalk, as it interferes the signals with same wavelength. Another main conclusion is that the main contributor of the performance degradation is the interferometric beat noise. [15, 16, 5] The interferometric beat noise is the beat noise between the primary and interfering signals that occurs at the photodetector of the receiver and becomes an relevant source of performance degradation in DD receivers [7].

Nowadays, the coherent detection is the chosen detection scheme in the transport networks, thereby, the quadrature phase-shift keying (QPSK) has became the modulation most used in these networks. In fact, the coherent detection allows the transmission of $M$-ary quadrature amplitude modulation (QAM), hence, the coherent detection allows the coexistence of a large variety of different modulation formats and bit rates in the optical networks [29]. This fact makes the study of the in-band crosstalk an even more relevant topic in the optical communication research, as the coherent detection enables crosstalk signals with different characteristics, such as, different modulation format order, symbol rate or bit rate, hence, leading to different impacts on the receiver performance. The impact of the in-band crosstalk on the performance of a polarization division multiplexing (PDM)-QPSK has been analytically analyzed, assuming that the in-band crosstalk has a Gaussian distribution [13]. The main conclusion was that the Gaussian model is valid for a large number of interferers. For the case of a single interfering signal, the Gaussian model overestimates the BER estimation in presence of in-band crosstalk. The weighted crosstalk has been proposed and experimentally validated as estimation method of performance penalties due to in-band crosstalk [12, 18].

Regarding the OFDM-based networks using QPSK and $M$-QAM modulation format, some works can be found in the literature. In [11], the performance degradation of a 112-Gb/s PDM-coherent optical-OFDM system due to the interaction between in-band crosstalk and fiber nonlinearity is estimated. The results found in [11] reveal that the fiber nonlinearity enhances the influence of the in-band crosstalk on the BER penalty of the PDM-OFDM coherent receiver. In [22] and [23], it is concluded that higher modulation format orders used in the OFDM subcarriers leads to lower in-band crosstalk tolerance of the OFDM DD receiver. These conclusions are similar to the ones presented in references [28] and [20], in which the impact of in-band crosstalk on the performance of optical communication systems with coherent detection due to different $M$-QAM crosstalk signals is assessed.

Regarding the assessment tools to estimate the impact of the DD receiver in presence of in-band crosstalk, the most common and accurate method is the DEC [14] and [2]. However, the estimation of very low error probabilities ($\leq 10^{-5}$) can be extremely time consuming [2]. So, several alternative performance assessment methods have been proposed and used in order to achieve the DEC accuracy with less computational effort. The moment generating function (MGF) has been proposed as a theoretical method to assess the influence of the in-band crosstalk on the performance degradation of the OFDM DD receiver [23]. It was concluded that, in absence of signal distortion due to the non-linearity of optical modulator, the MGF can predict accurately the BER of the OFDM DD receiver impaired by in-band crosstalk.

The EVM has been gaining popularity as performance assessment tool of $M$-QAM signals receivers, in fact, the EVM is the perfomance assessment tool used in reference [4]. The EVM is a semi-analytical method that makes use of the difference between the $M$-QAM symbol location in the received constellation (due to the noise detected at the receiver) and its transmitted constellation location in order to estimate the BER [25]. In absence of in-band crosstalk, the BER estimation performed by the EVM method has been reported to have a excellent agreement with the BER estimated using DEC with significantly less computation effort [2] and [24]. The accuracy of the BER estimation using EVM method in presence of in-band crosstalk of coherent detection system has been assessed in reference [21]. The main conclusion of was that, for higher crosstalk levels, the EVM method looses accuracy on the estimation of the performance degradation of the $M$-QAM coherent receiver. However, to the best of our knowledge, the EVM accuracy on the BER estimation of DD OFDM receiver in presence of in-band crosstalk is still to be evaluated.

The MORFEUS network has been proposed and its operation and optimization detailed elsewhere [4]. The MORFEUS transmits a single-side band (SSB) OFDM signal, i.e. only one side of optical signal is transmitted. The transmission of SSB optical signal is known to overtake the chromatic dispersion induced power fading (CDIPF). The CDIPF arises from the conjunction of the beat between the two sidebands of optical signal that occurs at the DD receiver and the accumulated dispersion of the optical fiber [1].

The MORFEUS network allows to aggregate several OFDM signals in a single wavelength, composing the MB-OFDM signal. The MB-OFDM signal comprises, in each band, a VC and the OFDM band. The power of the VC is set based on the VBPR, which relates the average power of the VC with the average power of the corresponding OFDM band. Increasing the VBPR is a mean to overcome the SSBI, however, this solution leads to higher power consumption, thereby, higher VBPR is undesirable option to accomplish the requirements of hybrid networks. In order to overcome this disad-

