

DOA-Estimation and Source-Localization in CR-Networks using Steerable 2-D IIR Beam Filters

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Abstract—The application of multi-dimensional (MD) infinite impulse response (IIR) space-time beam filters in radio source localization in cognitive radio (CR) environments is investigated. Knowledge of the position of radio sources in a CR network leads to the detection of white spaces in the MD frequency domain, thereby creating more opportunistic links for the secondary users. The use of MD IIR beam filters is motivated by their very low computational complexity and small side lobe levels compared to digital phased arrays. As a proof-of-concept, the two dimensional (2-D) propagation scenario including at least two receiver stations and a data fusion station, which combines the direction of arrival (DOA) estimates from the two receiver stations, to yield a position estimate, is considered. Each receiver station employs a uniform linear array (ULA) of antennas and a steerable 2-D IIR beam filter and provides information pertaining to peak energy directions. First order 2-D IIR beam filters are shown to provide acceptable DOA estimates with a SNR of 6 dB. The peak energy direction information leads to both position and MD white space detection.

I. INTRODUCTION

We explore the potential application of multi-dimensional (MD) spatio-temporal infinite impulse response (IIR) digital filters in location and direction estimation of radio sources, leading to increasing broadband access to the radio spectrum. Cognitive radio (CR) [1]–[3] offers robust spectrum access toward maximizing utility in the context of diverse applications [4]. Typically, CR “spectrum sensing” is attempted using traditional sensing algorithms such as cyclostationary feature detection based on spectral correlation functions, energy detection, waveform based sensing, radio identification based sensing, and matched filtering [5]–[7]. These traditional algorithms do not provide information about the direction and location information of primary and secondary users [6], [7] as well as the interference.

Here, we envision new applications of MD IIR spatio-temporal filters towards directional and location information estimation within a CR network, leading to enhanced access to radio spectrum (EARS) [4], through directional spectrum sensing [8], [9] and RF source localization. The use of MD IIR filters is motivated by their salient properties such as small side lobe levels and low computational complexity, compared to digital phased arrays [10]. We present the 2-D case using linear antenna arrays.

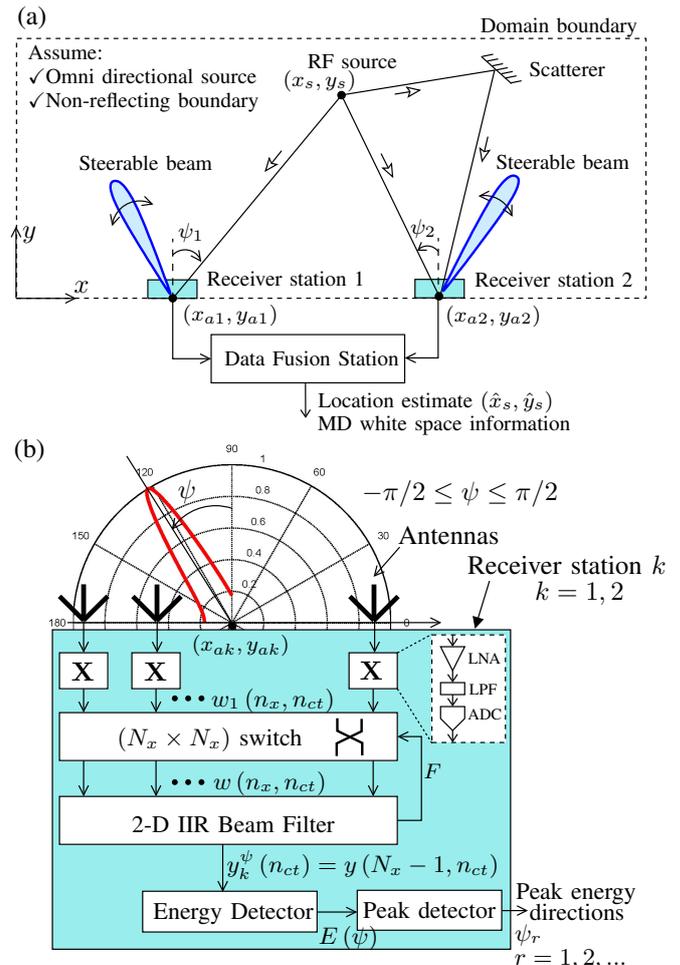


Fig. 1: Overview of the use of 2-D IIR space-time beam filters for source localization towards MD white space detection.

