A capacity-aware MIMO-beamforming approach for cognitive radio enabled smart grid systems

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Abstract: This paper proposes an adaptive multiple input multiple output-beamforming scheme (MIMO-BF) for cognitive radio enabled broad band smart grid (SG) systems concurrently sharing the same spectrum with the primary network (PN) and employing orthogonal frequency-division multiplexing with space division multiple access (OFDM-SDMA) technologies. The proposed algorithm uses gradient search of the channel capacity to seek, iteratively, the optimal transmit weight vectors that maximise the MIMO channel capacity for each cognitive user of the SG network, while controlling the interference levels to the PN. We evaluate the symbol error rate (SER) and system capacity performances of the proposed cognitive OFDM-SDMA system and show by simulation that they outperform cognitive systems based on opportunistic approaches. It is also shown that when the SG system is using the proposed schemes it has better control on the interference at the primary base station than the one based on opportunistic capacity-aware.

Keywords: cognitive radio; smart grid; OFDM-SDMA; MIMO-Beamforming.

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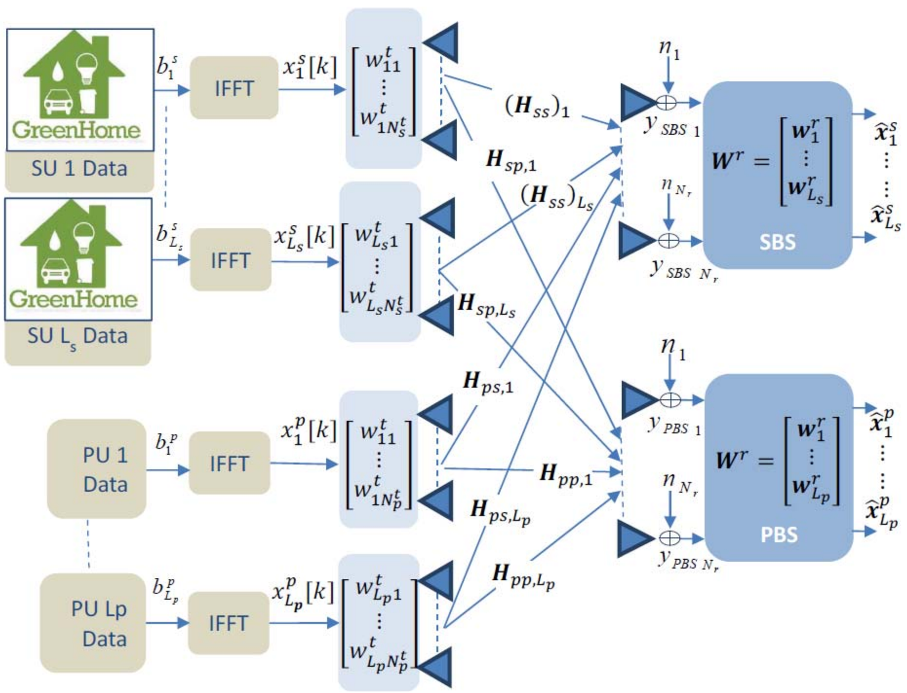
1 Introduction

