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INTERFERENCE CANCELLATION IN MULTIUSER HYBRID OVERLAY COGNITIVE RADIO

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ABSTRACT

In this paper, we consider an overlay cognitive radio (CR) consisting of a primary macro-cell and cognitive small cells of cooperative secondary base stations (SBS). We suggest studying a hybrid CR where a filter bank multicarrier (FBMC) is used for the secondary users (SU) whereas the primary users (PU) are based on orthogonal frequency division multiplexing (OFDM). Compared to OFDM, FBMC has the advantage of reducing the SU interference level that is induced by the differences between the SBS and PU carrier frequency offsets (CFO). Our contribution is threefold: 1/ we derive the interference expression due to SU at the PU receiver, 2/ we propose to use zero forcing beamforming (ZFBF) to cancel the interference, 3/ a comparative study with CR based on OFDM for both the PU and the SU confirms the efficiency of the proposed scheme.

***Index Terms*—** overlay CR, OFDM, FBMC, ZFBF.

1. INTRODUCTION

CR has been nominated as a promising technology to solve the problems of spectrum leakage and to re-employ the radio frequency spectrum. Several CR network paradigms exist. Among them, spectrum interweave, overlay and underlay are spectrum-sharing families[1] in CR [1]. In this paper, we focus our attention on an overlay approach. As the PU standards (LTE, Wifi, etc.) are assumed to be known by the SU, a precoding can be defined to cancel or mitigate the interference at the PU. However, applying a precoding in a context with a large number of PU and SU requires a SBS with a large number of antennas. It is not always possible to satisfy this constraint. Therefore, a solution consisting of virtual multiple-input multiple-output (MIMO) networks can be considered, based on small-cell SBS cooperation [2]. This strategy is of interest for overlay CR systems. For the last years, two scenarios have been addressed:

1/ CR based on OFDM [3]: OFDM is used in a wide range of high-profile wireless systems [4]. However, it is well-known that a guard interval, which may be composed of a cyclic prefix (CP), must be inserted to eliminate the inter-symbol interference (ISI). Hence, this decreases the system spectral efficiency. In addition, OFDM is sensitive to CFO. More particularly, the PU CFO must be estimated and compensated [5] at the PU receiver to eliminate the inter-carrier interference (ICI). However, a difference in CFO is induced at each SBS.

2/ CR based on FBMC [6]: FBMC based offset quadrature amplitude modulation (FBMC/OQAM) has gained a lot of popularity for the last years and been proposed for CR. Unlike an OFDM, a FBMC/OQAM does not require the redundant CP. Hence it achieves a better spectral efficiency. In addition, FBMC/OQAM is less sensitive to CFO [7].

However, FBMC/OQAM is not widely used in current primary systems compared with OFDM, which offers a large available frequency spectrum to be reused. Therefore, we propose to take the advantages of both previous systems to create a hybrid overlay CR where OFDM is used for the PU whereas the SU is based on FBMC/OQAM. In that case, the interference at the PU receiver due to the SU has to be canceled. More precisely, a precoding can be inserted at the SU transmitters to cancel them. Several interference cancellation techniques exist such as dirty paper coding (DPC) [8], interference alignment (IA) [9] and ZFBF[2] [10]. They allow the transmitter to send data to the desired users (i.e., the SU) without interfering with the undesired users (i.e., the PU) [11]. However, each technique requires *a priori* knowledge at the SU. Thus, in DPC the exchanged messages at the PU side have to be known. In IA, an *a priori* information about the PU channels must be known by the SU. With ZFBF, the only *a priori* required information consists of the PU standard knowledge. This allows ZFBF to be performed at the SBS. Nevertheless, the channels between the SBS and the PU have to be estimated. If we consider a primary system operating

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[1]The interweave CR system enables the SU to use the free bands of the PU on a non-interference basis. The underlay approach protects the PU by forcing the interference generated by the SU to be below an acceptable noise-plus-interference threshold of the PU signal.