II. DIRECTIONAL SPECTRUM SENSING USING MD-WHITE SPACES TOWARDS EARS

The concept of directional spectrum sensing takes into account the directional and positional information of the radio sources. Traditional spectrum sensing deals with time-frequency information and detects “white spaces”, which are vacant frequency channels. Recent efforts to include directional sensing [7], [11]–[13], although shown to successfully address some of the issues by fixed relay schemes [14], spatial

statistics techniques [12], [15], maximum power avoidance [7], and predicting the duration of spectrum holes [13], leave many opportunity for innovation.

A. MD-White Space Concept

The concept of a MD spatio-temporal white space is formulated by exploiting the frequency domain properties of propagating plane waves. Consider a plane wave $w_{pw}(x, y, ct)$ having the direction of arrival (DOA) (ψ, ϕ) , where $(x, y) \in \mathbb{R}^2$ is space, c is wave speed and t is time. We use the convention of $(\omega_x, \omega_y) \in \mathbb{R}^2$ to denote spatial frequencies in the $x-y$ plane and $\omega_{ct} \in \mathbb{R}$ denotes the radio channel (temporal) frequency scaled by c^{-1} . It is recalled that, for angular spread ϵ of the DOA, the corresponding 3-D spectrum of $w_{pw}(x, y, ct)$ is contained totally within the cone shaped region given by $(\omega_x - \tan \theta \cos \phi \omega_{ct})^2 + (\omega_y - \tan \theta \sin \phi \omega_{ct})^2 \leq \left(\frac{\tan \epsilon \omega_{ct}}{\cos \theta}\right)^2$, where $\theta = \tan^{-1}(\sin \psi)$ is called the space-time DOA [16]. Vacant radio channels along the direction (ψ, ϕ) therefore manifest as white spaces inside the conical region mentioned above in the 3-D frequency domain.

B. Linear Array 2-D Sensing

We consider the simplified propagation scenario with two dimensions x and ct . This allows the use of linear antenna arrays and 2-D IIR filters. Fig. 1 (a) provides an overview of the 2-D spectrum sensing and source localization scheme. For simplicity, we assume omni directional RF sources and reflection free boundaries. The system employs at least two receiver stations located at (x_{ak}, y_{ak}) , $k = 1, 2$. The receiver stations are equipped with uniform linear array (ULA) of N_x antennas and a 2-D IIR beam filters, as shown in Fig. 1 (b).

C. Receiver Stations for Beamforming

The 2-D IIR beam filter in receiver station $k = 1, 2$ provides the beamformed output $y_k^\psi(n_{ct})$ along the direction ψ , which is subsequently sent through an energy detector followed by a peak detector. The beam filter scans through the spatial angles $|\psi| \leq \pi/2$ leading to a spatial energy function $E(\psi)$ at the output of the energy detector, which is subsequently processed by the peak detector to find local maximum points of $E(\psi)$, leading to peak energy angles ψ_r^k , $r = 1, 2, \dots$, where k is the receiver station number. The data fusion station will be implemented, in future work, using correlation and feature detection algorithms to obtain the source position estimate $(\hat{x}_s, \hat{y}_s) \approx (x_s, y_s)$ and MD white space information.

In this paper, we focus on the receiver station implementation using 2-D IIR beam filters, which provide a robust low complexity solution compared to digital phased arrays.

