SIGNAL INTERCEPTION WITH MULTIPLE ANTENNAS FOR COGNITIVE RADIO

L. Bixio, G. Oliveri, M. Ottonello, M. Raffetto and C. S. Regazzoni
(Department of Biophysical and Electronic Engineering University of Genoa, Italy
{bixio, oliveri, marina, raffetto, carlo}@dibe.unige.it)

ABSTRACT

In the present contribution the problem of signal interception in a virtual MIMO scenario is considered. A possible distributed signal interception algorithm which is able to detect and discriminate between two similar OFDM signals is analyzed. Distributed and stand-alone algorithms are compared through simulations in a multipath environment and the different levels of cooperation required among the terminals are discussed.

1. INTRODUCTION

In the last few years, Cognitive Radio (CR) [1], [2], [3] has attracted the attention of a wide number of researchers due to its innovative approach to wireless terminal design and management [2], [3].

Recently, several fundamental applications in wireless communications have been effectively tackled by Cognitive Radio approaches [3]. Among the most important and classical ones, the "signal interception" problem [4] represents a complex challenge both in military and in civilian applications which has been already faced through the use of CR approaches [5].

In a broad sense, the signal interception problem can be considered as the problem of extracting valuable information from collected wireless signals which are corrupted by channel distortions and noise [4]. Such information can be useful in different scenarios.

On the one hand, signal interception techniques can be applied in passive applications for CR, for example, in a military context, in order to detect and decode protected wireless communications [4]. In such scenario, signal interception can be complicated by the fact that the used transmission techniques are designed in order to be confused with noise. As an example, the detection of spread spectrum transmission techniques can be a difficult task [4] since the power of such signals is often close to the noise threshold.

On the other hand, the recently introduced concepts of opportunistic communications and dynamic spectrum access [6] have enlarged the range of application of signal interception techniques, at present also used to solve problems such as the detection and prediction of "spectrum opportunities" [6]. As an example of a typical reference scenario for signal interception techniques applied in Cognitive Radio, it is possible to consider an Open Spectrum scenario in which the radio spectrum has to be dynamically shared among the users that exploit Orthogonal Frequency Division Multiplexing (OFDM) signals [7]. Such a technique, in fact, can guarantee an efficient spectral utilization since it allows a flexible and simple adaptation of the spectral occupancy of the transmitted signals. In such an Open Spectrum scenario, signal interception should be responsible for identifying the available resources and the standards used, in order to allow an efficient utilization of the shared spectrum. Such a task could be performed, in principle, by several different techniques which are available in the literature. As an example, cyclostationary approaches could be used in order to perform an effective detection of OFDM signals in low SNR environments.

Despite the available techniques, signal interception is a not trivial task if multipath channels are considered, since deep fading can happen in the band under investigation, and this can obviously affect the detection process of the CRs. Moreover, in these scenarios an active cooperation from the transmitter cannot be assumed, and therefore the signal interception task could even become impossible, at least in certain frequency bands. Such consideration is of particular importance also in opportunistic systems, since a "false" opportunity could be detected due to a sudden fading of the received signal caused by multipath.

However, it is well known that multipath fading can be mitigated if several receiving antennas are available, since in this case it is possible to exploit the "spatial diversity" of each antenna [8]. This is the case, for example, if several CR terminals coexist in the same scenario, or if a single multi-antenna system is considered.

In this context, different solutions could be proposed in order to combine the results of each receiving antenna, depending on the level of cooperation among them. On the one hand, if no explicit cooperation among receiving antennas is considered (and therefore independent terminals are assumed), distributed decisions have to be taken by each terminal by using implicit exchanges of information with the other ones. On the other hand, if a real (or virtual) MIMO receiving system is considered, a centralized decision can be taken on the basis of the complete knowledge of the RF signal perceived by each antenna. Of course, different intermediate degrees of cooperation can be considered, resulting in different performances and overhead.

In this paper, the application of multiple antennas in signal interception problems is considered. In particular, a cyclostationary spectral analysis technique is proposed in a virtual MIMO scenario to detect the presence of two similar OFDM signals in the same channel. In the considered application, the two OFDM signals belong to WiMAX [9] and WLAN IEEE 802.11a [10] standards and they are characterized by the same nominal bandwidth.

