COGNITIVE SUPPRESSION OF MULTIPATH INTERFERENCE IN ANGULAR DOMAIN

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ABSTRACT

This paper deals with a cognitive approach used to reduce the interference generated by/toward another system operating on the same frequency band. A typical scenario is represented by an Underlay Cognitive Networks where a secondary system makes use of the same frequency band of the primary system but should transmit without affecting the primary system reception. However, this situation can arise also when an intentional jammer tries to destroy the primary system communications.

In this paper the interference is detected by using a spatial sensing approach instead of the classical spectrum sensing: multiple-antenna technology is considered to exploit the angle dimension as a new spectrum opportunity. In particular Multiple Signal Classification (MuSiC) algorithm is used to detect the Direction of Arrival (DoA) of the interference source. We assume actual propagation environments, with multipath components characterized by large angle spread, and actual antenna size with a limited number of elements. This leads to scenarios in which the number of resolvable directions is higher than the number of antennas that typically limits the DoA estimation capabilities.

DoA information is then used in transmission inserting nulls in the estimated directions thus protecting the useful information. The proposed scheme permits to increase the signal to interference ratio at the receiver side thus reducing the achieved error rate.

1. INTRODUCTION

The increasing development of wireless systems and the insufficient spectrum availability lead the need of an efficient frequency utilization. However, this can introduce interference issues that must be carefully addressed.

For example in next generation cellular systems inter-cell interference and interference arising from heterogeneous network deployment have become significant limiting factors [1], [2]. Similarly, in Cognitive Networks where the coexistence of two systems, primary and secondary, over the same frequency resources is allowed [3], the primary network communications should not be degraded by the secondary interference. Hence, secondary network should employ advanced communication techniques to exploit underutilized dimensions in the signal space. In particular, in Underlay Cognitive networks primary and secondary systems communicate simultaneously, but secondary system has cognitive capabilities in order to learn from the environment and adapt its transmission by means distribute power control algorithms and/or suitable resource allocation schemes [3] to not interfere with the primary system.

Interference issues concern also with intentional jammers that are used to destroy specific communications.

In all the cases specific countermeasures must be adopted in transmission and/or in reception in order to reduce the effects of interferences and intentional disturbs and increase the communication robustness.

With recent advances in multi-antenna technologies, space and angle dimensions can be exploited to reduce the interference both in transmission or in reception.

An useful approach is represented by the use of beamforming. With Cognitive Beamforming (CB) the secondary system adapts its transmission/reception in order to maximize the secondary system performance while the interference on the primary system receiver is minimized [4], [5]. Similarly schemes can be adopted to reduce the inter-cell interference [6] or jamming [7]. However, beamforming requires complex numerical solutions and the knowledge of all propagation channels that can be impracticable in some actual systems.

Another opportunity is represented by the estimation of the Direction of Arrival (DoA): the interference can be mitigated by steering spatial nulls in the direction of the interference sources (in reception) or the primary system (in transmission) [8], [9].

This approach presents many challenges in wireless communication systems, in particular in the DoA estimation when actual propagation conditions are considered.

This paper proposes a cognitive system able to reduce the interference generated by a secondary network on the primary network. The secondary terminal (ST) is equipped with a multiple antenna system and is able to estimate the DoA of different signal replicas received from the primary terminal (PT) during suitable sensing intervals. Then the ST transmits using a null steering algorithm to reduce the interference generated toward the PT. This scheme could be easily applied also to different scenarios, where the null steering is applied in reception (i.e., inter-cell interference or jamming). The analysis considers actual propagation conditions. In particular different propagation paths with different DoAs varying during time are taken into account. Hence, the effects of not ideal conditions due to a number of signal higher than the number of antennas and due to DoA variations are considered. The paper is organized as follows: Sec. II and Sec. III present the working hypothesis and the proposed cognitive system, respectively. Numerical results are provided in Sec. IV and, finally in Sec. V some conclusions are shown.

