Spatial Spectrum Sensing for Cognitive Radios via Miniaturized Parasitic Antenna Systems

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***Abstract*— The paper describes an antenna system for portable lightweight cognitive radios employing opportunistic spectrum access. Our approach comprises a frequency-agile narrowband antenna that is capable of sensing over a wide bandwidth and over different spatial directions within a miniaturized single-radio system assisted by parasitic antennas.**

I. Introduction

The traditional licensing of specific-sized swaths of the radio spectrum for personal communications has led to the conclusion that a high percentage of the spectrum becomes underutilized at a specific time and in a specific geographic location [1]. The concept of the cognitive radio (CR) [2] was introduced as novel technology paradigm towards efficient, dynamic and flexible radio spectrum usage. This can be achieved through the adoption of techniques branded as *opportunistic spectrum access* (OSA) enabling sensing, prompt measurement, dissemination and adaptation to the real-time conditions of the network environment so that cognitive / secondary users (SU) can establish communication without interfering with incumbent / primary users (PUs) [3].

Under the OSA paradigm, the SU should be able to perform spectrum sensing and identify vacant frequency subbands, the so-called *spectral white spaces*, in order to communicate with its intended receiver. Due to its theoretical promise to establish orthogonal PU-SU transmissions over the spectral white spaces, the OSA is the approach adopted in the first standardization effort of the CR technology within the IEEE 802.22 standard on wireless regional area networks (WRANs) [4]. Thus, spectrum sensing is an essential component of the CR concept aiming at obtaining awareness regarding the spectrum occupancy and the PU activity in a specific region. Various approaches, enabling algorithms and aspects of spectrum sensing for CR applications can be found in [5].

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A SU employing OSA has to monitor the available frequency spectrum and reconfigure to transmit on a different frequency when necessary. Spectrum sensing over various frequency subbands and radio reconfiguration impose certain challenges on the CR hardware and the antenna design [6]. Apart from the frequency dimension, spectral white spaces can be observed across other dimensions such as the *angle* (referred to as *space* herein), rendering the spectrum sensing a multi-dimensional CR functionality [5]. The spatial dimension can reveal additional transmission opportunities through sensing along different directions over different beam-patterns. The so-called *spatial spectrum sensing* is conventionally implemented using multiple RF chains connected to antenna elements spaced apart typically by $\lambda/2$, where λ is the carrier wavelength, making the scheme practical for base stations and access points where size, cost and complexity are affordable [7]. However, spatial spectrum sensing has not attracted respectable attention when considering portable lightweight CR terminals. It is the purpose of this paper to address the major design challenges of cognitive antenna systems intented for users' handheld terminals supporting spatial spectrum sensing. Our approach is influenced by the seminal work in [10] and [11-12] where single RF chain transceivers incorporating low-cost passive or parasitic elements have been proposed for analogue beamforming and compact analogue multiple-input-multiple-output (MIMO) systems, respectively.

The rest of the paper is organized as follows. Section II provides an overview of the antenna design challenges and hardware constraints faced in CR systems employing OSA. A concise description of the spatial spectrum sensing approach and its implementation requirements is also given. Section III proposes an enhanced cognitive antenna system capable of performing spatial spectrum sensing and comprising a low-cost narrowband antenna tunable over a wide spectrum (frequency-agile antenna). This is done by properly tuning a set of reactive loads connected to a group of PEs closely coupled to the driven (active) element. By doing so, the operational frequency subband leaps to another subband (frequency tuning). Moreover, at every subband, swapping the reactive loads rotates the narrowband beam-pattern $180°$ (without affecting the frequency response of the antenna system) giving the cognitive transceiver the capability of sensing sequentially two distinct segments of the space. Finally, Section IV concludes the paper.

