Directional Cyclostationary Feature Detectors using 2-D IIR RF Spiral-Antenna Beam Digital Filters

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***Abstract*—Cognitive radio relies on accurate spectrum sensing for increasing the spectral efficiency of wireless networks. A novel array processing scheme is proposed based on a uniform linear array (ULA) of circularly-polarized spiral antennas having frequency range 2-6 GHz, which is used in conjunction with digital beam filters having 2-D IIR transfer functions for accurately and efficiently placing radio sources in wireless environment. Algorithms such as cyclostationary feature extraction is employed at beamformer to measure energy and realize feature/modulation detection, which in turn allows classification of a wireless environment. Simulation examples are provided for demonstrating the low-complexity directional feature detector with applications towards enhancing access to radio spectrum. Examples showing classification of sources by direction, frequency channels and modulation type in the 2-4 GHz band at SNR=6 dB are given.**

I. Introduction

Due to explosive growth in wireless communications, the electromagnetic spectrum has become increasingly congested [1]. Cognitive radio (CR) solutions for increasing spectral utilization requires "spectrum sensing". Conventional sense algorithms are based on techniques such as cyclostationary feature detection, energy detection, waveform sensing, and matched filtering [2]. However, these algorithms are generally non-directional and therefore *do not* provide information about the direction of primary and secondary users (PU/SUs) [2]–[4].

Beamforming allows the selective enhancement of radio frequency (RF) planar waves based on their direction of arrival (DOA), leading to increased flexibility at medium-access (MAC) and network layers. However, beamforming methods such as digital phased-arrays are computationally expensive and are typically narrowband in nature. We address this problem by proposing low complexity spatio-temporal aperture algorithms based on multi-dimensional (MD) digital recursive filters [5]. The ultimate objective of this work is to sense the primary and secondary users' DOAs, locations, carrier frequencies, modulation/features (waveforms), polarizations, and eventually other physical parameters such as higher order (non-planar) propagation modes.

II. Overview of Proposed System

We propose a combined approach using low complexity array processing based on two-dimensional (2-D) infinite impulse response (IIR) digital beam filters with cyclostationary feature extraction for sensing the DOA, frequency and modulation of radio sources in a CR environment. Towards this goal, we also propose an unobtrusive low-cost wideband Archimedean spiral antenna for uniform linear arrays (ULAs). Let S_i denote a radio source within the CR environment, where $i = 1, 2, \ldots$. The proposed directional feature extraction scheme can potentially be employed at the physical layer of a sensing station. The directional feature detection output for source S_i is denoted by $S_i\left[d, f, m\right]$, where d is the DOA, f is the RF carrier frequency and m is the modulation scheme.

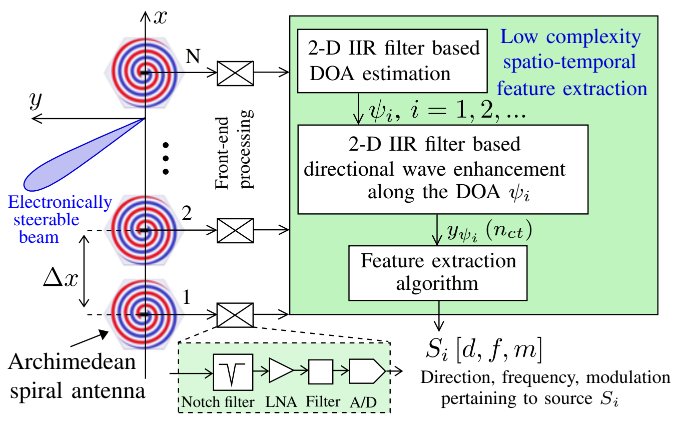

Fig. 1: Overview of the proposed 2-D IIR digital beam filter based directional feature extraction system employing a ULA of Archimedean spiral antennas.