2. WORKING HYPOTHESIS

The intensive use of the spectrum leads to the coexistence of several wireless communication systems sharing the same radio resources. This is the case of Cognitive Networks where a secondary system operates on frequencies already assigned to a primary system adopting cognitive capabilities to listen the surrounding environment. In particular, in the *Interwave Cognitive* Networks the secondary system looks for resource availability, not used by the primary, in the time or frequency domain. While in *Underlay Cognitive* Networks the secondary system transmits simultaneously with the primary, but without affecting its communications. Hence, the secondary system must adapt its transmissions in order to generate a negligible interference toward the primary. This is the operating scenario considered in the paper. However it is important to underline that the approach here proposed could be used also at the receiving end by the interference victim.

In particular, in this paper we introduce the spatial domain as a new transmission opportunity.

The secondary system detects the presence of a primary system and its spatial information through a suitable sensing step. The sensing is periodically repeated taking into account the mobility of the terminals. We set the sensing period equal to 1 *ms*.

The ST is equipped with an antenna system consisting of omnidirectional elements, separated by $d = \lambda/2$, where λ is the wavelength. The number of antenna elements is a trade-off between performance and size of the device. Indeed, it is known in literature that increasing the number of antenna elements allows to improve the accuracy in the beams steering and in the detection of the directions of arrival.

The carrier frequency of the secondary system is a crucial key in the choice of the number of antenna elements. For a given spacing between the antenna elements and low operational frequencies, good performance can be achieved only with unfeasible dimensions of the device. For these reasons, we select actual conditions. The ST is equipped with an Uniform Linear Array (ULA) with $L = 4$ elements, and the operating frequency is equal to f_0=2GHz resulting in a linear dimension of the array of D=21cm.

The antenna elements are spatially correlated and therefore the received signal can be used to perform DoA estimation and digital beamforming. These techniques are of particular interest when the signal of the primary devices is received through a series of temporal replicas which must be characterized in the spatial domain. For actual mobile environments where devices are able to move, this modeling is necessary because different paths are originated from multiple scatterers and obstacles existing between primary and secondary and they can temporarily change their response. In general a specific spatial relationship between the arrival directions of the different replicas doesn't exist but this is highly dependent on the specific environment and thus the assumption that the paths are randomly distributed in $[0, 2\pi]$ is justified [10]. The number of resolvable paths is a function of the sampling frequency of the receiving system and the channel model taken into consideration. In particular, the impulse response of the channel is modeled according to the tapped-delay-line described in M.1225 ITU-R Recommendation [11].

The "A-Channel" model is characterized by M multiple propagation paths and $\mathbf{h}$ contains the channel coefficients

$$\mathbf{h} = [\alpha_1 e^{j\varphi_1}, \alpha_2 e^{j\varphi_2}, \dots, \alpha_M e^{j\varphi_M}]^T$$

where α_i and φ_i are modeled as independent random variables following Rayleigh and uniform. The i-th replica on the antennas forms the angle θ_i with the array perpendicular. The temporal delay of the i-th signal between the consecutive elements of antenna system is

$$\tau = \frac{d \sin(\theta_i)}{c} = \frac{\sin(\theta_i)}{2 f_0}$$

where f is the carrier frequency and c is the speed of light. Considering a narrowband signal, $\tau \gg T_S$, where T_S is the sampling period, the arriving signal phase is rotated by $2\pi f_0 \tau$. Hence, the paths are independent of each other and the n-th sample of the multiplex received on the l-th antenna is

$$r_l[n] = \sum_{i=1}^{M} x[n - t_i] \alpha_i e^{j[\phi_i + (l-1)\pi \sin(\theta_i)]} + v_l[n]$$

where t_i is the delay due to scattered propagation of the i-th replica, $x[n]$ is n-th sample of the signal transmitted by the primary system and $v_l \sim \mathcal{N}(0, \sigma_v^2)$ is the AWGN noise which is independent among the antennas. Denoting $\mathbf{s}(\theta)$ as the steering vector, where $s_l(\theta) = e^{j\pi(l-1)\sin(\theta)}$ and $l = 1, 2, \dots, L$ then it can steer the antenna pattern on the direction θ. The matrix containing the steering vectors of the incoming signals is $\mathbf{S} = [\mathbf{s}(\theta_1), \mathbf{s}(\theta_2), \dots, \mathbf{s}(\theta_M)]$ and the arriving signals model can be represent in matrix form by

$$\mathbf{r} = \mathbf{S} \cdot \mathrm{diag}(\mathbf{h}) \cdot \mathbf{x} + \mathbf{v}$$

as $\mathbf{x} = [x[n - t_i]]^T$ and $\mathrm{diag}(\cdot)$ denotes the diagonal matrix. The number of replicas arriving to the receiver varies as a function of the sampling frequency of the secondary system, as shown in the Table 1