The aim of this work is to evaluate the performances of the proposed cooperative detection phase carried out by multiple terminals in a multipath environment. Such performances will be compared with that obtained in a stand-alone scenario, where a single antenna terminal exploiting an analogous cyclostationary spectral analysis technique is considered. The numerical simulations are carried out, in both cases, by considering a COST 273 channel model [11].

The paper is organized as follows. In Section II a brief overview of the signal interception approaches that could be applied in the considered multi-antenna scenario is provided, and the advantages and disadvantages of the proposed cyclostationary spectral analysis technique are discussed. Then, in Section III two different scenarios for the application of the proposed strategy are described. Finally, in Section IV, before concluding, simulation results are provided in order to evaluate the performances of the proposed virtual MIMO strategy.

2. SIGNAL INTERCEPTION TECHNIQUES

Interception of communications is performed in civilian and military applications for signal detection, automatic modulation classification, radio source localization, and communication jamming purposes [4].

Signal interception is a challenging task in both civilian and military applications, since, for example, spread spectrum techniques designed in order to obtain a low probability of interception are widely used. Moreover, such a task can be even more complex if similar signals are superimposed in the frequency band under investigation. As an example, in the Open Spectrum scenario described above, the presence of similar signals in the same frequency bands can result in an increased complexity for the signal interception task.

In order to achieve efficient signal interception in a wide range of applications, different algorithms, based on signal processing techniques, have been proposed in the last two decades [12].

The most commonly used approach is based on radiometry [4]. It is well known that this strategy is highly sensitive to unknown and varying noise level and it suffers when spread spectrum transmission techniques are used [4]: as a consequence, such technique will not be considered in the following.

Another approach to signal interception is the matched filter technique, which requires a priori knowledge of the transmitted signal and represents the optimal approach if a stationary Gaussian noise is considered [13]. Unfortunately, its performance degrades quickly with the accuracy of the prior knowledge of the transmitted signal (which should not be available in the considered scenario). Moreover, even if a partial knowledge is available, a detector needs a dedicated matched filter for every class of signal to be intercepted [13]. For these reasons, matched filtering is not a suitable solution for the signal interception problems of interest.

A more attractive approach to signal interception is based on feature detection techniques. In the considered context, a feature can be defined as a unique characteristic related to the signal of interest which is used to detect the signal itself [14]. Some of the most typical features considered for signal interception purposes are instantaneous amplitude, phase and frequency, moments and cumulants of the signal, for example [12].

One of the most successful among the different feature detection techniques is that based on the extraction of cyclic-features [14]. Modulated signals are usually coupled with sine wave carriers, hopping sequences, cyclic prefixes, spreading codes, or pulse trains, which result in built-in periodicities: these periodicities represent the cyclic features which can be detected by such techniques [13].

The extraction of cyclic features can lead to many advantages with respect to energy detector and matched filter techniques [4]. Cyclic-feature detector is well suited to signal interception thanks to its robustness in low SNR environments [4], and can therefore provide excellent performances with respect to radiometer in these conditions. Furthermore, this technique is more general than matched filter approaches, and it can be efficiently used in practical signal interception problems.

Due to the above considerations, in this paper we consider a cyclic-feature detector in the depicted Open Spectrum scenario, where similar OFDM signals are present in the frequency band of interest. In fact, as such signals are usually coupled with repeated preambles, cyclic prefixes, and pilot carriers, the resulting inherent periodicity can be easily used in order to extract features.

To this end, the Spectral Correlation Function (SCF), a recently proposed powerful analysis tool [14], is considered. In particular, a spectral correlation analysis is designed in order to distinguish between the two similar OFDM signals: WiMAX [9] and WLAN [10].

