Antenna competition to boost Active Interference Cancellation in cognitive MIMO-OFDM

Jorge F. Schmidt and Roberto López-Valcarce
Department of Signal Theory and Communications
University of Vigo, Spain

***Abstract*—Active Interference Cancellation (AIC) techniques for OFDM spectrum sculpting have gained interest over the last years, and several extensions to the MIMO case have been recently proposed. However, these designs do not fully exploit the spatial diversity provided by the multiple transmit antennas, as canceler allocation is fixed. This paper proposes a more general mechanism for the allocation of the cancellation subcarriers across antennas in order to better exploit spatial diversity. In particular, we present a novel AIC design for cognitive MIMO-OFDM systems, in which transmit antennas compete against each other for a fixed number of cancellation subcarriers. We show that this more general allocation approach results in significant performance improvements with respect to previous designs.**

I. Introduction

As the interest in wireless communication systems continues to grow, technologies capable of using the available spectrum efficiently need to be developed. Cognitive Radio [1] is one such technique, based on transmitting opportunistically over unused licensed spectrum. To this end, Orthogonal Frequency Division Multiplexing (OFDM) is a well suited modulation format, as the signal spectrum can in principle be shaped by turning off sets of subcarriers, and thus avoid interfering to licensed users [2], [3]. However, the high subcarrier sidelobes resulting from the FFT implementation of standard OFDM require the use of more sophisticated spectrum sculpting techniques. In particular, Active Interference Cancellation (AIC), has received considerable attention [4]–[8] because of its effectiveness and the advantage of being transparent to the receiver. Under AIC, a small subset of system subcarriers are not used for data transmission, but are instead appropriately modulated to reduce the amount of power transmitted within some portion of the system bandwidth. The receiver simply discards those subcarriers and decodes the rest.

AIC was originally formulated for single-antenna transmitters, with subsequent multiantenna extensions appearing in [9]–[11]. Although these extensions have considered different features of the resulting Multiple-Input, Single-Output (MISO) channel, neither of them fully exploits the available spatial diversity. In [9], the proposed multiantenna AIC schemes do not employ Channel State Information (CSI) from the cognitive transmitter to the licensed receiver, and thus are unable to benefit from the spatial diversity of the MISO channel. In [10]–[11], CSI is included in the problem formulation, resulting in significant improvements. However, in [10], all of the cancellation subcarriers are relegated to the same antenna, whereas in [11] the positions of the cancellation subcarriers are the same for all transmit antennas, independently of available CSI. Thus, neither [10] nor [11] efficiently exploits all available degrees of freedom.

In this context, the main contribution of this paper is to derive a more flexible multiantenna AIC approach, showing that significant performance improvements can be achieved by resorting to more general schemes for the allocation of cancellation subcarriers across antennas. Specifically, we allocate the total number of cancellation subcarriers based on an heuristic allocation policy, built on the placement optimization approach for SISO-AIC from [7], in which antennas compete for the available resources. We show with simulations that this approach clearly outperforms previous schemes.

This paper is organized as follows. The signal model and AIC basics are presented in Section II. In Section III the proposed multiantenna AIC design is derived. Performance evaluation and comparison with previous methods are given in Section IV. Finally, conclusions are drawn in Section V.

II. Problem Statement

A. Signal Model

We consider a cognitive MIMO-OFDM system having M transmit antennas and R receive antennas. Each antenna uses OFDM modulation with N subcarriers. A licensed user is known to operate in a frequency band $\mathcal{B}$ within the cognitive bandwidth and needs to be protected from interference as depicted in Fig. 1.

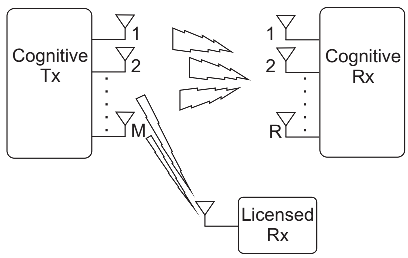

Fig. 1. Multiantenna AIC communication setting.

