Software-Defined Radio for Spectrum Sensing Using Independent Component Analysis

Paulo Ixtânio Leite Ferreira
Post-Grad. Prog. in Elec. Engineering, PPgEE – COPELE
Federal University of Campina Grande, UFCG
Campina Grande, Paraíba, Brazil
paulo.ferreira@ee.ufcg.edu.br

G. Fontgalland, Bruno B. Albert, and Edmar C. Gurjão
Department of Electrical Engineering, DEE
Federal University of Campina Grande, UFCG
Campina Grande, Paraíba, Brazil
{fontgalland, albert, ecandeia}@dee.ufcg.edu.br

***Abstract*—With the increment in data rates and new wireless services, the necessity for more radio frequency (RF) bandwidth for data transmission increases. Frequency spectrum is a scarce resource, and there is a necessity to optimize its use; in cognitive radio, spectrum sensing is the first task toward this optimization. It consists of detecting unused spectrum portions, allowing its use by a secondary user. In this paper, we apply the blind source separation method called Independent Component Analysis (ICA) for spectrum sensing, by detecting the presence and bandwidth of transmitted signals and by a complementary analysis to obtain non-used spectrum portions. A measurement setup with three uncorrelated sources and predefined bands is proposed. A software-defined radio implementing three independent transmitters and a broadband receiver antenna used to capture all signals. The results show the feasibility of using ICA for spectrum sensing.**

Keywords-Spectrum sensing; ICA; blind sources; software-defined radio; cognitive radio.

I. INTRODUCTION

Cognitive radios are communication systems with capabilities of monitoring the environment, to analyze the obtained parameters, to decide about possible adjusts, and to adapt itself according to this decision [1]. In this scenario, cognitive radio can adjust the transmission frequency to an unused frequency band to optimize the spectrum use. Spectrum sensing is the determination of empty frequency bands, realized in two steps: sensing the channels and using the obtained information to decide about what channels are empty.

Spectrum sensing methods are in three broad categories, namely energy detection, stochastic methods, and analysis of signal characteristics [2], [3]. Energy detection methods due their simplicity have low performance, mainly in a noisy environment. The stochastic methods are implemented by analyzing some statistical characteristics of the signal. These methods have good performance, even in noisy environment, but they have high computational complexity. Whereas signal features analysis is also very accurate, it implies in a previous knowledge of the signal characteristics, what may be difficult to detect in transmission of other secondary users, using their own systems.

Independent component analysis (ICA) is a blind method for source separation that has been very efficient in various scenarios. It has been applied in communications, image processing, audio separation [4], determination of direction-of-arrival (DoA) [5]. In this work, ICA is applied to identify signal sources in a broad band of frequencies and to use this information for spectrum sensing. Besides its low computation complexity [4], the ICA algorithm has good performance in presence of low signal-to-noise ratio (SNR), and it does not require prior information about the sources that occupy the monitored spectrum [6].

The spectrum sensing by ICA was implemented in a software-defined radio. An experimental setup was used to validate the proposed method.

The paper is organized as follows: the basic principle of ICA method is described in Section II. The software-defined radio is presented in Section III. We describe the experiment setup in Section IV. The results and some comments about them are shown in Section V. Finally, the conclusions are drawn in Section VI.

II. INDEPENDENT COMPONENT ANALYSIS

The ICA method uses statistical assumptions for blind source separation, and it allows recovering statistically independent signals from compositions of this signal, called mixture signals [7]. A linear model relates independent signals and mixed signals. This is model let us consider a vector of n signals $\mathbf{s} = [s_1, s_2, \ldots, s_n]^T$, and a vector of m measured signals $\mathbf{x} = [x_1, x_2, \ldots, x_m]^T$, where each signal x_i ($i = 1, \ldots, m$) is a linear combination of the n source signals. We consider $n < m$ to obtain the best ICA performance, as in [7].

Fig. 1 represents the basic principles of ICA, where the measurement vector **x** is formed by combining elements of vector sources **s,** via a matrix **A** (**x** = **As**). Even **s** and **A** are unknown, ICA can find a separation matrix **W**, such that the output vector **y** (**y** = **Wx**) is the optimal approximation of **s**.

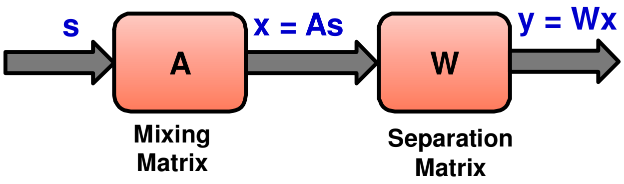

Figure 1. The ICA block diagram.