Let us provide some notation in order to describe the designed analysis tool. A signal $x(t)$ is second order cyclostationary in wide sense if its autocorrelation $R_x(t,\tau)$ is periodic in t for each lag parameter τ [14]:

$$R_x(t,\tau) = E\{x(t+\tau/2)x(t-\tau/2)\}.$$

Since $R_x(t,\tau)$ is a periodic function, it can be represented as a Fourier series whose coefficients are given by [14]:

$$R_x^{\alpha}(\tau) = \lim_{\Delta t\to\infty} \frac{1}{\Delta t} \int_{-\Delta t/2}^{\Delta t/2} x(t+\tau/2)x(t-\tau/2)e^{-j2\pi\alpha t}dt,$$

where Δt is the observation time, α is the discrete cyclic frequency, $j=\sqrt{-1}$ and $R_x^{\alpha}(\tau)$ represents the Cyclic Autocorrelation Function (CAF) [14]. It has to be noted that in practical situation the observation time Δt is finite and an estimation of the SCF has to be provided. In our application a time-smoothed cyclic periodogram estimator of the SCF has been used [14]. It is well known that, in order to examine the cyclostationarity of a given signal the SCF can be employed:

$$S_x^{\alpha}(f) = \lim_{\Delta f\to\infty} \lim_{\Delta t\to\infty} \frac{\Delta f}{\Delta t} \cdot \int_{-\Delta t/2}^{\Delta t/2} X_{1/\Delta f}(t, f+\alpha/2) X_{1/\Delta f}^{*}(t, f-\alpha/2)dt$$

where the complex envelope of the narrowband spectral component with centre frequency v and bandwidth Δf is given by:

$$X_{1/\Delta f}(t,v) = \int_{t-1/2\Delta f}^{t+1/2\Delta f} x(u)e^{-j2\pi uv}du.$$

Furthermore, for discrete cyclic frequency $\alpha = 0$ the CAF reduces to the conventional autocorrelation function and the SCF reduces to the conventional power spectral density function [14].

In the next section the application of such a technique to a virtual MIMO scenario will be considered.

3. CONSIDERED APPLICATIONS AND PROPOSED VIRTUAL MIMO ALGORITHM

In order to introduce the proposed virtual MIMO cyclostationary spectral analysis technique, two different applications are considered.

In the first case, a security scenario is considered in which a set of cognitive radio sensors exploiting a single antenna try to identify signals transmitted in an environment affected by shadowing (e. g. a room or a floor of a building). In such scenario, the cognitive radio sensors, exploiting spatial diversity (inherent to their displacement) have to perform a signal interception in order to identify illegal access to a restricted area. It is important to remark that such application could be integrated in video surveillance systems by using different kind of sensors (i. e. video cameras), to achieve a global security strategy.

In the second proposed scenario we consider the case of a personal computer equipped with a SDR wireless network card, provided with multiple antennas, which is able to process several wideband signals (e.g. WLAN and WiMAX signals). The personal computer is allowed to access all the channels in the band of interest. The task of the resulting SDR base station is to maximize the number of connected terminals by employing the available bandwidth in the most effective way. We remark that such a scenario can be considered a particular case of "Opportunistic Communications" which represent one of the most interesting concepts developed in the last years in the context of high-efficiency wireless communications [15], [16]. In an Opportunistic Communication scenario, *primary* (licensed) users are defined as those users who have the right to use a certain radio resource; on the contrary, *secondary* (unlicensed) users are those users who are allowed to transmit only if they can avoid interference to primary users: in this sense, they exploit the radio "opportunities" which occur because of the low utilization of the spectrum by primary users. In order to reach this goal, secondary systems, in practice, have to transmit in orthogonal way with respect to primary terminals [16]. As it can be seen from such description, the problem of Opportunistic Communications can be formulated as a particular signal interception problem, where in this case the characteristics to be detected are represented by the "opportunities". In the case of interest, the opportunistic paradigm can be applied by defining an opportunity as a connection-ready terminal (i.e. a terminal that supports one of the considered communication standards and is searching to communicate) in the domain of interest (with its associated communication mode and position). It is worth noting that such application could be also of interest for emergency situation scenarios, as an example in order to provide wireless connection through mobile SDR stations in the case of failures of the basic wireless networks due to natural disasters.