[2]ZFBF is used in MISO system whereas block diagonalization (BD) is considered for the MIMO system. In this paper, as the PU consists of one antenna, the system is MISO.

in the time division duplex (TDD) mode, the uplink (i.e., PU to SBS) and the downlink (i.e., SBS to PU) channels are assumed to be the same. Hence, the channels can be estimated during the uplink transmission [12]. Thus, although it does not lead to higher sum rate [13] compared with DPC and IA, ZFBF seems to be the most practical among the above interference cancellation techniques.

Given the above considerations, our contribution in this paper is threefold:
1/ we derive the interference expression due to SU at the PU receiver,
2/ we propose to use ZFBF to cancel these interference,
3/ a comparative study with CR based on OFDM for both the PU and the SU confirms the efficiency of the proposed scheme. In this paper, the channels are first assumed to be known. It should be noted that this assumption has been adopted by many authors such as in [14]. Then, we investigate the sensitivity of the approach regarding the channel estimation error.

The rest of this paper is organized as follows: the main notations used in this paper are shown in Table 1. Section 2 considers the hybrid overlay CR system model and presents the interference. Section 3 describes the singular value decomposition (SVD) based ZFBF for subchannel interference cancellation. Section 4 provides simulation results. Finally, conclusions and perspectives are provided.

Notations	Description
T_p	Time duration of the PU/OFDM symbol
T_s	Time duration of the SU/FBMC symbol
T	Symbol time for the PU
K	Oversampling factor
N_p	Number of the subcarriers for the PU
$N_s = KN_p$	Number of the subchannels for the SU
$\Delta f_p = 1/N_pT$	Subcarrier spacing for the PU
$\Delta f_s = 1/T_s$	Subcarrier spacing for the SU
$S_{p,m}$	Transmitted symbol on the mth subcarrier of the PU signal
$S_m^{a,u}$	Transmitted symbol on the mth subchannel through the ath antenna for the uth BS of SU
h_p	Impulse response of the channel for the PU
$h_s^{a,u}$	Impulse response of the channel between the ath antenna for the uth BS and the PU
$\mathbf{h}_s^u$	Impulse response of the channel between the uth BS and the PU $\mathbf{h}_s^u = [h_s^{1,u} ... h_s^{a,u} ... h_s^{A,u}]$
L	Length of the CP
A	Number of transmitting antennas for the SU
U	Number of cooperative BS for the SU
$\mathbf{g}$	Transmitter prototype pulse shaping filter
$\mathbf{h}^T$	Transpose of $\mathbf{h}$
Re and Im	Real and imaginary parts, respectively
$*$	Convolution product
$\lceil\ \rceil$	Ceil value

Table 1: Notations used in this paper

2. SYSTEM MODEL

In this section, we propose to evaluate the relevance of the proposed hybrid overlay CR. Therefore, let us first define the PU/OFDM transmitted signal shown in Fig. 1:

$$\mathbf{x}_p = [\underbrace{x_p(-L)\cdots x_p(-1)}_{CP}\, x_p(0)\cdots x_p(N_p-1)] \tag{1}$$

with

$$x_p(l) = \frac{1}{\sqrt{N_p}} \sum_{m=0}^{N_p-1} S_{p,m} e^{j2\pi \frac{lm}{N_p}} \tag{2}$$

where $-L \leq l \leq N_p - 1$.
The FBMC/OQAM signal transmitted by the uth SBS from the ath antenna is $\mathbf{x}_s^{a,u} = [x_s^{a,u}(0)\cdots x_s^{a,u}(N_s-1)]$ with:

$$x_s^{a,u}(l') = \sum_{n=-\infty}^{+\infty} \sum_{m=0}^{N_s-1} y_m^{a,u}(l'-nN_s) e^{j2\pi \frac{l'm}{N_s}} \tag{3}$$

where $y_m^{a,u}(l'-nN_s)$ is defined, up to the multiplicative factor j^{m+n}, from the OQAM symbol as follows:

$$\begin{aligned} y_m^{a,u}(l'-nN_s) = j^{m+n}(&Re[S_m^{a,u}]g(l'-nN_s) \\ &+ jIm[S_m^{a,u}]g(l'-nN_s-N_s/2)) \end{aligned} \tag{4}$$

and $0 \leq l' \leq KN_p - 1$.