Recently, cognitive radio networks (CRNs) have been identified as a key wireless technology to reduce the communication interferences and improve the bandwidth efficiency for smart grid communication (Deng et al., 2013; Gungor and Sahin, 2012; Haykin, 2005; Huang et al., 2013; Mitola and Maguire, 1999; Qiu et al., 2010; Ranganathan et al., 2011; Wang et al., 2011; Yu et al., 2011). The smart grid is widely considered to be the next-generation smart electricity delivery system that uses a two-way communication infrastructure to exchange real-time information, such as advanced metering infrastructure (AMI) data transmissions, between the generators and the consumers. This information is then used to detect, protect and optimises the operation of the interconnected SG network. Also, it is expected that the SG communication infrastructure (SGCI) will experience considerable pressure due to the explosive growth of smart metres users and the amount and bandwidth of data exchanges. To fulfil these purposes, on one hand, the SGCI has to integrate a technology with the capabilities to sense the operating environment, learn and adapt in real time according to environment. On the other hand, the SGCI should be reliable, secure, and cost-effective enough to meet the requirements in terms of bandwidth and latency. To this end, cognitive radio (CR) has been proposed as the communication infrastructure and the essential technology needed to make significantly better use of available spectrum in smart grid environments by providing broadband and opportunistic access to unused spectrum. It is also proposed to address the main challenges of smart grid applications, which are time and space varying spectrum characteristics, reliability, channel impairments, and energy constraints for low-power sensor nodes. However, all existing work on such cooperative CR enabled SG networks are based on opportunistic spectrum sharing which may not be reliable since it suffers from the interruptions imposed by primary users (PUs) to secondary users (SUs) who must leave the licensed channel when PUs emerge. Also, unlicensed SG users can still cause interference to the primary network (PN) due to their imperfect spectrum sensing. Therefore, CRNs with highly flexible and adaptable physical layer that provide a concurrent broadband access to the spectrum without causing interference to licensed users are more suitable. Among many possible technologies, orthogonal frequency-division multiplexing with space division multiple access (OFDM-SDMA) has been widely recognised as a versatile multiple access scheme for CRs that may increase the CR-based SG network capacity (Bixio et al., 2010; Hefnawi, 2012; Hamdi et al., 2009; Yang and Wang, 2008; Yiu et al., 2008; Zhang and Liang, 2008). OFDM mitigates the channel impairments by transforming a frequency-selective channel into a set of frequency-flat channels. SDMA on the other hand, helps to achieve higher spectral efficiency, by multiplexing multiple users on the same time-frequency resources. OFDM-SDMA techniques has been successfully deployed in 3G/4G cellular systems based on traditional static spectrum access approach and a vast number of multi-user detection algorithms, such as maximum ratio combining (MRC) and minimum mean-squared error (MMSE), are presently being tailored towards solving the SDMA processing in MIMO cognitive networks (Hefnawi, 2012; Yang and Wang, 2008; Yiu et al., 2008), where additional constraints to protect licensed users' QoS are imposed. Within this context, we are proposing a new OFDM-SDMA technique for dynamic communications smart grid environments to concurrently access the same channel as the PN. More specifically, we propose a new adaptive beamforming algorithm that targets the maximisation of the channel capacity of the SG system, while controlling the interference levels to the PN. Using the steepest ascent gradient of the constrained OFDM-SDMA channel capacity, the proposed algorithm seeks, iteratively, the transmit/receive weight vectors that maximise the channel capacity of the SG system, while controlling the interference levels to the PN. We evaluate the SER and system capacity performances of the SG cognitive OFDM-SDMA system, in the presence of secondary and primary multiuser access interferences and correlated fading encountered in antenna array systems, when both conventional opportunistic OFDM-SDMA and the proposed constrained OFDM-SDMA beamforming schemes are the underlying Tx/Rx weights optimisation schemes. Simulation results show that the proposed concurrent algorithm achieves substantially lower SER and higher capacity than the opportunistic approach. It is also noted that when the SG system is using the proposed cognitive OFDM-SDMA scheme, it could efficiently control the interference to the PN.

2 System model

We consider the uplink multiuser access scenario shown in Figure 1 where a secondary network, consisting of L_s smart metre SUs connected to a secondary base station (SBS), is coexisting with L_p PUs and one primary base station (PBS)

Figure 1 CR enabled SG system using OFDM-SDMA technology (see online version for colours)



signals and L_p PUs signals, respectively, transmitted on each subcarrier, $k = 1, \ldots, N_c$, where N_c denotes the number of subcarriers per OFDM symbol in the system. It is assumed that x_i^s and x_i^p are complex-valued random variables with unit power, i.e., $E[\|x_i^s\|^2] = E[\|x_i^p\|^2] = 1$. The expression for the array output of the SBS in Figure 1 can be written for each subcarrier as

$$\mathbf{y}_{SBS}[k] = \sum_{l_s=1}^{L_s} \mathbf{H}_{ss,l_s}[k]\mathbf{w}_{s,l_s}^t[k]\mathbf{x}_{l_s}^s[k] + \mathbf{n}[k] + \mathbf{I}_{PU}[k] \qquad (1)$$

