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A Hybrid Spatial Adaptive Modulation and Frequency Stochastic Approach for MU-MIMO-OFDM Systems in the Context of Underlay Cognitive Radios

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Abstract

In this paper, low complexity rate and power optimization schemes operating in the spatial and frequency domains are proposed in a cognitive radio (CR) setting involving multi-user multiple-input-multiple-output-orthogonal frequency division multiplexing (MU-MIMO-OFDM). Under the assumption of a perfect secondary channel state information (CSI) at the receiver, the presented architectures encompass two main stages. In the first one, spatial power waterfilling-like method is performed per each MIMO subchannel pertaining to each subcarrier of each secondary user (SU). The resulting allocated power per each eigen-channel is considered as the power budget in the second stage. In this latter, stochastic algorithm-based approach wherein the transmit parameters per each subcarrier of each SU are adapted such that to maximize the achievable sum-rate capacity of the SUs. Three different schemes are introduced in this work. First, the derivation of the continuous rate MU-MIMO-OFDM-CR version, referred to as C-MU-MIMO-OFDM-CR is presented. Obviously, this proposition is theoretical and is taken as a benchmark for the two remaining counterparts. The second proposition we called discrete-rate MU-MIMO-OFDM-CR, and briefly designated as D-MU-MIMO-OFDM-CR which is to round the provided allocated rate. Finally, the third modified solution, denoted as P-D-MU-MIMO-OFDM-CR proceeds in a similar way as the D-MU-MIMO-OFDM-CR alternative, but superimposes the non/over-used amount of power to the power budget in next iteration. The simulation results show that, compared to the discrete rate D-MU-MIMO-OFDM-CR solution, the P-D-MU-MIMO-OFDM-CR approach exhibits an approximate power gain of 1 dB when the SNR level is low, and of 5 dB at high SNR range.

Keywords

multi-user, MIMO-OFDM, stochastic algorithms, adaptive modulation

1 Introduction

Multiple-input-multiple-output (MIMO) technology received considerable attention and has gone through significant elaboration stages in last years, since its first apparition. One of the main reasons for its widespread use lies in the high spectral efficiency it allows through the multiplexing gain feature, or the yielded spatial or spatio-temporal diversity gains [1–3]. When combined with cognitive inherent techniques such as adaptive modulation (AM), MIMO approach in a mono-user scenario allows to adapt the communication to channel characteristics, thus offering a good compromise between the two conflicting metrics, which are spectral efficiency and BER [4, 5]. The role of the AM technique in that architecture is to maintain a constant SNR, while tuning the transmit parameters such as transmit power, coding scheme, constellation size or their combination to the channel variations [6–10].

Cognitive radio (CR) paradigm aims at circumventing the ill-usage of the scarce spectrum resources by the current communication systems and standards, by more judiciously exploiting them, either in the absence of the licence holders, also referred to as primary users (PUs), or through the co-existence or collaboration of these latter with the secondary users (SUs), also known as CR users. In this context, whether through co-existence or collaboration with the PU, the resulting configurations, known as underlay systems, in which the SUs are allowed to

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simultaneously communicate over the sensed frequency band provided that they proceed with low transmit powers such that to avoid causing interference to the PUs license holders, are more flexible multi-user (MU) scenarios compared to the first configuration [11]. Indeed, intuitively, without any calculations, it is expected that underlay systems reach a higher sum-rate capacity relative to the first configuration, known as overlay alternative, in which the SUs are permitted to transmit only if the PUs are off. The co-existence with the PU is of interest to us in this work, and in that scenario, SUs are allowed to communicate simultaneously with the PU, provided that they are meeting the interference constraint imposed by this latter. Furthermore, CR technique may adopt AM-like principle, in tuning the communication parameters to the channel state, hence enhancing the data reliability, while supporting multiple CR users in the licensed band. On the other hand, and due to the high-data rates involved in current and future communications, orthogonal frequency division multiplexing (OFDM)-based techniques are commonly adopted to fulfill these rate needs and combat the inherent frequency selectivity of the resulting channels. In this context, combining OFDM and MIMO capabilities was shown to further improve the achievable spectral efficiency [12–14]. Due to the fact that the resulting system should support the increasing number of subscribers to wireless services, a trend towards the investigation of MU-MIMO-OFDM architectures has rather been noted these last years. It was shown in [13, 15] that the combination of multi-user, spatial and frequency diversities with AM improves the overall system performance in a non-cognitive setting.