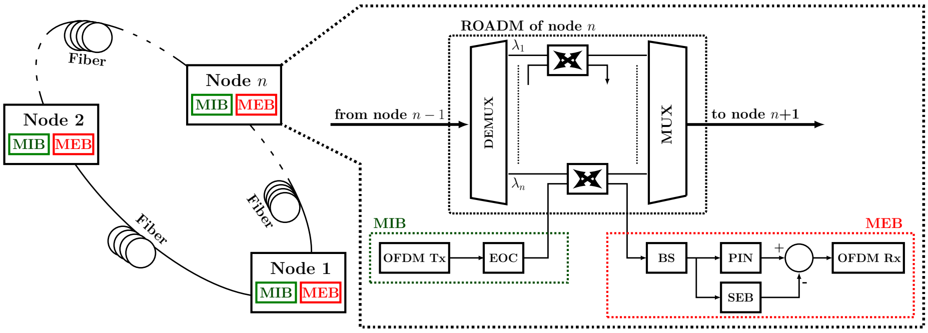



**Fig. 3.1.** MORFEUS metro network and respective nodes block diagram, consisting of reconfigurable optical add-and-drop multiplexer (ROADM), MORFEUS insertion block (MIB) and MORFEUS extraction block (MEB). EOC, BS and SEB stand for electrical-optical converter, band selector and SSBI estimation block, respectively.

vantage, the MORFEUS network uses a SSBI mitigation algorithm at the OFDM demodulation. Hence, the SSBI term is eliminated and, consequently, allows to reduce the VBPR. Moreover, since the SSBI term is eliminated on the OFDM detected signal, the frequency of VC can be set closely to the corresponding OFDM band, which means that the spectral efficiency is higher than in conventional OFDM networks. In these networks, in order to avoid degradation of the DD OFDM receiver performance due to SSBI, the VBG is equal or larger than the OFDM signal bandwidth [23]. The drawback of using SSBI mitigation algorithms is the increase of the receiver complexity. The implementation of SSBI mitigation algorithms is performed by digital signal processing (DSP) at the receiver that reconstructs and removes the SSBI from the photodetected signal[4].

The MORFEUS network detects each OFDM band separately using a dual band optical filter. The filter drops the desired band with its VC, enabling the demodulation of the information of the OFDM band at the DD OFDM receiver. This solution increases remarkably the spectral efficiency and reduces the required bandwidth of the DD OFDM receiver [4] in comparison with the conventional OFDM optical systems.

This work intents to make a contribution on the study of the impact of the in-band crosstalk on performance of VC-assisted DD OFDM receivers, in particular, analyzing the influence of the VBPR and VBG on the tolerance to in-band crosstalk for different modulation format orders. We also intend to investigate the accuracy of the EVM method as a figure of merit of VC-assisted DD OFDM receiver impaired with in-band crosstalk.

## 3.3 MORFEUS Network

The MORFEUS network and its model will be described in this section, the MB-OFDM signal main parameters detailed and finally the MC simulation layout sketched.

**3.3.1 Network Model** The block diagram of the MORFEUS metro network [4] is depicted in Figure 3.1. The MORFEUS network has a ring topology. Each network

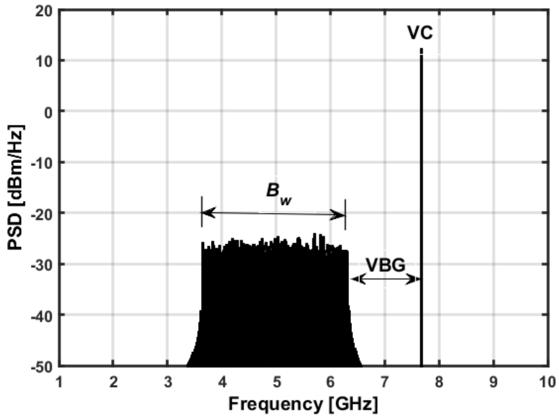



**Fig. 3.2.** PSD of the electrical MB-OFDM signal at the OFDM Tx output, with an average power of 11 mW, considering one pair band-VC.

node includes a reconfigurable optical add-and-drop multiplexer (ROADM), a MORFEUS insertion block (MIB) and a MORFEUS extraction block (MEB). The MIB generates the electrical OFDM bands and VCs at the OFDM transmitter (Tx). The electrical OFDM signal is then converted to the optical domain by means of an electrical-to-optical converter (EOC), inserted in the optical network [4]. The band extraction in the MIEB is performed by a tunable optical filter (BS), which tunes to the desired OFDM signal. The tuned OFDM signal is then issued to the SSBI estimation block (SEB) and also to the PIN photodiode, to be detected. Afterwards, the estimated SSBI, obtained from the SEB, is extracted from the photodetected OFDM signal, and the signal demodulation without SSBI is carried out at the OFDM Rx.

A single OFDM band was taken into account in evaluating the impact of in-band crosstalk on the DD OFDM receiver. Under these conditions, the OFDM signal can be assumed has having only one pair OFDM band-VC, thus having the PSD spectrum as in Fig. 3.2.

The PSD spectrum shown in Fig. 3.2 is representing the OFDM signal at the transmitter output having a 11 mW average power. The OFDM band is characterized by a 2.675 GHz bandwidth, $B_w$, and a 5 GHz central frequency. The bandwidth $B_w$ is stated here as $N_{sc}/T_s$, where $N_{sc}$ is the number of subcarriers and $T_s$ is the OFDM symbol duration without guard time. The frequency gap between the OFDM band and the VC is the VBG, which in Fig. 3.2 is $0.5B_w$. To maximize the SE system, the VBG is set to 20.9 MHz and the ratio between VC average power and the OFDM power of the corresponding band is VBPR.

**3.3.2 Monte Carlo Simulation** This section deals with the MC simulation details and the methods used to obtain the BER.