where $\mathbf{y}_{SBS}[k]=[y_1^s[k], y_2^s[k], \dots, y_{N_s^r}^s[k]]^T$ is the $N_s^r \times 1$ vector containing the outputs of the N_s^r – element array at the SBS, with $(.)^T$ denoting the transpose operation, $\mathbf{H}_{ss,l_s}[k]$ is the $N_s^r \times N_s^t$ frequency-domain channel matrix representing the transfer functions from SU l_s's N_s^t – element antenna array to the SBS's N_s^r – element antenna array, $\mathbf{w}_{s,l_s}^t[k]=[w_{l_s1}^t[k], w_{l_s2}^t[k]\dots, w_{l_sN_s^t}^t[k]]^T$ is the $N_s^t \times 1$ complex transmit weight vector for SU l_s, l_s = 1, …, L_s, $\mathbf{n}[k]=[n_1[k], n_2[k], \dots, n_{N_r}[k]]^T$ is the $N_s^r \times 1$ complex additive white Gaussian noise vector, and $\mathbf{I}_{PU}[k]$ represents the interference introduced by PUs at the SBS, given by

$$\mathbf{I}_{PU}[k]=\sum\nolimits_{l_p=1}^{L_p}\mathbf{H}_{ps,l_p}[k]\mathbf{w}_{p,l_p}^t[k]\mathbf{x}_{l_p}^p[k] \tag{2}$$

where $\mathbf{H}_{ps,l_p}[k]$ is the $N_s^r \times N_p^t$ channel matrix representing the fading coefficients from PUs to the SBS's N_s^r – element antenna array. On the other hand, the interference power seen by the PBS due to secondary transmission is given by

$$J_{sp}[k]=\sum\nolimits_{i=1}^{L_s}\mathbf{H}_{sp,l_s}[k]\mathbf{w}_{s,l_s}^t[k]\mathbf{w}_{s,l_s}^{t,H}[k]\mathbf{H}_{sp,l_s}^H[k] \tag{3}$$

where $(.)^H$ denotes the Hermitian transpose and $\mathbf{H}_{sp,l_s}[k]$ is the $N_p^r \times N_s^t$ channel matrix representing the fading coefficients from the l_s^{th} SU to the PBS's N_p^r – element antenna array. In practical antenna array systems, the array elements are closely spaced such that the signals emanating from or arriving at the elements experience significant fading correlations. Therefore, we assume that $\mathbf{H}_{ss,l_s}[k]$, $\mathbf{H}_{sp,l_s}[k]$, $\mathbf{H}_{ps,l_p}[k]$ and $\mathbf{H}_{pp,l_p}[k]$ consists of correlated elements and can be modelled as $\mathbf{H}_{ss,l_s}[k]=\mathbf{R}_{rs}^{1/2}\mathbf{H}_{ss,l_s}^{\omega}[k]\mathbf{R}_{ts}^{1/2}$, $\mathbf{H}_{sp,l_s}[k]=\mathbf{R}_{rp}^{1/2}\mathbf{H}_{sp,l_s}^{\omega}[k]\mathbf{R}_{ts}^{1/2}$, $\mathbf{H}_{ps,l_p}[k]=\mathbf{R}_{rs}^{1/2}\mathbf{H}_{ps,l_p}^{\omega}[k]\mathbf{R}_{tp}^{1/2}$ and $\mathbf{H}_{pp,l_p}[k]=\mathbf{R}_{rp}^{1/2}\mathbf{H}_{pp,l_s}^{\omega}[k]\mathbf{R}_{tp}^{1/2}$, respectively, where $\mathbf{R}_{rs}\in\mathbb{C}^{N_s^r\times N_s^r}$, $\mathbf{R}_{rp}\in\mathbb{C}^{N_p^r\times N_p^r}$, $\mathbf{R}_{ts}\in\mathbb{C}^{N_s^t\times N_s^t}$ and $\mathbf{R}_{tp}\in\mathbb{C}^{N_p^t\times N_p^t}$ are positive definite Hermitian matrices specifying the receive and transmit fading correlations. $\mathbf{H}_{ss,l_s}^{\omega}[k]\in\mathbb{C}^{N_s^r\times N_s^t}$, $\mathbf{H}_{sp,l_s}^{\omega}[k]\in\mathbb{C}^{N_p^r\times N_s^t}$, $\mathbf{H}_{ps,l_p}^{\omega}[k]\in\mathbb{C}^{N_s^r\times N_p^t}$ and $\mathbf{H}_{pp,l_s}^{\omega}[k]\in\mathbb{C}^{N_p^r\times N_p^t}$ consist of independent and identically distributed (iid) complex Gaussian entries, with zero mean and unit variance. The transfer functions from the l_s^{th} SU device to the SBS antenna array (the cascade of $\mathbf{H}_{ss,l_s}[k]$ and $\mathbf{w}_{s,l_s}^t[k]$), result in a unique spatial signature for each SU, which can be exploited to effect the separation of the user data at the SBS using appropriate multiuser detection techniques. The SBS detects all L_s SUs simultaneously at the multiuser detection module of the SDMA system, by multiplying the output of the array with $\mathbf{w}_{s,l_s}^r[k]=[w_{l_s1}^r[k], w_{l_s2}^t[k]\dots, w_{l_sN_s^r}^r[k]]^T$, the $N_s^r \times 1$ receiving weight vectors for each SU l_s. The detection of SU l_s out of $L = L_s + L_p$ users (with L-1 interfering users) can thus be depicted as