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II. Design Challenges of Spatial Spectrum Sensing

In order to utilize all the available spectral opportunities, a versatile CR should sense a wide bandwidth, often spanning a frequency range greater than 1.4 GHz [6]. However, wideband antennas generally have higher complexity and bigger size than narrowband antennas [5] which creates problems in designing wideband antennas for compact CR terminals. Furthermore, narrowband antennas are inherently privileged with a level of bandpass filtering alleviating the need of complicated RF filter circuits with sharp pass and stop bands. It should be also noted that the large operating bandwidths impose additional requirements to the power amplifiers [5].

While spectrum sensing is a wideband operation, the SUs often communicate over a narrower channel bandwidth (e.g. in GSM, UMTS, ATSC / NTSC, etc.). For this reason, it is proposed that a wideband antenna is used for sensing while a narrowband antenna with a reconfigurable frequency would handle communications [6]. For example, the IEEE 802.22 customer premise equipments (CPEs) are equipped with a wideband omni-directional antenna for spectrum sensing whereas a narrowband directional antenna communicates with the base station [4]. This approach is often combined with a dual-radio architecture allowing both spectrum sensing and communication to run in parallel over two distinct radio chains [6]. It has the advantage of continuous, thus, more accurate spectrum monitoring at the expense of increased DC power consumption and extra RF hardware cost and complexity[1]. On the other hand, in [9] an integrated wideband / narrowband antenna into the same volume for switched operations is presented. The switching between wideband / narrowband operations usually implies a single-radio architecture supporting spectrum sensing and communication on different time slots. This is an implementation choice of great importance in handheld devices with limited physical area but only certain accuracy can be guaranteed for the spectrum sensing results due to the non-continuous sensing over limited time intervals [5]. However, due to its simplicity and lower cost, the integrated wideband / narrowband antenna in a single-radio architecture is a strong candidate for compact CR devices [6].

On the other hand, conventional sensing methodologies identify transmission opportunities across two main dimensions a) frequency: at a particular time instant, certain frequency subbands may be occupied and others may be empty, b) time: a certain frequency subband may be occupied in one time instant and might be vacant in another time [5]. However, it has been suggested that orthogonal PU-SU transmissions can also be achieved by exploiting the angular or spatial dimension [5] [6]. For example, knowing the angle of arrival (AoA) of the PU signal, a transmission opportunity can be created by communicating on another direction without causing interference to the PU. Alternatively, a SU equipped with a directive steerable antenna can monitor the frequency spectrum in all directions supporting spatial spectrum sensing. In this manner, the SU is able to identify angular directions vacant of PU activity in a given frequency, referred to as *spatial-spectral white spaces*. Thus, spatial spectrum sensing unveils new opportunities for transmission enhancing the secondary system capacity.

Increasing significantly the spatial resolution by creating very narrow steerable beams would theoretically increase the transmission opportunities. However, this would also result in a higher sensing time in order to scan the whole space as well as in a larger computational and storage task. For this reason, the spatial discrimination should be compromised in accordance with the aforementioned limitations, a design aspect that is considered in the proposed spatial spectrum sensing approach described in Section III.

It should be noted that the authors in [7] propose a space-time frequency sensing technique assuming the SUs equipped with antenna arrays that create a number of concurrent orthogonal beam-patterns. Nevertheless, such systems, as well as the conventional steerable directive antennas, incorporate an array of active elements, and thus, extra RF hardware amplifying the cost, complexity and DC power consumption requirements. Moreover, the spacing of the multiple antenna elements is usually set to $\lambda/2$, leading to large array implementations, especially at low frequencies. The size limitations of portable CR front-ends are also taken into account within the proposed sensing approach, as explained in the following.

III. Spatial Spectrum Sensing via Tunable Parasitic Antenna Systems

A parasitic antenna consists of one or more parasitic elements (PEs), i.e., antenna elements terminated with passive loads rather than being connected to the RF port. The PE is fed inductively by radiated energy coming from the driven element. If the PE radiates away from (*toward*) the driven element, it is called a director (*reflector*) which is usually the case when loading the PE with an inductive (*capacitive*) load, i.e., a positive (*negative*) reactance.

