Influence of the SSBI Mitigation on the In-Band Crosstalk Tolerance of Virtual Carrier-Assisted DD Multi-Band OFDM Metro Networks

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***Abstract*—In this work, the tolerance to in-band crosstalk of virtual carrier (VC)-assisted direct detection (DD) multi-band orthogonal frequency division multiplexing (MB-OFDM) metro networks, with and without signal-to-signal beat interference (SSBI) mitigation, is compared numerically for 4-ary, 16-ary and 64-ary quadrature amplitude modulation (QAM) formats in the OFDM subcarriers. Our results show that the tolerance to in-band crosstalk is improved for lower modulation format orders. The tolerance to in-band crosstalk of DD OFDM receivers considering 4-QAM modulation format at the DD OFDM subcarriers is above 14 dB higher than the one obtained for the 64-QAM modulation format, regardless the receiver configuration. We have also shown that, the tolerance to in-band crosstalk for a given modulation format order depends on the difference between the virtual carrier-to-band power ratio (VBPR) of the selected and interfering signals, as interferers with same VBPR as the selected signal leads to equal tolerance to in-band crosstalk, independently from the DD OFDM receiver configuration and the subcarrier modulation format order considered.**

Keywords: Direct detection, in-band crosstalk, Monte-Carlo simulation, multi-band orthogonal frequency division multiplexing, signal-signal beat interference mitigation.

I. Introdution

Orthogonal frequency division multiplexing (OFDM) has emerged as a solution to increase the capacity of optical networks due to its high spectral efficiency (SE), capacity granularity and robustness against fibre dispersion [1]. The bandwidth allocation flexibility is also considered an important feature for future metro optical networks [2] and it can be achieved with the multi-band (MB) OFDM technique, in which several OFDM bands are simultaneously transmitted [3]. Moreover, direct detection (DD) OFDM has been appointed as a promising candidate to be the detection technique for future optical networks [4], due to its simpler detection scheme in comparison with the coherent detection. The use of a virtual-carrier (VC) to assist the DD in the MB-OFDM system, allows to reduce the receiver bandwidth [3], [4]. Recently, a VC-assisted DD MB-OFDM system has been proposed for high capacity metropolitan networks (MORFEUS) [2].

The signal-to-signal beat interference (SSBI) is an important performance limitation on DD OFDM networks and it results from the photodetection. In order to overcome the SSBI limitation, the frequency gap between the VC and the correspondent OFDM band is set to be higher than the OFDM bandwidth [5], or by making use of digital signal processing algorithms in order to mitigate the SSBI at the receiver [2]. In this work, the SSBI mitigation technique presented in [6] is used, where the SSBI is estimated and removed from the photodetected signal using two optical branches, and an additional PIN photodetector at the receiver.

In OFDM optical networks, the system performance can be impaired by in-band crosstalk [7], which is a signal with the same nominal wavelength as the primary signal and it is caused from imperfect isolation of optical devices, for example, in a reconfigurable add-drop multiplexer (ROADM) [8]. In-band crosstalk has been studied in the context of conventional DD OFDM systems [7]. However, the performance degradation due to in-band crosstalk is still to be assessed, in a VC-assisted DD MB-OFDM systems with and without SSBI mitigation. This work assess and compares, using Monte-Carlo (MC) simulation, the tolerances to in-band crosstalk of VC-assisted DD OFDM systems networks with and without SSBI mitigation, considering different M-ary quadrature amplitude modulation (M-QAM) orders in the OFDM subcarriers. Additionally, we also investigate the influence of the VBPR on the in-band crosstalk tolerance.

II. Network description and modelling

In this section, the MORFEUS network is described and its model is presented. The main characteristics of the OFDM band are also detailed. To conclude this section, the MC simulation used to assess the network performance in presence of in-band crosstalk is described.