$f_S(MHz)$	2	4	7.5	15	30	40
Model paths	1	2	3	4	6	6

Table 1: working sampling frequencies and related numbers of paths

In our performance analysis, the outdoor model was selected that is suitable for many scenarios. Finally, the temporally related channel samples of $\mathbf{h}$ are filtered to obtain a relationship between the different directions of the arrival of the signal. First a set of K angles of arrival is generated through a random distribution in the $[0, \pi]$ interval and then it is interpolated by a k factor related to the devices speed [12]. In particular k can be derived as

$$k = \frac{f_S}{f_{Ch}}$$

where f_{Ch} can be calculated as a function of the wavelength, the speed of primary device and a suitable parameter A:

$$f_{Ch} = \frac{1}{T_C} = \frac{\lambda A}{v}$$

In this manner some representative values of k have been set, as shown in Table 2

	k	v [km/h]
No mobility	Inf	0
Low mobility	1500	5
Medium mobility	300	15
High mobility	150	25

Table 2: channel speed parameters

3. PROPOSED COGNITIVE SYSTEM

In the described context the secondary system must coexist with the primary system operating on the same area. The most critical scenario occurs when the two systems use the same carrier frequency and bandwidth. For this reason, this condition has been considered as a worst case scenario and it has been used to obtain numerical results. The purpose of the proposed system is to identify a technique that enables the secondary system to share resources without causing interference and other degradations in the performance of the devices already deployed. Initially, the secondary system must determine if the primary system is present or not in its coverage area through a sensing stage. The knowledge of the noise power in the absence of signal allows it to detect the presence of a primary system. If it is identified it is necessary to estimate the direction of arrival of the different signal replicas received from different propagation paths. This is done by using the antenna array with which the secondary system is equipped. The ST must periodically repeat this step to update the tracking relating to the mobility of detected devices. When the directions of arrival have been identified it is possible to provide this information to the Null Steering algorithm which will include some nulls in suitable positions of the radiation pattern.

3.1. DOA Estimation

In literature are proposed many algorithms to identify the direction of arrival of the incident signal on the antennas [13], [14]. The algorithms based on the autocorrelation matrix decomposition in its eigenvectors provide an efficient compromise between accuracy and resolution of performance and reduced computational complexity [15]. The autocorrelation matrix of the received signal is defined as

$$\begin{aligned}\mathbf{R_r} = E[\mathbf{r}\mathbf{r}^H] &= E[\mathbf{S}\,\mathrm{diag}(\mathbf{h})\mathbf{x}\mathbf{x}^H\,\mathrm{diag}(\mathbf{h})^H\,\mathbf{S}^H] \\ &= \mathbf{SPS}^H + \sigma_v^2\mathbf{Id}_L\end{aligned}$$

where $(\cdot)^H$ represents hermitian operator, $\mathbf{Id}_L$ is the identity matrix with dimension $L \times L$ and $\mathbf{P}$ is defined as

$$\mathbf{P} = E[\mathrm{diag}(\mathbf{h})\mathbf{x}\mathbf{x}^H\mathrm{diag}(\mathbf{h})^H]$$

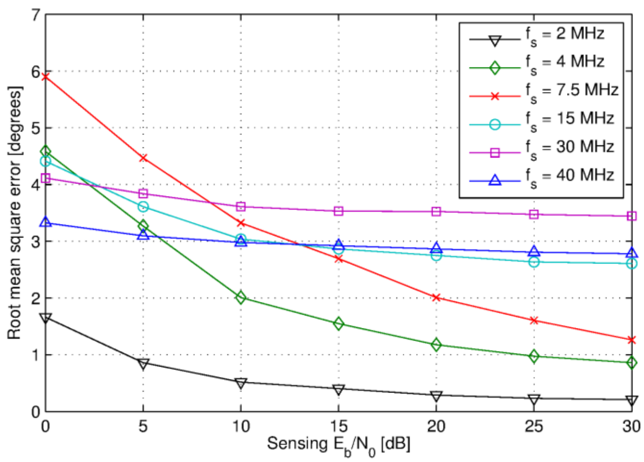

Figure 1: DOA estimation error for different sampling frequencies.