The spectrum of the OFDM signal transmitted by antenna m is the superposition of all its subcarrier spectra, affected by their corresponding modulating coefficients $x_{m,k}$

$$X_m(f) = \sum_{k=0}^{N-1} x_{m,k}\phi_k(f) = \boldsymbol{x}_m^T \boldsymbol{\phi}(f), \quad m = 1, \ldots, M, \tag{1}$$

with $\boldsymbol{\phi}(f) \triangleq [\phi_0(f) \cdots \phi_{N-1}(f)]^T$, $\boldsymbol{x}_m \triangleq [x_{m,0} \cdots x_{m,N-1}]^T$, and where $\phi_k(f)$ is the *periodic sinc* spectrum[1] of the k-th subcarrier, times the frequency response of the interpolation filter in the Digital-to-Analog converter [12]. Using (1), the spectrum of the signal received by the licensed user antenna is

$$S(f) = \sum_{m=1}^{M} H_m(f) X_m(f), \tag{2}$$

with $H_m(f)$ the frequency response of the channel from transmit antenna m and the licensed user[2]. AIC aims at sculpting $S(f)$ such that interference over band $\mathcal{B}$ is minimum.

B. AIC basics - single antenna scenario

With a single transmit antenna, (2) becomes $S(f) = H(f)X(f)$. If the variation of $H(f)$ within band $\mathcal{B}$ is assumed small, the AIC problem reduces to minimizing the power *transmitted* over $\mathcal{B}$ [4]–[7]. Assuming $\mathcal{B}$ spans N_P contiguous subcarriers, these N_P subcarriers, plus N_C more are reserved to generate a spectrum notch over $\mathcal{B}$, usually under a transmit power constraint. This leaves $N_D = N - N_P - N_C$ subcarriers for data transmission.

The modulating vector $\boldsymbol{x} \in \mathbb{C}^N$ in (1) can be written as

$$\boldsymbol{x} = \alpha \boldsymbol{S}\boldsymbol{d} + \boldsymbol{T}\boldsymbol{c}, \tag{3}$$

where $\boldsymbol{d} \in \mathbb{C}^{N_D}$ is the zero-mean data vector, with covariance $E\{\boldsymbol{d}\boldsymbol{d}^H\} = \boldsymbol{I}_{N_D}$, and $\boldsymbol{c} \in \mathbb{C}^{N_P+N_C}$ is the vector of cancellation coefficients. Matrices $\boldsymbol{S} \in \mathbb{C}^{N \times N_D}$ and $\boldsymbol{T} \in \mathbb{C}^{N \times (N_P+N_C)}$ comprise different sets of columns of $\boldsymbol{I}_N$, and map data and cancellation coefficients to the data and reserved subcarrier locations respectively. The scaling factor α $(0 < \alpha \leq 1)$ controls how the available transmit power is shared between data and cancellation subcarriers.

In [7], cancellation coefficients are linear combinations of data, i.e., $\boldsymbol{c} = \boldsymbol{\Theta}\boldsymbol{d}$ with $\boldsymbol{\Theta} \in \mathbb{C}^{(N_P+N_C) \times N_D}$. Hence,

$$\boldsymbol{x} = \boldsymbol{G}(\boldsymbol{\Theta})\boldsymbol{d}, \qquad \text{with} \quad \boldsymbol{G}(\boldsymbol{\Theta}) \triangleq \alpha \boldsymbol{S} + \boldsymbol{T}\boldsymbol{\Theta}, \tag{4}$$

and $\boldsymbol{\Theta}$ is the design parameter. This parametrization leads to a formulation in terms of the power spectral density (PSD) of the OFDM signal. Specifically, from (1) and (4), and following [7], the signal PSD is obtained in terms of $\boldsymbol{\Theta}$ as