In 2000, the ATR labs in Japan developed a smart parasitic antenna system referred to as the electronically steerable parasitic array radiator (ESPAR) antenna [13]. An $(N+1)$-element ESPAR antenna is a smart antenna system that presents a significant advantage over its predecessors: it is able to control its beam-patterns as any smart antenna system, while being implemented using a *single active element* and N PEs placed around the active one. Every PE is short-circuited and loaded with variable reactors (varactors). The imaginary part of the PEs' input impedances is controlled in the analogue domain via DC control signals that properly reverse bias the varactor diodes within a given range of values. By adjusting the varactors' response, the beam-pattern of the ESPAR antenna system can be controlled to direct its gain and null toward certain directions in an adaptive or predefined fashion. The N PEs are kept at $\lambda/4$ away from the central active element so that tuning the PEs' loads does not affect the driving point impedance (and hence the efficiency) of the antenna system.

The ESPAR was mainly intended as an adaptive antenna that maximizes the signal to interference and noise ratio (SINR) by properly steering the beam gain and null [10]. Parasitic antenna

[1] It should be noted that a single wideband antenna could be sufficient for both chains as suggested in [5] [6].

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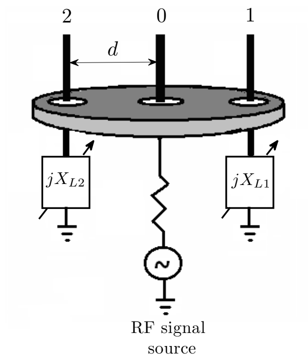

Fig. 1. The classical 3-element ESPAR antenna configuration of monopoles above a ground plane.

systems with compact dimensions have been proposed in [11-12] for analogue MIMO where the different datastreams are smartly encoded onto the set of the reactive loads, i.e., the information is embedded within the angular variations of the beam-patterns.

In this work, we shift the paradigm of the parasitic antenna design from analogue beamforming and analogue MIMO into an analogue cognitive antenna system that is tunable over the frequency dimension and steerable over the spatial dimension. For this reason, we propose a new antenna system, similar to the 3-element ESPAR antenna ($N = 2$) in principle, but designed specifically as a spatial spectrum sensing antenna system for compactness-constrained transceivers. We refer to the new antenna system as *3-element Electronic Spatial Spectrum Sensing Parasitic Array Receptor (E3SPAR)*. In the following, we present the basic theory of the classical 3-element ESPAR antenna as well as its extension for spatial spectrum sensing for lightweight CRs, i.e., the 3-element E3SPAR.

A. Three-Element Electronically Steerable Parasitic Array Radiator (ESPAR)

The 3-element ESPAR antenna is implemented using a single active antenna element and $N = 2$ PEs surrounding the active element at relative local angles of 0 and π, as in the example shown in Fig. 1 for a 3-element ESPAR configuration of 3 monopoles above a ground plane. The PEs are terminated with varactors that control the imaginary part of the PEs input impedances. The currents on the antenna elements are induced by mutual coupling with the current on the central active element according to the following equation [13]

$$\mathbf{i}(f) = v_s \left[\mathbf{Z}(f) + \mathbf{X}\right]^{-1} \mathbf{u} = \left[i_0(f) \quad i_1(f) \quad i_2(f)\right]^T, \quad (1)$$

where v_s represents the transmitted voltage signal source with the amplitude and the phase from the driving RF port at the central element[2]. The vector $\left[\mathbf{Z}(f) + \mathbf{X}\right]^{-1} \mathbf{u}$ is termed as the "*equivalent weight vector*" [10]. $\mathbf{Z}(f)$ is the 3×3 mutual impedance matrix given by

$$\mathbf{Z}(f) = \begin{bmatrix} Z_{00}(f) & Z_{01}(f) & Z_{01}(f) \\ Z_{01}(f) & Z_{11}(f) & Z_{12}(f) \\ Z_{01}(f) & Z_{12}(f) & Z_{11}(f) \end{bmatrix}, \quad (2)$$