In this work, we propose three CR schemes merging, in a MU-MIMO-OFDM architecture, the capabilities of AM in optimally allocating power in the spatial domain, and the functionalities of the stochastic resource allocation (RA) approach in optimizing such a distribution in the temporal domain per each subcarrier of each SU. Under perfect channel state information (CSI) knowledge at each SU receiver side, the proposed configurations undergo two processing steps. Subsequently to the singular value decomposition (SVD) of the MIMO channel matrix, the first one concerns the application of the power-only AM method on each MIMO subchannel pertaining to each subcarrier of each SU, under BER and total power constraints. Power waterfilling is carried out over only the space domain because no gain is noted when performing it simultaneously over space and time domains [12, 13, 15, 16]. This leads to the evaluation of the average power budget in the second stage which is equal to the allocated power per each eigen-channel. Then, the second stage carries out the temporal-domain application of the stochastic algorithms-based approach for the assignment of the transmit power and rate for each subcarrier of each SU, under the constraints of available power budget and probability of interference to the PU. As a result, the achievable sum-rate capacity of the SUs is maximized, while co-existing with the PU.

The choice of the stochastic algorithms in this work is fuelled by their simplicity, their robustness to channel variations, and their capabilities in maximizing the sum-rate performance of the CR network [17, 18].

As mentioned earlier, three different schemes are presented in the scope of this work. The derivation of the continuous rate MU-MIMO-OFDM-CR version, referred to as C-MU-MIMO-OFDM-CR, is first shown wherein it is assumed that an infinite modulation order is affordable. Obviously, this proposition is theoretical and is taken as a benchmark for the two remaining counterparts. The principle of the second proposition we called discrete-rate MU-MIMO-OFDM-CR, and briefly designated as D-MU-MIMO-OFDM-CR, is to round the provided allocated rate in the stochastic stage to the nearest rate level in the allowable modulation rates set. Finally, the third modified solution, denoted P-D-MU-MIMO-OFDM-CR, targets to more viably exploit available power resources, and starts by proceeding in a similar way as the D-MU-MIMO-OFDM-CR alternative, by quantizing the allocated rate and adapting consequently the power level, but unlike the latter, superimposes the non/over-used amount of power to the power budget in next iteration.

The simulation results show that, compared to the discrete rate D-MU-MIMO-OFDM-CR solution, the P-D-MU-MIMO-OFDM-CR approach exhibits an approximate power gain of 1 dB when the SNR level is low, and of 5 dB at high SNR range.

The performance of the best performing discrete rate P-D-MU-MIMO-OFDM-CR scheme was also compared with continuous rate C-MU-MIMO-OFDM-CR alternative and was shown to be quite acceptable.

The remainder of this paper is organized as follows. Section 2 is devoted to the description of our system model along with the operating parameters. In Section 3, the solution to the wireless resources optimization problem in the CR MU-MIMO-OFDM system, under power budget, BER and interferences constraints, is explicitly formulated with the three schemes. Simulation results and conclusion wrap-up this paper.

2 System model

The cognitive MU-MIMO-OFDM architecture investigated herein comprises one Base Station (BS), K SUs (indexed by k with $k = 1 \ldots K$) communicating opportunistically over N sub-carriers (indexed by n with $n = 1 \ldots N$), wherein n_T transmit and n_R receive antennas are involved. The mentioned BS of the system is in charge of assuring the allocation of the resources (power and rate) obtained through the hybrid optimization process applied to the SUs. We denote $\boldsymbol{h}_{n,\mathrm{SU}}^{k}(t)$, the $n_R \times n_T$ k-th SU MIMO CSI matrix over the n-th subcarrier, representing the power at the link between the transmit and the receive arrays andcomposed of independent complex Gaussian variables. In the following, the discussion is carried out for each subcarrier of each SU. The channel input is denoted by a $n_T \times 1$ signal vector $\boldsymbol{x}$, the channel output by the $n_R \times 1$ vector $\boldsymbol{y}$, and the $n_R \times 1$ additive white Gaussian noise (AWGN) vector at the receiver by $\boldsymbol{w}$. The total power available at the transmitter is denoted by P_T, we assume a noise power of unity, hence the average SNR per spatial sub-channel SNR $= P_T$. It follows that the channel input/output relation pertaining to the n-th subcarrier of the k-th user could be written as

$$\boldsymbol{y}_n^k = \boldsymbol{h}_{n,\mathrm{SU}}^k \boldsymbol{x}_n^k + \boldsymbol{w}_n^k \tag{1}$$

while satisfying the total power constraint given by Eq. (2):

$$E\left[\boldsymbol{x}_n^{k*}\boldsymbol{x}_n^k\right] = \sum_{l=1}^{L} \tilde{p}_n^{l,k} \le P_T, \forall k \tag{2}$$

where the superscript * denotes the conjugate transpose of the operand and $\tilde{p}^{l,k}$ represents the average power budget at the l-th sub-channel for each k-th SU.

Then, applying the SVD operation on the channel matrix $\boldsymbol{h}_{n,\mathrm{SU}}^{k}(t)$, yields:

$$\boldsymbol{h}_{n,\mathrm{SU}}^k = \boldsymbol{U}_{n,\mathrm{SU}}^k \boldsymbol{Z}_{n,\mathrm{SU}}^k \boldsymbol{V}_{n,\mathrm{SU}}^{k*} \tag{3}$$

where $\boldsymbol{U}_{n,\mathrm{SU}}^k$ and $\boldsymbol{V}_{n,\mathrm{SU}}^k$ are $n_R \times n_R$ and $n_T \times n_T$ unitary matrices composed of the left and right singular vectors of $\boldsymbol{h}_{n,\mathrm{SU}}^{k}(t)$, respectively, and $\boldsymbol{Z}_{n,\mathrm{SU}}^k$ is the relative $n_R \times n_T$ diagonal and non-negative matrix constituted of the channel eigen-values of $\boldsymbol{h}_{n,\mathrm{SU}}^k \times \boldsymbol{h}_{n,\mathrm{SU}}^{k*}$.