From the above discussion, it is possible to deduce that the fundamental task in both the considered applications is represented by the capability to detect the presence of radio terminals in the domain of interest by listening to the radio spectrum. As it is clear, such operation could be also performed by using a stand-alone single antenna terminal. However, by using multiple antennas, the following advantages can be obtained:

1. in the detection phase, the problems due to multipath fading can be significantly reduced
2. the overall capacity of the system is increased
3. in the opportunistic case, a connection with spatially uncorrelated terminals can exploit the same channel (SDMA)

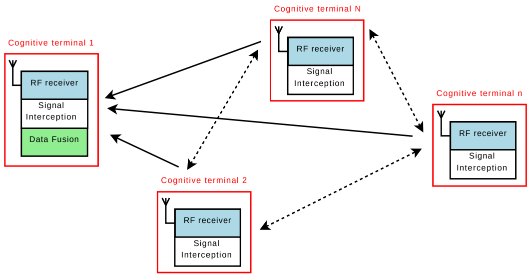

Figure 1: Virtual MIMO scenario

Let us concentrate on the first of these advantages, which is that regarding the detection phase. As it can be seen, the detection of the presence or absence of a terminal can be performed by a using the antenna set in a centralized or distributed way.

To this end, different methods are available in the literature [17] in accordance with the amount of exchanged information between cognitive radio terminals [17] (or on the basis of the computational capabilities of such terminals). In the former approach, a cognitive entity collects sensing information sent by others terminals, processes collected data, and performs an overall decision. In this case the data fusion is concentrated in one part of the set of sensors. In the latter approach each cognitive entity performs its own decision and exploits the presence of the other terminals to improve its performances.

In the present paper, a virtual MIMO strategy is considered in which the terminals are coordinated and exchange synthetic information obtained from cyclostationary analysis of the incoming signals, as shown in Figure 1. In particular, the following approach, whose block diagram is reported in Figure 2, can be applied:

- the signal coming from each antenna is sampled at a sufficient frequency, and a resulting signal vector is obtained for each terminal;
- the signal vector is processed by each terminal independently, and a SCF estimation [14] is obtained for each terminal;
- the estimated SCF are gathered in a coordinating terminal, and an overall SCF estimation is obtained for the domain under investigation;
- the overall estimated SCF is processed to detect the presence of cyclic features revealing the presence of terminals.

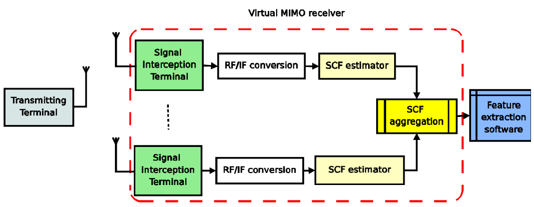

Figure 2: Block diagram of the virtual MIMO receiver

Simulation results of the considered approach are provided in the following Section.

4. NUMERICAL RESULTS

In the following, one RF channel is analyzed at a time. As a consequence, all the signals are treated through their equivalent baseband representation.

In order to evaluate the performances of the proposed virtual MIMO approach and to compare it with the stand-alone case, two C++ simulators have been developed which are responsible for simulating the RF transmission, channel propagation, reception and signal analysis. The objective of the signal analysis tool is to detect the presence of a RF source in a given environment, and to distinguish similar OFDM sources on the basis of the different pattern of their pilot carriers. In the considered simulations the two possible OFDM signals are represented by WLAN [10] and WiMAX signals [9].

Generally speaking, the time-smoothed cyclic periodogram estimator of the SCF [14] should be tailored on the parameters of the transmitted signal to provide reliable results. Therefore, in principle, a terminal (each terminal in the virtual MIMO case) should be provided, in the considered scenario, with two SCF estimators, i.e. one for the WLAN and one for the WiMAX signal. However, to minimize the computational complexity of the considered system and reduce the hardware costs, we make the following hypotheses:

- each terminal is provided with a single SCF estimator.
- the parameters of the SCF estimator (FFT size, sampling frequency, etc.) are chosen so that the WLAN signal can be easily detected by features extracted from the projection of the estimated SCF. In the proposed work, a FFT size of 160 samples and a sampling frequency of 40 MHz are chosen. By using these parameters the estimated SCF for an observation time of 10 ms and E_b / N_0=-5 dB for a WLAN signal is reported in Figure 3.
- the features that can allow the detection of WiMAX signals are deduced from the simulations, again taking the projection of the estimated SCF.
- the considered features are represented by:

$$F_\Omega = \frac{\sum_{\alpha \in \Omega} \max_k |S_x^\alpha(k)|}{\sum_{\alpha \notin \Omega} \max_k |S_x^\alpha(k)|},$$

where $S_x^\alpha(k)$ represents the SCF estimator and Ω is the set of α which characterize the cyclic repetition of the considered signals, as it can be easily seen from Figure 4, which represents the projection of the estimated SCF for the signals of interest. In particular, for the WLAN signal the set of α is $\Omega_{wlan} = \{17, 18, 35, 52\}$ and for WiMAX it is $\Omega_{wimax} = \{1\}$.