which is a function of the operating frequency f. $Z_{00}(f)$ is the self-impedance of the central active element (the 0^{th} element), $Z_{11}(f)$ is the self-impedance of the 1^{st} and the 2^{nd} PE (as we assume the two PEs to be identical) and $Z_{ij}(f)$ is the mutual coupling impedance between the i^{th} element and the j^{th} PE ($Z_{ij}(f) = Z_{ji}(f), i, j \in \{0, 1, 2\}$ by reciprocity). $\mathbf{X}$ is a 3×3 diagonal matrix defined as

$$\mathbf{X} := \text{diag}([Z_0 \quad jX_1 \quad jX_2]), \quad (3)$$

where Z_0 is the terminal impedance at the central active port (equal to the characteristic impedance of 50 Ohm for matching purposes), whereas jX_k is the loading of the k^{th} PE. $\mathbf{u}$ is a selection vector given by $\mathbf{u} = [1 \quad 0 \quad 0]^T$.

The beam-pattern of the 3-element ESPAR antenna in the far-field is obtained as

$$\mathcal{A}(\varphi, f) = \mathbf{i}^T(f)\boldsymbol{\alpha}(\varphi, f). \quad (4)$$

In the above, φ denotes the azimuthal angle representing the AoA. $\boldsymbol{\alpha}(\varphi, f)$ is a column vector of the isolated patterns of the ESPAR antenna elements corresponding to the response vector and given by

$$\boldsymbol{\alpha}(\varphi, f) = [1 \quad e^{-j\frac{2\pi f}{c}d\cos(\varphi-0)} \quad e^{-j\frac{2\pi f}{c}d\cos(\varphi-\pi)}]^T, \quad (5)$$

where d is the antenna inter-element spacing in meters (m) and c is the speed of the electromagnetic wave in m/s.

B. Three-Element Electronic Spatial Spectrum Sensing Parasitic Array Receptor (E3SPAR)

The main goal in a cognitive front-end is to jump to different parts of the spectrum in a dynamic manner aiming at detecting spectral holes as well as to exploit the precious spatial resource (thus extracting extra degrees of freedom). Along this direction, we focus on shifting the operational (resonant) subband of the conventional 3-element ESPAR antenna by properly controlling the set of varactors (reactive frequency tuning). For this reason, we reduce significantly the distance between the PEs and the central driven element of the classical 3-element ESPAR antenna. This results in a highly directive [14] but sensitive array structure due to the strong reactive fields at quite small spacing, referred to as 3-element E3SPAR. The sensitivity of the array structure to any loading conditions is exploited in a way that the set of the PEs are used as a dynamic matching circuit at a given desired frequency subband. This means that the PEs are properly controlled so that the antenna system resonates at the desired frequency subband by minimizing the input reflection coefficient $\Gamma_{\text{in}}(f)$. Moreover, having found the set of the optimal reactive loads at a given frequency, swapping the reactive loads over the PEs shifts the narrow beam-pattern to one of the $N = 2$ angular positions (i.e., rotates the beam-pattern 180°) without affecting $\Gamma_{\text{in}}(f)$.

[2]In this paper, vectors and matrices are denoted by boldface letters whereas the superscript T denotes transposition.

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In order to find the set of the optimal reactive loads that allow the 3-element E3SPAR antenna system to operate at a given subband, we solve the following optimization problem over the set of reactive loads $\mathbf{X}$ at the given desired subband

$$\begin{aligned} \underset{\mathbf{X}}{\text{minimize}} \quad & \Gamma_{\text{in}}(f) = (Z_{\text{in}}(f) + Z_o)^{-1}(Z_{\text{in}}(f) - Z_o) \\ \text{subject to} \quad & X_{\min} \leq X_k \leq X_{\max},\ k \in \{1, 2\}\,. \end{aligned} \tag{6}$$