A. MORFEUS Network

Figure 1 depicts a simplified diagram of the MORFEUS network [2]. The metro network consists of a ring topology. Each network node comprises a ROADM, a MORFEUS insertion block (MIB) and a MORFEUS extraction block (MEB). In the MIB, the OFDM transmitter (Tx) generates OFDM bands and virtual carriers in the electrical domain, and then the OFDM signal is converted to the optical domain using an electrical-to-optical converter (EOC) and inserted in the optical network [2]. The MEB is responsible for two tasks: band extraction and band blocking [2]. In this work, we focus only on the band extraction as illustrated in Fig.1. The band

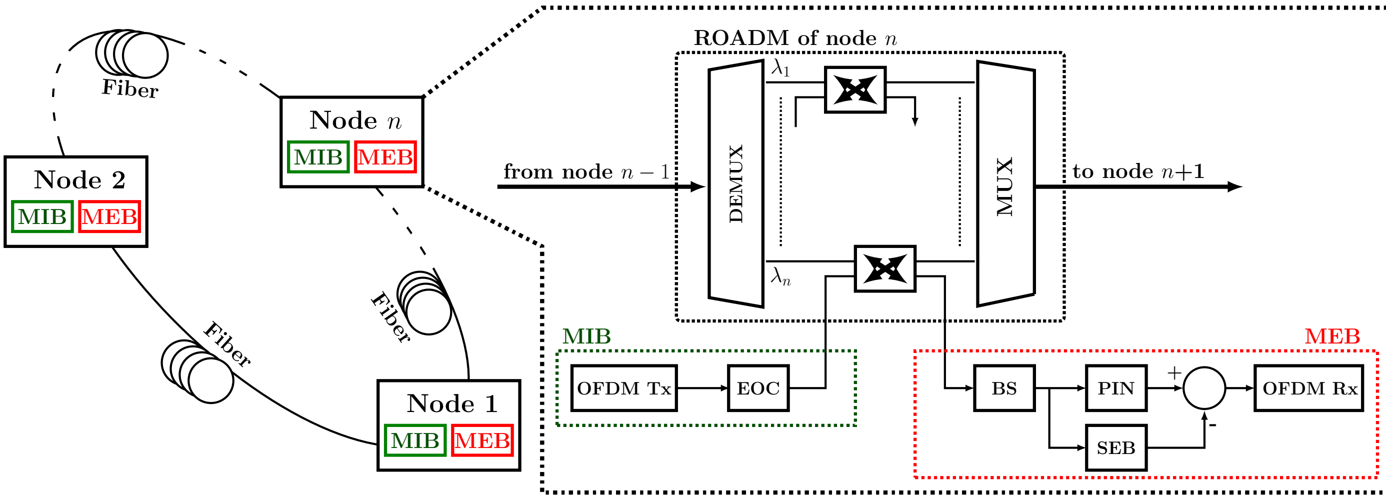


Fig. 1: Block diagram of the MORFEUS network and the corresponding nodes.

extraction/selection is performed by a tunable optical filter (BS), which selects the desired OFDM band. Then, the selected OFDM band is sent to the SSBI estimation block (SEB) and to the ideal PIN photodiode. Before the OFDM signal is demodulated by the OFDM receiver (Rx), the SSBI estimated by the SEB is removed from the photodetected signal.

A single OFDM band is suffice to assess the impact of in-band crosstalk on the receiver performance. Hence, we consider that the OFDM signal has only one pair OFDM band-VC, whose spectrum is depicted in Fig. 2. Fig. 2 shows an OFDM signal with a radio-frequency (f_{RF}) of 5 GHz and a bandwidth, B_w, of 2.7 GHz. The frequency gap between the OFDM band and the VC frequency is the virtual carrier-to-band gap (VBG), which in Fig. 2 is $0.5B_w$. The ratio between the average powers of the VC and OFDM band is the virtual carrier-to-band power ratio (VBPR) [2]. In conventional OFDM systems, a narrow VBG can be achieved by increasing the VBPR, thereby reducing the signal distortion due to the SSBI. However, it also reduces the OFDM band power and, consequently, the system performance is degraded [2]. Hence,