The MORFEUS network simulation model used to assess the performance tolerance to in-band crosstalk is shown in Fig 3.3. Basically, it includes a Tx having VC generation, a dual parallel Mach-Zehnder modulator (DP-MZM), a tunable band selector (BS), an ideal photodetector, a SEB and an OFDM receiver. One aims to estimate

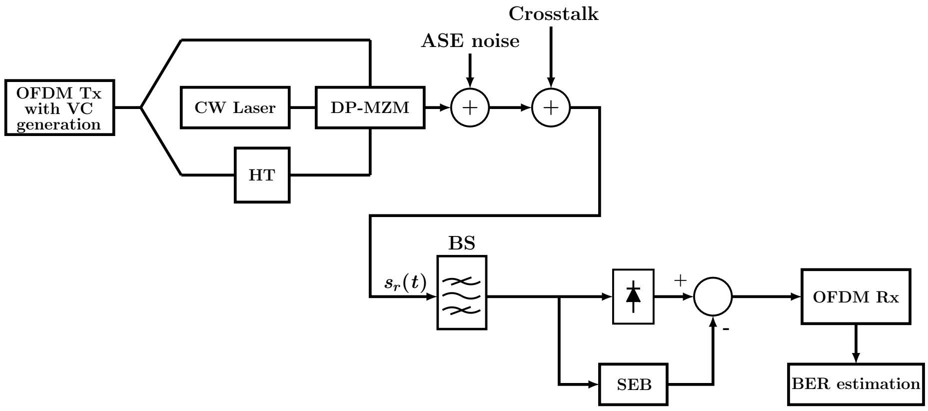



**Fig. 3.3.** Model of the VC-assisted DD OFDM system. The acronym DP-MZM, HT and CW stand for dual parallel Mach-Zehnder modulator, Hilbert transform and continuous wave.

the BER at the OFDM receiver output. At the optical receiver input, just before the BS, amplified spontaneous emission (ASE) noise and in-band crosstalk are placed together with the OFDM signal.

The MC simulation begins with a $M$-QAM symbol sequence [14] representative of the electrical OFDM signal, comprising the OFDM band with a VC. The electrical-optical conversion is then carried out by the DP-MZM, which generates a single-side band OFDM optical signal by applying the electrical OFDM signal and its Hilbert transform (HT) in both arms of the modulator. Here, the OFDM signal HT is assumed ideal. The DP-MZM modulation index considered is 5%, which is the optimized value [4]. Then, ASE noise and in-band crosstalk sample functions are added to the optical OFDM signal, by considering a back-to-back configuration.

The SEB model, sketched in Fig. 3.4, is based on the SSBI mitigation technique described in reference [17]. At the lower SEB branch, Fig. 3.4 the VC of the selected OFDM signal is tuned by means of an ideal optical filter - a virtual carrier selector (VCS). The VC is then withdrawn from the upper branch OFDM signal and subsequently, the SSBI is predicted after the photodetection of the OFDM signal without the VC. Finally, to conclude the SSBI mitigation algorithm, the SSBI is withdrawn from the photodetected OFDM signal before reaching the OFDM receiver, as shown in Fig. 3.3. It is assumed here that both SEB branches are synchronized.

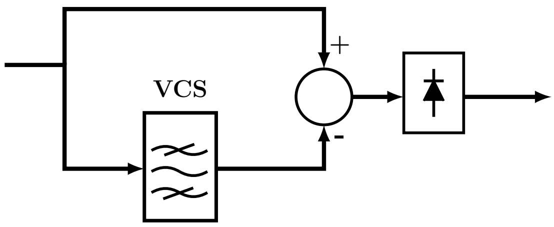



**Fig. 3.4.** The SEB model. VCS stands for VC selector.

At the input of the BS, the OFDM signal, $s_r(t)$, impaired by the interferer and ASE noise can be written as

$$s_r(t) = s_0(t) + \sum_{i=1}^{N_x} s_{x,i}(t - \tau_i)e^{j\phi_i} + N_0(t) \tag{3.1}$$

where $s_0(t)$ is the selected OFDM signal, $s_{x,i}(t)$ is the $i$-th interfering signal of $N_x$ interferers and $N_0(t)$ is the ASE noise complex envelope. It is assumed here that, the ASE noise is following a zero mean Gaussian distribution with a variance of $N_0 B_{sim}$, where $N_0$ is the ASE noise power spectrum density and $B_{sim}$ is the bandwidth used in the MC simulation, $\tau_i$ and $\phi_i$ are, respectively, the time delay and the phase difference between the selected and the $i$-th interfering signals. The $\tau_i$ parameter is considered as an uniformly distributed random variable between zero and $T_s$, and $\phi_i$ has a uniform distribution within the interval [0, $2\pi$] [27]. The crosstalk level is taken as the ratio between the average powers of the *i*-th interferer and the selected OFDM signal [28]. A sample function of ASE noise and in-band crosstalk are generated in each MC simulation and added to the optical OFDM signal.