$$P_x(f, \boldsymbol{\Theta}) = E\left\{|X(f)|^2\right\} = \mathrm{Tr}\{\boldsymbol{G}^H(\boldsymbol{\Theta})\boldsymbol{\Phi}(f)\boldsymbol{G}(\boldsymbol{\Theta})\}, \tag{5}$$

where $\boldsymbol{\Phi}(f) \triangleq \boldsymbol{\phi}(f)\boldsymbol{\phi}^H(f)$. Based on (5), the AIC design problem subject to a transmit power constraint P_{max} is

$$\min_{\boldsymbol{\Theta}} \int_{\mathcal{B}} P_x(f, \boldsymbol{\Theta}) \mathrm{d}f \quad \text{s.t.} \int_{-\infty}^{\infty} P_x(f, \boldsymbol{\Theta}) \mathrm{d}f \leq P_{\text{max}}, \tag{6}$$

which is a convex problem that can be efficiently solved for the optimal $\boldsymbol{\Theta}_{\text{opt}}$ by means of the generalized singular value decomposition [7], [14].

[1] As in [7], conventional cyclic-prefix OFDM is assumed for simplicity.

[2] Similarly to [10]–[11], we assume $\{H_m(f)\}$ are known. Assuming channel reciprocity, which is practical for slowly varying scenarios, this CSI can be obtained without explicit cooperation from the licensed user, e.g. as in [13].

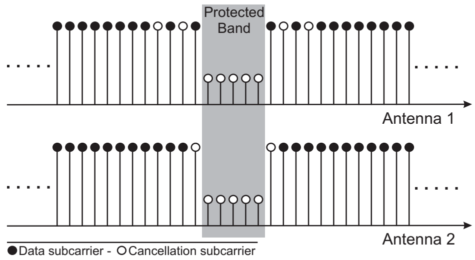

Fig. 2. Allocation example for AC-AIC ($M = 2$, $N_P = 5$, $N_C = 6$).

III. MISO-AIC WITH COMPETING ANTENNAS

The simplest AIC extension to the multiantenna setting is to apply (6) from Sec. II-B on each antenna as in [9], without exploiting the MISO structure. However, it is clear that by using knowledge about $\{H_m(f)\}$ a better solution should be achievable. For example, [10]–[11] exploit CSI to jointly distribute the cancellation power between the antennas. Generalizing (3) to the multiantenna setting, one has

$$\boldsymbol{x}_m = \alpha \boldsymbol{S}_m \boldsymbol{d}_m + \boldsymbol{T}_m \boldsymbol{c}_m \qquad m = 1, \ldots, M, \tag{7}$$

with $\boldsymbol{d}_m$, $\boldsymbol{c}_m$, $\boldsymbol{S}_m$ and $\boldsymbol{T}_m$ the analogous quantities to those in (3) but for transmit antenna m. We assume that the number of cancellation subcarriers to allocate across antennas is a fixed design parameter. In [10] the signal model (7) is restricted to

$$\boldsymbol{x}_m = \begin{cases} \alpha \boldsymbol{S}_1 \boldsymbol{d}_1 + \boldsymbol{T}_1 \boldsymbol{c} & \text{for } m = 1 \\ \alpha \boldsymbol{d}_m & \text{for } m = 2, \ldots, M, \end{cases} \tag{8}$$

giving all cancelers to the first antenna. On the other hand, the corresponding model adopted in [11] is given by

$$\boldsymbol{x}_m = \alpha \boldsymbol{S}\boldsymbol{d}_m + \boldsymbol{T}\boldsymbol{c}_m \qquad m = 1, \ldots, M, \tag{9}$$

so that all antennas are allocated the same cancelers (N_P cancelers aligned with $\mathcal{B}$, plus an equal number of cancelers at each side of $\mathcal{B}$) through matrices $\boldsymbol{S}$, $\boldsymbol{T}$. Both (8) and (9) inserted in (2) exploit the knowledge of $H_m(f)$ to compute $\boldsymbol{c}$ and $\boldsymbol{c}_m$ respectively. However, both schemes underutilize the degrees of freedom available for allocation of the cancelers. For instance, in the single-antenna scenario it has been shown in [7] that performance can be improved with a more general placement of the cancelers not aligned with $\mathcal{B}$ (i.e. not necessarily clustered at both sides of $\mathcal{B}$). An efficient algorithm to optimize the cancelers' locations was also provided in [7].