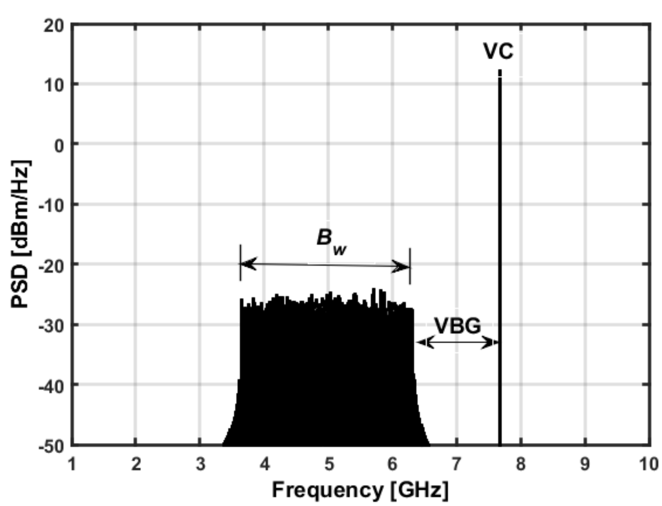


Fig. 2: Spectrum of a MB-OFDM signal considering one OFDM band and VC.

this method is undesirable, since it demands a great amount of power consumption in order to achieve a good receiver performance [2]. SSBI mitigation techniques enable the use of low VBPRs with very narrow VBGs [2], [6].

B. *Monte-Carlo Simulation*

In this subsection, the MC simulation is described and the analytical models used for the sample functions of the amplified spontaneous emission (ASE) noise and in-band crosstalk are detailed.

The simulation model of the MORFEUS network used to assess the tolerance to in-band crosstalk is depicted in Fig. 3. The system model consists of an OFDM Tx with VC generation, a dual parallel Mach-Zehnder modulator (DP-MZM), a BS, an ideal PIN photodetector, a SEB and an OFDM Rx. The bit error rate (BER) is estimated at the output of the OFDM receiver by using direct error counting (DEC).

The MC simulation starts with the generation of the VC together with the OFDM band in the electrical domain. Then, a single-side band (SSB) OFDM optical signal is obtained at the DP-MZM output, by applying the electrical OFDM signal to one branch of the DP-MZM and the ideal Hilbert transform (HT) of that electrical signal to the other branch. The MORFEUS network employs the transmission of SSB optical signals to overcome the chromatic dispersion induced power fading [2]. The modulation index of the DP-MZM is set to 5%. This value is obtained from the modulation index optimization presented in [2]. At the receiver, after band selection and before the photodetected OFDM signal arrives at the OFDM electrical receiver, the SSBI estimated by the SEB is ideally removed from the photodetected signal.

The structure of the SEB is depicted in Fig. 4. The main goal of the SEB is to estimate the SSBI in the presence of ASE noise and in-band crosstalk. The SEB is composed of two branches. The lower branch comprises an ideal optical filter, named virtual carrier selector (VCS), whose function is to select the VC of the OFDM selected signal. After the VC selection, the subtractor removes the VC from the band+VC signal at the upper branch. Then, the selected OFDM signal without the VC is photodetected leading to the estimated SSBI. Using this estimation, the SSBI is then removed from the

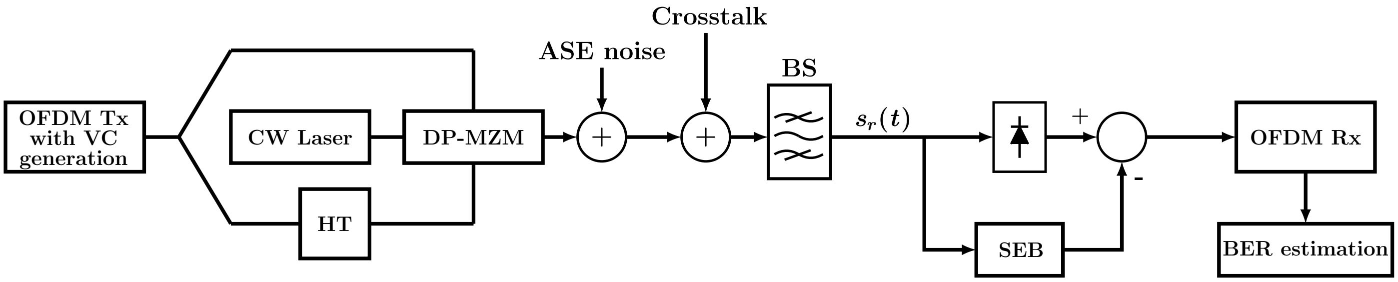


Fig. 3: System model of the DD OFDM communication system assisted with VC, in back-to-back configuration.