$$\hat{\mathbf{x}}_{l_s}[k]=\mathbf{w}_{s,l_s}^{r,H}[k]\mathbf{y}_{SBS}[k]=\mathbf{S}_d[k]+\mathbf{S}_{I_s}+\mathbf{S}_{I_p}[k]+\mathbf{N} \tag{4}$$

where $\mathbf{N}[k]=\mathbf{w}_{s,l_s}^{r,H}[k]\mathbf{n}[k]$ is the noise signal at the array output of the SBS, $\mathbf{S}_d[k]$ is the desired signal for the detection of user l_s's signal, $\mathbf{S}_{I_s}[k]$ is the multiple-access interference (MAI) contributed by the $L_s - 1$ other SUs and $\mathbf{S}_{I_p}[k]$ is the MAI from L_p PUs. $\mathbf{S}_d[k]$, $\mathbf{S}_{I_s}[k]$ and $\mathbf{S}_{I_p}[k]$ are given by

$$\mathbf{S}_d[k]=\mathbf{w}_{s,l_s}^{r,H}[k]\mathbf{H}_{ss,l_s}[k]\mathbf{w}_{s,l_s}^{t}[k]\mathbf{x}_{l_s}^{s}[k], \tag{5}$$

$$\mathbf{S}_{I_s}[k]=\mathbf{w}_{s,l_s}^{r,H}[k]\left[\sum\nolimits_{i=1,i\neq l_s}^{L_s}\tilde{\mathbf{H}}_{ss,i}^{t}[k]\mathbf{x}_{i}^{s}[k]\right], \tag{6}$$

$$\mathbf{S}_{I_p}[k]=\mathbf{w}_{s,l_s}^{r,H}[k]\left[\sum\nolimits_{l_p=1}^{Lp}\mathbf{H}_{ps,l_p}^{t}[k]\mathbf{x}_{l_p}^{p}[k]\right], \tag{7}$$

where $\tilde{\mathbf{H}}_{ss,i}^{t}[k]=\mathbf{H}_{ss,i}[k]\mathbf{w}_{s,i}^{t}[k]$ and $\tilde{\mathbf{H}}_{ps,l_p}^{t}[k]=\mathbf{H}_{ps,l_p}[k]\mathbf{w}_{s,l_p}^{t}[k]$.

3 Ergodic capacity maximisation of MIMO CR enabled SG

Our objective is to find the optimal beamforming vector, $(\mathbf{w}_{s,l_s}^{t}[k])_{opt}$, that maximises the Ergodic capacity of the cognitive OFDM-SDMA channel for each SU l_s of the OFDM-SDMA SG network imposing the following two sets of constraints:

1 each SU l_s has a limited maximum transmission power equal to $P_{\max,l}^{t}$

2 the total maximum interference power at the PBS from the SN's SUs is constrained to be at maximum equal to $J_{sp}^{\max}$.

In mathematical terms, these two constraints are expressed as follows:

$$\begin{aligned}&\max_{\mathbf{w}_{s,l_s}^{t}[k]}\left[E\left(\log_2\left\{\mathbf{I}+\frac{\rho_{l_s}}{N_s^t}\left|B_{l_s}^{-1/2}[k]\mathbf{H}_{ss,l_s}^{t}[k]\right|^2\right\}\right)\right]\\&\text{Subject to}:\left\{\begin{matrix}\mathbf{w}_{s,l_s}^{t,H}[k]\mathbf{w}_{s,l_s}^{t}[k]\leq P_{\max,l_s}^{t}\\ J_{sp}=\sum_{i=1}^{Ls}\tilde{\mathbf{H}}_{sp,l_s}^{t}[k]\tilde{\mathbf{H}}_{sp,l_s}^{t,H}[k]\leq J_{sp}^{\max}\end{matrix}\right\},\end{aligned} \tag{8}$$