Further, as in general antenna separation is such that independent antenna subchannels $H_m(f)$ result, better exploitation of their knowledge is possible. The signal in (2) adds spatial diversity, such that cancelers on a given antenna might be more effective to reduce interference than those on others. Therefore, we focus on the general MISO-AIC model in (7), where each $(\boldsymbol{S}_m, \boldsymbol{T}_m)$ pair represents a possibly different partition of the identity matrix, and the number of cancelers per antenna $N_C^{(m)}$ may also differ along antennas[3]. This is illustrated in Fig. 2 for $M = 2$.

[3] Note that $N = N_D^{(m)} + N_P + N_C^{(m)}$ for all m, and $N_C = \sum_{m=1}^{M} N_C^{(m)}$ is fixed.

We assume that independent data streams are transmitted over each antenna, and thus $E\{\boldsymbol{d}_i \boldsymbol{d}_j^H\} = \boldsymbol{0}$ for $i \neq j$. Using the AIC framework in (4), i.e. $\boldsymbol{c}_m = \boldsymbol{\Theta}_m \boldsymbol{d}_m$, and the signal model from (7), the PSD of the signal in (2) and the total transmit power are respectively given by

$$P_s(f, \{\boldsymbol{G}_m\}) = \sum_{m=1}^{M} |H_m(f)|^2 P_x^{(m)}(f, \boldsymbol{G}_m), \quad (10)$$

$$P_T = \sum_{m=1}^{M} \int_{-\infty}^{\infty} P_x^{(m)}(f, \boldsymbol{G}_m) \mathrm{d}f, \quad (11)$$

where $P_x^{(m)}(f, \boldsymbol{G}_m) \triangleq \mathrm{Tr}\{\boldsymbol{G}_m^H \boldsymbol{\Phi}(f) \boldsymbol{G}_m\}$ is the PSD transmitted by antenna m, with $\boldsymbol{G}_m \triangleq \alpha \boldsymbol{S}_m + \boldsymbol{T}_m \boldsymbol{\Theta}_m$. The MISO-AIC problem is therefore

$$\min_{\{\boldsymbol{G}_m\}} \int_{\mathcal{B}} P_s(f, \{\boldsymbol{G}_m\}) \mathrm{d}f \quad \text{s.t.} \quad P_T \leq P_{\max}, \quad (12)$$

in which the design parameters are the matrices $\{\boldsymbol{S}_m, \boldsymbol{T}_m, \boldsymbol{\Theta}_m\}$. The optimal $\{\boldsymbol{\Theta}_m\}$ can be efficiently computed analogously to (6) for fixed subcarrier mapping matrices $\{\boldsymbol{S}_m, \boldsymbol{T}_m\}$. On the other hand, optimization of these subcarrier mapping matrices is a difficult combinatorial problem. We adopt a greedy approach inspired by the one from [7] for the single antenna case; the proposed extension to MISO-AIC is as follows.

The antenna competition allocation is initialized assigning the N_P subcarriers aligned with $\mathcal{B}$ as cancelers to all antennas. The remaining N_C cancelers are allocated sequentially in pairs[4] as follows. For each new pair of cancelers to be allocated, each antenna computes its candidate subcarrier pair (the one that if included as canceler would result in the greatest performance gain) based on the cancelers it has already been allocated. This results in M possible allocations for this canceler pair, one for each antenna. The cancelers are given to the antenna reporting the largest improvement. This procedure is repeated until all canceler pairs have been allocated. The MISO-AIC with competing antenna design is summarized in Table I. Although not necessarily optimal, this greedy allocation scheme provides substantial performance gain with respect to the models in (8) and (9), as shown next.