III. STEERABLE 2-D IIR SPACE-TIME FILTERS

A. Filter Transfer Function: A Review

The concept of MD passive network resonance has been used to derive practical bounded-input-bounded-output (p-BIBO) stable [17] 2-D IIR discrete domain transfer functions $H(z_x, z_{ct})$ [16]. Here, $z_k \in \mathbb{C}$ is the \mathbf{z} -transform variable in the dimension $k \in \{x, ct\}$. Such 1st-order transfer functions

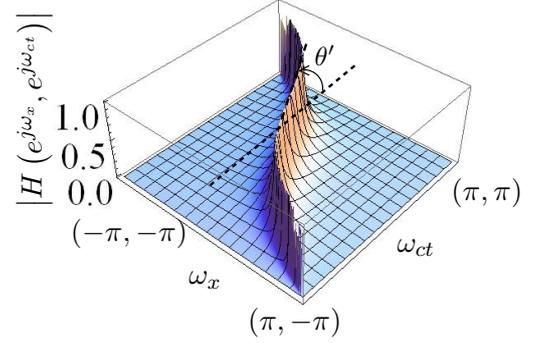


Fig. 2: Magnitude frequency response $|H(e^{j\omega_x}, e^{j\omega_{ct}})|$.

with beam-shaped passband in the $-+$ quadrant of the 2-D frequency domain $(\omega_x, \omega_{ct}) \in \mathbb{R}^2$ is recalled as [18]

$$H(z_x, z_{ct}) = \frac{(1 + z_x^{-1})(1 + z_{ct}^{-1})}{1 + \sum_{p=0}^1 \sum_{q=0}^1 b_{pq} z_x^{-p} z_{ct}^{-q}}, \quad (1)$$

where $p + q \neq 0$. The coefficients b_{pq} are given by $b_{pq} = \frac{R + (-1)^p \cos \theta' + (-1)^q \sin \theta'}{R + \cos \theta' + \sin \theta'}$, where $\theta' = \tan^{-1} \left\{ \frac{\tan(\omega_{ct} \sin \psi / 2)}{\tan(\omega_{ct} / 2)} \right\}$ and ψ is the beam direction. Magnitude frequency response of $H(z_x, z_{ct})$ obtained by computing (1) on the unit bi-circle $z_k = e^{j\omega_k}$ for $k \in \{x, ct\}$ has a beam shaped passband, that leads to an AF of the form $G(\alpha, \omega_{ct}) = |H(e^{-j \sin \alpha \omega_{ct}}, e^{j\omega_{ct}})|$, where α is the spatial angle measured anticlockwise from array broadside [10], [18]. It is clear that, $G(\alpha = \psi, \omega_{ct}) = 1$ leading to a beam pointing at ψ . The parameter $R > 0$ in b_{pq} sets the -3 dB bandwidth of $|H(e^{j\omega_x}, e^{j\omega_{ct}})|$ hence the half power beam width (HPBW) of the AF $G(\alpha, \omega_{ct})$. The HPBW is defined as $HPBW = |\psi_1^{HP} - \psi_2^{HP}|$, where ψ_k^{HP} , $k = 1, 2$ are the half-power angles corresponding to the beam pointing at ψ . The choice of R depends on the required HPBW and, therefore, on ψ_k^{HP} and is given by

$$\psi_k^{HP} = \sin^{-1} \left[\frac{2}{\omega_{ct}} \tan^{-1} \left(\tan \theta' \tan \left(\frac{\omega_{ct}}{2} \right) + (-1)^k \frac{R}{2 \cos \theta'} \right) \right], \quad (2)$$

where $\theta' = f(\psi)$ is defined above. An example 2-D magnitude frequency response is shown in Fig. 2. Real time implementation of $H(z_1, z_2)$ is based on the following 2-D difference equation, which is obtained by following the inverse \mathbf{z} -transform of (1) under zero initial conditions (ZICs) [18].

$$y(n_x, n_{ct}) = \sum_{a=0}^1 \sum_{b=0}^1 w(n_x - a, n_{ct} - b) - \sum_{p=0}^1 \sum_{q=0}^1 b_{pq} y(n_x - p, n_{ct} - q), \quad (3)$$

where $p + q \neq 0$.