Fig. 1 shows an overview of the proposed directional feature extraction system. A ULA of N Archimedean spiral antennas are employed to spatially sample the propagating radio waves. The inter-antenna spacing is $\Delta x = \lambda_{min}/2 = c/2F_{max}$, where λ_{min}, c and F_{max} are the shortest wave length, propagation speed and the maximum frequency of the RF signal of interest. Output of each antenna is connected to a front-end RF processing block, which typically contains a tunable notch filter to attenuate known out-of-band interference, a low noise amplifier (LNA), a low pass filter and an analog to digital converter (A/D). This results in a 2-D discrete domain spatio-temporal input sequence $w\left(n_x, n_{ct}\right)$, where $n_x = 0, 1, \ldots N-1$ is the antenna index and $n_{ct} = 0, 1, \ldots$ is the temporal sample index. The signal $w\left(n_x, n_{ct}\right)$ is processed by the proposed system to extract features pertaining to a given source S_i such as the direction, frequency and modulation scheme.

III. Center-Fed Archimedean Spiral Antenna

Spiral antennas are frequency independent with radiation mechanism occurring at regions where the circumference of

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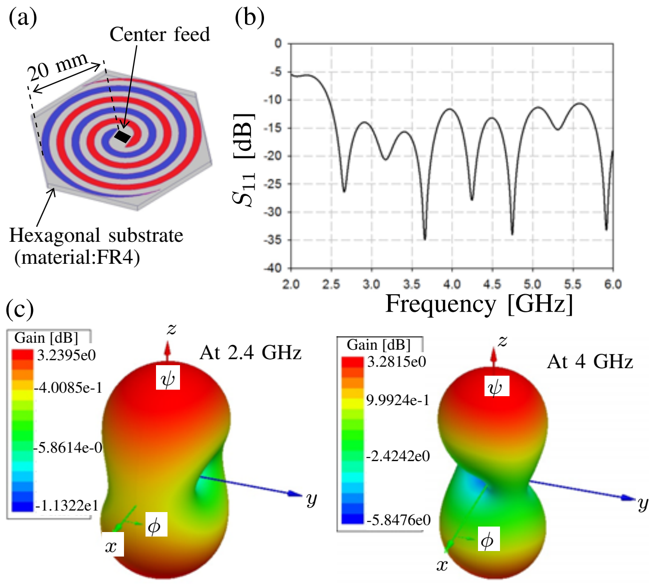

Fig. 2: (a) Structure, (b) scattering parameter S_{11} and (c) far-field radiation pattern of the proposed Archimedean spiral antenna. Full-wave simulations are from Ansoft HFSS computational electromagnetic software.

the spiral equals an integer multiple of a wavelength [6]. Thus, for a circular spiral, the radiation bands occur when the antenna diameter $D = n\lambda/\pi$. The lowest operating frequency of the antenna is determined by the spiral outer circumference while, the highest operating frequency can be varied by adjusting the number of turns [7].

We propose the use of a spiral antenna in Fig. 2(a), which consists of 2.7 turns and an expansion coefficient of 1.1. This antenna was simulated using Ansoft HFSS computational electromagnetic tool for FR4 substrate with a dielectric constant of 4.4, a dielectric loss tangent of 0.02, and a thickness of 1.6 mm. The antenna has a center-feed that was simulated as a lumped port with a 50 Ω impedance. The diameter is 40 mm. Fig. 2(b) shows the full-wave simulated reflection coefficient (S_{11}). The frequency performance demonstrates a broad impedance bandwidth from 2.4 GHz to 6 GHz. Fig. 2(c) shows the 3-D far-field radiation pattern simulated at 2.4 GHz and 4 GHz, respectively. The patterns are nearly symmetrical in the azimuthal plane as required.

IV. 2-D IIR Directional Wave Enhancement

A. 2-D IIR Digital Beam Filters

Two dimensional IIR digital beam filters have been proposed for the directional wave enhancement using ULA of antennas [5]. Such filters have beam shaped passbands in the 2-D spatio-temporal frequency domain $\boldsymbol{\omega} \equiv (\omega_x, \omega_{ct}) \in \mathbb{R}^2$, where ω_k is the frequency variable corresponding to $k \in \{n_x, n_{ct}\}$ [8]. For the first order case, 2-D IIR digital beam filters have the **z**-transform domain transfer function given by [5]