In the above, Z_{in} is the driving point impedance given by

$$Z_{\text{in}}(f) = Z_{00}(f) + \alpha_{10}(f)Z_{01}(f) + \alpha_{20}(f)Z_{01}(f),$$

where the coefficients $\alpha_{10}(f)$ and $\alpha_{20}(f)$ are calculated as in [16] to be

$$\begin{aligned} \alpha_{10}(f) &= \frac{i_1(f)}{i_0(f)} \\ &= \frac{Z_{12}(f)Z_{01}(f) - Z_{01}(f)\,(Z_{11}(f) + jX_{L2})}{(Z_{11}(f) + jX_{L1})\,(Z_{11}(f) + jX_{L2}) - Z_{12}^2(f)}, \end{aligned} \tag{7a}$$

$$\begin{aligned} \alpha_{20}(f) &= \frac{i_2(f)}{i_0(f)} \\ &= \frac{Z_{12}(f)Z_{01}(f) - Z_{01}(f)\,(Z_{11}(f) + jX_{L1})}{(Z_{11}(f) + jX_{L1})\,(Z_{11}(f) + jX_{L2}) - Z_{12}^2(f)}. \end{aligned} \tag{7b}$$

The constraint on X_k depends on the tunable range of the varactor diodes, where usually $X_{\min} \leq 0$, i.e., capacitive whereas $X_{\max} \geq 0$, i.e., inductive. The $\mathbf{Z}(f)$ matrix at every desired frequency subband is obtained by the method of moments (MoM) using the commercial electromagnetic simulator IE3D®.

As the dimension of the reactance space is limited to $N = 2$, the problem (6) is solvable by direct search over the range of the loads X_1 and X_2. The set of the optimal loads for a given subband is found *off-line*. The cognitive transceiver can simply store the sets of the optimal loads in a look-up table, thus reducing the time required for changing the loading conditions.

The novel aspects of the proposed antenna system intended for spatial spectrum sensing are summarized below:

- The 3-element E3SPAR antenna has a single RF chain, thus it meets the cost constraints of mobile handheld terminals, where the cost scales with the complexity of the RF hardware.
- The 3-element E3SPAR antenna requires the PEs to be very close to the central active element; hence, the antenna system meets the compactness constraints of the mobile terminals where the physical area is limited.
- The strong mutual coupling decreases the antenna bandwidth at a given frequency, and hence the narrowband antenna system is suitable for cognitive transceivers that try to avoid any out-of-band radiation when transmitting. Another consequence is that the cognitive transceiver needs not have a sharp (expensive) RF filter as the 3-element E3SPAR antenna is a filter by itself.
- Swapping the reactive loads rotates the narrowband beam-pattern to one of the $N = 2$ angular positions while keeping the driving point impedance unchanged due to symmetry. Consequently, the 3-element E3SPAR antenna is capable of exploiting the spatial dimension by sensing over one of the $N = 2$ narrowband beam-patterns.
- The spatial resolution is limited to a small number of distinct beam-patterns in order not to increase prohibitively the time for executing a space scan as well as to avoid complicated antenna designs.
- The strong reactive field at such small spacing results in high gain arrays [14]. The directive beam-pattern, not only spatially filters out the PU signal, but also enhances the quality of reception due to the high beamforming gain.

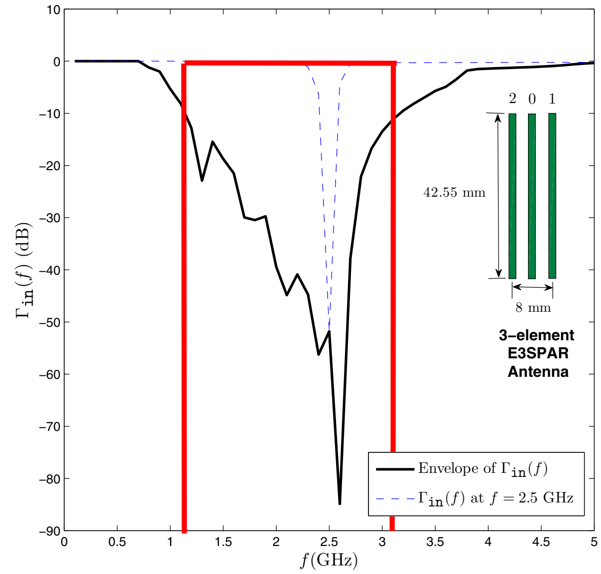

Fig. 2. Input reflection coefficient for the 3-element E3SPAR antenna of flat dipoles intended for spatial spectrum sensing.