TABLE I
CANCELER ALLOCATION WITH ANTENNA COMPETITION

Definition:
Subcarriers aligned with $\mathcal{B} \rightarrow k \in \{a_1, \ldots, a_{N_P}\}$
Canceler pairs to allocate $\rightarrow N_C/2$
Search distance around $\mathcal{B} \rightarrow \Delta$
Cancelers set for each antenna $\rightarrow \mathcal{C}_m$
Search set for each antenna $\rightarrow \mathcal{S}_m$
Initialization:
$\mathcal{C}_m = \{k : k \in \{a_1, \ldots, a_{N_P}\}\} \ \forall \ m$
$\mathcal{S}_m = \{k : k \in \{1, \ldots, \Delta\}\} \ \forall \ m$
for Cancel $= 1$ to $N_C/2$ **do**
  for $m = 1$ to M **do**
    for $k \in \mathcal{S}_m$ **do**
      Augment set $\mathcal{C}^* = \mathcal{C}_m \cup \{a_1 - k, a_{N_P} + k\}$
      Construct $\boldsymbol{S}_m^*$ and $\boldsymbol{T}_m^*$ based on $\mathcal{C}^*$
      Solve (12) using $\boldsymbol{S}_m^*$ and $\boldsymbol{T}_m^*$ for Antenna m
      Compute resulting power spill $P_{\mathcal{B}}^*(k)$
    end for
    Candidate canceler $\rightarrow k_m^* = \min_k P_{\mathcal{B}}^*(k)$
    $\bar{P}_{\mathcal{B}}(m) = P_{\mathcal{B}}^*(k_m^*)$
  end for
  winning antenna $\rightarrow m^* = \min_m \bar{P}_{\mathcal{B}}(m)$
  $\mathcal{C}_m = \mathcal{C}_\cup \{a_{1,m} - k_m^*, a_{N_P,m} + k_m^*\}$
  Remove k_m^* from $\mathcal{S}_m$
end for

TABLE II
MEAN NOTCH DEPTH OVER $\mathcal{B}$ FOR CONSIDERED MISO-AIC SCHEMES.

	$M=2$	$M=3$	$M=4$
SA-AIC [10]	1.06	1.06	1.07
EA-AIC [11]	6.22	6.43	6.72
Basic-AIC [7]	9.08	9.09	9.11
AC-AIC	12.55	12.99	12.64

Results are in dB gain with respect to Null Subcarriers.

IV. PERFORMANCE EVALUATION

The performance of the proposed Antenna Competition MISO-AIC design, termed AC-AIC in what follows, is evaluated in this section. Performance is assessed for transmitters with $M = 2$, 3 or 4 antennas. Further, comparison against MISO-AIC designs based on the models of (8) from [10] and (9) from [11], termed single-allocation MISO-AIC (SA-AIC) and equal-allocation MISO-AIC (EA-AIC) respectively in what follows are provided. The extension to the multi-antenna scenario of the single-antenna AIC design of [7] using improved canceler placement individually at each antenna is considered for reference. In that case, termed *Basic-AIC* in the following, power and cancelers are equally distributed among antennas, which are optimized independently (without CSI). For a fair comparison, all allocation schemes are inserted in the framework of (4) in order to compute the optimal cancellation weights for each of them. We consider a cognitive MIMO-OFDM system operating at a 2 GHz carrier frequency, with 5.12 MHz bandwidth and 20 kHz subcarrier spacing. The number of subcarriers is set to $N = 256$ and a cyclic prefix of 12 samples (5%) is used. A licensed user occupying a band $\mathcal{B}$ spanning subcarriers 80–99 is assumed. In all cases considered, all antennas are allocated these $N_P = 20$ subcarriers as cancelers, and a typical value of $N_C = 6M$ additional subcarriers to be also used for interference cancellation. In all cases the power share given to the cancellation subcarriers is set to 2% (see parameter α in (4)). We consider independent realizations of the *3GPP Typical Urban* wireless channel specification for each antenna, which results in a 12-tap frequency selective channel for the given system parameters [15]. Fig. 3 shows the PSD of the cognitive signal arriving to the licensed user antenna, in the vicinity of the protected band. Results are shown for $M = 2$ antennas and for the different AIC designs. The case where AIC is not employed, i.e. subcarriers

[4]Cancelers are allocated in pairs of subcarriers symmetrically located around the protected band, based on the symmetry of the AIC problem [7].