When estimating the EVM, the MC simulation stops after 75 iterations [2], and then, the root mean square (rms) of the EVM , $EVM_{rms}$, of each $k$-th OFDM subcarrier is evaluated using [2]

$$EVM_{rms}[k] = \sqrt{\frac{\sum_{n=1}^{N_s} |s_r^n[k] - s_t^n[k]|^2}{\sum_{n=1}^{N_s} |s_t^n[k]|^2}} \quad k \in \{1, 2, ..., N_{sc}\} \tag{3.2}$$

where $s_r^n[k]$ and $s_t^n[k]$ are, respectively, the received and transmitted symbol at the $k$-th subcarrier of each $n$-th OFDM symbol of the total number of generated OFDM symbols, $N_s$. Then, the BER of each subcarrier, $BER[k]$ is calculated from [25]

$$BER[k] = 4\frac{(1 - 1/\sqrt{M})}{\log_2(M)} Q\left(\sqrt{\frac{3}{(M-1) \cdot EVM_{rms}[k]^2}}\right) \tag{3.3}$$

and the OFDM signal overall BER is given as follows

$$BER = \frac{1}{N_{sc}} \sum_{k=1}^{N_{sc}} BER[k] \tag{3.4}$$

It should be remarked that equation (3.3) assumes a Gaussian distribution for the amplitude distortion at each OFDM subcarrier [2].

The BER is estimated from DEC after a total of 5000 counted errors, $N_e$, is reached in the OFDM received signal, and is obtained using $N_e/(N_s N_{it} N_{sc} N_b)$, where $N_{it}$ is the number of iterations of the MC simulation and $N_b$ is the number of bits per symbol in each OFDM subcarrier [2].

### 3.4 Results and Discussion

In this section, the tolerance to in-band crosstalk of the VC-assisted DD MB-OFDM communication system will be numerically assessed. The maximum tolerated crosstalk level, $X_{c,max}$, will be considered as the crosstalk level that leads to a 1 dB optical signal-to-noise ratio (OSNR) penalty. The OSNR penalty is defined as the difference in dB between the OSNR in presence of crosstalk and the OSNR without crosstalk that lead to a BER of $10^{-3}$ [28].

Table 1 displays the parameters used in MC simulation to assess the tolerance to in-band crosstalk of the VC-assisted DD OFDM system for 4, 16 and 64-QAM modulation formats in the OFDM subcarriers. The $-3$ dB bandwidth of the BS ($2^{nd}$-order Super-Gaussian), and the modulation indexes are obtained from reference [4].

**Table 1.** VC-assisted DD OFDM system simulation parameters.

| Modulation format | 4-QAM | 16-QAM | 64-QAM |
|---|---|---|---|
| Bit rate per band [Gbps] | 5.35 | 10.7 | 16.05 |
| Number of subcarriers ($N_{sc}$) | 128 | | |
| Bandwidth per band [GHz] | 2.7 | | |
| OFDM symbol duration [ns] | 47.85 | | |
| Radio-frequency ($f_{RF}$) [GHz] | 5 | | |
| Modulation index [%] | 5 | | |

The evaluation of the tolerance to in-band crosstalk of the DD OFDM receiver starts with the estimation of the required OSNR to attain a $10^{-3}$ BER without in-band crosstalk. It was first assumed here that the selected and interferer OFDM signals have identical VBPR and VBG.

The plot of Fig. 3.5 shows the required OSNR as a function of the VBPR for a BER of $10^{-3}$ for different modulation format orders, without in-band crosstalk. It can be seen from Fig. 3.5, that the required OSNR for a BER of $10^{-3}$ increases almost linearly with the VBPR increase. This behavior is due to the SEB. As shown in Fig. 3.4, the SEB uses the OFDM subcarriers impaired by ASE noise to estimate and remove the SSBI from the OFDM signal. After the subtraction is performed, the ASE noise is partially removed and the OFDM performance degradation is solely determined by the VC-ASE beat noise in the received OFDM signal. Higher VBPR corresponds to a lower power on the OFDM band, thus, less tolerance to ASE noise. Therefore, in order to achieve the target BER, a higher OSNR is required.

The influence of the VBPR on the VC-assisted DD OFDM system performance is evaluated in section 3.4.1. The impact of the VBG of the interferer on the in-band crosstalk tolerance is evaluated in section 3.4.4, making use of two distinct scenarios as follows: scenario (a), the frequencies of the selected signal and interferer VCs are the same, and scenario (b) the central frequencies of the OFDM band of the selected signal and interferers have the same value.

**3.4.1 Effect of the VBPR on the In-band Crosstalk Tolerance** In this section, the effect of the VBPR of the interferer and selected signal on the tolerance to in-band crosstalk of DD OFDM receiver is addressed, taking into account two different situations. In section 3.4.2, it is assumed that the selected and interfering signals have the 16-QAM modulation format in the OFDM subcarriers, but the VBPR of the interferer, $VBPR_x$, is changed. In section 3.4.3, the study presented in section 3.4.2 was extended by evaluating the VBPR impact on the tolerance to in-band crosstalk of the DD OFDM receiver for different modulation formats orders.

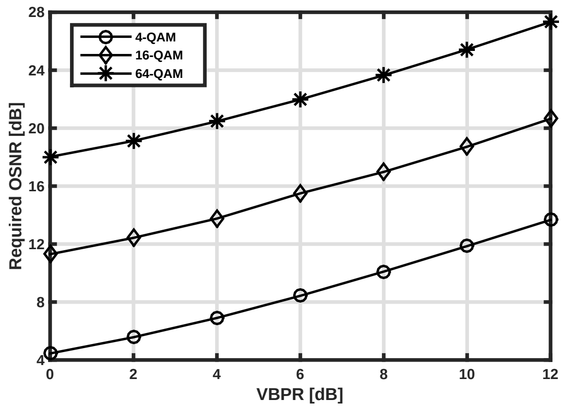



**Fig. 3.5.** OSNR required values for a BER of $10^{-3}$ in the absence of in-band crosstalk as a function of VBPR, for different $M$-QAM modulation format orders.