Substituting Eq. (3) into Eq. (1), we obtain the following expression:

$$\bar{\boldsymbol{y}}_n^k = \boldsymbol{Z}_{n,\mathrm{SU}}^k \bar{\boldsymbol{x}}_n^k + \bar{\boldsymbol{w}}_n^k, \tag{4}$$

where $\bar{\boldsymbol{y}}_n^k = \boldsymbol{U}_{n,\mathrm{SU}}^{k*}\boldsymbol{y}_n^k$, $\bar{\boldsymbol{x}}_n^k = \boldsymbol{V}_{n,\mathrm{SU}}^{k*}\boldsymbol{x}_n^k$, and $\bar{\boldsymbol{w}}_n^k = \boldsymbol{U}_{n,\mathrm{SU}}^{k*}\boldsymbol{w}_n^k$.

It is important to notice that the powers of $\boldsymbol{x}_n^k$ and $\bar{\boldsymbol{x}}_n^k$, $\boldsymbol{y}_n^k$ and $\bar{\boldsymbol{y}}_n^k$, and $\boldsymbol{w}_n^k$ and $\bar{\boldsymbol{w}}_n^k$ are equal, since $\boldsymbol{U}_{n,\mathrm{SU}}^k$ and $\boldsymbol{V}_{n,\mathrm{SU}}^k$ are unitary matrices. Subsequently, denoting the vector of the MIMO channel eigen-values $\boldsymbol{\rho}$, with elements $\sqrt{\boldsymbol{\rho}}^{k,l}$, with $l = 1 \ldots L$ and $L = \min(n_R, n_T)$, Eq. (4) could be further modified to show the decomposition of the MIMO channel into its L independent sub-channels as follows:

$$\bar{\boldsymbol{y}}_n^{k,l} = \sqrt{\boldsymbol{\rho}_n}^{k,l}\,\bar{\boldsymbol{x}}_n^{k,l} + \bar{\boldsymbol{w}}_n^{k,l},\ 1 \le l \le L\,. \tag{5}$$

3 Proposed quantization approach for MU-MIMO-OFDM-CR

3.1 Spatial adaptive modulation

As mentioned, the three hybrid power and rate adaptations per sub-carrier per SU architecture we are proposing in a MU-MIMO-OFDM-CR context, share a common first stage which conducts power tuning AM on each spatial dimension under BER and total power constraints. The application of the SVD technique on $\boldsymbol{h}_{n,\mathrm{SU}}^k$ gives birth to L spatial tunnels on which power waterfilling is performed according to the state of these eigen-channels. To achieve this, the fulfillment of the BER requirement is sought along with the one of average power budget. In this work, we investigate the adoption of MQAM scheme for which the upper bound of the BER within 1 dB for $M_l \ge 4$, on each obtained spatial sub-channel in each subcarrier of the SU could be formulated as follows [4]:

$$\mathrm{BER}_n^{k,l} \le 0.2\exp\left[\frac{-1.5}{M_l - 1} p_n^{k,l}\rho_n^{k,l}\right], \tag{6}$$

where M_l is the constellation size, and $p_n^{k,l}\rho_n^{k,l}$ stands for the received SNR. Thus, defining the factor $\Gamma_n^{k,l} = \dfrac{-1.5}{\ln\left(5\mathrm{BER}_n^{k,l}\right)}$ as the penalty power, the optimal power allocation policy obeying the rule of the waterfilling procedure could be formulated as

$$\tilde{p}_n^{k,l} = \left(\mu_n^{k,l} - \left(\Gamma_n^{k,l}\rho_n^{k,l}\right)^{-1}\right)^{+}. \tag{7}$$

The difference between the three proposed schemes resides in the way the $C_n^{k,l}$ is evaluated and the corresponding power is obtained. In C-MU-MIMO-OFDM-CR proposed scheme, it is assumed that all the provided rate values are affordable.