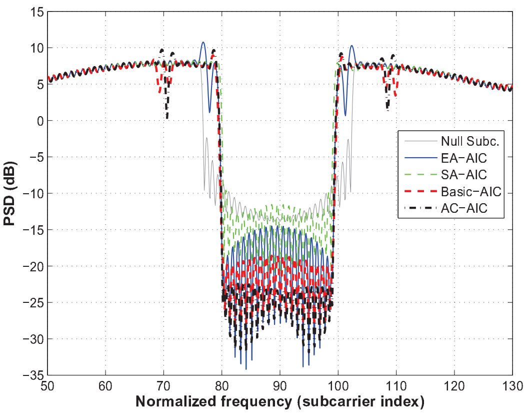

Fig. 3. PSD for compared MISO-AIC designs for $M = 2$ and $N_C = 12$.

80–99 plus 3 more at each side are simply turned off at both antennas, is shown for reference; this baseline case is termed *Null Subcarriers*. It is seen that the proposed AC-AIC scheme outperforms SA-AIC, EA-AIC and Basic-AIC as expected. In particular, the improvement with respect to Basic-AIC is entirely due to the inclusion of the spatial dimension in AC-AIC. This better use of the spatial diversity becomes clear in Fig. 4, which shows the canceler allocation for AC-AIC in the scenario of Fig. 3. This figure emphasizes that spatial diversity turns into different canceler sets for each antenna.

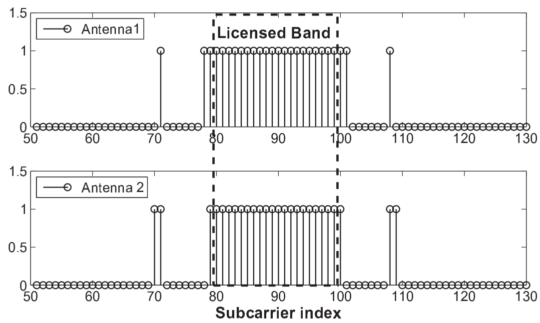

Fig. 4. Canceler allocation for AC-AIC in the scenario of Fig. 3.

Table II reports the performance gain of the proposed design for different number of transmit antennas M, in terms of the average notch depth of the PSD over $\mathcal{B}$ with respect to the *Null Subcarriers* baseline. It can be noted that AC-AIC significantly outperforms all considered schemes, as it is the one that better exploits the spatial diversity. For instance, AC-AIC provides about 6 dB and 3.5 dB improvement with respect to EA-AIC and Basic-AIC (which also optimizes canceler placement but separately for each antenna), respectively. It is observed that SA-AIC (most restrictive design) performs the worst; this is due to the fact that all cancelers are placed at the same antenna, so the system cannot effectively cancel the interference from other antennas if its channel condition is not good enough.

The significant performance gain of AC-AIC is obtained at the cost of an increased computational cost. Different to SA-AIC and EA-AIC, the proposed scheme requires to optimize the cancelers allocation as shown in Table I. The optimization process has to be executed anew every time the channel changes, but not for each OFDM symbol. Thus, the proposed scheme is better suited for slowly-varying scenarios.

V. Conclusions

A novel multiantenna AIC design was presented, allowing more efficient exploitation of the spatial diversity of the associated MISO channel. In the proposed design, antennas compete to get a share of the total available cancelers based on their CSI. This approach is shown to outperform previously reported MISO-AIC solutions in all considered scenarios.

