

A SOFTWARE-DEFINED RADIO APPROACH FOR DIRECTION FINDING

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The increasing demand for wide bandwidth wireless communication in the context of a finite available frequency spectrum has led to an acute need for spectrum-efficient technologies. One solution is the Cognitive Radio approach, a device aware of the environment and able to modify its own parameters accordingly in order to optimize the performance. An important capability that leads to a higher spectrum-efficiency is the ability to accurately localize the target transceiver in order to “steer” its antenna directivity towards it. This paper proposes a practical implementation of a passive Software-Defined Radio localization system, suitable for integration in a Cognitive Radio device.

Keywords: Software-Defined Radio, Direction-of-Arrival, Antenna Array, Multiple Signal Classification

1. Introduction

In the context of an accelerated growth in amount of information transported over wireless communication networks the quest for more spectrum-efficient technologies becomes compulsory [1].

Current technologies exploit Time Division Multiplexing and Frequency Division Multiplexing techniques in order to increase the capacity of a communication channel. As a consequence, in order to further improve the capacity beyond the current level it is necessary to address a different, previously unused parameter, namely space [2, 3].

This paper addresses Space Division Multiple Access technique from an experimental point of view, by proposing a practical Software Defined Radio approach capable of implementing direction finding, the first stage of the implementation of this multiple access technique.

The information about the direction of the radio source obtained from this stage will be used in the following stage of the system for “steering” the

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directivity of its antenna in order to obtain a minimum of interference between the users and therefore to increase the channel capacity.

Nevertheless, the proposed system can be used as a standalone, general purpose passive radar.

2. Related work

Similar Software-Defined Radio direction finding systems are presented in [4-6]. All of them use the Universal Software Radio Peripheral (USRP) development platform for acquiring the RF signals.

The implementation presented in [4] consists of two USRP 2920 connected through a MIMO cable.

The implementations described in [5] and [6] consist of 4 USRP2 boards, each fitted with a RFX2400 daughterboard. The systems also contain a synchronization unit providing a 10MHz reference oscillator signal and a 1 PPS digital clock signal. The host computer collects data via a gigabit Ethernet switch.

As a conclusion, all the USRP based Software-Defined Radio direction finding systems available in the scientific literature consist of at least 2 devices, making them a rather expensive approach, unsuitable for low-budget applications.

However, our system takes advantage of the newly released USRP dedicated TVRX2 daughterboard, implementing two radio frequency channels per device, in order to reduce the number of USRP devices to only one and thus significantly reducing the costs.

3. Proposed system architecture

The proposed system consists of a USRP N200 platform fitted with a TVRX2 RF daughterboard. This configuration provides two input channels, each channel connecting to a Vivaldi antenna. The choice for this particular antenna is motivated by its wide-band and ease of fabrication [7]. The other components of the proposed system are the RF transmitter acting as a calibration source and a computer, as depicted in Fig. 1 and Fig. 2.