Here, we assume $n = 0$. In addition, for the sake of simplicity, all SBS are assumed to be synchronized in time[3].

[3] Techniques to allow this synchronized transmission are out of the scope of this paper and will concern a perspective of this work.

Therefore, by downsampling (3) to the same sampling rate in the OFDM receiver, the received signal $r(l)$ at the primary receiver satisfies:

$$r(l) = x_p(l) * h_p(l) + \eta(l) + \sum_{u=1}^{U} e^{j2\pi\varepsilon_u \frac{l}{N_p}} \sum_{a=1}^{A} x_s^{a,u}(l) * h_s^{a,u}(l) \tag{5}$$

where $\eta(l)$ is a complex additive white Gaussian noise, ε_u is the CFO of the uth SBS normalized to the subcarrier spacing of the primary system.
After removing the CP and performing the OFDM demodulation, the received not-equalized PU symbol on the kth subcarrier is:

$$\widehat{X}_{p,k} = S_{p,k}H_{p,k} + DFT\{\eta(l)\} + \sum_{u=1}^{U} I_k^u \tag{6}$$

where

$$I_k^u = DFT\{e^{j2\pi\varepsilon_u \frac{l}{N_p}} \sum_{a=1}^{A} x_s^{a,u}(l) * h_s^{a,u}(l)\} \tag{7}$$

and $H_{p,k} = DFT\{h_p(l)\} = \frac{1}{\sqrt{N_p}} \sum_{l=0}^{N_p-1} h_p(l) e^{-j2\pi \frac{lk}{N_p}}$.
According to (6), the OFDM detected symbol $S_{p,k}H_{p,k}$ is disturbed by the influence of the additive noise and the FBMC/OQAM interference. Using (3) as well as (7) and as $n = 0$, the interference on the kth PU subcarrier created by the uth SBS satisfies:

$$I_k^u = \frac{1}{\sqrt{N_p}} \sum_{a=1}^{A} \sum_{l=0}^{N_p-1} (\sum_{m=0}^{N_s-1} y_m^{a,u}(l) e^{j2\pi \frac{lm}{N_s}} * h_s^{a,u}(l)) e^{-j2\pi l \frac{(k-\varepsilon_u)}{N_p}} \tag{8}$$

The above equation can be reformulated as follows:

$$I_k^u = \frac{1}{\sqrt{N_p}} \sum_{a=1}^{A} \sum_{l=0}^{N_p-1} (\sum_{m=0}^{N_s-1} y_m^{a,u}(l) * h_s^{a,u}(l) e^{-j2\pi \frac{lm}{N_s}}) e^{-j2\pi l (\frac{(k-\varepsilon_u)}{N_p} - \frac{m}{N_s})} \tag{9}$$

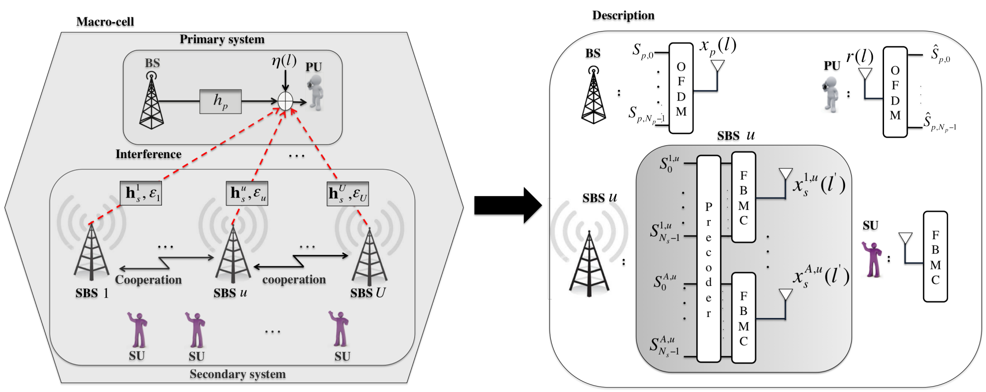

Fig. 1: Proposed hybrid overlay CR system. (For the sake of simplicity, the primary system and the secondary system are considered to be a single-input single-output (SISO) system and multiple-input single-output (MISO) system, respectively.)