$$H(z_x, z_{ct}) = \frac{\left(1+z_x^{-1}\right)\left(1+z_{ct}^{-1}\right)}{1+b_{10}z_x^{-1}+b_{01}z_{ct}^{-1}+b_{11}z_x^{-1}z_{ct}^{-1}}, \quad (1)$$

where the coefficients b_{pq} are recalled as $b_{pq} = \frac{R+(-1)^p\cos\theta_i+(-1)^q\sin\theta_i}{R+\cos\theta_i+\sin\theta_i}$ [5] with $p+q \neq 0$. Here, $R > 0$ is a parameter that sets the sharpness (i.e. selectivity) of the beam passband and θ_i sets the orientation of the beam passband. A beam passband oriented at θ_i in $\boldsymbol{\omega}$ corresponds to an RF beam at angle ψ_i in the array pattern, where $\tan\theta_i = \sin\psi_i$ [8].

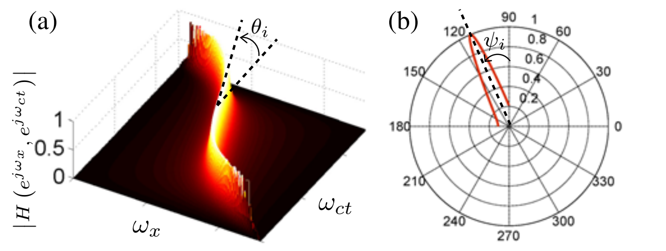

Fig. 3: Example (a) magnitude frequency response and (b) array factor of a first order 2-D IIR digital beam filter.

Fig. 3(a) shows an example 2-D magnitude frequency response computed by evaluating (1) on the unit bi-circle $z_k = e^{j\omega_k}$, $k \in \{x, ct\}$, for beam orientation $\theta_i = 20°$ and $R = 0.05$. The directionally enhanced 2-D output is given by $y(n_x, n_{ct}) = \sum_{p=0}^{1}\sum_{q=0}^{1} w(n_x-p, n_{ct}-q) - \sum_{p=0}^{1}\sum_{q=0}^{1} b_{pq}y(n_x-p, n_{ct}-q)$, where the 1-D output is obtained as $y_{\psi_i}(n_{ct}) = y(N-1, n_{ct})$ [5].

The array factor produced by $H(z_x, z_{ct})$ is obtained by evaluating the 2-D frequency response $H\left(e^{j\omega_x}, e^{j\omega_{ct}}\right)$ at a given temporal frequency ω_{ct0} as function of the spatial angle ψ by setting $\omega_x = -\omega_{ct0}\sin\psi$ [9]. The array factor is given by $A_H(\psi, \omega_{ct0}) = \left|H\left(e^{-j\omega_{ct0}\sin\psi}, e^{j\omega_{ct0}}\right)\right|$. Fig. 3(b) shows the array factor corresponding the beam response in Fig. 3(a). Let the radiation pattern of a single spiral antenna is $A_E(\psi, \phi, \omega_{ct})$, where ψ and ϕ are the elevation and azimuth angles, respectively. The total array response at temporal frequency ω_{ct0} is given by $A_E(\psi, \phi_0, \omega_{ct0})\, A_H(\psi, \omega_{ct0})$, where we fix the azimuth angle at ϕ_0 in the 3-D antenna pattern.

The 2-D frequency response $H\left(e^{j\omega_x}, e^{j\omega_{ct}}\right)$ exhibits frequency warping due to the application of bilinear transform during the filter synthesis stage [5]. Due to warping, when the beam filter is designed for DOA ψ_i, the actual beam direction in the array factor is not exactly ψ_i and is given by

$$\psi_i' = \sin^{-1}\left[\frac{2}{\omega_{ct0}}\tan^{-1}\left[\sin\psi_i\tan\left(\frac{\omega_{ct0}}{2}\right)\right]\right], \quad (2)$$

where ω_{ct0} is the temporal frequency at which the array factor is computed.