Hence, in C-MU-MIMO-OFDM-CR, the rate per each subcarrier of the l-th spatial subchannel of the k-th SU, could thus be given as

$$C_n^{k,l}\left(p_n^{k,l}, p_n^{k,l}\left(\rho_n^{k,l}\right)\right) = \log_2\left(1 + \rho_n^{k,l} p_n^{k,l}\Gamma_n^{k,l}\right). \tag{8}$$

On the other hand, in both D-MU-MIMO-OFDM-CR and P-D-MU-MIMO-OFDM-CR alternatives, which are more practical schemes, in the spatial processing stage, the transmit data rate domain per spatial dimension for each sub-carrier of each CR user is quantized into finite given rate levels. Assuming that square MQAM constellations of size $M_0 = 0$, $M_1 = 2$ and $M_j = 2^{2(j-1)}$, $j = 2, \ldots, O$ are used. $O + 1$ possible data rates, $\{0, 1, 2, 4, \ldots, 2(O-1)\}$ are available. In order to find the optimal adaptation with the constellations restrictions, the range of $\rho_n^{k,l}$ is equivalently divided into $O + 1$ fading regions, and the constellation M_j is attributed if $\rho_n^{k,l} \in j\text{-th}$ region. Hence, the data rate of the l-th sub-channel when $\rho_n^{k,l} \in j\text{-th}$ region is thus $\log_2 M_j$ bits per symbol.

In order to set the boundaries, we define:

$$\rho_n^{k,l} = \rho_{\Gamma_n^{k,l}} M_l\left(\rho_n^{k,l}\right), \tag{9}$$

where $\rho_{\Gamma_n^{k,l}} \succ 0$ is a parameter optimized to maximize the spectral efficiency.

Knowing that the maximum constellation size for a given BER according to Eq. (6) is given as

$$M_l = 1 + \Gamma_n^{k,l} p_n^{k,l} \rho_n^{k,l}. \tag{10}$$

According to Eq. (10), the power adaptation policy for a fixed BER, for the constellationis $M_j \succ 0$ given by

$$p_n^{k,l} = \begin{cases} \dfrac{M_j - 1}{\Gamma_n^{k,l} \rho_n^{k,l}}, & p\left(M_j \prec \dfrac{\rho_n^{k,l}}{p_{\Gamma_n^{k,l}}} \prec M_{j+1}\right). \\ 0, & M_j = 0 \end{cases} \tag{11}$$

Then, the allocated rate per region is associated with the probability of falling in that region through Eq. (12):

$$C_n^{k,l} = \log_2\left(M_j\right) p\left(M_j \prec \frac{\rho_n^{k,l}}{\rho_{\Gamma_n^{k,l}}} \prec M_{j+1}\right). \tag{12}$$

To satisfy the total transmit power constraint, the value of the parameter $\rho_{\Gamma_n^{k,l}}$ in Eq. (9) is found by verifying the following constraint:

$$\sum_{n=1}^{N} \sum_{l=1}^{L} \sum_{j=1}^{O} p_n^{k,l}\left(\rho_n^{k,l}\right) p\left(\rho_n^{k,l}\right) d\left(\rho_n^{k,l}\right) = P_T. \tag{13}$$

The difference between the D-MU-MIMO-OFDM-CR and the P-D-MU-MIMO-OFDM-CR approaches lies in the way each one exploits the power, which impinges directly on the achievable rate, as this will be explain in next subsection.

3.2 Rate and power optimization through stochastic approach

The power optimally distributed on the spatial dimension in each MIMO channel instance constitutes the average power budget for next step evolving around the temporal assignment of transmit power, subcarrier index and rate for each user per each subcarrier by the aid of the stochastic algorithms-based approach, under the constraints of average power budget and probability of interference to the PU. Hence, the optimization problem, which maximizes the sum-rate capacity of the SUs, while ensuring the co-existence of the SUs with the PU, could be formulated as follows:

- Objective function:

$$\overline{C}^{k,l} = \max_{\left\{s_n^{k,l}\left(\rho_n^{k,l}\right), p_n^{k,l}\left(\rho_n^{k,l}\right)\right\}} \sum_n E_{\rho_n^{k,l}}\left(s_n^{k,l}\left(\rho_n^{k,l}\right) \times C_n^{k,l}\left(\rho_n^{k,l}, p_n^{k,l}\left(\rho_n^{k,l}\right)\right)\right) \tag{14}$$

- Subject to:

$$\sum_k s_n^{k,l}\left(\rho_n^{k,l}\right) \le 1, \forall n \tag{15}$$

$$E_{\rho_n^{k,l}} \sum_n s_n^{k,l}\left(\rho_n^{k,l}\right) p_n^{k,l}\left(\rho_n^{k,l}\right) \le \tilde{p}^{k,l}, \forall k \tag{16}$$

$$E_{\boldsymbol{h}_{n,\mathrm{PU}}^k}\left[s_n^{k,l}\left(\rho_n^{k,l}\right) 1_{\left\{p_n^{k,l} \boldsymbol{h}_{n,\mathrm{PU}}^k \succ \sigma_n\right\}}\right] \le \tilde{\theta}_n, \forall n \tag{17}$$