where $E[.]$ denotes the expectation operator, $\tilde{\mathbf{H}}_{ss,l_s}^{t}[k]=\mathbf{H}_{ss,l_s}[k]\mathbf{w}_{s,l_s}^{t}[k]$, $\tilde{\mathbf{H}}_{sp,l_s}^{t}[k]=\mathbf{H}_{sp,l_s}[k]\mathbf{w}_{s,l_s}^{t}[k]$, $\mathbf{B}_{l_s}[k]=\mathbf{B}_{ss}[k]+\mathbf{B}_{ps}[k]+\sigma_n^2\mathbf{I}_{N_s^r}[k]$, $\mathbf{B}_{ss}[k]=\sum\nolimits_{i=1,i\neq l_s}^{L_s}\tilde{\mathbf{H}}_{ss,l_s}^{t}[k]\mathbf{H}_{ss,l_s}^{t,H}[k]$ and $\mathbf{B}_{ps}[k]=\sum\nolimits_{l_p=1}^{L_p}\tilde{\mathbf{H}}_{sp,l_s}^{t}[k]\tilde{\mathbf{H}}_{sp,l_s}^{t,H}[k]$. This problem is a constrained optimisation problem which is highly non-convex and complicated to solve. However, a sub-optimal solution can be obtained by exploiting the method of Lagrange multipliers as follows:

$$\begin{aligned}\mathcal{L}_{CCA}\left(w_{s,l_s}^t, v_{l_s}, \lambda_{l_s}\right) &= E\left(\log_2\left\{\mathbf{I} + \frac{\rho_{l_s}}{N_s^t}\left|B_{l_s}^{-1/2}[k]\tilde{\mathbf{H}}_{ss,l_s}^t[k]\right|^2\right\}\right) \\ &- v_{l_s}\left(\sum_{l_s=1}^{L_s}\tilde{\mathbf{H}}_{sp,l_s}^t[k]\tilde{\mathbf{H}}_{sp,l_s}^{t,H}[k]\Big/J_{sp}^{\max} - 1\right) \\ &- \lambda_{l_s}\left(\mathbf{w}_{s,l_s}^{t,H}[k]\mathbf{w}_{s,l_s}^t[k]\Big/P_{\max,l_s}^t - 1\right),\end{aligned} \tag{9}$$

where v_{l_s} and λ_{l_s} are the Lagrange multipliers associated with the l_s^{th} SU transmission power and the PBS received interference, respectively. In the proposed cognitive capacity-aware (CCA) algorithm, the weight vector for user l_s is updated at each iteration n, according to

$$\mathbf{w}_{s,l_s}^{t,CCA}(n+1) = \mathbf{w}_{s,l_s}^{t,CCA}(n) + \mu\nabla_{\mathbf{w}_{s,l_s}^{t,CCA}}\mathcal{L}_{CCA}\left(\mathbf{w}_{s,l_s}^{t,CCA}, \eta_{l_s}, \lambda_{l_s}\right) \tag{10}$$

where $\nabla_{\mathbf{w}_{s,l_s}^{t,CCA}}$ is the gradient of $\mathcal{L}_{CCA}(w_{s,l_s}^{t,CCA}, \eta_{l_s}, \lambda_{l_s})$ w.r.t. to $\mathbf{w}_{s,l_s}^{t,CCA}$ and μ is an adaptation constant. Notice that SDMA is subcarrier parallel (Alias et al. 2003; Vandename et al. 2000), and that the update is done separately on each subcarrier. For brevity therefore, we drop the frequency index [k] and concentrate on the iteration index (n) in this recursion. Using the matrix derivative formula (Hjorungnes and Gesbert, 2007), $\partial\log|\mathbf{A} + \mathbf{BXC}|/\partial\mathbf{X}^* = [\mathbf{C}(\mathbf{A} + \mathbf{BXC})^{-1}\mathbf{B}]^H$, the gradient of the Lagrangian can be expressed as