B. DOA Estimation

The DOA estimation block shown in Fig. 1, scans the CR environment by producing an electronically steered beam using a 2-D IIR digital beam filter. For each beam direction $\psi \in [0, \pi/2]$, the energy of the directionally enhanced output $y_\psi(n_{ct})$ is computed, leading to a spatial energy distribution function $E(\psi)$. For each RF source (and reflection thereof), $E(\psi)$ contains a local maxima, which is found by employing a peak detection on $E(\psi)$. The output of the DOA estimation block is therefore a set of directions ψ_i, $i = 1, 2, \ldots$.

V. Feature Extraction Algorithm

Cyclostationary feature extraction has been proposed for spectrum sensing in CR systems [2]. Typically, modulated signals can be considered as cyclostationary processes having

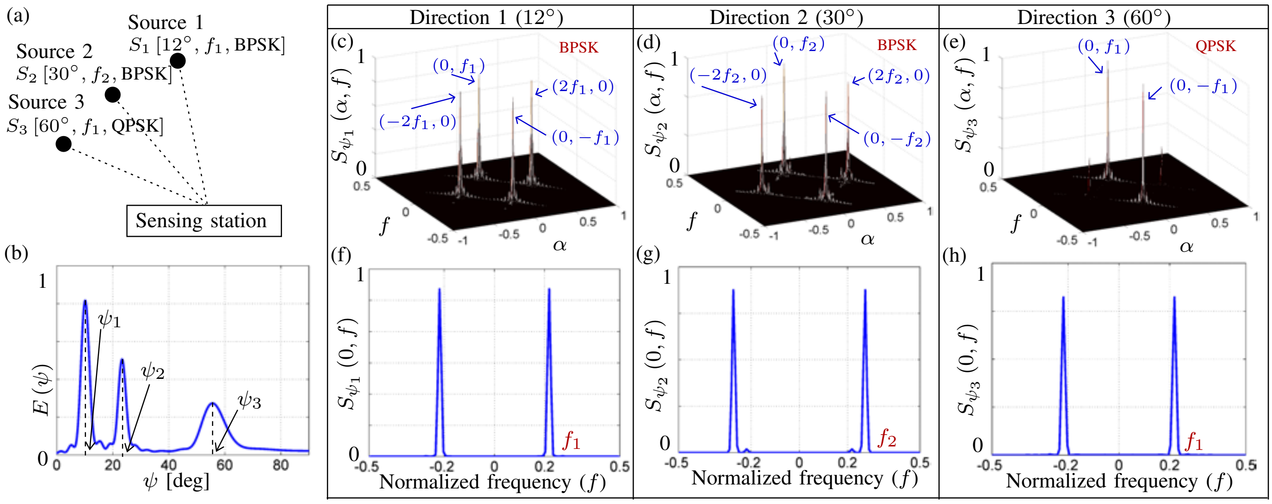

Fig. 4: (a) Source distribution, (b) spatial energy distribution $E(\psi)$ and (c)-(h) various feature detection outputs corresponding to the simulation scenario 1.

Algorithm 1 Spatio-temporal directional feature extraction

Require: 2-D spatio-temporal ULA input signal $w(n_x, n_{ct})$.
Ensure: Direction (d), frequency (f), modulation (m)

Step 1: Estimate the DOAs using steerable 2-D IIR beam filter to obtain direction estimates ψ_i, $i = 1, 2, ...$
Step 2: For each estimated DOA ψ_i, compute the directionally enhanced output $y_{\psi_i}(n_{ct})$.
Step 3: Compute the SCF $S_{\psi_i}(\alpha, f)$ using (3).
Step 4: Estimate the frequency f_i in each direction using $S_{\psi_i}(0, f)$.
Step 5: For each ψ_i, compute the corrected source direction ψ_i' using (2), where $\omega_{ct0} = 2\pi f_i/c$.
Step 6: Examine unique signatures of $S_{\psi_i}(\alpha, f)$ to decide the modulation scheme in each direction ψ_i

periodic statistics [10]. Unique features of cyclostationary processes can be extracted by deriving the Spectral Correlation Function (SCF), $S_x(\alpha, f)$. Here, α is called the cyclic frequency [10] and f is the temporal frequency. The SCF provides unique peak profiles for different modulation schemes. Power Spectral Density (PSD) is a special case of the SCF, when the parameter $\alpha = 0$ and $S_x(0, f)$ can be used to estimate the carrier frequency of the signal.