**3.4.2 Same Modulation Format Order.** In this section, the VBPR of the selected OFDM signal is set to 6 dB and the $VBPR_x$ is changed in the 0 to 12 dB range. The VBPR of 6 dB is achieved from the optimization carried out in [4].

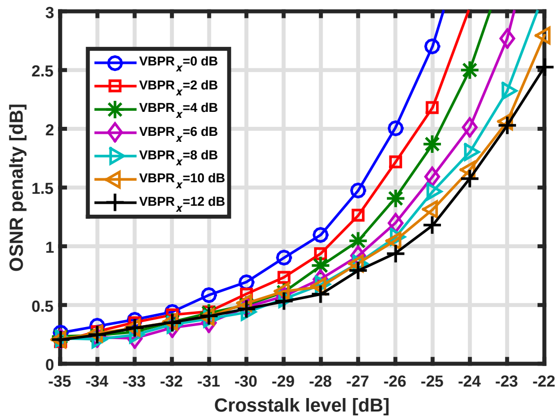



**Fig. 3.6.** OSNR penalty as a function of the crosstalk level obtained from the EVM method for 16-QAM modulation format, for interfering signals with different $VBPR_x$, and VBPR of the selected signal of 6 dB.

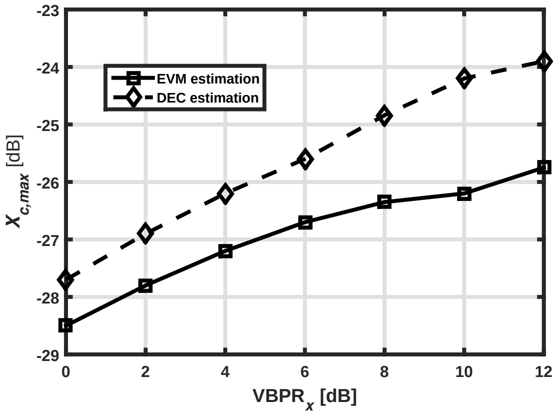



**Fig. 3.7.** Crosstalk tolerated level versus interferer VBPR, considering DEC (dashed lines) and EVM (solid lines) estimations.

The tolerated crosstalk level is assessed using the DEC and EVM methods. The accuracy of the EVM method is evaluated by comparing its estimates with the ones obtained using the DEC method.

The OSNR penalty is plotted in Fig. 3.6, obtained using the EVM method, versus crosstalk level due to a single interferer having different $\text{VBPR}_x$. Fig. 3.6 shows that higher $\text{VBPR}_x$ lead to lower OSNR penalties. In Fig. 3.7, the tolerated crosstalk level of Fig. 3.6 is shown as solid line, as a function of the $\text{VBPR}_x$. In this plot the tolerated crosstalk level as a function of the $\text{VBPR}_x$, estimated using DEC, is also shown by the dashed line. A difference of about 2.8 dB between the tolerated crosstalk level for $\text{VBPR}_x$ of 0 and 12 dB can be observed, and the receiver performance degradation is seen to enhance with the $\text{VBPR}_x$ increase. In this case, the interfering band overlaps the selected OFDM band in the frequency domain, hence, the $\text{VBPR}_x$ increase reduces the power of its OFDM band, leading to less interference.

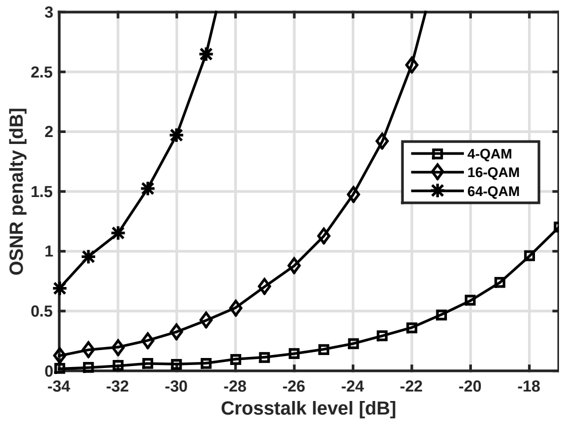



**Fig. 3.8.** OSNR penalty versus crosstalk level for different modulation format orders, for interferers and selected signals having a VBPR of 6 dB.

The tolerated crosstalk levels obtained using the DEC method are 0.8 to 1.8 dB higher than the ones obtained using the EVM method. Furthermore this difference revealed to be higher with the increase of the $\text{VBPR}_x$. For example, for 6 dB $\text{VBPR}_x$, the EVM estimates a tolerated crosstalk level of $-26.7$ dB, while, the DEC predicts a tolerated crosstalk of $-25.6$ dB. Taking into account these differences between both methods, we can conclude that the EVM is imprecise on the estimation of the tolerated crosstalk level, when the selected and interferer OFDM signal have the same VBG but different VBPRs. As the in-band crosstalk sample functions are not modelled by a Gaussian distribution, the BER calculated from equation (3.3) can give rise to a imprecise BER predictions [2].

**3.4.3 Different Modulation Format Orders.** In this section, it is intended to address the influence of the VBPR on the tolerance to in-band crosstalk of the DD OFDM receiver for different modulation formats in the OFDM receivers. Since, in the previous section, it was concluded that the EVM method is inaccurate on the tolerated crosstalk level estimation for different VBPRs of the interfering and selected OFDM signals, the study presented in this section is based only on the DEC estimation of the DD OFDM receiver performance in presence of in-band crosstalk.