In this work, we use the FastICA algorithm. Fast ICA is an iterative fixed-point algorithm that minimize the mutual information of the estimated components from contrast function ($g = y^3$, for example) [9]. Assuming a whitened data vector and $\mathbf{w}^T$ is one of the rows of the separating matrix $\mathbf{W}$ (Fig. 1). Estimation of $\mathbf{w}^T$ is done iteratively optimizing the nongaussianity of the contrast functions and symmetric orthogonalization of $\mathbf{W}$ until a convergence is achieved. The convergence means that the old and new value of $\mathbf{w}$ point in the same direction, i.e. their dot-product is (almost) equal to 1[3].

III. SOFTWARE-DEFINED RADIO

Software-Defined Radio (SDR) proposed by Joseph Mitola III [10] as the implementation of flexible and reconfigurable radio based on software. Compared to traditional hardware implementations, SDR gives the possibility of implementing various radios on the same hardware, or changing the configuration by adjusting the software parameters. In addition, with the increase of processing power it becomes possible the use of sophisticated signal processing in the implemented radios.

GNU Radio [11] is an open source framework for development of SDR. Each SDR in GNU Radio is composed by a set of independent interconnected signal processing blocks, obtained from the built-in library or created by the user. The SDR developed using GNU Radio can run in a general-purpose processor, as a personal computer, and using a Radio Frequency (RF) interface, it is possible to transmit or to receive real signals.

The Universal Software Radio Peripheral (USRP) [12] is a RF front-end composed by a motherboard and a set of daughterboard. In the motherboard, there are analog-to-digital converters in the reception path (antenna to computer), digital-to-analog converters in the transmission path (computer to antenna), and a Field-Programmable Gate Array (FPGA) to multiplex the data from the reception daughterboard to computer and vice-versa.

The daughterboard performs the down conversion (reception) or up conversion (transmission). Each daughterboard is projected to a range of frequencies, and in a typical configuration have four daughterboard: two to transmission and two to reception.

IV. EXPERIMENTAL SETUP

To validate the use of ICA for spectrum sensing, an experimental setup is implemented, where three SDRs, as a signal sources, and another one as receiver of the mixed signals. Each source is considered as primary user (channel owner) to transmit a signal occupying a bandwidth in a specific frequency. Care was taken for signal bandwidths to not overlap. Transmitting antennas were arranged side-by-side, and they are positioned $d = \lambda_0/2$ (λ_0 is wavelength in free space at 1.252 GHz) a part. The SDR receiver is composed by an antenna and a spectrum analyzer, it receives the mixture signal. Once captured, the data are recorded and used in an offline application of ICA.

Fig. 2 shows the measurement setup with three primary users, and up to four measurements positions. The distances (l_i, $i = 1, 2, 3, 4$) between the transmitters and receiver antennas can be chosen randomly, assured the far field condition. For obtained results, the chosen distances are: $l_1 = 2.0$ m, $l_2 = 2.06$ m, $l_3 = 2.06$ m, and $l_4 = 2.24$ m.

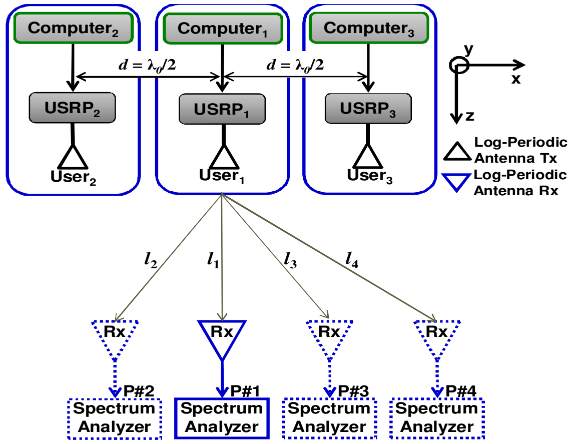

Figure 2. Measurement setup with three sources implemented in SDR.

As depicted in Fig. 2, each signal source is composed by one USRP connected to GNU Radio (computer). The SDR permits to configure the transmitted signal parameters like bandwidth, transmission frequency and amplitude. Dotted parts in Fig. 2 indicate the measurement points P#1, P#2, P#3 and P#4, sequentially.

Compared to other available setups, namely the ones that use signal generator as transmitters, the SDR provides more flexibility. In the former, waveforms are pre-programmed, and in the later the user has the capability of to configure the waveforms according to the application, e.g., by choosing the probability distribution of the signals, or any other parameter of interest.