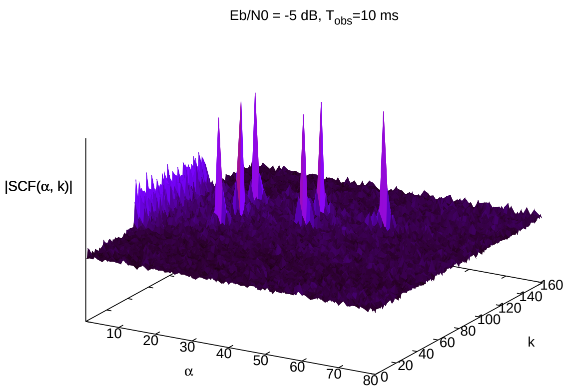

Figure 3: Estimated SCF for a WLAN signal with an observation time of 10 ms and $E_b / N_0 = -5$ dB

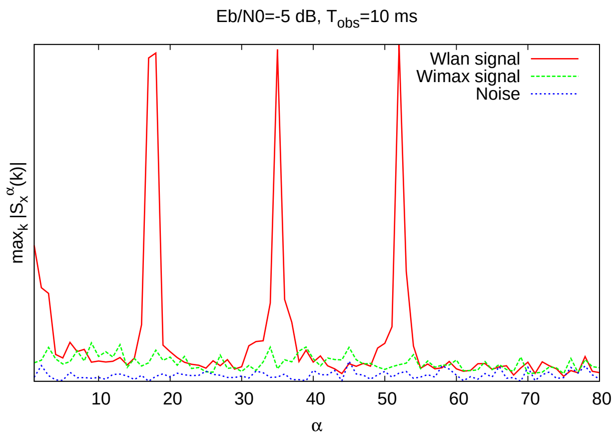

Figure 4: Projection of the estimated SCF for the considered signals with an observation time of 10 ms and $E_b / N_0 = -5$ dB

To evaluate the capability of the designed SCF estimator to highlight features that can allow the detection of the considered OFDM signals in a realistic environment, and to evaluate the enhancement of the performances allowed by the proposed virtual MIMO scheme, a set of simulations have been performed by considering a COST207 Bad Urban channel model [11]. In the numerical simulations a maximum Doppler frequency of 100 Hz has always been utilized, and several values of the energy per bit to noise power spectral density ratio E_b / N_0 have been considered.

In Figure 5, Figure 6 and Figure 7 the features obtained for E_b / N_0=-5 dB for an observation time of 2 ms are reported for the cases of stand-alone receiver, and of virtual MIMO receivers (4 and 15 receivers considered). As it can be seen, the performances of the virtual MIMO scheme are higher than the stand-alone situation, for an equal time of observation of the signal. Moreover, the capabilities of the considered features to allow an easy identification of the desired signals improve with the number of involved terminals, as expected. It can be also of interest, however, to evaluate the performances of the considered virtual MIMO scheme with respect to a stand alone receiver which is allowed to listen to the channel for a longer time. To this end, in Figure 8 the features obtained again for E_b / N_0=-5dB but for an observation time of 15 ms is reported for the case of stand-alone receiver.

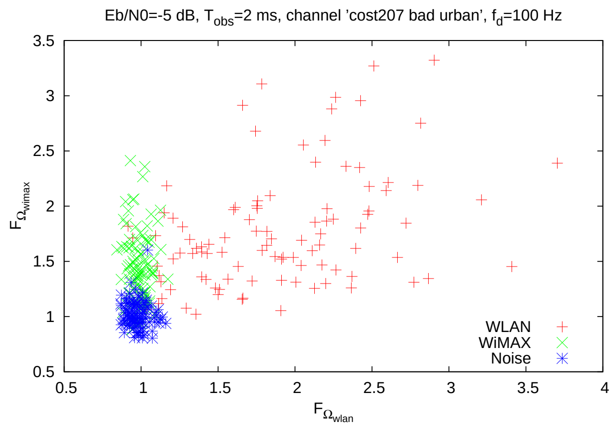

Figure 5: Features plane for the classes of interest for a stand-alone terminal with an observation time of 2 ms