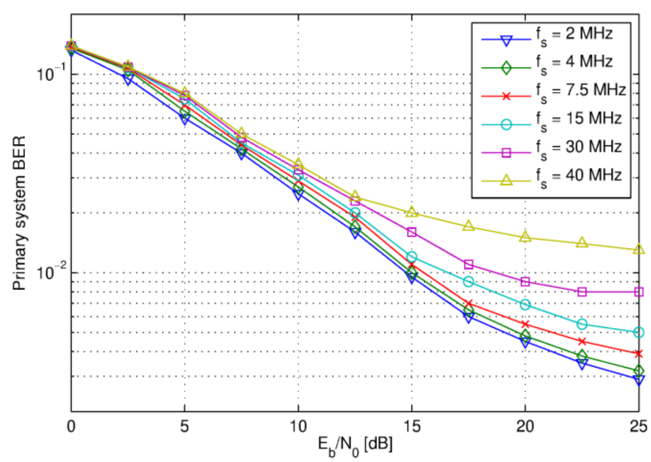

Figure 2:Primary system BER for different sampling frequencies.

The $\mathbf{R_r}$ decomposition in eigenvectors identifies two disjointed eigenspaces: the first is composed of the eigenvectors of the signal and is named *signal subspace* $\mathbf{U}_S$ and the latter is named *noise subspace* $\mathbf{U}_N$ and it is made up of the remaining eigenvectors. The eigenvectors are sorted according to the value of its eigenvalue and the M largest eigenvalues are associated with the M signal replicas. Therefore the two eigenspaces have dimension $L \times M$ and $L \times (L - M)$ and all possible steering vectors belong to one of the two subspaces, in particular the steering vectors related to signal DOAs belong to the signal subspace. Among all the steering vectors the MuSiC algorithm looks for ones that are orthogonal to the noise subspace, maximizing the function

$$P_{SM}(\theta) = \frac{1}{\|\mathbf{s}^H(\theta)\mathbf{U}_N\|}$$

where $\|\cdot\|$ is the norm of the vector. The function $P_{SM}(\theta)$ has a very wide codomain and the identification of the maxima can be hard. The introduction of a logarithm that compresses the shape and two derivatives which underline the curve concavities allow to achieve better performance resulting in a DOA estimation which is much more concentrated around the correct value. Hence we have

$$P'_{SM}(\theta) = \frac{d^2(\log_{10}P_{SM}(\theta))}{d\theta^2}$$

The identification of the maxima is based on the detection of local maxima greater than an suitable threshold. The MuSiC algorithm provides performance that depends on the noise overlapping on the signal and on the snapshot dimension. The snapshot represents the amount of signal samples received through which the autocorrelation matrix is estimated. Another key contribution is the number of antenna elements in the array: the maximum number of paths that are identifiable by Spectral MuSiC and by other algorithms of the same family is $L - 1$ because otherwise the decomposition in two disjointed subspaces is unfeasible. It is therefore evident that a greater number of antennas allows to identify a high number of DOA angles but it also increases the overall receiver dimensions and the computational complexity of the estimation. In an actual environment it can't be taken for granted, except in particular scenarios, that the several replicas come from neighboring directions and therefore they may be considered as separate signals. The Spectral MuSiC takes into account that the number of paths to be searched is $K = L - 1$. All angles of arrival can be detected as long as the number of paths M is smaller than $L - 1$, whereas the estimates of DOAs are limited to K when $M > L - 1$.

3.2. Null Steering

The information obtained by the algorithm of DOA estimation is used as input for subsequent cognitive phase. The secondary system needs to adjust its radiation pattern by placing some nulls to avoid interference in the directions just detected. This change is achieved by means of a pre-processing of the signal, in particular the symbols to be transmitted are multiplied by a weight vector $\mathbf{w}$ with dimension $L \times 1$.