$$\begin{aligned}\nabla_{\mathbf{w}_{s,l_s}^t}\mathcal{L}_{CCA}\left(\mathbf{w}_{s,l_s}^t, \eta_{l_s}, \lambda_{l_s}\right) = (1/\ln 2)\Big[&\left(\rho_{l_s}B_{l_s}^{-1}(n)\mathbf{w}_{s,l_s}^t(n)\right)\Big/ \\ &\left(1+\rho_{l_s}\mathbf{w}_{s,l_s}^{t,H}(n)\mathbf{w}_{s,l_s}^t(n)\right)\Big] \\ &-\left(\lambda_{l_s}(n)\Big/P_{\max,l_s}^t\right)\mathbf{w}_{s,l_s}^t(n) \\ &-\left(v_{l_s}(n)\Big/J_{sp}^{\max}\right)\mathbf{H}_{sp,l_s}^H(n)\mathbf{H}_{sp,l_s}(n)\mathbf{w}_{s,l_s}^t(n)\end{aligned} \tag{11}$$

The Lagrange multipliers, $v_{l_s}(n)$ and $\lambda_{l_s}(n)$, are updated iteratively using the subgradient-based method, as described in Mijangos (2007), where the parameters $\alpha_{\lambda_{l_s}}$ and $\alpha_{v_{l_s}}$ are the subgradients' step sizes, whose values are to be chosen relatively small in order to achieve convergence:

$$\lambda_{l_s}(n+1) = \lambda_{l_s}(n) - \alpha_{\lambda_{l_s}}\left[\mathbf{w}_{s,l_s}^{t,H}(n+1)\mathbf{w}_{s,l_s}^t(n+q) - P_{\max,l_s}^t\right] \tag{12}$$

$$v_{l_s}(n+1) = v_{l_s}(n) - \alpha_{v_{l_s}}\left[\sum_{l_s=1}^{L_s}\tilde{\mathbf{H}}_{sp,l_s}^t(n)\tilde{\mathbf{H}}_{sp,l_s}^{t,H}(n) - J_{sp}^{\max}\right] \tag{13}$$

In our optimisation procedure we consider that the initial values of $\mathbf{w}_{s,l_s}^t(n)$ at iteration index n = 0 is given by the Eigen beamforming weight, i.e., $\mathbf{w}_{s,l_s}^t(0) = \sqrt{P_{\max,l_s}^t}\,\mathbf{u}_{\max,l_s}$, where $\mathbf{u}_{\max,l_s}$ denotes the eigen vector corresponding to $\boldsymbol{\lambda}_{\max,l_s}$, the maximum eigen value of $\mathbf{H}_{ss,l_s}^H\mathbf{H}_{ss,l_s}$. This value is then used to compute the initial value of the received beamforming vector at iteration index n = 0:

$$\mathbf{w}_{s,l_s}^{r}(0) = \left(\mathbf{B}_{l_s}(0)\right)^{-1} \tilde{\mathbf{H}}_{ss,l_s}^{t} \tag{14}$$

Our proposed concurrent cognitive OFDM-SDMA capacity-aware scheme will be compared to the opportunistic one where it is assumed that SG networks are turning off the subcarriers occupied by the PN instead of imposing the constraints given by equation (8). In such a case the weight vector for user l_s is updated at each iteration n, according to Sulyman and Hefnawi (2008):

$$\mathbf{w}_{s,l_s}^{t}(n+1) = \mathbf{w}_{s,l_s}^{t}(n) + \left(\mu/\ln 2\right)\Big[\left(\rho_{l_s} B_{l_s}^{-1}(n)\mathbf{w}_{s,l_s}^{t}(n)\right)\Big/ \left(1+\rho_{l_s}\mathbf{w}_{s,l_s}^{t,H}(n)B_{l_s}^{-1}(n)\mathbf{w}_{s,l_s}^{t}(n)\right)\Big] \tag{15}$$

4 SER performance of cognitive OFDM-SDMA systems

The symbol error rate, SER_{k,l_s}, associated with k^{th} subcarrier of user l_s, can be expressed as (Wong et al., 2001)

$$SER_{k,l_s} = E_{\gamma_{k,l_s}}\left[aQ\left(\sqrt{2b\gamma_{k,l_s}}\right)\right] \tag{16}$$

where E[.] denotes the expectation operator, Q(.) denotes the Gaussian Q-function, γ_{k,l_s} is the signal-to-interference-plus-noise ratio (SINR) associated with the k^{th} subcarrier of user l_s, and a and b, are modulation-specific constants. For binary phase shift keying (BPSK), $a = 1$ and $b = 1$, for binary frequency shift keying (BFSK) with orthogonal signaling $a = 1$ and $b = 0.5$, while for M-ary phase shift keying (M-PSK) $a = 2$ and $b = \sin^2(\pi/M)$. The SINR for SU l_s at iteration n, $\gamma_{k,l_s}(n)$, , is given by