The feature extraction block in Fig. 1 computes the SCF of the directionally enhanced output, $y_{\psi_i}(n_{ct})$ using [10],

$$S_{\psi_i}(\alpha, f) = \sum_{l=-\infty}^{\infty} R_{\psi_i}^{\alpha}[l] e^{-i2\pi f l}, \qquad (3)$$

where $R_{\psi_i}^{\alpha}[l] = \left[\lim_{N\to\infty} \frac{1}{2N+1} \sum_{m=-N}^{N} y_{\psi_i}[n] y_{\psi_i}^{*}[n-l] e^{-i2\pi\alpha n}\right] e^{i\pi\alpha l}$.

By using the unique signatures in the SCF $S_{\psi_i}(\alpha, f)$, the frequency and modulation pertaining to each direction ψ_i is estimated. The complete directional feature extraction process corresponding to Fig. 1 can be summarized by Algorithm 1.

VI. Simulated Directional Feature Extraction

Three simulation scenarios are considered to illustrate the directional feature extraction scheme described by Algorithm 1. We consider three carrier frequencies 2.4, 3 and 4 GHz that correspond to normalized temporal frequencies $f_1 = 0.22$, $f_2 = 0.27$ and $f_3 = 0.36$, where $0 \leq f_i \leq 0.5$, assuming a maximum frequency of $F_{max} = 5.5$ GHz. We also consider two modulation schemes, binary phase shift keying (BPSK) and quadrature phase shift keying (QPSK) with signal to noise ratio (SNR) of 6 dB and a ULA of 64 spiral antennas.

TABLE I: Source direction estimation

Source	S_1	S_2	S_3
Actual angle (ψ_i) [Deg]	12	30	60
Estimated angle[Deg]	12.11	30.10	60.17

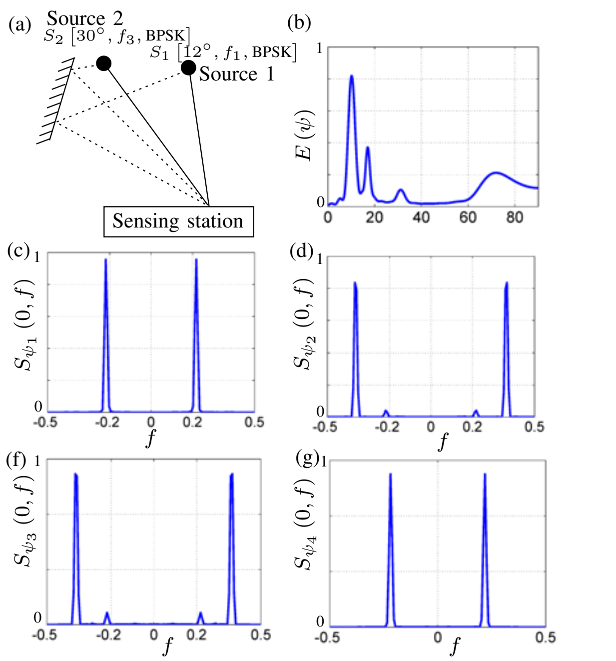

Fig. 5: (a) Source distribution, (b) spatial energy distribution $E(\psi)$ and (c)-(f) SCF at $\alpha = 0$ corresponding to simulation scenario 2.

Scenario 1: Consider three RF sources S_i, $i = 1, 2, 3$ as in Fig. 4(a), where sources S_1 and S_2 have the same modulation type, BPSK, and occupy two different carrier frequencies 2.4 GHz and 3 GHz. Sources S_1 and S_3 have the same channel frequency 2.4 GHz, and different modulation types. Fig. 4(b) shows the spatial energy distribution $E(\psi)$ obtained from step 1 in Algorithm 1, leading to three DOAs ψ_i, $i = 1,2,3$. As given by (2), the actual source directions ψ_i' have to be obtained from ψ_i , after the carrier frequencies are estimated using the SCF. We then compute the SCF $S_{\psi_i}(\alpha, f)$ for each DOA ψ_i, $i = 1,2,3$ as shown in Fig. 4(c)-(e). Fig. 4(f)-(h) show the corresponding $S_{\psi_i}(0, f)$ for each DOA, from which the carrier frequency pertaining to each DOA can be found (step 4), since $\alpha = 0$ line represent the PSD of the signal. As step 5, we compute the source directions ψ_i' using (2) and table I lists the actual and estimated source directions for each source S_i, $i = 1,2,3$. As shown in Fig. 4(c) and (e) the modulation schemes BPSK (of S_1) and QPSK (of S_3) can be resolved based on their different peak profiles in the SCF. For S_1 and S_2, we have the same SCF peak profiles as shown in Fig. 4(c) and (d). However, these peaks occur at distinct points in the (α, f) plane due to different carrier frequencies.