The Null Steering algorithm is based on the same mathematical construct used by the classical beamformer. The weights are complex numbers that modify the amplitude and the phase of the output signal transmitted from each antenna. This allows algorithm to adjust the value of the radiated power in a certain direction and then it generates a set of K nulls. The power radiated after the pre-processing doesn't vary and therefore the secondary system maintains coverage performance similar to the previous case. This algorithm inherits the main limitation from the MuSiC and then it isn't able to generate more than $L - 1$ nulls [16]. In this scenario, we used the algorithm described in [13], that is

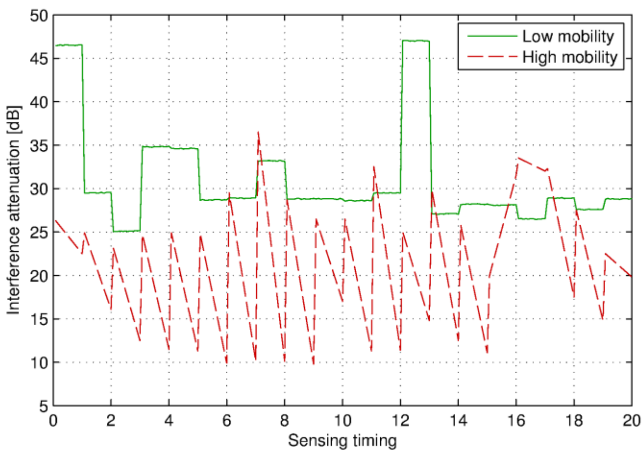

Figure 3: Interference attenuation on the primary user directions.

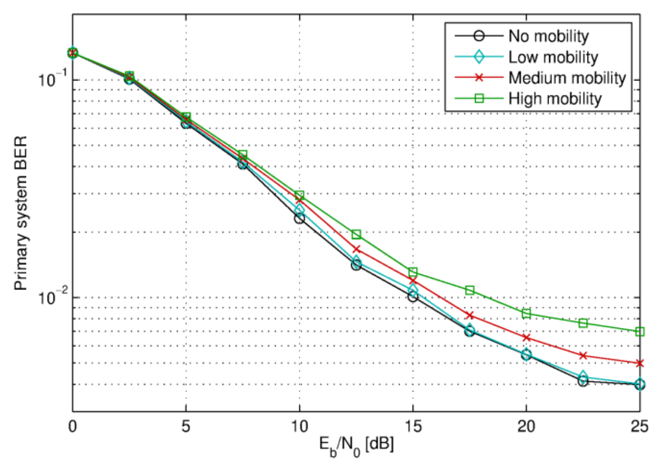

Figure 4: Primary system BER for different channel speeds.

$$\mathbf{w}^H = \mathbf{c}^H \mathbf{A}^H (\mathbf{A}\mathbf{A}^H)^{-1}$$

The weights $\mathbf{w}$ are obtained by imposing the steering vector $\mathbf{s}(\theta_0)$ equal to 1 and the steering vectors where null beams are required, $\mathbf{s}(\theta_1), \dots, \mathbf{s}(\theta_K)$, equal to 0. Let us denote the matrix containing the steering vectors of interest as $\mathbf{A} = [\mathbf{s}(\theta_0), \mathbf{s}(\theta_1), \mathbf{s}(\theta_2), \dots, \mathbf{s}(\theta_K)]$ and the vector $\mathbf{c} = [1, 0, \dots, 0]^T$ which contains $K+1$ elements. The system can perform some nulls depending on the number of paths estimated by DOA algorithm.

The obtained pattern is very effective because nulls are very deep. Its shape is similar to a notch filter which excludes the transmission in the θ_i directions and the values of interference mitigation are about same decades. The limit due to the number of feasible nulls can be overcome by increasing the antenna elements which are installed on the secondary system, as explained in [13], [16] and [17]. This introduces the same problems addressed about the eigenstructure algorithms used for the DOA estimation. Anyway, when the number of paths is greater than $L-1$, the nulls can be placed in the direction of the strongest sources of interference.

4. NUMERICAL RESULTS

In order to evaluate the performance of the proposed scheme, we resorted to a numerical approach by computer simulations. The results are provided in this section.