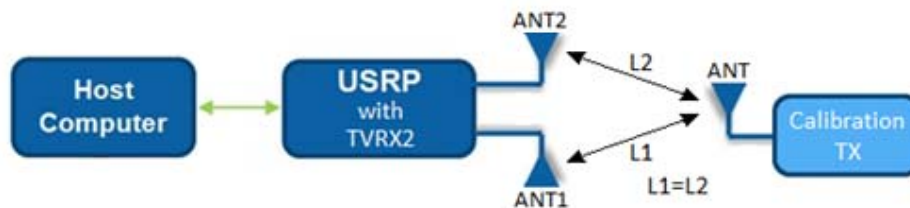


Fig. 1. Direction finding system – block diagram

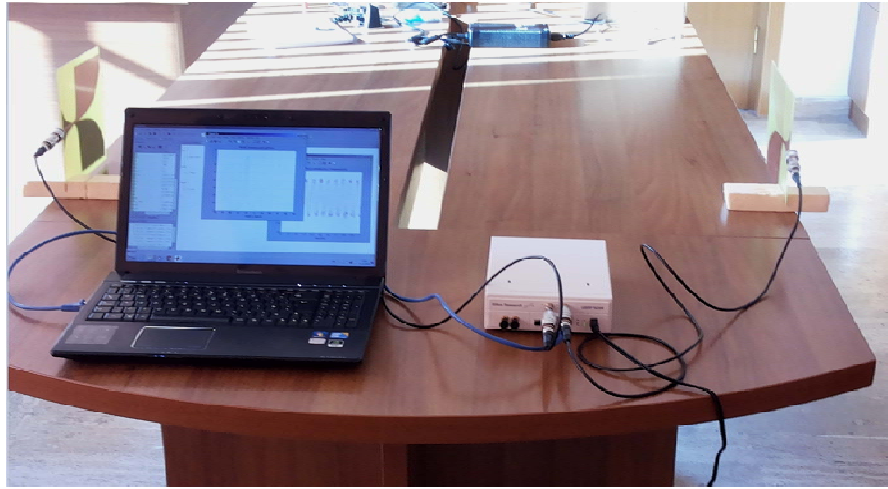


Fig. 2. Direction finding system – practical implementation

The TVRX2 board provides two down-converter chains, implementing a low-IF architecture. The local oscillator signals for both channels are derived from the same on-board reference oscillator using two fractional-N synthesizers. Therefore, after each retune, a random phase offset between the two channels will occur [8]. As a consequence, this random phase offset has to be measured and compensated in order to implement the direction-of-arrival algorithm. For this purpose, a RF transmitter is used as a calibration source and a calibration procedure is performed after each retune.

Two algorithms are tested for implementing direction of arrival estimation. The first tested algorithm is a subspace-based method, called MUSIC (*MUltiple Signal Clasification*). This algorithm is characterized by its higher resolution at lower number of antennas compared to other algorithms [9]. MUSIC algorithm relies on the received signal covariance matrix *eigen*-decomposition. In our case, the received signal matrix is:

$$\mathbf{X} = [\mathbf{x}(1), \mathbf{x}(2), \dots, \mathbf{x}(N)] \quad (1)$$

where $\mathbf{x}(n)$ is a column vector containing the samples at time n from both antennas, x_1 from the first antenna, x_2 from the second one:

$$\mathbf{x}(n) = \quad (2)$$

By taking into account the “signal model”, according to Schmidt [9] the previously defined matrix \mathbf{X} can be expressed as:

$$\mathbf{X} = \mathbf{a}(\varphi)\mathbf{S} + \mathbf{W} \quad (3)$$

where $\mathbf{a}(\varphi)$ is the steering vector computed according to equation (4).

$$\mathbf{a}(\varphi) = \begin{bmatrix} 1 \\ e^{j\frac{2\pi d}{\lambda} \sin \varphi} \end{bmatrix} \quad (4)$$

with the following notations:

φ - angle between the direction of the target source and the normal to the antenna array;

d - distance between the two antennas;

λ - wavelength of the target source signal.

\mathbf{S} is the source signal vector containing the samples of the target source signal:

$$\mathbf{S} = [s(1), s(2), \dots, s(N)] \quad (5)$$

\mathbf{W} is the additive Gaussian observation noise matrix:

$$\mathbf{W} = [\mathbf{w}(1), \mathbf{w}(2), \dots, \mathbf{w}(N)] \quad (6)$$

By using these notations, the received signal covariance matrix, \mathbf{R}_{xx} , can be computed using the following relationship:

$$\mathbf{R}_{xx} = \frac{1}{N} \mathbf{X} \mathbf{X}^H \quad (7)$$

By taking into account equation (3), \mathbf{R}_{xx} can be expressed as:

$$\mathbf{R}_{xx} = \mathbf{a}(\varphi) \mathbf{R}_{ss} \mathbf{a}^H(\varphi) + \sigma_w^2 \mathbf{I} \quad (8)$$

where \mathbf{R}_{ss} is the target source signal covariance matrix.

According to [9], equation (8) leads to the following eigenvalue decomposition of the received signal matrix:

$$\mathbf{R}_{xx} = [\mathbf{U}_s \quad \mathbf{U}_n] \begin{bmatrix} \lambda_s & 0 \\ 0 & \lambda_n \end{bmatrix} \begin{bmatrix} \mathbf{U}_s^H \\ \mathbf{U}_n^H \end{bmatrix} \quad (9)$$

where \mathbf{U}_s and \mathbf{U}_n are the signal and noise eigenvectors, λ_s and λ_n their associated eigenvalues, with $\lambda_s > \lambda_n$.