By introducing the rectangular window $w(l)$ of size N_p and as $N_s = KN_p$, this leads to:

$$I_k^u = \frac{1}{\sqrt{N_p}} \sum_{a=1}^{A} \sum_{l=-\infty}^{+\infty} \left(\sum_{m=0}^{N_s-1} y_m^{a,u}(l) * h_s^{a,u}(l) e^{-j2\pi \frac{lm}{KN_p}} \right) w(l) e^{-j2\pi l \frac{K(k-\varepsilon_u)-m}{KN_p}} \quad (10)$$

where $w(l) = \begin{cases} 1 & , \quad l = 0, 1, \ldots, N_p - 1 \\ 0 & , \quad otherwise \end{cases}$.

Thus, I_k^u corresponds to the Fourier transform (FT) of a sum of convolution products. Hence it can be expressed as follows:

$$I_k^u = \sum_{a=1}^{A} \sum_{m=0}^{N_s-1} Y_m^{a,u}(f) H_s^{a,u}\left(f + \frac{m}{KN_p}\right) * W(f) \Big|_{f = \frac{K(k-\varepsilon_u)-m}{KN_p}} \quad (11)$$

where, $Y_m^{a,u}(f)$, $H_s^{a,u}(f)$ and $W(f)$ denote the FT of $y_m^{a,u}(l)$, $h_s^{a,u}(l)$ and $w(l)$ respectively. In the following and for the sake of simplicity, let us denote for $m = 0, \ldots, N_s - 1$:

$$f_{k,m} = \frac{K(k-\varepsilon_u) - m}{KN_p} = f_{k,0} - \frac{m}{KN_p} = f_{k,0} - \frac{m}{N_s} \quad (12)$$

In the next section, we propose to get rid of the interference I_k^u. For this purpose, we suggest using a ZFBF strategy.

3. INTERFERENCE CANCELLATION

We propose to insert the ZFBF at the SU transmitter before the inverse fast Fourier transform (IFFT), i.e., to weight the transmitted symbols $S_m^{a,u}$ by the beamformer $Z_k^{a,u}$. In that case and assuming we can neglect the influence of the convolution by $W(f)$ in (11), we propose to search the set of beamformers $\{Z_k^{a,u}\}_{a=1,\cdots,A}$ that satisfies:

$$\sum_{a=1}^{A} \sum_{m=0}^{N_s-1} Z_k^{a,u} Y_m^{a,u}(f) H_s^{a,u}\left(f + \frac{m}{KN_p}\right)\Big|_{f=f_{k,m}} = 0 \quad (13)$$

or equivalently,

$$\sum_{a=1}^{A} \sum_{m=0}^{N_s-1} Z_k^{a,u} Y_m^{a,u}(f_{k,m}) H_s^{a,u}(f_{k,0}) = 0 \quad (14)$$

In (14), the $N_s - 1$ subchannels in the SU system are considered, even if some SU subchannels do not interfere much with the kth PU subcarrier. Therefore, we propose a way to select the most interfering SU subchannels around the kth PU subcarrier. Then, the ZFBF design is presented.

3.1. Selecting the most interfering subchannels

When considering the kth PU subcarrier, one has to look at the $\lceil \frac{\Delta f_p}{\Delta f_s} \rceil \times k$th SU subchannel and its $2N_{sc}$ neighbors (i.e., N_{sc} on each side). For example, in Fig. 2, if $N_{sc} = 1$ the interference on the 1st PU subcarrier is due to the 1st, 2nd and 3rd SU subchannels.