The center frequency considered here was set to 2 GHz, while different sampling frequency have been taken into account. Indeed, as explained in the Sec. 2, different sampling frequencies may lead to a different numbers of paths, according to [11].

We start our analysis by investigating the DOA estimation accuracy. Figure 1 shows the root mean square error of the MuSiC algorithm as a function of the sensing E_b/N_0 for different sampling frequencies. It is possible to see that the higher is the number of paths, the worse is the performance. Moreover, if the number of resolvable path is greater than the number of antennas, the accuracy does not improve significantly when the E_b/N_0 grows. However, a higher sampling frequency allows to collect a larger number of samples during the sensing interval, hence, if the number of path is the same (as for 30 and 40 MHz), it leads to better performance.

Figure 2 presents the performance of the primary link (primary transmitter and primary receiver) in terms of bit error rate (BER) as a function of the E_b/N_0 at the primary receiver for different sampling frequencies. By a joint analysis of Figure 1 and Figure 2, it is evident that the performance degradation of the primary link is strictly dependent on the DOA estimations of the secondary receiver.

Relevant interest relies on the sensing and mitigation algorithm capability to adapt to channel variations. Hence, the estimation has to be performed on a periodical base.

Figure 3 presents an example of interference attenuation on the primary user directions introduced by the proposed scheme during the time. Two different channel speed have been considered: when the speed is slow (i.e., 5 km/h), the algorithm is able to follow the DOA variations, in fact the SIR maintains constant over the time until the next estimation. On the other hand, when the channel speed is higher (25 km/h) the estimation accuracy has a general deterioration and gets worse until the following sensing period. However, in both the cases the proposed scheme allows a remarkable improvement of the SIR, and hence the secondary transmission has a small impact on the performance of the primary receiver. This is evident from Figure 4, where the BER of the primary system is shown for different channel speeds. It is possible to see that the primary performance degradation is limited to the case of high E_b/N_0 values at the primary receiver, and is modest

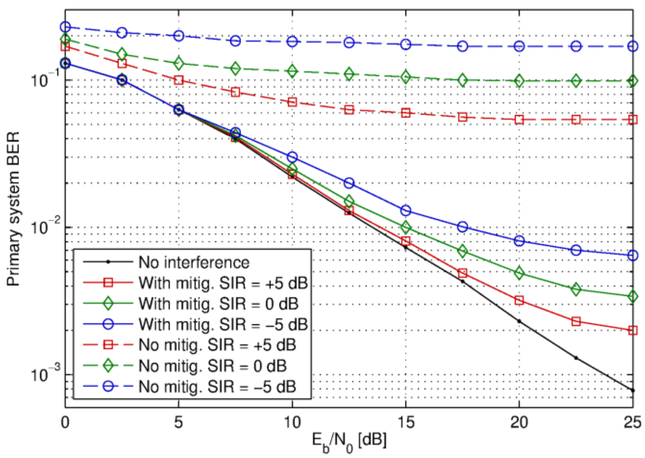

Figure 5: Primary system BER for different SIR.

even in that case. Finally, Figure 5 provides the comparison of the primary system performance with and without the proposed interference mitigation scheme for different value of mean signal-to-interference ratio (SIR, the power of the primary signal is assumed to be normalized). From this figure is evident the remarkable improvement due to the jointed use of MuSiC and null steering algorithm: without a suitable interference cancellation scheme, the performance quickly reaches a floor, and the BER does not decrease even if the E_b/N_0 grows. On the other hand the proposed scheme allows to approach the curve relative to the performance without interference.

5. CONCLUSIONS

This paper has dealt with a cognitive scheme used to reduce the interference generated toward another system. The interference detection is based on a spatial sensing approach: beamforming technology has been considered to exploit the angle dimension as a new spectrum opportunity. The paper has focused on the Multiple Signal Classification (MuSiC) algorithm, used to detect the Direction of Arrival (DOA) of the interference source, and on a null-steering technique to cancel interference. The analysis has considered an actual scenario: the propagation environment has been characterized by large angle spread multipath components, while actual antenna size with a limited number of elements has been considered at the receiver.
The proposed scheme has been evaluated by means of computer simulations, showing the capability to increase the signal to interference ratio at the receiver side, thus reducing the achieved error rate.

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