B. Electronic Beam-Scanning

By computing the output $y(n_x, n_{ct})$ in (3) with $b_{pq} = f(\psi)$ for $|\psi| \leq \pi/2$ in real time, the CR environment can be

scanned. For $0 \leq \psi \leq \pi/2$, spectra of the ULA received signal $w_1(n_x, n_{ct})$ (in Fig. 1) lie in the $-+$ quadrant of $(\omega_x, \omega_{ct}) \in \mathbb{R}^2$. However, for $-\pi/2 \leq \psi < 0$, the input spectra lie in the $++$ quadrant of $(\omega_x, \omega_{ct}) \in \mathbb{R}^2$ and the filter coefficients b_{pq} corresponding to a beam-shaped passband in the $++$ quadrant do not meet the passivity requirement for the structural and p-BIBO stability of $H(z_x, z_{ct})$ [17], [18]. Therefore, in order to scan in the region $-\pi/2 \leq \psi < 0$ region, we spatially flip the input signal $w_1(n_x, n_{ct})$ before feeding to the beam filter [16]. The $(N_x \times N_x)$ switch shown in Fig. 1 is employed for this purpose and is defined as

$$w(n_x, n_{ct}) = \begin{cases} w_1(n_x, n_{ct}) & \text{for } F = 0 \\ w_1(N_x - 1 - n_x, n_{ct}) & \text{for } F = 1 \end{cases}, \quad (4)$$

where the control signal $F = 1$ for $\psi \in [-\pi/2, 0)$ and $F = 0$ for $\psi \in [0, \pi/2]$. The input signal $w(n_x, n_{ct})$ in (4) is then processed according to (3) for $|\psi| \leq \pi/2$ to obtain $y_k^\psi(n_{ct}) = y(N_x - 1, n_{ct})$ as shown in Fig. 1 (b), where $k = 1, 2$.

C. Peak Energy based Direction Search

The output $y_k^\psi(n_{ct})$, that contains signals along the DOA ψ is passed through an energy detector to obtain the spatial energy distribution $E(\psi) = \sum_{n_{ct}=0}^{M-1} |y_k^\psi(n_{ct})|^2$, where M is the size of first-in-first-out (FIFO) buffer used to accumulate the samples. Once a complete scan is done $E(\psi)$ is subjected to a peak search to identify the local maximum points, leading to a set of peak energy directions ψ_r^k , $r = 1, 2, \dots$ at the receiver station k , such that $\left[\frac{d}{d\psi}(E(\psi))\right]_{\psi=\psi_r^k} = 0$.

Now, we consider an example to illustrate this process as follows. Let there be three sinusoidal sources located at $(x_{s1}, y_{s1}) = (-10, 10)$, $(x_{s2}, y_{s2}) = (-5, 10)$ and $(x_{s3}, y_{s3}) = (-2, 10)$, respectively. Let one receiver station be located at the origin $(x_{a1}, y_{a1}) = (0, 0)$ with a ULA of size N_x . We use the 1st-order 2-D IIR beam filter given in (1) to scan the three sources. Fig. 3 (a) and (b) show the resulting energy distribution $E(\psi)$ for $N_x = 16$ and $N_x = 32$, respectively computed at $\omega_{ct} = 0.9\pi$. The simulation assumes a signal to noise ratio (SNR) of 6 dB at the receiver station. Table I shows the peak energy directions ψ_r for $r = 1, 2, 3$ after performing peak detection on $E(\psi)$.