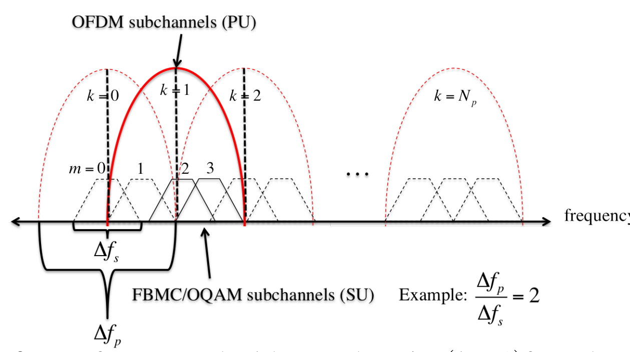

Fig. 2: Interference on the kth PU subcarrier ($k = 1$)from the SU subchannels. $\varepsilon_u = 0$ is assumed to be 0.

To select N_{sc}, we suggest taking into account the error vector magnitude P_{EVM}, which can be defined by:

$$P_{EVM}(n_{sc}) = 10\log_{10}\left(\frac{P_e(n_{sc})}{P_r}\right) \quad (15)$$

where P_r is the average power of the PU symbol constellation. In addition, n_{sc} is the number of considered SU subchannels around the kth PU subcarrier; depending on the PU carrier, its upper bound varies from 0 to $\frac{N_s-1}{2}$. Moreover, $P_e(n_{sc})$ is the power of the error vector, which is defined by:

$$P_e(n_{sc}) = \sum_{k=0}^{N_p-1} \left(\frac{\widehat{X}_{p,k}(n_{sc})}{H_{p,k}} - S_{p,k}\right)^2 \quad (16)$$

where $\widehat{X}_{p,k}(n_{sc})$ is the estimation of the not-equalized detected symbol in the PU disturbed by $2n_{sc} + 1$ subchannels.
After computing $P_{EVM}(n_{sc})$ for different values of n_{sc}, one selects N_{sc} as follows:

$$N_{sc} = argmax_{n_{sc}} P_{EVM}(n_{sc}) \leq T_H \quad (17)$$

where T_H is a threshold defined by the practitioner.
In Fig. 3, one can notice that increasing the number of interfering subchannels increases the performance. However, the number of required antennas at the SBS is also increased.

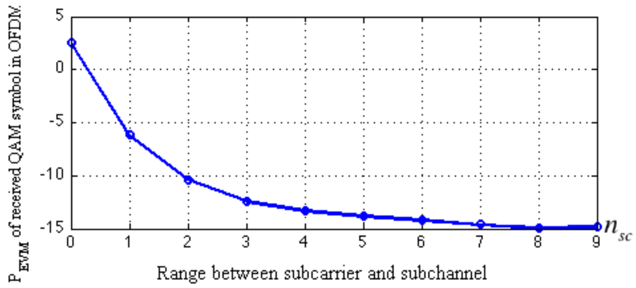

Fig. 3: P_{EVM} vs. number of the interfering subchannels N_{sc}.

Therefore, depending on the OFDM subchannel, (14) can be rewritten as:

$$\sum_{a=1}^{A} \sum_{m=k\lceil \frac{\Delta f_p}{\Delta f_s} \rceil - N_{sc}}^{k\lceil \frac{\Delta f_p}{\Delta f_s} \rceil + N_{sc}} Z_k^{a,u} Y_m^{a,u}(f_{k,m}) H_s^{a,u}(f_{k,0}) = 0 \tag{18}$$

<u>Remarks:</u> Depending on the PU subcarrier, the upper or the lower bound for n_{sc} can be $\frac{N_s-1}{2}$ and 0, respectively.

3.2. Designing the ZFBF

To perform the ZFBF, let us set all the symbols to be equal i.e., $S_m^u = S_m^{a,u}$, thus $Y_m^u(f) = Y_m^{a,u}(f)\ \forall u \in \{1,\cdots,U\}$ and $\forall a \in \{1,\cdots,A\}$. In that case (18) can be rewritten in a matrix form as follows:

$$(\mathbf{H}_k^u.\mathbf{Z}_k^u)^T \mathbf{Y}^u \quad = \quad 0 \tag{19}$$

To make the presentation simpler, let us denote $m_c = k\lceil \frac{\Delta f_p}{\Delta f_s} \rceil$,