A. *Description of Measurement Setup*

In the setup, each transmitter uses a log-periodic antenna; model WA5JVB, 0.9 – 2.6 GHz, and in the receiver was used a high gain broadband antenna (R_X) (log-periodic A.H Systems, SAS 510-7, 0.29 – 7.0 GHz). USRP and computer are connected via a Universal Serial Bus (USB) cable; and USRPs and antenna by coaxial cables of 1.10 m long. Measurements in positions P#1, P#2, P#3, and P#4 were done using a spectrum analyzer, R&S FSL6 (9 kHz – 6 GHz). The R_X positions (P#1 to P#4) were randomly chosen.

B. *Measurement Procedure*

Each primary user transmits a chirp signal generated by the SDR with 6 MHz bandwidth. Primary user frequency transmissions are $\text{User}_1 = 1.240$ GHz, $\text{User}_2 = 1.252$ GHz, and $\text{User}_3 = 1.264$ GHz. The receiver was configured to operate from 1.235 GHz to 1.270 GHz, with RBW 30 kHz , VBW 100 kHz, trace mode: max hold, and sweep point: 10,000.

The system was initially calibrated for each user individually. Firstly, the User_2 and User_3 are OFF, and measurement taken from User_1 as a single canal; secondly, by setting User_1 and User_3 in OFF, User_2 is measured; and finally, by setting User$_1$ and User$_2$ in OFF, the User$_3$ is measured.

V. RESULTS AND DISCUSSION

the spectra of primary users are show in Fig. 3. They were obtained for measurements in position P#1. These measurements were done for comparison purposes with the recovered spectrum by ICA.

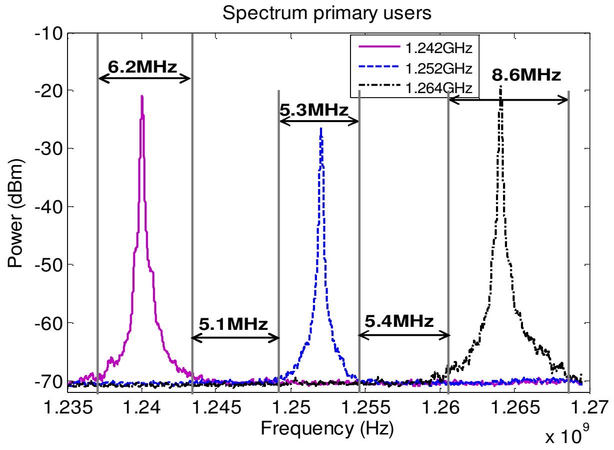

Figure 3. Spectrum original of the users, measured in position P#1.

In Fig. 3, it can be observed that the bandwidth between User$_1$ and User$_2$ is 5.1 MHz, and between users User$_2$ and User$_3$ is 5.4 MHz. The main goal in cognitive radio is to detect these empty spaces. Therefore, using ICA to detect the SDR transmission the empty band can be identified. All graphs presented here have undergone a smoothing of 0.005% through the method of moving average.

Details about signals of each user are given in Table I.

TABLE I. PARAMETERS OF USERS

Primary users	Parameters		
	Carrier Frequency (MHz)	*BW (MHz)*	*Maximum Power (dBm)*
User$_1$	1.240	6.2	– 21.01
User$_2$	1.252	5.3	– 26.51
User$_3$	1.264	8.6	– 19.34

After measured each individual signal, the next step is to measure the three users simultaneously (User$_1$, User$_2$ and User$_3$ in ON) transmitting. The transmitters (Users) are positioned near to each other. The measurements were conducted in free space, covering the band from 1.235 to 1.27 GHz (*BW* = 35 MHz). This bandwidth is six times larger than the one used in [13]. The spectrum of the received signals (User$_1$, User$_2$ and User$_3$) in four different positions is shown in Fig. 4.

At the top of Fig. 4 is shown the spectrum of the received signal that is composed by three users, measured at positions P#1 and P#2 (User$_1$ + User$_2$ + User$_3$); in the bottom it is shown the spectrum measured in positions P#3 and P#4. Note that the spectrum has bandwidths available between the one allocated by primary users. In a practical case, such space must be found by the spectral detection method. In this work ICA was used.