Next, we consider how the directional feature extraction can be used to reduce detection space in a multipath environment.

Scenario 2: As shown in Fig. 5(a), we consider two sources S_1, S_2 with same modulation and different carrier frequencies, where we assume one reflection for each source. The energy distribution shown in Fig. 5(b) implies four DOAs, two of which are in fact due to reflections. With apriori knowledge on the number of sources within the domain of interest (in this case two), one can reduce the detection space by exploiting the SCF for each direction. However, additional parameters such as signal strength has to be employed to differentiate the direct and the reflected wave. Since both sources use the same modulation, frequency is the differentiation factor and can be extracted by SCF when $\alpha = 0$ ($S_{\psi_i}(0, f)$) as shown in Fig. 5(c)-(g). $S_{\psi_1}(0, f)$ and $S_{\psi_4}(0, f)$ correspond to the same frequency and therefore we can assume that the two directions correspond to the direct and reflected paths of the same source.

Scenario 3: As shown in Fig. 6(a), we consider two sources S_1 and S_2 with different modulations and same carrier frequency. The energy distribution in Fig. 6(b) implies four source directions, where two of them are due to reflections. Fig. 6(c)-(f) show the SCF for the four directions. We obtain two pairs of identical peak profiles, from which the detection space can be halved when considering the identical SCFs to be corresponding to the source S_i and its reflection.

VII. Conclusions

A combined approach of low complexity antenna array signal processing and cyclostationary feature extraction is proposed for spatio-temporal directional feature detection in a CR environment. An Archimedean spiral antenna operating in the frequency range 2-6 GHz is proposed and is used in a linear array configuration to spatially sample the radio waves. 2-D IIR digital beam filters are proposed for the directional radio wave enhancement. Simulated examples are discussed, where spatio-temporal features such as direction, frequency and modulation of radio sources are estimated, which in turn can be used to derive high level network protocols towards achieving enhanced access to radio spectrum.

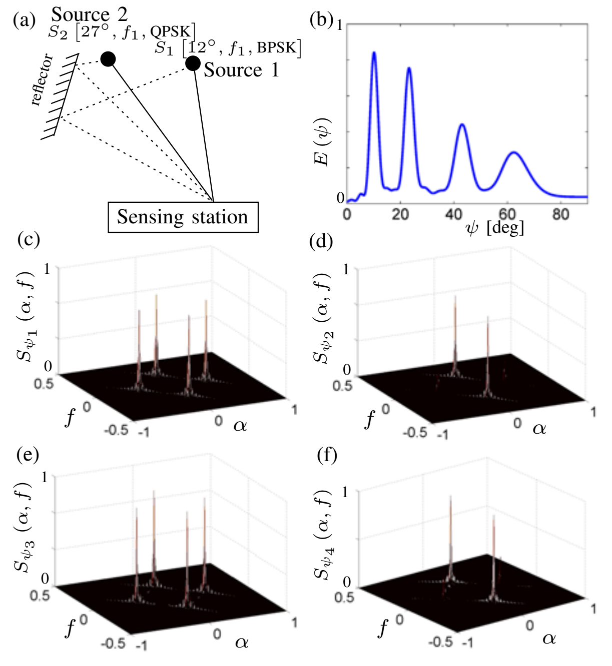

Fig. 6: (a) Source distribution, (b) spatial energy distribution $E(\psi)$ and (c)-(f) SCF for different DOAs corresponding to simulation scenario 3.

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