$$\mathbf{Y}^u = \left[Y_{m_c-N_{sc}}^u(f_{k,m_c-N_{sc}}) \cdots Y_{m_c+N_{sc}}^u(f_{k,m_c+N_{sc}}) \right]^T \tag{20}$$

and $\mathbf{H}_k^u$ is the $(2N_{sc}+1) \times A$ matrix that contains all the channels interfering with the kth PU subcarrier:

$$\mathbf{H}_k^u = \begin{bmatrix} H_s^{1,u}(f_{k,0}) & \cdots & H_s^{A,u}(f_{k,0}) \\ \vdots & \ddots & \vdots \\ H_s^{1,u}(f_{k,0}) & \cdots & H_s^{A,u}(f_{k,0}) \end{bmatrix} \tag{21}$$

and the column vector $\mathbf{Z}_k^u = \left[Z_k^{1,u}\ Z_k^{2,u}\ \ldots\ Z_k^{A,u} \right]^T$ with length $(A \times 1)$ storing the beamformers.
To solve this issue, we suggest finding a set $\{Z_k^{a,u}\}$ that satisfies:

$$\mathbf{H}_k^u \mathbf{Z}_k^u = \mathbf{0} \tag{22}$$

In addition to the trivial solution $\mathbf{Z}_k^u = \mathbf{0}$, another solution is based on a property of the SVD of the channel matrix $\mathbf{H}_k^u$ when $A > (2N_{sc}+1)$. Indeed, one thing the SVD of the matrix H_k^u does is to supply an orthonormal basis of its kernel [4].

[4] As an alternative to SVD, QR factorization could be also considered.

Therefore, provided that the channel matrix is *a priori* known or estimated, the SVD of the channel matrix $\mathbf{H}_k^u$ can be computed. It can be shown that when Z_k^u is the pth right singular vector, (22) is satisfied. Then, $\mathbf{Z}_k^u$ can be set to the value of the pth right singular vector, where $2N_{sc}+1 < p \leq A$.

4. SIMULATION RESULTS

In this section, we consider the CR shown in Fig. 1. We assume $N_p = 64$ subcarriers are all used and the CP length is set to $L = 16$. Both are known by the SU. A QPSK modulation is used in the OFDM system whereas OQAM modulation is used for FBMC. Root raised-cosine is the pulse shape filter used for FBMC. In addition, the channels are first assumed to be perfectly known.
1/ let us assume the case of CR where the secondary system consists of one SBS with a large number of antennas. Considering five interfering subchannels (i.e., $N_{sc} = 2$) plays a key role in the definition of the interference term I_k^u for a CR based on FBMC/OQAM in the SU. Taking into account more subchannels could be more accurate, but this would increase the complexity of the system by adding more transmit antennas depending on the assumption $A > (2N_{sc}+1)$. We propose to use $A = 6$ transmit antennas.

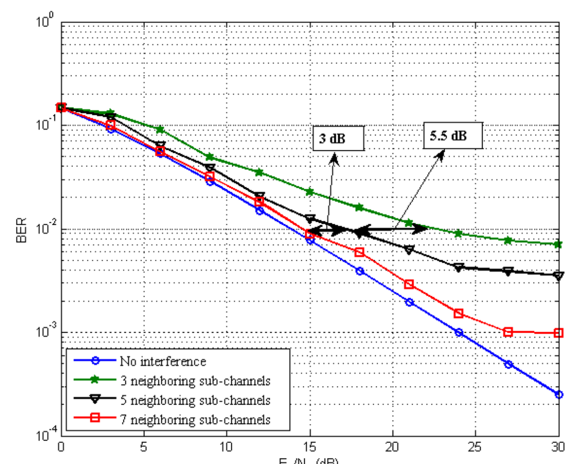

Fig. 4: ZFBF in CR based FBMC/OQAM in the SU with different numbers of antennas.