D. Computational Complexity of Beam Filters

The use of 2-D IIR beam filters in receiver stations is motivated by their low complexity compared to digital phased arrays and higher order FIR filter-and-sum beamforming methods. The multiplier and adder complexities of 1st-order 2-D IIR beam filter for a ULA of size N_x are given by $MUL_{IIR} = 3N_x$ and $ADD_{IIR} = 5N_x$, respectively [18]. The multiplier and adder complexities for a digital phased arrays with a fast Fourier transform (FFT) of size N_{FFT} are given by $MUL_{PA} = 3N_x N_{FFT}$ and $ADD_{PA} = 5N_{FFT}(N_x - 1)$, respectively, assuming the Gauss algorithm for complex multiplication and *without considering the computational complexity of the N_{FFT} point FFT*. Therefore,

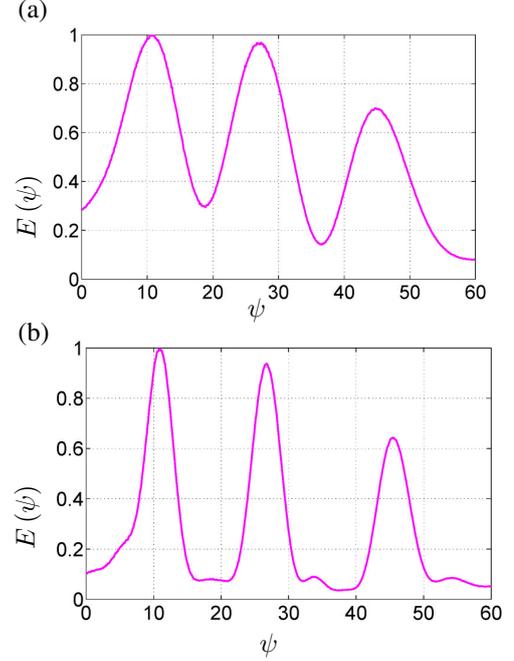


Fig. 3: Energy distribution $E(\psi)$ from (a) $N_x = 16$ and (b) $N_x = 32$ antennas using 1st-order 2-D IIR beam filters. The peak directions are given in Table I.

TABLE I: Directions of the peak energy $\psi_{1,2,3}$ for $N_x = 16, 32$ using 1st-order 2-D IIR beam filters.

	Actual	$N_x = 16$	$N_x = 32$
ψ_1	11.3 ^o	10.9 ^o	10.9 ^o
ψ_2	26.6	26.9 ^o	26.8 ^o
ψ_3	45 ^o	45.1 ^o	45.4 ^o

the use of 2-D IIR filters reduces the multiplier and adder complexities of the receiver station by $(1 - 1/N_{FFT}) \times 100\%$ and $\left(1 - \frac{1}{N_{FFT}(1-1/N_x)}\right) \times 100\%$, respectively compared to digital phased array based implementation.

IV. DATA FUSION STATION

We propose a data fusion station, that can be potentially implemented with a multitude of high level algorithms. In general, the receiver station k provides information including the peak energy directions ψ_r^k , $r = 1, 2, \dots, N_k$, frequency, modulation scheme and receiver station location to the data fusion station. The data fusion station can utilize the peak energy directions from two receiver stations given by ψ_r^1 , $r = 1, 2, \dots, N_1$ and ψ_m^2 , $m = 1, 2, \dots, N_2$ and the locations of the receiver stations (x_{ak}, y_{ak}) , $k = 1, 2$ to obtain the location estimate candidates (\hat{x}_s, \hat{y}_s) using geometry (ray model) as

$$\hat{x}_s = \frac{\tan \psi_m^2 (x_{a1} + \tan \psi_r^1 y_{a1}) - \tan \psi_r^1 (x_{a2} + \tan \psi_m^2 y_{a2})}{(\tan \psi_m^2 - \tan \psi_r^1)} \quad (5)$$

$$\hat{y}_s = \frac{\tan \psi_r^1 y_{a1} + x_{a1} - \tan \psi_m^2 y_{a2} - x_{a2}}{(\tan \psi_r^1 - \tan \psi_m^2)}, \quad (6)$$

where $r = 1, 2, \dots, N_1$ and $m = 1, 2, \dots, N_2$. This leads to a set of $N_1 N_2$ solutions for (\hat{x}_s, \hat{y}_s) , where only a subset of that correspond to the actual locations of the sources. The spurious