Because \mathbf{U}_s and $\mathbf{a}(\varphi)$ span the same subspace, called the signal-subspace, which is orthogonal to the noise-subspace, spanned by \mathbf{U}_n , the following relation holds [9]:

$$\|\mathbf{U}_n^H \mathbf{a}(\varphi)\| = 0 \quad (10)$$

The MUSIC pseudo-spectrum, also called Spatial pseudo-spectrum, is defined in [9] as:

$$P_{MUSIC}(\varphi) = \frac{1}{\|\mathbf{U}_n^H \mathbf{a}(\varphi)\|} = \frac{1}{\mathbf{a}^H(\varphi) \mathbf{U}_n \mathbf{U}_n^H \mathbf{a}(\varphi)} \quad (11)$$

It can be seen from equation (10) that the MUSIC pseudo-spectrum, $P_{MUSIC}(\varphi)$, has a pole in the direction of the target source. Using this property, it is possible to determine its direction.

In real world situations, equation (10) is not exactly satisfied since the true covariance matrix of the received signal is replaced by an estimate obtained from the acquired samples. As a consequence, the MUSIC pseudo-spectrum has finite values for each φ , so the direction of the source is represented by the argument of the maximum value of the pseudo-spectrum.

The second algorithm, described in [10], involves a more straightforward approach. It relies on the Cross-Spectral Density (CSD) function of the signals received by the two antennas. The CSD can be computed as the Fourier Transform of the Cross-Correlation of the two received signals or as the product between the Fourier Transform of the first antenna signal and the complex conjugate of the Fourier Transform of the second antenna signal. The second method highlights the ability of the CSD to provide the phase-shift between the two input signals, as follows:

$$CSD(f) = |X_1(f)| |X_2(f)| e^{j(\theta_1 - \theta_2)} \quad (12)$$

where $X(f)$ is the Fourier Transform of $x(n)$ and θ its corresponding phase.

The direction of the source is determined with the following relation:

$$\varphi = \sin^{-1}(\theta \frac{\lambda}{2\pi d}) \quad (13)$$

where θ is the phase of the CSD at the target source frequency.

4. Experimental results

In order to test the proposed implementation, a radio transmitter, employed as target source, is configured to generate an unmodulated sine wave with a frequency of 80.01 MHz. The selected frequency lies in the TVRX2 frequency range, extending from 50 to 860 MHz. In order to acquire the received signal, both channels of the TVRX2 board are configured with the same central frequency value, 80 MHz. Antennas are separated by a distance of 186 cm, nearly half a wavelength.

For the MUSIC algorithm, the complex baseband signals provided by the system after demodulation are filtered with a complex band-pass filter centered on 10 kHz, the deviation of the target source signal from the receiver center frequency. Five measurements were made with the target source placed at different bearings, as shown in Fig. 3.

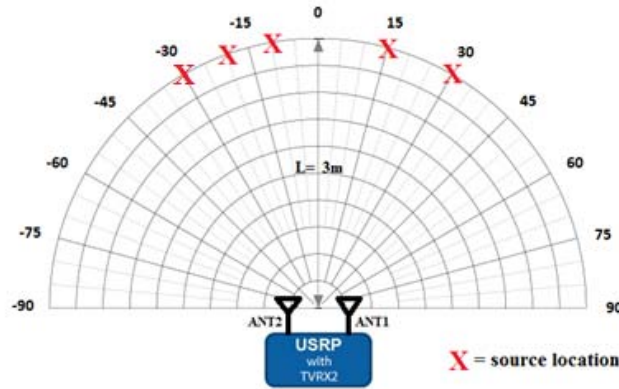


Fig. 3. Target source locations

The following figures show the MUSIC Spatial pseudo-spectrum, $P_{\text{MUSIC}}(\varphi)$, computed according to equation (11), for target source bearings φ of -30, -20, -10, 15 and 30 degrees between the target source direction and the normal to the antenna array. The direction of the source is obtained as the argument of the maximum value of the pseudo-spectrum.