- Optimization variables:

$$\left\{p_n^{k,l}\left(\rho_n^{k,l}\right), s_n^{k,l}\left(\rho_n^{k,l}\right)\right\}, \tag{18}$$

where $E_{\rho_n^{k,l}}$ represents the expectations over all CSI realizations, $\overline{C}^{k,l}$ is the overall average allocated rate to maximize, $C_n^{k,l}$ and $p_n^{k,l}$ are, respectively, the corresponding n-th subcarrier rate and power assigned to the k-th SU over the l-th spatial eigen-channel, $s_n^{k,l}$ is the subcarrier index which is equal to 1 if and only if the n-th subcarrier is assigned to the k-th SU over the l-th spatial eigen-channel. The primary CSI denoted by $\boldsymbol{h}_{n,\mathrm{PU}}^k(t)$, represents the power of the link between the k-th SU transmitter and the n-th PU receiver at an instant t. Moreover, $\tilde{p}^{k,l}$ stands for the average power budget the k-th SU is allowed to transmit over the l-th spatial sub-channel, and is equal to the summation of the powers assigned to the k-th SU per sub-carrier in each spatial dimension and provided in the spatial power adaptation prior stage, σ_n and $\tilde{\theta}_n$ are, respectively the threshold and the probability of interference per subcarrier and the notation $1_{\left\{p_n^{k,l} \boldsymbol{h}_{n,\mathrm{PU}}^k > \sigma_n\right\}}$ equals 1 if $p_n^{k,l} \boldsymbol{h}_{n,\mathrm{PU}}^k > \sigma_n$ is true and zero otherwise.

Regarding the constraints, Eq. (15) allows at most one CR user to transmit over each sub-carrier n, whilst Eq. (16) defines the power budget (i.e., maximum power) the k-th SU can benefit from for his transmission, and finally Eq. (17) imposes a threshold perceived at the PU level which is not to be exceed.

Then, the MIMO sum-rate channel capacity with Rayleigh fading could be written as follows:

$$\begin{aligned} C &= \sum_k \sum_l E_{|\rho_n^{k,l}|} \overline{C}^{k,l}\left(\left|\rho_n^{k,l}\right|\right) \\ &= \sum_k L \int_0^{\infty} \overline{C}^{k,l} p\left(\left|\rho_n^{k,l}\right|\right) d\left(\left|\rho_n^{k,l}\right|\right) \end{aligned}, \quad (19)$$

where in writing Eq. (19), it was assumed that the spatial sub-channel eigenvalues are independent and have the same distribution. In Eq. (19), $E_{|\rho_n^{k,l}|}$ is the expectation over the corresponding eigen-value, and $p(.)$ represents the probability density function (pdf) of the operand.

3.3 Algorithm description

The whole hybrid allocation policy carrying out the power and rate assignment in both spatial, and temporal domains per each subcarrier of each SU could be easily outlined based on the previous subsections. The distinction between the D-MU-MIMO-OFDM-CR and the P-D-MU-MIMO-OFDM-CR allocation schemes resides in the way the power budget is exploited. Indeed, in both approaches, the rate is rounded off to the closest available discrete rate level. However, to carry out the communication, the transmit power should be increased or decreased. P-D-MU-MIMO-OFDM-CR solely considers this aspect by recalculating the value of the transmit power, leading to a lack or an excess in the power budget. Hereafter is the listing of the whole generic procedure encompassing the three approaches. In the P-D-MU-MIMO-OFDM-CR version (Algorithm 1) [9], all the steps 1 through 15 are followed, whilst in D -MU-MIMO-OFDM-CR alternative the steps 7 through 9 are skipped, since the adaptation of the power budget is not performed. Finally, in C-MU-MIMO-OFDM-CR counterpart, the steps 6 through 9 are ignored. Note that the parameter *Len* in the listing refers to the coherence time of the channel.

4 Simulation results

Throughout this section, the performances of our proposed schemes are assessed, and the results are then discussed. The expectation of CSI is approximated over 1 000 independent realizations of the channel matrix. In performing this study, the following parameters are retained: $K = 4$, $N = 8$, $L = 2$ and BER = 10^{-3}. Furthermore, the channel is assumed to experience Rayleigh fading, and in incorporating spatial stage into the whole processing for the discrete schemes, a set of 15 possible discrete rate levels was offered.

Algorithm 1 P-D-MU-MIMO-OFDM-CR [9]

1. Put iteration index $i = 0$;
2. Put user index $k = 1$, the subcarrier index $n = 1$;
3. Put the initial total transmit power $P_n^k(i) = P_T$;
4. Perform spatial power water-filling on $\rho_n^{k,l}$ with the total transmit power $P_n^k(i)$;
5. Compute the allocated rate of each user per each subcarrier of each spatial eigen-channel, $C_n^{k,l}$ as given in Eq. (8);
6. Round $C_n^{k,l}$ to the nearest rate level for all $l = 1 \ldots L$ as per Eq. (12);
7. Re-derive $P_n^{k,l}$ by replacing $C_n^{k,l}$ in Eq. (8);
8. Compute $P_{\text{remain}}^{k,n}(i) = P_T^{k,n}(i) - \sum_{l=1}^{L} p_n^{k,l}$;
9. Update $P_T^{k,n}(i+1) = P_T + P_{\text{remain}}^{k,n}(i)$;
10. $i = i + 1$, go to step 4;
11. If $i = Len$, put $i = 0$;
12. $n = n + 1$, Go to step 3;
13. If $n = N$, put $k = k + 1$ and $n = 1$, and go to step 3;
14. If $k = K$, put $n = N$, perform the optimization over subcarrier and user dimension while calculate $\overline{C}^{k,l}$ as in Eq. (14) obtained through stochastic optimization;
15. Calculate the instantaneous sum-rate capacity C as in Eq. (19);
16. End.