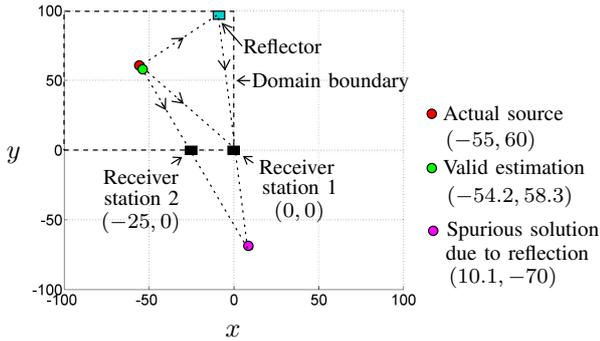


Fig. 4: A simplified example illustrating the potential use of steerable 2-D IIR beam filters for locating RF sources.

solutions due to multi-path effects and scattering should be eliminated by employing a third receiver station or/and by considering the frequency, modulation and other features of the sources and domain boundary.

In Fig. 4 we show a simplified example of location estimation of a single RF source in the presence of one reflection, by employing ray model based solution at the data fusion station. Two receiver stations located at (0, 0) and (-25, 0) each contains a 1st-order 2-D IIR beam filter with a ULA of $N_x = 16$ antennas. The data fusion station receives the peak energy directions $\psi_1^1 = 8.2^\circ$, $\psi_2^1 = 42.9^\circ$ from receiver station 1 and $\psi_2^2 = 26^\circ$ from the receiver station 2, where $\psi_1^1 = 8.2^\circ$ is due to reflection. By following (5) and (6), two solutions are obtained as (-54.2, 58.3) and (10.1, -70), where based on the domain boundary, the latter is identified as the spurious solution due to reflection.

Although we assume a simplified ray model based solution for the data fusion station, in practice, algorithms based on correlation techniques and signature detection [5], [19] have to be employed to resolve ambiguities due to multi-path effects, and requires extensive future study.

V. CONCLUSIONS AND FUTURE WORK

The potential applications of steerable, low complexity 2-D IIR space-time beam filters for RF source localization and direction finding, towards EARS was studied. The proposed location and directional information can potentially be utilized for the detection of MD spectral white spaces, thereby creating more opportunistic links in a CR environment. Two receiver stations equipped with ULA of antennas and a 2-D IIR beam filter are used to scan the CR environment to obtain the directions, where maximum energy is detected. The 1st-order 2-D IIR beam filters are shown to provide satisfactory results in finding the peak energy directions with an SNR of 6 dB.

Existing algorithms based on feature detection, correlation techniques can be used to implement the data fusion station. As a proof-of-concept, an example is provided using the 2-D ray model to find the source location by using the peak energy directions provided by the two receiver stations. A comprehensive study on possible algorithms for implementing the data fusion station is required in order to resolve ambiguities due to multi path propagation effects.