$$\gamma_{k,l_s}(n) = \frac{\left(\mathbf{w}_{l_s}^{r}(n)\right)^{H}\tilde{\mathbf{H}}_{ss,l_s}^{t}(n)\left(\tilde{\mathbf{H}}_{ss,l_s}^{t}(n)\right)^{H}\mathbf{w}_{l_s}^{r}(n)}{\left(\mathbf{w}_{l_s}^{r}(n)\right)^{H}\mathbf{B}_{l_s}(n)\mathbf{w}_{l_s}^{r}(n)} \tag{17}$$

The average SER_{l_s} performance for user l_s, can be estimated as (Gungor and Sahin, 2012)

$$SER_{l_s} = \frac{1}{N_c}\sum_{k=0}^{N_c-1} SER_{k,l_s} \tag{18}$$

5 Simulation results

In our simulation setup we consider a cognitive OFDM-SDMA system with $N_s^t = N_p^t = 2$ transmit antennas, $N_s^r = N_p^r = 8$ receive antennas, L_s = 3 SUs and L_p = 3 PUs. We assume BPSK modulation. We impose $P_{\max,l}^{t} = 0$ dB and

$J_{sp}^{\max} = -20$ dB on the SUs. We assume the 256-OFDM system (N_c = 256) for the SN, which is widely deployed in broadband wireless access services, and we assume 128-OFDM system for the PN with non-constrained MIMO-MRC. Figure 2 compares the SER performance of SN achieved by the proposed CCA and the opportunistic one. When using opportunistic scheme we assume that SUs are turning off the 128 subcarriers occupied by the PN. It is observed from the results that the proposed algorithm achieves substantially lower SER compared to the opportunistic approach. For example, for SER = 10^{-1}, at least 2.5 dB enhancements in SER is observed with the proposed algorithm. Figure 3, on the other hand, shows the impact of $J_{sp}^{\max}$ on the SER performance of the PN. It is noted that when the SN is using the proposed CCA, it could efficiently control the interference to PBS, especially at low SNR (SNR < 8 dB) of practical interest in OFDM-SDMA applications, where the SNR of operation is very low due to high noise level (noise here denoting noise plus interference). It is noted that as $J_{sp}^{\max}$ becomes larger, the SER of the PUs is improved due to the decreased interferences. It is also noted that the most significant interference at PBS is caused when the SN is using opportunistic OFDM-SDMA scheme, because it is designed without considering the constraints imposed by the PN. Figure 4 compares the system capacity of SN achieved by the concurrent and opportunistic capacity-aware for $J_{sp}^{\max} = -20$ dB. It is observed that the proposed concurrent algorithm achieves substantially higher system capacity than the opportunistic one. For example, for an SNR = 10 dB, at least 5 bits/sec/Hz enhancements in system capacity is observed with the proposed algorithm. For broadband wireless services like the LTE system with channel size up to 50 MHz, this translates to 250 Mbps capacity enhancement per channel in each cell, which can be very significant in a cellular deployment.

Figure 2 SER performance of SUs with CCA: concurrent versus opportunistic (see online version for colours)

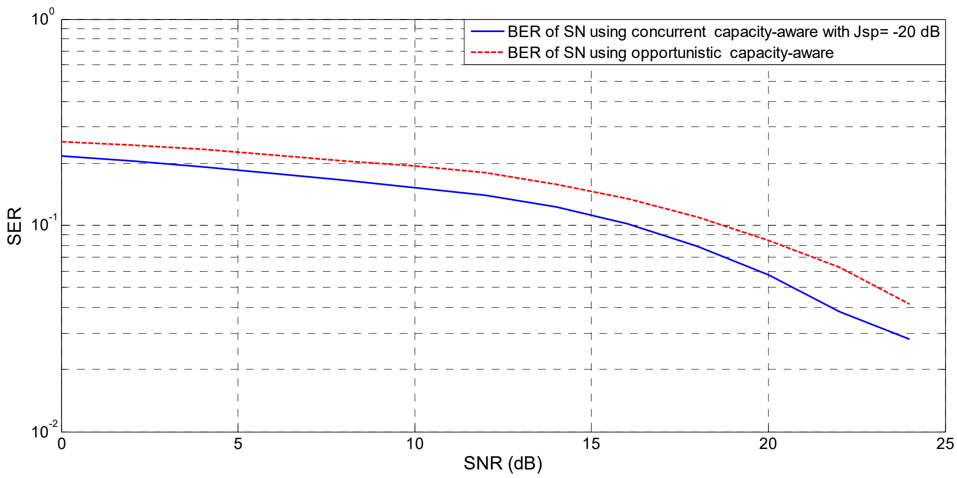


Figure 3 SER of PUs when SN is using CCA: concurrent versus opportunistic (see online version for colours)