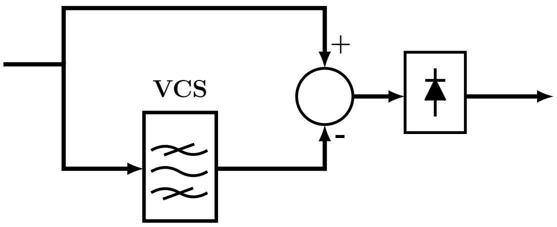


Fig. 4: Model of the SSBI estimation block (SEB).

TABLE I: Simulation parameters of the VC-assisted DD OFDM system.

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		

photodetected OFDM signal, as shown in Fig. 3. In this work, we assume that the two branches of the SEB are synchronized.

The ASE noise is modelled as a zero mean white stationary Gaussian noise with variance of $N_0 B_{sim}$, where N_0 is the power density of the ASE noise and B_{sim} is the bandwidth used in the MC simulation. In each run of the MC simulator, an ASE noise sample function is added to the OFDM optical signal. An in-band crosstalk sample function is also generated and added to the optical signal in each run of the MC simulation.

The OFDM signal, in presence of ASE noise and in-band crosstalk, at the BS output, $s_r(t)$, is given by

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

where $s_0(t)$ is the selected OFDM signal, $s_{x,i}$ is the i-th interferer of N_x interfering signals, and $N_0(t)$ is the complex envelope of the ASE noise. Each interferer has a time misalignment, τ_i, and a phase difference ϕ_i, relative to the selected signal. τ_i and ϕ_i are modelled as random variables with a uniform distribution, varying between 0 and the OFDM symbol duration, T_s, (without guard time), and within the [0,2π] interval [9], respectively. The crosstalk level of the i-th interferer is the ratio between the average powers of the i-th interferer and of the selected OFDM signal.

The MC simulator runs are repeated until a total number of 5000 counted errors in the OFDM signal, N_e, is reached. Then, the bit error rate (BER) is estimated using BER = $N_e/(N_r N_s N_b N_{sc})$, where N_r is the number of runs of the MC simulator, N_s is the number of simulated OFDM symbols per run, N_b is the number of bits per symbol in each OFDM subcarrier and N_{sc} is the number of subcarriers in one OFDM symbol.

III. Numerical Results and Discussion

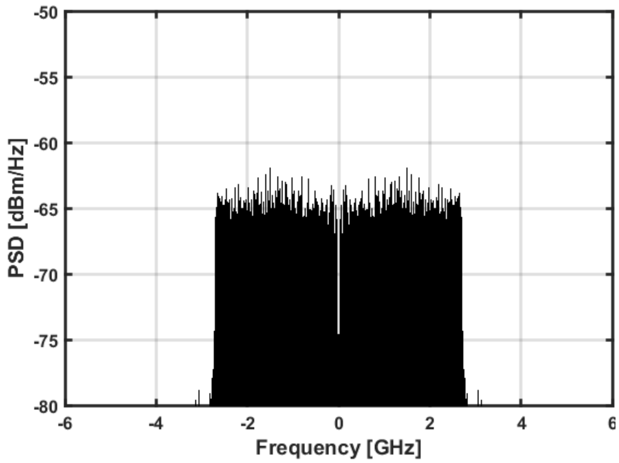
In this section, the impact of the in-band crosstalk on the VC-assisted DD OFDM system performance is assessed through MC simulation and the BER is estimated using DEC. The tolerated crosstalk level, $X_{c,max}$, is the crosstalk level that leads to a penalty of 1 dB in the optical signal-to-noise ratio (OSNR). The OSNR penalty is defined as the difference between the OSNR with and without in-band crosstalk that leads to a BER of 10^{-3} [8].