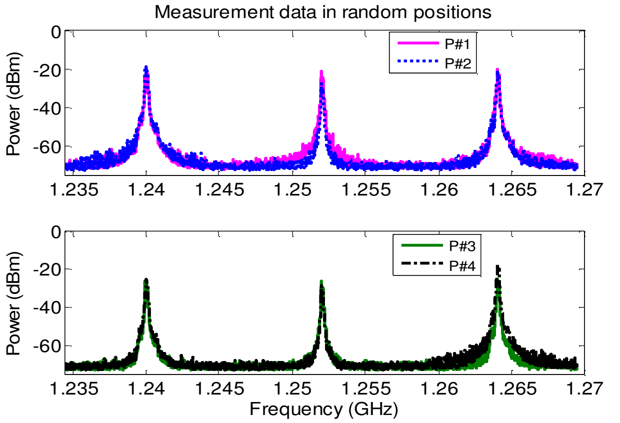

Figure 4. Composition of the spectrum received in positions P#1 to P#4.

The obtained measurements were used as the input of the ICA method. No additional information is needed in the receiver, as in [13] for instance, where it is assumed that the receiver already knows the bandwidth of the channels and the carrier frequency.

ICA was applied to the data measured in positions P#1 to P#4. They are the elements of the **x** vector (see Fig. 1). Initially, only three measured positions of the spectrum presented in Fig. 4 were considered. The results for the estimated spectrum using FastICA algorithm are shown in Fig. 5.

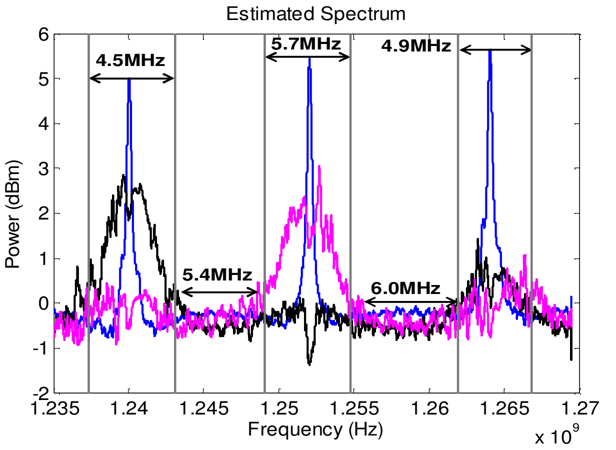

Figure 5. Estimated spectrum by ICA, from data shown in Fig. 4, in positions P#1 to P#3.

The spectrum obtained by ICA (Fig. 5) shows the frequency bands occupied by the primary users (4.5 MHz, 5.7 MHz and 4.9 MHz). The detected empty bandwidths are (2.2431 - 2.2485 GHz, and 2.2556 - 2.2665 GHz). The information about empty bands is the objective of this work, since it indicates where secondary users can be allocated to transmit. To determine the bandwidths, we consider points where the signal reaches 0 dBm. We can observe that the bandwidths are not the same as the original (Fig. 4), but are close to, except for the primary User$_3$. To overcome this problem, another measurement was considered in the estimation. Fig. 6 shows the spectrum estimated to four measurements in positions P#1 to P#4.

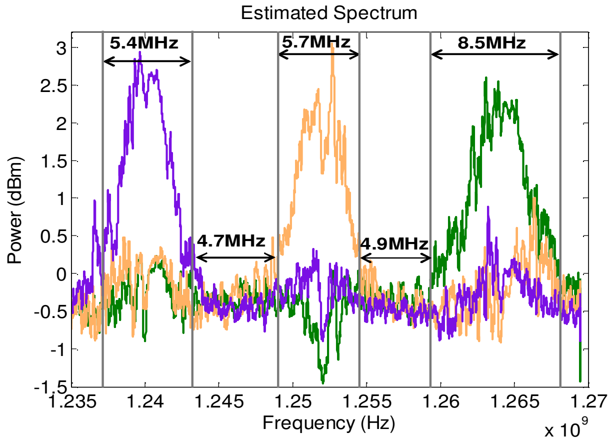

Figure 6. Estimated spectrum by ICA, from data shown in Fig. 4, in positions P#1 to P#4.

In the new estimated spectrum, shown in Fig. 6, it can be observed that the frequency bandwidths occupied by primary users are closer to the original spectrum, particularly for User$_3$. Estimated and occupied bandwidths by primary users are: 5.45 MHz, 5.75 MHz and 8.5 MHz. Once these bands are detected, such channels can be used to identify the empty bands, which are: 2.2438 - 2.2485 GHz (4.7 MHz) and 2.2546 - 2.2595 GHz (4.9 MHz). As expected, one can conclude that with more input data the ICA method was able to identify more precisely the primary users and the free frequency bands, which can be used for cognitive radio applications.