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REFERENCES

- [1] N. Devroye, M. Vu, and V. Tarokh, "Cognitive radio networks," *IEEE Signal Processing Magazine*, vol. 25, no. 6, pp. 12–23, Nov. 2008.
- [2] D. Cabric, "Addressing feasibility of cognitive radios," *IEEE Signal Processing Magazine*, vol. 25, pp. 85–93, 2008.
- [3] A. Vinod, E. Lai, P. Meher, J. Palicot, and S. Mirabbasi, "Guest editorial: Special issue on embedded signal processing circuits and systems for cognitive radio-based wireless communication devices," *Circuits, Systems, and Signal Processing*, vol. 30, pp. 683–688, 2011, 10.1007/s00034-011-9299-4. [Online]. Available: <http://dx.doi.org/10.1007/s00034-011-9299-4>
- [4] Final Report, Workshop on Enhancing Access to the Radio Spectrum (EARS), NSF, Arlington, Virginia, Aug. 2010.
- [5] Z. Tian, Y. Tafesse, and B. M. Sadler, "Cyclic feature detection with sub-nquist sampling for wideband spectrum sensing," *IEEE Journal of Selected Topics in Signal Processing*, vol. 6, pp. 58–69, 2012.
- [6] T. Yucek and H. Arslan, "A survey of spectrum sensing algorithms for cognitive radio applications," *IEEE Communications Surveys and Tutorials*, vol. 11, pp. 116–130, Oct. 2009.
- [7] B. L. Mark and A. O. Nasif, "Estimation of maximum interference-free transmit power level for opportunistic spectrum access," George Mason University, NAPL Technical Report TR-GMU-NAPL-Y08-N1, Aug. 2008.
- [8] T. K. Gunaratne and L. T. Bruton, "Adaptive complex-coefficient 2D FIR trapezoidal filters for broadband beamforming in cognitive radio system," *Circuits, Systems, and Signal Processing*, vol. 30, no. 3, pp. 587–608, June 2011.
- [9] A. Madanayake, C. Wijenayake, N. Tran, S. V. Hum, L. T. Bruton, and T. Cooklev, "Directional spectrum sensing using tunable multi-D space-time discrete filters," in *IEEE Intl. Symp. on World of Wireless, Mobile and Multimedia Networks (WoWMoM)*, June 2012, pp. 1–6.
- [10] C. Wijenayake, A. Madanayake, and L. Bruton, "Broadband multiple cone-beam 3D IIR digital filters applied to planar dense aperture arrays," *IEEE Trans. on Antennas and Propagation*, vol. Early Access, 2012.
- [11] M. Wellens, J. Riihijarvi, and P. Mahonen, "Spatial statistics and models of spectrum use," *Elsevier Computer Communications*, vol. 32, no. 18, pp. 1998–2011, Dec. 2009.
- [12] J. Riihijarvi and P. Mahonen, "Exploiting spatial statistics of primary and secondary users towards improved cognitive radio networks," in *International Conference on Cognitive Radio Oriented Wireless Networks and Communications*, May 2008, pp. 1–7.
- [13] Z. Chen, Z. Hu, and R. C. Qiu, "Quickest spectrum detection using hidden markov model for cognitive radio," *IEEE Proceedings of SoutheastCon*, pp. 196–201, March 2007.
- [14] G. Ganesan, Y. Li, B. Bing, and S. Li, "Spatiotemporal sensing in cognitive radio networks," *IEEE Journal on Selected Areas in Communications*, vol. 26, no. 1, pp. 5–12, Jan. 2008.
- [15] Y. Zhao, M. Song, C. Xin, and M. Wadhwa, "Spectrum sensing based on three-state model to accomplish all-level fairness for co-existing multiple cognitive radio networks," in *IEEE Proceedings INFOCOM*, March 2012, pp. 1782–1790.
- [16] L. Bruton and N. Bartley, "Three-dimensional image processing using the concept of network resonance," *IEEE Transactions on Circuits and Systems*, vol. 32, no. 7, pp. 664–672, July 1985.
- [17] P. Agathoklis and L. Bruton, "Practical-BIBO stability of n-dimensional discrete systems," *IEE Proceedings G on Electronic Circuits and Systems*, vol. 130, no. 6, pp. 236–242, Dec. 1983.
- [18] A. Madanayake and L. T. Bruton, "A speed-optimized systolic array processor architecture for spatio-temporal 2-d IIR broadband beam filters," *IEEE Trans. on Circuits and Systems I: Regular Papers*, vol. 55, pp. 1953–1966, Aug. 2008.
- [19] A. Adams, M. Tummala, and J. McEachen, "Source localization in a cognitive radio environment consisting of frequency and spatial mobility," in *IEEE Intl. Symp. on a World of Wireless, Mobile and Multimedia Networks (WoWMoM)*, 2012.