Table I presents the VC-assisted DD MB-OFDM system simulation parameters, in order to assess its tolerance to in-band crosstalk. The -3 dB bandwidth of the BS (2^{nd}-order Super Gaussian filter) is 3.6 GHz and this value is taken from the work presented in [2].

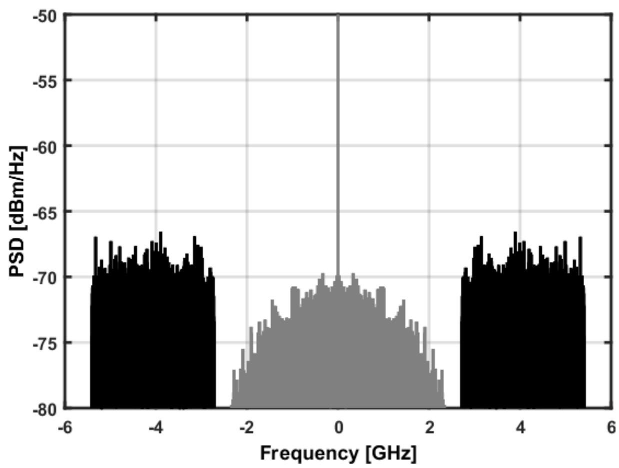
In this paper, two values for the VBG are considered. The use of SEB allows to have a narrow VBG (20.9 MHz), hence, leading to a very high SE. When the SEB is not considered, in order to accommodate the SSBI term, the VBG must be larger than B_w. We assume a VBG of 2.7 GHz. Moreover, in order to avoid the VC filtering, the -3 dB bandwidth of the BS is enlarged to 7.2 GHz.

Figure 5 depicts the spectrum without noise of the OFDM signal at the input of the OFDM Rx, considering a (a) VBG of 20.9 MHz (using SEB) and a (b) VBG of 2.7 GHz (without SEB). Fig. 5(a) depicts a spectrum with a very narrow gap between the photodetected bands, completely free of SSBI. Fig. 5(b) shows that, for a VBG larger than the OFDM signal bandwidth, the SSBI spectrum is totally out-of-band of the desired OFDM signal. Remark that in Fig. 5(b), the SSBI spectrum is represented with gray color excluding the DC component.

The evaluation of the influence of the VBPR on the tolerance to in-band crosstalk of the VC-assisted DD OFDM system, with and without the SEB, starts with the estimation of the required OSNR to get a BER of 10^{-3} without in-band crosstalk for both receiver configurations. In our study, we first assume that the selected and interferer OFDM signals have



(a)



(b)

Fig. 5: Spectrum of the photodetected OFDM band, at the OFDM Rx input, in absence of ASE noise with (a) VBG= 20.9 MHz and with SSBI mitigation and (b) VBG=2.7 GHz without SSBI mitigation. Desired OFDM bands (black); SSBI plus DC component (grey).

identical VBPR. Then, in order to compare the influence of the VBPR of the interferer on the in-band crosstalk tolerance, the VBPR of the selected OFDM signal is set to 6 dB and the VBPR of the interferer is varied between the 0 and 12 dB. The VBPR of 6 dB is obtained from the optimization performed in [2].