Acknowledgment

Work supported by the Spanish Government, European Regional Development Fund (ERDF) and the Galician Regional Government under agreement for funding the Atlantic Research Center for Information and Communication Technologies (AtlantTIC) and projects TACTICA, TEC2010-21245-C02/TCM DYNACS and CONSOLIDER-INGENIO CSD2008-00010 COMONSENS.

References

[1] S. Haykin, “Cognitive radio: brain-empowered wireless communications,” *IEEE J. Sel. Areas Commun.*, vol. 23, no. 2, pp. 201–220, Feb. 2005.

[2] T. A. Weiss and F. K. Jondral, “Spectrum pooling: an innovative strategy for the enhancement of spectrum efficiency,” *IEEE Commun. Mag.*, vol. 42, no. 3, pp. S8–14, Mar. 2004.

[3] H. Arslan, H. A. Mahmoud, and T. Yucek, “OFDM for cognitive radio: merits and challenges,” in *Cognitive Radio, Software Defined Radio, and Adaptive Wireless Systems*, H. Arslan, Ed. Dordrecht, The Netherlands: Springer, 2007.

[4] H. Yamaguchi, “Active interference cancellation technique for MB-OFDM cognitive radio,” in *34th European Microwave Conf.*, vol. 2, Oct. 2004, pp. 1105 –1108.

[5] E. H. M. Alian and P. Mitran, “Improved active interference cancellation for sidelobe suppression in cognitive OFDM systems,” in *IEEE Global Commun. Conf. (GLOBECOM)*, Dec. 2012, pp. 1460–65.

[6] J. F. Schmidt and R. López-Valcarce, “Low complexity primary user protection for cognitive OFDM,” in *21st European Signal Process. Conf. (EUSIPCO)*, Sep. 2013.

[7] J. F. Schmidt, S. Costas-Sanz, and R. López-Valcarce, “Choose your subcarriers wisely: Active interference cancellation for cognitive OFDM,” *IEEE J. Emerg. Sel. Topics Circuits Syst.*, vol. 3, no. 4, Dec. 2013.

[8] J. F. Schmidt and R. López-Valcarce, “OFDM spectrum sculpting with active interference cancellation: keeping spectral spurs at bay,” in *IEEE Int. Conf. Acoust., Speech, Signal Process.*, May 2014, accepted.

[9] Y. Wang and J. Coon, “Active interference cancellation for systems with antenna selection,” in *IEEE Int. Conf. on Comm. (ICC)*, May. 2008, pp. 3785–3789.

[10] H.-J. Chou and J.-M. Wu, “MIMO active interference cancellation for stealth cognitive radio in MB-OFDM UWB,” in *Int. Conf. on Comm. and Networking in China (ChinaCom)*, Aug. 2008, pp. 173–177.

[11] E. H. M. Alian, H. E. Saffar, and P. Mitran, “Cross-band interference reduction trade-offs in SISO and MISO OFDM-based cognitive radios,” *IEEE Trans. Wireless Commun.*, vol. 11, no. 7, pp. 2436–45, Jul. 2012.

[12] T. van Waterschoot, V. Le Nir, J. Duplicy, and M. Moonen, “Analytical expressions for the power spectral density of CP-OFDM and ZP-OFDM signals,” *IEEE Signal Proc. Letters*, vol. 17, no. 4, pp. 371 –374, Apr. 2010.

[13] C. Shin, R. W. Heath, and E. J. Powers, “Blind channel estimation for MIMO-OFDM systems,” *IEEE Trans. Vehicular Tech.*, vol. 50, no. 2, Mar. 2007.

[14] G. H. Golub and C. F. van Van Loan, *Matrix Computations*, 3rd ed. The Johns Hopkins University Press, Oct. 1996.

[15] 3GPP, “Physical layer aspects for evolved UTRA,” 3GPP technical report, TR 25.814, Ver. 1.0.3, Feb. 2006.