The main limitation of the proposed antenna system is that the beam-patterns are directive at some of the subbands but not at all of them due to the fundamental limitation of electrically small-sized antennas (the gain-bandwidth product of an arbitrary antenna system is constrained by its size [15]).

C. Three-Element E3SPAR Antenna Example

In this part, we propose a concrete 3-element E3SPAR set-up of flat dipoles which is constrained to the two dimensions, and hence can be easily integrated in the users' mobile terminals. The antenna system illustrated in Fig. 2 is composed of three flat dipoles (dipole 0 is the driven one) with an inter-element spacing of 4mm corresponding to $\lambda/30$ at an operating frequency of 2.5 GHz (so as to better control $\Gamma_{\text{in}}(f)$) and integrated onto a substrate of a dielectric constant of $\varepsilon_r = 4.2$ and a thickness of 0.813 mm.

Fig. 2 shows the envelope of $\Gamma_{\text{in}}(f)$, i.e. the minimum $\Gamma_{\text{in}}(f)$, in dB, where $\Gamma_{\text{in}}(f)$ is optimized for the corresponding frequency bin (the x-axis), as well as $\Gamma_{\text{in}}(f)$ optimized at $f = 2.5$ GHz as an example. In general, a bandwidth of K:1 denotes that the highest frequency is K times the lowest frequency in the frequency range where $\Gamma_{\text{in}}(f)$ is less than -10 dB, i.e. where the antenna efficiency is above 90%. Fig. 2 shows that the antenna system has a dynamic tunable bandwidth of 2.6:1,

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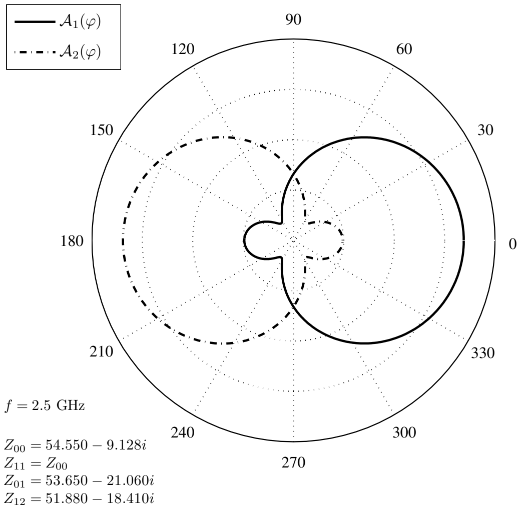

Fig. 3. The two narrowband beam patterns of the 3-element E3SPAR antenna of Fig. 2 at the resonant frequency of 2.5 GHz with 5.0 dBi gain.

indicated by the red rectangle, ranging from the GSM bands up to the ISM bands.

The 3-element E3SPAR can exploit the spatial dimension mostly over $N = 2$ narrowband beam-patterns (Fig. 3) by simply swapping the optimal loads of the two parasitic flat dipoles at a given frequency. Every beam-pattern samples a different part of the space, hence the probability of detecting a spectrum hole at a given subband almost doubles i.e., scales linearly with the number of the beam-patterns.

IV. Conclusion

The paper proposed a novel low-profile frequency-agile antenna for SUs' mobile terminals addressing the design challenges of spatial spectrum sensing in OSA. The 3-element E3SPAR antenna, unlike the classical 3-element ESPAR, exploits the mutual coupling between the PEs and the central active element for tuning the operational subband rather than for maximizing the SINR. The resonant frequency is varied by properly controlling the varactor diodes, a task not intended by the classical approach of using the ESPAR antennas with relatively larger inter-element spacing merely for beam-steering. Moreover, the narrowband beam-patterns are controlled in the analogue domain allowing the tunable cognitive antenna system to exploit the precious spatial resource.

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