Figure 3.8 depicts the OSNR penalty as a function of the crosstalk level for 4, 16 and 64-QAM modulation format considering that the selected and the interfering OFDM signals have a VBPR of 6 dB. From Fig. 3.8, it can be concluded that the reduction of the modulation format order, used in the OFDM subcarriers, leads to an increase of the tolerance to in-band crosstalk of the DD OFDM receiver. This conclusion has been already reported [28], when the tolerance to in-band crosstalk of a $M$-QAM single carrier system with coherent detection was investigated. The 4-QAM OFDM signal is about 15 dB more tolerant to in-band crosstalk than the 64-QAM OFDM signal. Fig. 3.8 shows that the tolerated crosstalk levels for the DD OFDM receiver are $-18$, $-25.5$ and $-33$ dB for the 4, 16 and 64-QAM modulation formats, respectively.

Figure 3.9 depicts the tolerated crosstalk level as a function of the VBPR for 4, 16

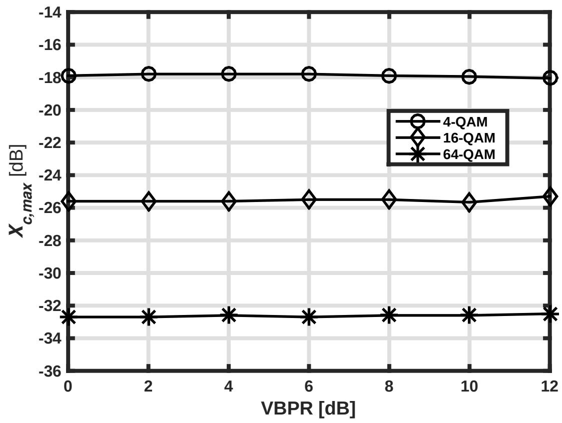



**Fig. 3.9.** Tolerated crosstalk level versus $\text{VBPR}_x$ for different modulation format orders for 6 dB VBPR of the selected OFDM signal.

and 64-QAM modulation formats. Remark that, in this case, the VPBR of the interferer and the selected OFDM signals are the same. From Fig. 3.9, it can be observed that the tolerated crosstalk level is only dependent on the modulation format order of the OFDM subcarriers and it is essentially independent of the VBPR.

Figure 3.10 depicts the tolerated crosstalk level as a function of the $\text{VBPR}_x$, for different modulation format orders for a 6 dB VBPR level of the selected OFDM. In this figure it can be seen that the tolerated crosstalk level increases with the $\text{VBPR}_x$, as already seen in section 3.4.2. For $\text{VBPR}_x$ of 0 dB, the VC-assisted DD OFDM system is 4 to 5 dB less tolerant to in-band crosstalk than the one estimated for $\text{VBPR}_x$ of 12 dB, regardless the format modulation order used in the OFDM subcarriers. Accordingly, by taking into account the conclusions arising from the results depicted in Figs. 3.9 and 3.10, one can conclude that the tolerance to in-band crosstalk, for a given modulation format order, is dependent on the difference between the VBPRs of the selected and interferer OFDM signals. When the $\text{VBPR}_x$ is different from the VBPR of the selected OFDM signal, the tolerance to in-band crosstalk is enhanced with higher $\text{VBPR}_x$.

**3.4.4 In-band Crosstalk Tolerance Dependence on VBG** In this section, the influence of the VBG of the interferer on the VC-assisted DD OFDM system performance is evaluated, at the light of two different scenarios. In scenario (a), the frequency of the VC of the interfering OFDM signal is the same as the VC of the selected signal, and the variation of the VBG of the interferer leads to a frequency deviation between the central frequencies of the selected and interferer OFDM bands, as it can be seen in graph of Fig. 3.11(a). In the graph of Fig. 3.11(a), the spectrum of the selected OFDM signal is displayed in black while that of the interfering OFDM signal spectrum is displayed in gray. The interferer has a VBG of 1.34 GHz and a crosstalk level of $-20$ dB. Fig. 3.11(b) exemplifies the scenario (b), in which, the central frequencies of the interfering and the selected OFDM bands are the same, and the variation of the VBG of the interferer leads to a frequency difference between the VC frequencies of the selected and interferer signals. In graph of Fig. 3.11(b), the VBG of the interferer is also 1.34