In Fig. 6, the required OSNR as a function of the VBPR for a BER of 10^{-3}, in absence of in-band crosstalk, for different modulation format orders, with the SSBI mitigation technique (solid lines) and without the SSBI mitigation technique (dashed lines) is depicted. Considering the VC-assisted DD OFDM system with SSBI mitigation technique, the required OSNR for a BER of 10^{-3} increases almost linearly with the increase of the VBPR. The SEB shown in Fig. 4, uses the OFDM subcarriers impaired by ASE noise to subtract the SSBI from the desired OFDM signal. When this subtraction is performed, the ASE noise is partially removed and only remains the VC-ASE beat noise as the main contributor to the OFDM receiver performance degradation. Higher VBPR leads to a lower power on the OFDM band, hence, the OFDM subcarriers become more sensitive to ASE noise and a higher OSNR is required

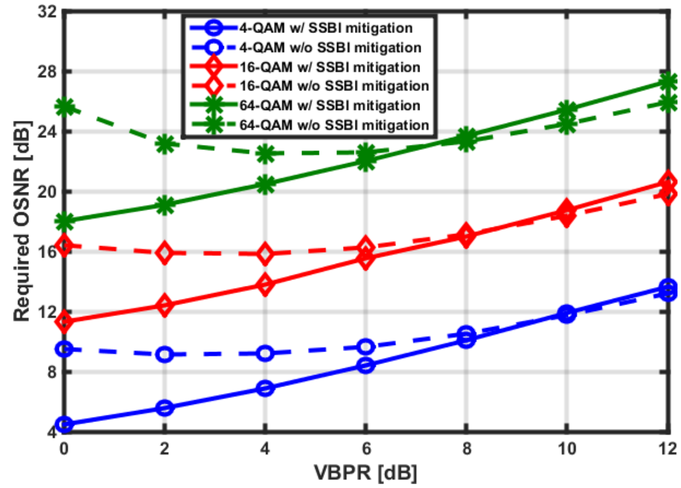


Fig. 6: Required OSNR for a BER of 10^{-3} in absence of in-band crosstalk as a function of the VBPR for different modulation format orders and with SSBI mitigation technique (solid lines) and without SSBI mitigation technique (dashed lines).

to achieve the target BER.

Regarding the DD OFDM receiver without the SSBI mitigation technique, Fig. 6 shows that the required OSNR for OFDM signal with a VBPR of 0 dB is around 5 dB higher for the 4-QAM and 16-QAM modulation formats and 7 dB higher for 64-QAM, in comparison with the required OSNR with the use of SSBI mitigation technique. In this case, in spite of the SSBI spectrum is out-band of the OFDM signal, the system performance is also diminished due to the signal-ASE noise beating. Remark that, without the use of the SEB, all the ASE noise power is photodetected with the OFDM signal, and thereby, the beating between the ASE noise and the OFDM signal enhances and leads to a stronger degradation of the DD OFDM receiver performance. For OFDM signals with VBPR higher than 6 dB, the required OSNR are practically the same

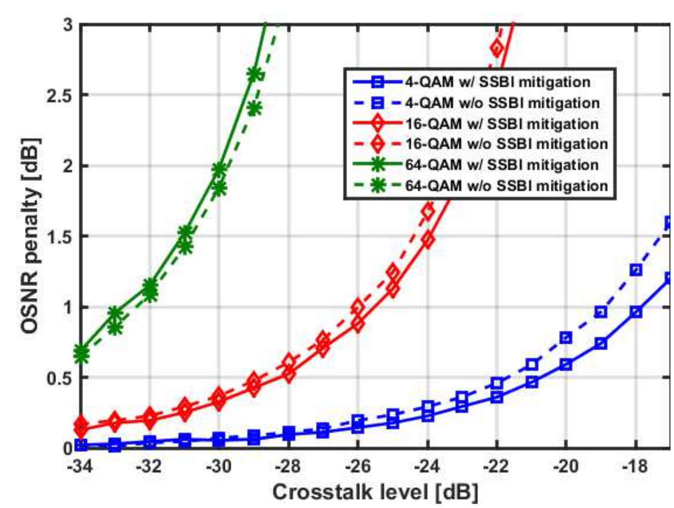


Fig. 7: OSNR penalty as a function of the crosstalk level for different modulation format orders and with SSBI mitigation technique (solid lines) and without SSBI mitigation technique (dashed lines) for a interferers and selected signals with a VBPR of 6 dB.