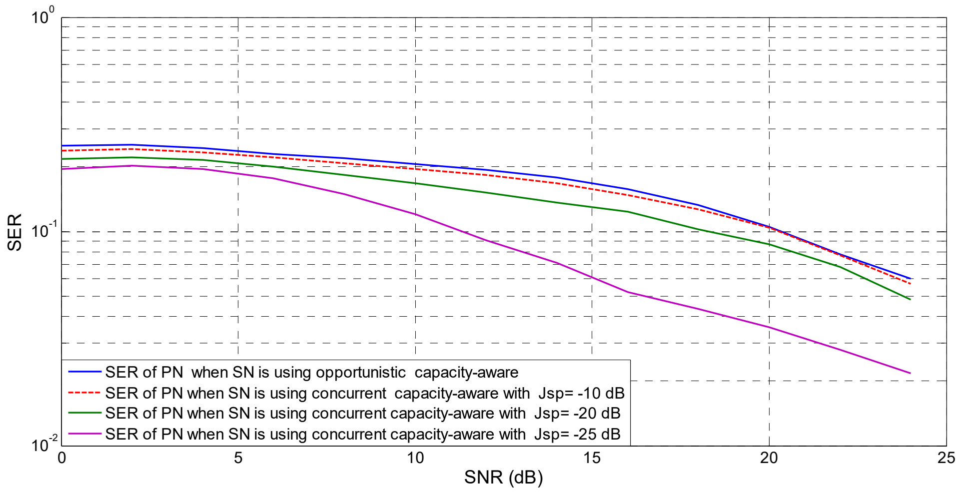
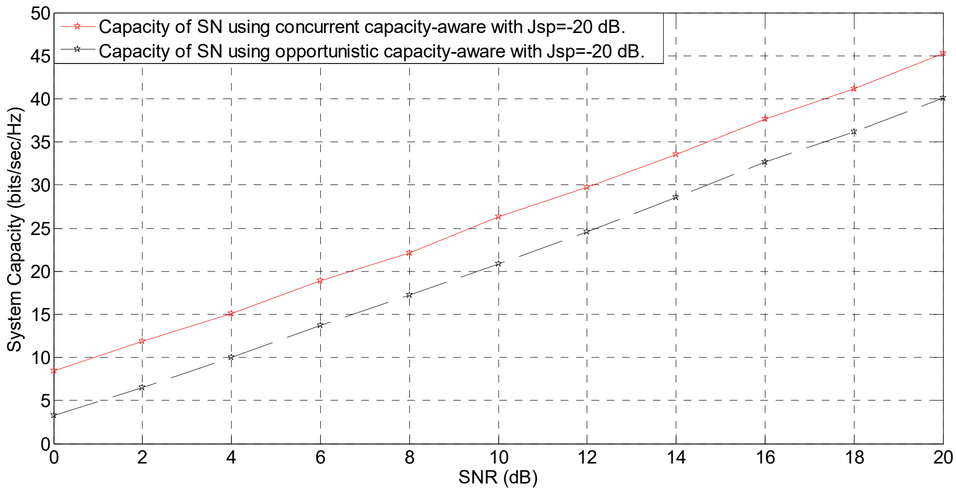


Figure 4 Channel capacity of SN using CCA: concurrent versus opportunistic (see online version for colours)



6 Conclusions

This paper presents a new OFDM-SDMA scheme for CR enabled smart grid systems. The proposed algorithm iteratively seeks the optimal transmit weight vectors that maximise the SG system capacity while protecting PUs from SUs' interferences, and thus allowing a concurrent access to the same channel as the PN. It is shown that the SER and system capacity performances of the OFDM-SDMA systems with the transmit weights obtained using the proposed algorithm is substantially higher than that with the opportunistic approach. It is also noted that the proposed scheme could efficiently control the interference to PBS.

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