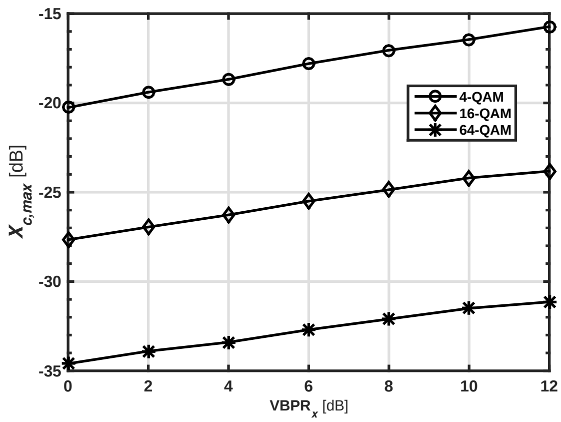
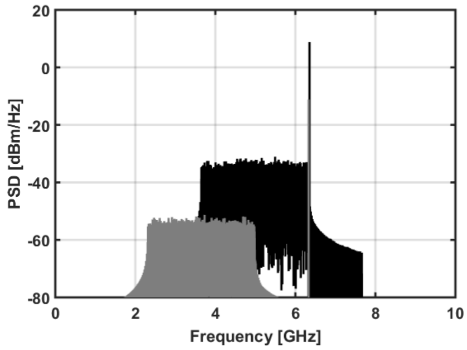
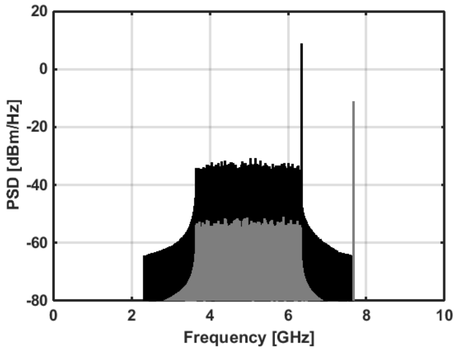



**Fig. 3.10.** Tolerated crosstalk level versus $\text{VBPR}_x$ for different modulation format orders, a 6 db VBPR of the selected OFDM signal is considered.




(a)




(b)

**Fig. 3.11.** PSDs of the selected OFDM signal (black) and interferer signal (gray) with a crosstalk level of $-20$ dB and a VBG=$B_w/2$ considering (a) same VCs frequencies and (b) equal OFDM bands central frequencies.

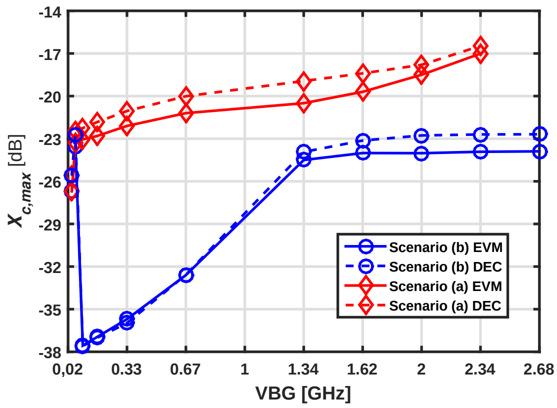



**Fig. 3.12.** Tolerated crosstalk level versus VBG.

GHz. The influence of the VBG on the tolerance to in-band crosstalk of the DD OFDM receiver is evaluated using the DEC and EVM methodologies, and their estimations are confronted in order to evaluate the influence of the VBG on EVM estimation accuracy of the tolerated crosstalk level.

The plot of Fig. 3.12 represents the tolerated crosstalk level versus the interferer VBG, for both simulation scenarios and estimated by the DEC method (dashed line) and EVM method (solid line). Focusing on scenario (a), Fig. 3.12 shows that the tolerance to in-band crosstalk increases with the interferer VBG. The crosstalk level with a VBG of 2.34 GHz is about 9 dB higher than the one obtained with a VBG of 20.9 MHz. As mentioned before, this scenario gives rise to the misalignment between the interferer central frequencies and selected bands. Therefore, as the VBG increases, less subcarriers of the selected band are being affected by the in-band crosstalk, and which causes the enhancement of the robustness of the DD OFDM system to in-band crosstalk. For a 2.68 GHz VBG, the interferer OFDM band is totally misaligned from the selected signal OFDM band, meaning that the OFDM subcarriers of the selected signal are not influenced by in-band crosstalk and leading to a null OSNR penalty. It can then be con-

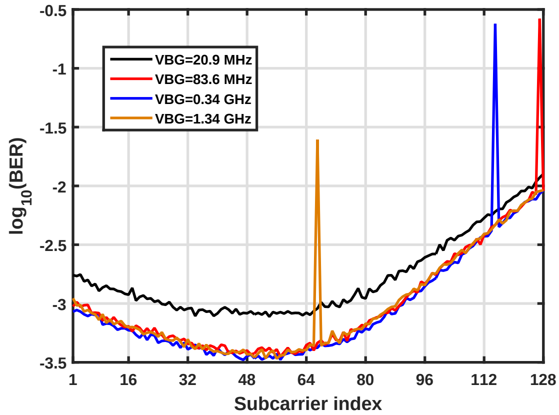


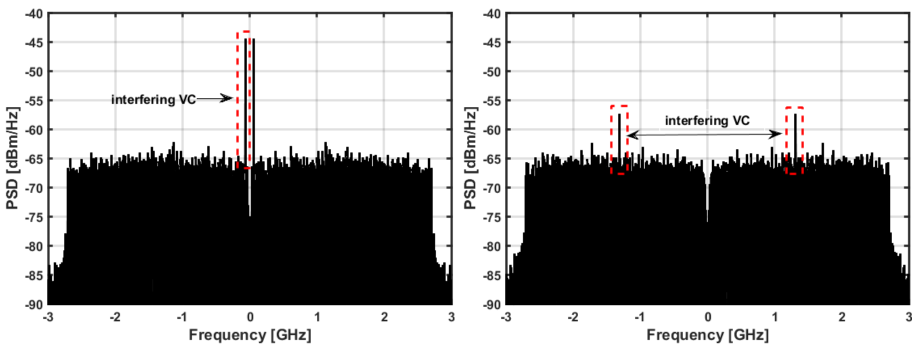

**Fig. 3.13.** BER versus subcarrier index.

cluded that, in scenario (a), the DD OFDM receiver is completely tolerant to interfering OFDM signals with VBG equal or wider than the selected OFDM signal bandwidth.