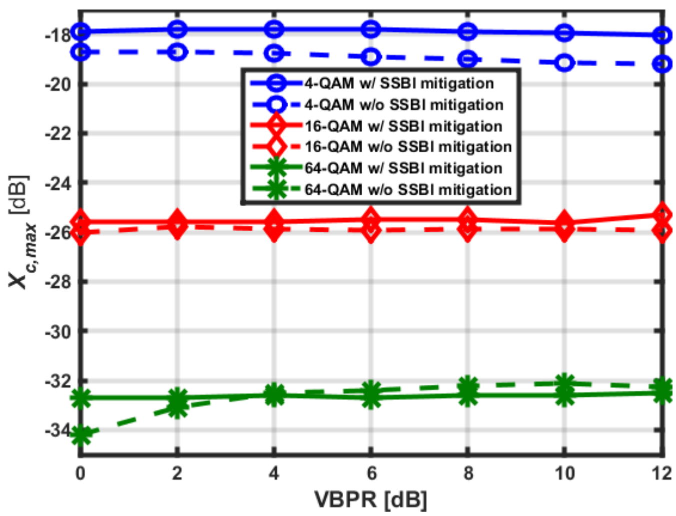


Fig. 8: Tolerated crosstalk level as a function of the VBPR for different modulation format orders and with SSBI mitigation technique (solid lines) and without SSBI mitigation technique (dashed lines).

as the ones needed when considering the SSBI mitigation. Therefore, we can conclude that besides of enhancing the system SE, the SSBI mitigation technique allows to reduce the required average power of the VC for a good system performance.

Figure 7 depicts the OSNR penalty as a function of the crosstalk level for 4-QAM (blue), 16-QAM (red) and 64-QAM (green) mapping, with the SSBI mitigation technique (solid lines) and without SSBI mitigation technique (dashed lines) considering that the interferer and the selected OFDM signals have a VBPR of 6 dB. From Fig. 7, it can be concluded that the tolerance to in-band crosstalk of the DD OFDM receiver reduces with the increase of the modulation format used in the OFDM subcarriers. This behaviour has been already observed in M-QAM single carrier systems with coherent detection [8]. From Fig. 7, a reduction of the in-band crosstalk tolerance above 14 dB is observed for the 64-QAM OFDM signals in comparison with the 4-QAM OFDM signal. This conclusion holds for both receiver configurations. Fig. 7 shows that the tolerated crosstalk levels for the DD OFDM receiver without mitigation of the SSBI are -19, -26 and -32.4 dB for the 4-QAM, 16-QAM and 64-QAM modulation format, respectively. With SSBI mitigation technique, the tolerated crosstalk levels are -18, -25.5 and -32.5 dB for the 4-QAM, 16-QAM and 64-QAM modulation format orders, respectively.

Figure 8 depicts the tolerated crosstalk level as a function of the VBPR for 4-QAM (blue), 16-QAM (red) and 64-QAM (green) modulation formats and considering an OFDM receiver with the SEB (solid lines) and without the SEB (dashed lines) and for different VBPRs. From Fig. 8, it can be concluded that, for both OFDM receiver configurations, the tolerated crosstalk level is practically independent of the VBPR level and depends only on the modulation format order of the OFDM subcarriers. The exception occurs for 64-QAM modulation format with VBPR of 0 to 4 dB and considering a DD OFDM receiver without the SEB. The tolerated crosstalk level for a VBPR of 0 dB is 1.5 dB higher than the one estimated for the same VBPR but considering the SEB. However, for VBPR higher than 4 dB, the tolerances to in-band crosstalk of both receiver configurations are practically the same. Fig. 8 also shows that the tolerance to in-band crosstalk of the VC-assisted DD OFDM system for 4-QAM modulation format order in the OFDM subcarriers and with the use of the SEB is about 1 dB higher than the one for the DD OFDM receiver without SSBI mitigation for the same modulation format order. While, the tolerance to in-band crosstalk for 16-QAM modulation format at the subcarriers with the use of SEB is about 0.5 dB higher than the one obtained without the SSBI removal on the photodetected signal. Hence, we can concluded that tolerance difference between both receiver configurations becomes smaller with the increase of the modulation format order used in the OFDM subcarriers.