Fig. 4 shows the *BER* performance at the PU receiver when $\varepsilon_u = 0$. FBMC/OQAM is used for the SU, for various numbers of neighbor subchannels (namely 1, 2 and 3 corresponding respectively to $2N_{sc}+1$ equal to 3, 5 and 7). The results are compared with CR based on OFDM of two antennas. As shown in the Fig. 3 and the results in Fig. 4, choosing $2N_{sc}+1 = 5$ is the trade-off between the complexity and performance of the system. Given the simulations we carried out, the assumption we made to get (18) holds. In addition, CR based on OFDM for both PU and SU gives better performance.
Now, let us assume the system in Fig. 1, where the secondary system consists of cooperative SBS with different values of

CFO. Fig. 5 shows a comparative study between the proposed system based on FBMC/OQAM and the CR based on OFDM. On the one hand, using two antennas for a CR based OFDM is no longer relevant. On the other hand, increasing the number of antennas to $A = 6$ confirms the performance of the proposed system based on FBMC/OQAM. It improves the efficiency compared with CR based OFDM (i.e., gain of 5.5 dB at BER=10^{-2}). This improvement is due to the neighboring subchannels, which are already taken into account in the proposed scheme. When the secondary system consists of a large number of SU, we can now perform a multi-user MIMO (MU-MIMO) system such as in [15].

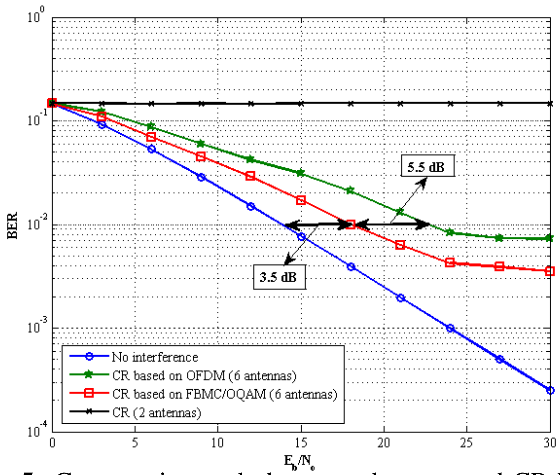

Fig. 5: Comparative study between the proposed CR based on FBMC/OQAM and CR based OFDM ($A = 6$).

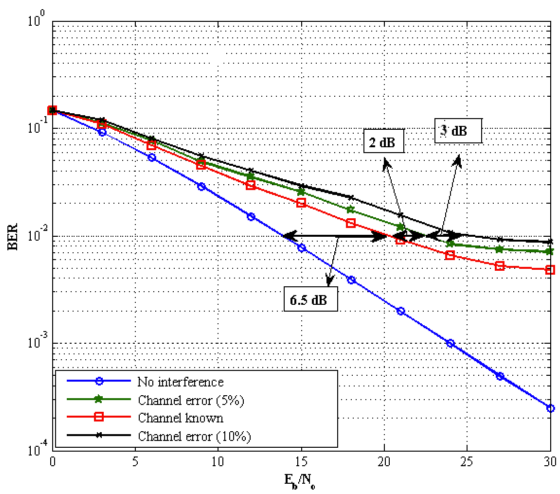

Fig. 6: The sensitivity of SU-transmitter interference cancellation to the channel estimation at the PU receiver side.

2/ In practice, the channels between PU and SU need to be estimated and tracked. In that case, we need to estimate the uplink channels in order to design the ZFBF. Kalman-filter (KF) based methods such as extended KF (EKF), unscented KF (UKF) or quadrature KF (QKF) can be for instance considered for channel estimation. The effect of the channel estimation error on the proposed system performance is shown in Fig. 6. When the channel error is equal to 5% (resp. 10%), the decrease in BER of ZFBF is 2 dB (resp. 5 dB).

5. CONCLUSION

In this paper, we have investigated the relevance of the FBMC/OQAM over OFDM for the SU in an overlay multiuser CR system. In that case, performing the ZFBF by taking into account the signal at the receiver after OFDM demodulation has the advantage of reducing the number of subchannels needed for the interference cancellation. The comparative study that is carried out confirms the spectral and bit error rate efficiencies of the proposed system. It should be noted that our approach is based on some approximations such as the influence of the $W(f)$ in (11). As perspectives, we would like to look at the impact of these approximations.

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