The graph of Figure 3.12 also indicate that the EVM estimations for the tolerated crosstalk level are not in accordance with the DEC estimations, as a 2 dB difference between both estimations can be attained. Again, this disagreement between the two methods can be attributed to the non-Gaussian distribution of the in-band crosstalk sample functions.

Concerning scenario (b), Fig. 3.12 shows that the interfering signals having VBGs between 83.6 MHz and 0.67 GHz show a significant reduction on the tolerated crosstalk level, in comparison with smaller VBG. For a VBG of 83.6 MHz, the tolerated crosstalk level is about 11 dB smaller than the one obtained for a VBG of 20.9 MHz.

To go further in investigating this behavior, the BER estimated from the EVM is plotted versus the subcarrier index as shown in Fig. 3.13. In this figure, the crosstalk level was set to $-26$ dB, in order to allow a performance comparison with different interferer VBGs. Under this compliance it can be seen that for a 83.6 MHz VBG, the subcarrier 128 is the subcarrier with the worst performance due to the presence of the




(a) (b)

**Fig. 3.14.** PSDs of the photodetected signal for a crosstalk level of $-20$ dB for (a) VBG of 83.6 MHz and (b) VBG of 1.34 GHz.

detected VC interferer. The increase of interferer VBG changes the subcarrier with less performance, in such a way that the BER per subcarrier is reduced, thus, decreasing the overall BER. The BS filtering was seen to account for this behavior. As the VBG increases, the frequency of the interferer VC becomes closer to the BS cut-off region, and thus, the VC power of is attenuated, so that after photodetection, the performance of the subcarrier that suffers the VC interference is incremented. For interferers having a VBG of 2.68 GHz, the frequency of the VC interferer is outside the BS passband, conducting to a full suppression of the interfering VC. This behavior can be outlined from the comparison of the OFDM signal spectrums at the photodetector output displayed in Figs. 3.14.

The graph of Fig. 3.14(a) displays the photodetection of the selected band in the presence of an interfering band having a VBG of 83.6 MHz, while, the one of Fig. 3.14(b), displays the interferer band VBG is 1.34 GHz. By comparing the behavior of both graps, it can be concluded that the VBG increase is giving rise to a frequency shift of the detected interferer VC and to an attenuation of its power imposed by the BS.

Finally, comparing the estimations of the tolerated crosstalk levels obtained from both methods, in scenario (b), Fig. 3.12 reveals that, for interferers with VBGs between 83.6 MHz and 0.67 GHz, the obtained tolerated crosstalk level estimations from the EVM and DEC are in compliance. Regarding remaining VBGs, for which higher tolerated crosstalk levels are estimated, a maximum difference of 1.2 dB between both estimations can be attained. It can then be asserted that the tolerated crosstalk level increase leads to a disagreement between the EVM and the DEC estimations, as the BER estimated from EVM, through equation (3.3), looses accuracy.

### 3.5 Conclusions

The OSNR penalty due to the in-band crosstalk on the performance of the VC-assisted OFDM metropolitan systems has been assessed using numerical simulations. The influences of the VBPR for different modulation format orders in the OFDM subcarriers and of the VBPR and the VBG of the interferer on the OSNR penalty have also been investigated.

It was shown that the influence of in-band crosstalk on the DD OFDM receiver performance depends on the difference between the VBPR of the selected and interferer OFDM signals and diminishes with the interferer VBPR increase. Higher VBPR was seen to lead to a reduction of the power of the interferer OFDM band, causing less interference on the detection of the selected signal. The increase of the modulation format order of the OFDM subcarriers also lead to less tolerance to in-band crosstalk. The 64-QAM modulation format has around 15 dB less tolerance to in-band crosstalk than the one found for the 4-QAM modulation format.

The impact of the interferer VBG on the in-band crosstalk tolerance, according with two different simulation scenarios, has also been analyzed. In a scenario (a), the VCs of the selected signal and interferer are set at the same frequency. In this case, results revealed that the increase of the overlapping between the interferer and selected OFDM subcarriers bands lead to higher system performance degradation. Larger VBG leads to a system performance improvement as the number of subcarriers that suffer in-band crosstalk is reduced. When the VBG of the interferer is equal to the selected OFDM signal bandwidth, the subcarriers of the interferer and selected OFDM signals are non-overlapped and the receiver performance is not degraded by in-band crosstalk. Regarding a scenario (b), selected and interferer OFDM bands are overlapped and the VBG of the interferer varied. For VBGs narrower than 1 GHz, the tolerance to in-band crosstalk is severely reduced and reaches a 11 dB less tolerance, for a VBG of 83.6 MHz. This behavior is caused by the detection of the interferer VC on the selected signal subcarriers that significantly degrades the DD OFDM receiver performance. For larger VBG, the VC of the interferer becomes closer to the cut-off region of the band selector, its power is attenuated and the performance of the DD OFDM receiver is slightly improved.

It has been also shown that the EVM method predicts inaccurate estimates of the maximum tolerated crosstalk level.

**3.5.1 Acknowledgments.** This work was supported by Fundação para a Ciência e Tecnologia (FCT) from Portugal through Project MORFEUS-PTDC/EEITEL/2573/2012. The project UID/EEA/50008/2013 is also acknowledged.

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