Figure 9 depicts the tolerated crosstalk level as a function of the VBPR of the interferer, VBPR$_x$, for different modulation format orders, with the SSBI mitigation technique (solid lines) and without the SSBI mitigation technique (dashed lines) considering that the VBPR of the selected OFDM signal is 6 dB. Fig. 9, shows that the tolerated crosstalk level increases with the increase of the VBPR$_x$. For VBPR$_x$ of 0 dB, the VC-assisted DD OFDM system has 4 to 5 dB less tolerance to in-band crosstalk than the one estimated for interferers with a VBPR of 12 dB, regardless the OFDM receiver configuration and the modulation format order used in the OFDM subcarriers. Hence, by considering the conclusions drawn regarding the results presented in Figs. 8 and 9, we can conclude that the tolerance to in-band crosstalk, for a given modulation format order, depends on the difference between the VBPRs of the selected and interferer OFDM signals. When the VBPR$_x$ is different than the VBPR of the selected OFDM signal, the tolerance to in-band crosstalk increases for higher VBPR$_x$.

IV. Conclusions

In this work, the impact of in-band crosstalk in a VC-assisted DD MB-OFDM system has been assessed, considering two different receiver configurations at the OFDM receiver: with and without SSBI mitigation technique. Additionally, the influence of the VBPR on the tolerance to in-band crosstalk of

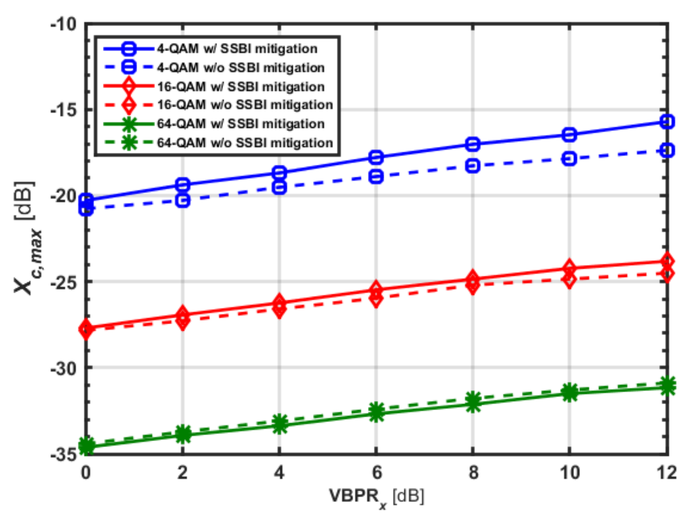


Fig. 9: Tolerated crosstalk level as a function of the VBPR$_x$ for different modulation format orders and with SEB (solid lines) and without SEB (dashed lines) considering that the VBPR of the selected OFDM signal is 6 dB.

the VC-assisted DD OFDM system considering both receiver configurations and different M-QAM modulation format orders has been also studied.

Our results have revealed that higher modulation format orders in the OFDM subcarriers lead to less tolerance to in-band crosstalk for both DD OFDM receiver configurations, since higher modulation format orders are more sensitive to noise. The VC-assisted DD OFDM system, with and without SSBI mitigation, has about 14 dB less crosstalk tolerance with 64-QAM OFDM signal than with 4-QAM OFDM signals. We have also shown that the VC-assisted DD OFDM system with SSBI mitigation is 1 and 0.5 dB more tolerant to in-band crosstalk than the ones obtained without SSBI mitigation for the 4-QAM and 16-QAM modulation format, respectively. For the 64-QAM modulation format, our results shown that the tolerated crosstalk level for both system configurations is identical.

The comparison between the tolerated crosstalk levels for both receiver configurations has shown that the tolerated crosstalk level variation with the VBPR, depends on the modulation format order used in the OFDM subcarriers and on the difference between the VBPRs of the selected and interfering OFDM signals. Moreover, when comparing both receiver configurations tolerance to in-band crosstalk, the increase of the modulation format order leads to practically the same maximum tolerated crosstalk level.

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