Fig. 1 illustrates the sum-rate capacity versus the average SNR of the three proposed architectures. First, as it was expected, the theoretical C-MU-MIMO-OFDM-CR scheme is the best performing since it corresponds to an infinite number of rate levels. Second, P-D-MU-MIMO-OFDM-CR solution allows to better approach the former. For low SNR range, in order to achieve the same sum-rate capacity, P-D-MU-MIMO-OFDM-CR provides 1 dB saving in transmit power compared with D-MU-MIMO-OFDM-CR. At high SNR level, its performance is even better since an approximate 5 dB gain is yield.

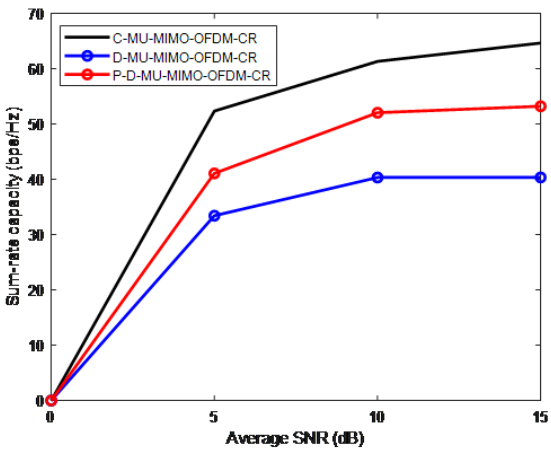

Fig. 1 Sum-rate capacities versus average SNR of C-MU-MIMO-OFDM-CR, D-MU-MIMO-OFDM-CR and P-D-MU-MIMO-OFDM-CR schemes

Next, the impingement of the frequency diversity (number of subcarriers) on the performance is investigated and Fig. 2 illustrates the results for C-MU-MIMO-OFDM-CR and P-D-MU-MIMO-OFDM-CR. As it can be seen, when the number of subcarriers is low, the performances of the two schemes are close. Increasing this number greatly enhances the corresponding performances; however, the gap between the two architectures is also accentuated. Obviously, this comes at the expense of increased hardware complexity and cost, which may become prohibitive for practical applications.

In Fig. 3, the behavior of sum-rate capacity in terms of number of users is studied when this number is varied between 4 and 8. It can be noted from Fig. 3, that despite the increase of multiple access interference (MAI), the sum-rate capacity is increased, because this interference is still within the threshold for co-existence with the PU. More interesting, the performance difference between the two allocation schemes is maintained with the MAI increase and is approximately 13 bps/Hz at an SNR of 15 dB.

Next, the sum-rate capacities of C-MU-MIMO-OFDM-CR and P-D-MU-MIMO-OFDM-CR are evaluated for different numbers of spatial sub-channels L. It is clear from the corresponding Fig. 4 that the spatial dimension is the most impacting parameter on the performances of the proposed systems, since opting for an 8×8 MIMO solution instead of 2×2 MIMO provides more than 200 bps/Hz gain in sum-rate capacity at an SNR of 15 dB. Moreover, increasing the spatial diversity induces a higher degree in performance enhancement for C-MU-MIMO-OFDM-CR than the P-D-MU-MIMO-OFDM-CR alternative. Finally, for both 2×2 and 4×4 solutions, starting from 5 dB in SNR, increasing the transmit power brings almost no gain in performance, and it is better to operate at 5 dB to target power efficiency. Regardless of

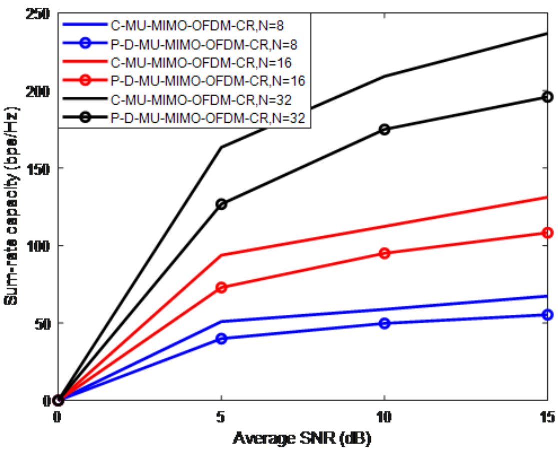

Fig. 2 Sum-rate capacities versus average SNR of C-MU-MIMO-OFDM-CR, and P-D-MU-MIMO-OFDM-CR for different numbers of subcarriers