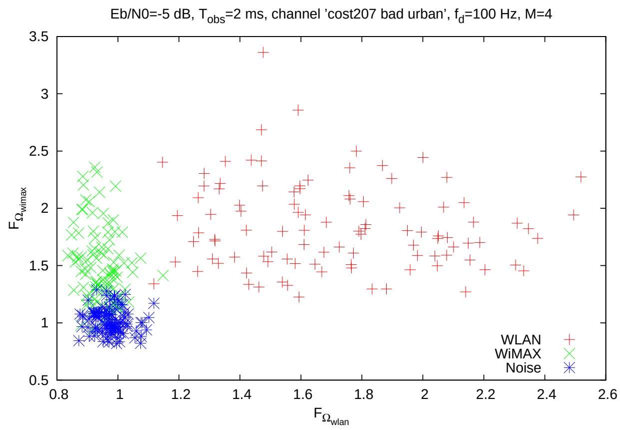

Figure 6: Features plane for the classes of interest for a virtual MIMO receiver with M=4 with an observation time of 2 ms

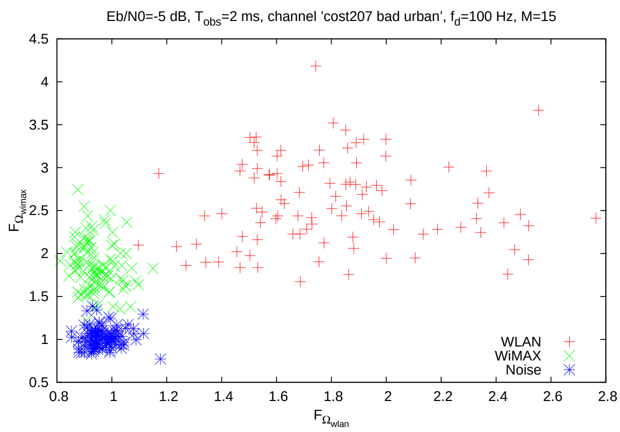

Figure 7: Features plane for the classes of interest for a virtual MIMO receiver with M=15 with an observation time of 2 ms

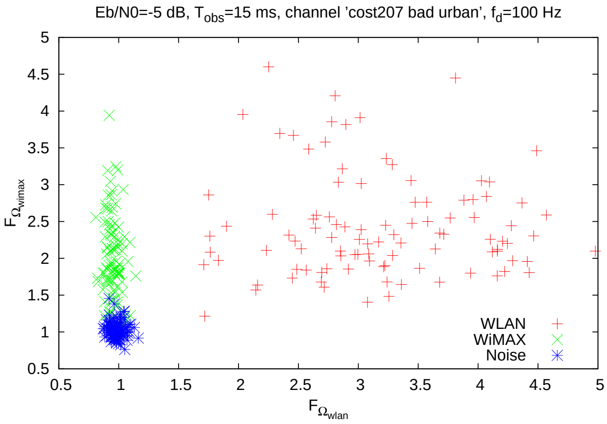

Figure 8: Features plane for the classes of interest for a stand-alone terminal with an observation time of 15 ms

As it can be seen by comparison with the previous figures, the performance of a stand-alone receiver can approach that of the considered virtual MIMO receiver, but at the cost of an increased listening time. Such a consideration can be of fundamental importance in practice: in fact, especially in military scenarios, the duration of the transmission of a terminal on a given band is often very short. Therefore, the capability of the proposed virtual MIMO scheme to reduce the listening time (while allowing a high probability of detection) can be of interest in those scenarios where short transmissions are expected.

5. CONCLUSIONS

In this paper the problem of detecting different but similar OFDM signals is solved by using a virtual MIMO approach that exploits cyclostationary feature analysis. Different possible application scenarios are discussed, and numerical results of the proposed virtual MIMO scheme are reported and compared with those that could be obtained in a stand-alone configuration.

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