The necessity of more input data to make a better estimation does not compromise the computational cost of the FastICA algorithm. Although the signals used in the experiment do not have a defined bandwidth, the obtained results show that ICA can be applied to spectrum sensing in cognitive radio.

VI. CONCLUSION AND FUTURE WORK

In this paper, it was shown the application ICA methods to spectrum sensing. Results showed that ICA has advantages over traditional methods for spectrum detection, since it does not requires prior information about the channels to be detected. This fact allows it to detect the existence of other users that are not regulated (primary users). ICA can also sweep a wide frequency range without compromising the complexity and speed of the algorithm.

As a future work, we propose to compare ICA methods with traditional spectrum sensing methods in same conditions, to analyze the response of ICA in three scenarios: when the user bandwidth is not constant; in the low SNR regime (around 2 dB) that is different from was shown here; and when users are occupy open TV channels.

We also intend to use SDR in the receiver, instead of the spectrum analyzer, for implementing real time spectrum estimation.

ACKNOWLEDGMENT

The authors wish to thank the Applied Microwave and Electromagnetics Laboratory (LEMA), Signal Processing Laboratory (LAPS), Federal University of Campina Grande (UFCG), the Federal Institute of Science and Technology of Paraíba (IFPB) – *Campus* Princesa Isabel, and the Brazilian Agency (CAPES).

REFERENCES

[1] S. Haykin, “Cognitive radio: brain-empowered wireless communications”. IEEE Journal on Selected Areas on Communications, vol. 23, No 2, February, 2005, pp. 201–220.

[2] S. G. Mohapatra, A. G. Mohapatra, and Dr. S. K. Lenka, “Cyclo-stationarity Based Windowing Method for Spectrum Sensing in Cognitive Radio Networks”, in International Conference Information Communication and Embedded Systems (ICICES 2013), Tamilnadu, India, 2013, pp.603 – 608.

[3] R. S. Babu and M. Suganthi, “Review of energy detection for spectrum sensing in various channels and its performance for cognitive radio applications”, American Journal of Engineering and Applied Sciences (AJEAS), ©2012 Science Publication, 2012, pp. 151 – 156.

[4] A. Hyvärinen and E. Oja, “Independent component analysis: algorithms and applications,” in Neural Network, vol. 13, Iss. 4-5, May – Jun 2000, pp. 411 – 430.

[5] A. K. Khan, T. Onoue, K. Hashiodani, Y. Fukumizu, and H. Yamauchi, “Signal and noise separation in medical diagnostic system based on independent component analysis,” in IEEE Asia Pacific Conf. on Circuits and Systems (APCCAS 2010), Kuala Lumpur, Malaysia, 2010, pp. 812 – 815.

[6] P. I. L. Ferreira, G. Fontgalland, and B. B. Albert, “Spread-out overlapping sources by independent component analysis for location positioning,” in IEEE Transactions on Magnetics, vol. 49, No 5, May 2013, pp.1805 – 1808.

[7] P. I. L. Ferreira, G. Fontgalland, S. E. Barbin, and G. F. Aragão, “Separation of electromagnetic sources by the method of independent component analysis,” in IEEE International Instrumentation and Measurement Technology Conference (I2MTC 2013), May 6-9, 2013, Minneapolis, MN, EUA, pp. 476 – 479.

[8] P. I. L. Ferreira and G. Fontgalland, “Blind separation of multiple electromagnetic radiation sources,” Antenna Measurement Techniques Association, (AMTA 2013), in press.

[9] P. I. L. Ferreira, G. Fontgalland, and B. B. Albert, “Identification of sources with small phase difference by the method of independent component analysis,” IEEE CEFC 2012, Oita, Japan, Nov. 11 – Nov. 14, 2012 [Digests of the 15th Biennial IEEE Conference on Electromagnetic Field Computations].

[10] J. Mitola III, Software Radio Architecture: Object-Oriented Approaches to Wireless Systems Engineering. New York: Third John Wiley & Sons, 1996.

[11] GNU Radio home page, http://gnuradio.org/trac, accessed May 2013.

[12] Universal Software Radio Peripheral website, http://www.ettus.com/, accessed May 2013.

[13] N. Han, S. H. Shon, J. H. Chung, and J. Moung. Kim, “Spectral correlation based signal detection method for spectrum sensing in IEEE 802.22 WRAN systems”, the 8th International Conference Advanced Communication Technology (ICACT 2006), Gangwon-Do, Republic of Korea, 2006, pp. 1765 – 1770.