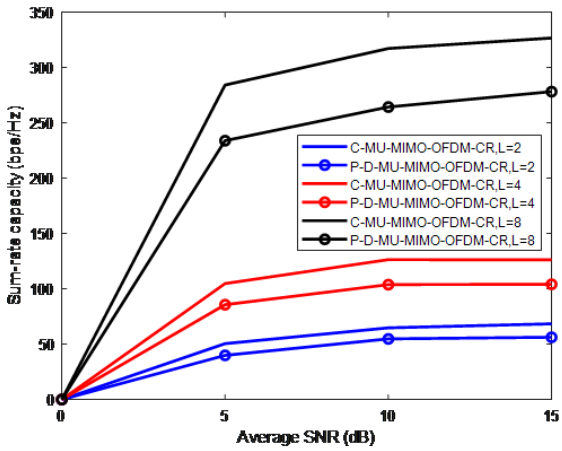

Fig. 4 Sum-rate capacities versus average SNR for C-MU-MIMO-OFDM-CR, and P-D-MU-MIMO-OFDM-CR for different numbers of spatial sub-channels

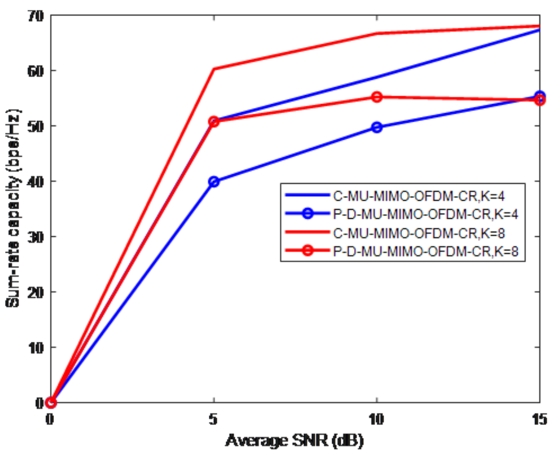

Fig. 3 Sum-rate capacities versus average SNR of C-MU-MIMO-OFDM-CR and P-D-MU-MIMO-OFDM-CR for different numbers of users

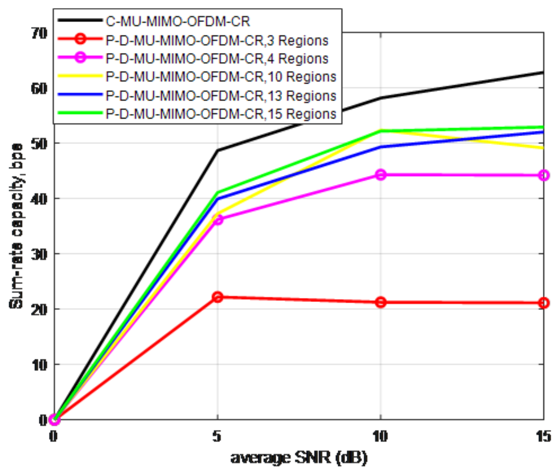

Fig. 5 Sum-rate capacity versus average SNR of P-D-MU-MIMO-OFDM-CR for different numbers of discrete rate levels

the spatial order, a constant performance gap is observed between the achievable sum-rate capacities of P-D-MU-MIMO-OFDM-CR and C-MU-MIMO-OFDM-CR architectures at high SNR.

Last study concerns the effect of the number of discrete rate levels on the performance of P-D-MU-MIMO-OFDM-CR solution and the corresponding curves are represented in Fig. 5. For this, the pertaining sum-rate capacities with 3, 4, 10, 13 and 15 regions are evaluated, by taking as a reference the C-MU-MIMO-OFDM-CR architecture. As it can be seen, migrating from 3 to 4 rate levels gives rise to a significant performance gain. By contrast, increasing further the cardinal of the discrete rates set provides a relatively low gain in the achievable sum-rate capacity. Consequently, fixing the number of discrete rate levels at 10, 13 and 15 results in a close performance and a reasonable distance from the theoretical P-D-MU-MIMO-OFDM-CR alternative.

5 Conclusion

In this study, three rate and power allocation schemes per each SU in a CR setting and merging the capabilities of the power waterfilling along with adaptive modulation in the spatial domain, and the stochastic approach in the frequency domain, are proposed. It is seen that the spatial order of the architectures is the predominant factor impinging the sum-rate capacity, and that quite a viable performance is achieved with the two discrete rate solutions, despite a superiority of the P-D-MU-MIMO-OFDM-CR which exploits more wisely the power excess to improve the available power budget, hence closing the gap with the theoretical continuous rate version.

References

[1] Telatar, E. "Capacity of Multi-antenna Gaussian Channels", European Transactions on Telecommunications, 10(6), pp. 585–595, 1999.
https://doi.org/10.1002/ett.4460100604

[2] Foschini, G. J., Gans, M. J. "On Limits of Wireless Communications in a Fading Environment When Using Multiple Antennas", Wireless Personal Communications, 6(3), pp. 311–335, 1998.
https://doi.org/10.1023/A:1008889222784

[3] Goldsmith, A. J., Chua, S.-G. "Variable-rate Variable-power MQAM for Fading Channels", IEEE Transactions on Communications, 45(10), pp. 1218–1230, 1997.
https://doi.org/10.1109/26.634685

[4] Ghanem, K., Hall, P. S. "Power and Bit Allocation in On-body Channels using MIMO antenna arrays", IEEE Transactions on Vehicular Technology, 62(1), pp. 404–408, 2013.
https://doi.org/10.1109/TVT.2012.2212009

[5] Zhou, Z., Vucetic, B., Dohler, M., Li, Y. "MIMO Systems with Adaptive Modulation", IEEE Transactions on Vehicular Technology, 54(5), pp. 1828–1842, 2005.
https://doi.org/10.1109/TVT.2005.853886

[6] Ghanem, K., Denidni, T. A., Ghanem, F. "Modified-rate-quantization Algorithm for Multiple-input Multiple-output Systems under Imperfect Channel Knowledge", Wireless Personal Communications, 43(4), pp. 1241–1255, 2007.
https://doi.org/10.1007/s11277-007-9298-8

[7] Cavers, J. "Variable-Rate Transmission for Rayleigh Fading Channels", IEEE Transactions on Communications, 20(1), pp. 15–22, 1972.
https://doi.org/10.1109/TCOM.1972.1091106

[8] Goldsmith, A. J., Chua, S.-G. "Adaptive Coded Modulation for Fading Channels", IEEE Transactions on Communications, 46(5), pp. 595–602, 1998.
https://doi.org/10.1109/26.668727

[9] Chung, S. T., Lozano, A., Huang, H. C. "Low complexity algorithm for rate and power quantization in extended V-BLAST", In: IEEE 54th Vehicle Technology Conference. VTC Fall 2001. Proceedings (Cat. No.01CH37211), Vol. 2, Atlantic City, NJ, USA, 2001, pp. 910–914. ISBN 0-7803-7005-8
https://doi.org/10.1109/VTC.2001.956905

[10] Goldsmith, A., Jafar, S. A., Maric, I., Srinivasa, S. "Breaking Spectrum Gridlock with Cognitive Radios: An Information Theoretic Perspective", Proceedings of the IEEE, 97(5), pp. 894–914, 2009.
https://doi.org/10.1109/JPROC.2009.2015717

[11] Shen, Z., Heath Jr, R. W., Andrews, J. G., Evans, B. L. "Space-Time Water-Filling for Composite MIMO Fading Channels", EURASIP Journal on Wireless Communications and Networking, 2006(1), 016281, 2006.
https://doi.org/10.1155/WCN/2006/16281

[12] Blum, R. S., Li, Y. G., Winters, J. H., Yan, Q. "Improved space-time coding for MIMO-OFDM wireless communications", IEEE Transactions on Communications, 49(11), pp. 1873–1878, 2001.
https://doi.org/10.1109/26.966049

[13] Amouri, B., Ghanem, K., Kaddeche, M. "Hybrid relay selection-based scheme for UWB BANs combining MB-OFDM and decode-and-forward cooperative architectures", Electronics Letters, 52(24), pp. 2017–2019, 2016.
https://doi.org/10.1049/el.2016.3318

[14] Labdaoui, R., Ghanem, K., Ettoumi, F. Y., Belaoura, W. "Sum-rate maximization for cognitive radios in multi-user MIMO-OFDM context", In: 2018 International Conference on Electrical Sciences and Technologies in Maghreb (CISTEM), Algiers, Algeria, 2018, pp. 1–5. ISBN 978-1-5386-4989-3
https://doi.org/10.1109/CISTEM.2018.8613482

[15] Ghanem, K., Denidni, T. A. "New variable-rate variable-power adaptive modulation scheme for time-varying MIMO channels", In: 2005 IEEE Antennas and Propagation Society International Symposium, vol. 2A, Washington, DC, USA, 2005, pp. 325–328. ISBN 0-7803-8883-6
https://doi.org/10.1109/APS.2005.1551806

[16] Ribeiro, A. "Ergodic Stochastic Optimization Algorithms for Wireless Communication and Networking", IEEE Transactions on Signal Processing, 58(12), pp. 6369–6386, 2010.
https://doi.org/10.1109/TSP.2010.2057247

[17] Wang, X., Giannakis, G. B., Marques, A. G. "A Unified Approach to QoS-Guaranteed Scheduling for Channel-Adaptive Wireless Networks", Proceedings of the IEEE, 95(12), pp. 2410–2431, 2007.
https://doi.org/10.1109/JPROC.2007.907120

[18] Marques, A. G., Lopez-Ramos, L. M., Giannakis, G. B., Ramos, J. "Resource allocation for interweave and underlay CRs under probability-of-interference constraints", IEEE Journal on Selected Areas in Communications, 30(10), pp. 1922–1933, 2012.
https://doi.org/10.1109/JSAC.2012.121108