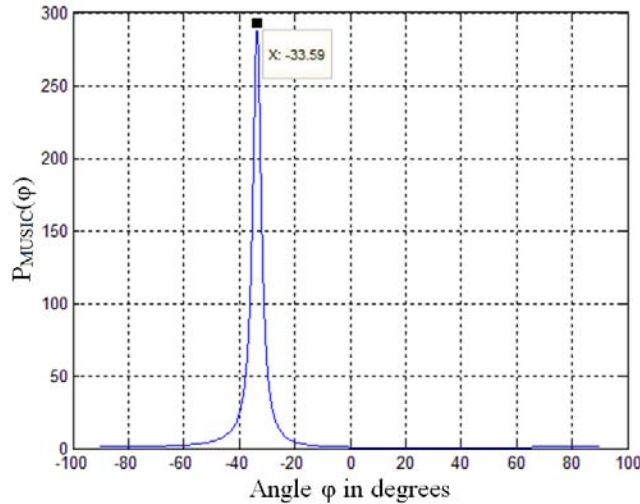


Fig. 4. Spatial pseudo-spectrum for an angle of -30 degrees between the target source direction and the normal to the antenna array

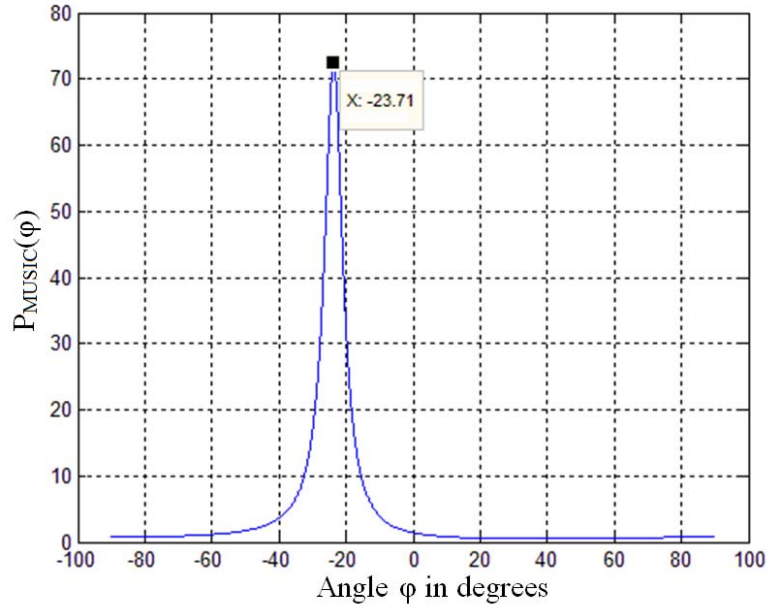


Fig. 5. Spatial pseudo-spectrum for an angle of -20 degrees between the target source direction and the normal to the antenna array

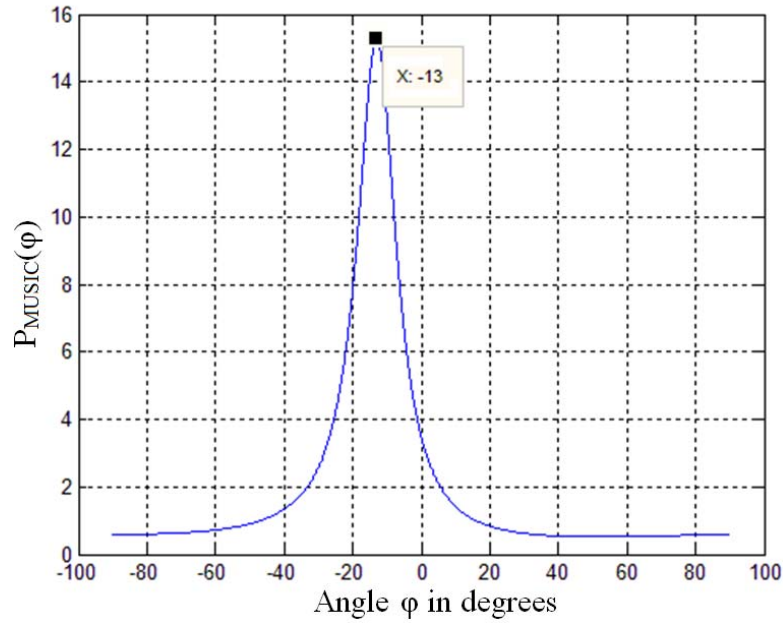


Fig. 6. Spatial pseudo-spectrum for an angle of -10 degrees between the target source direction and the normal to the antenna array

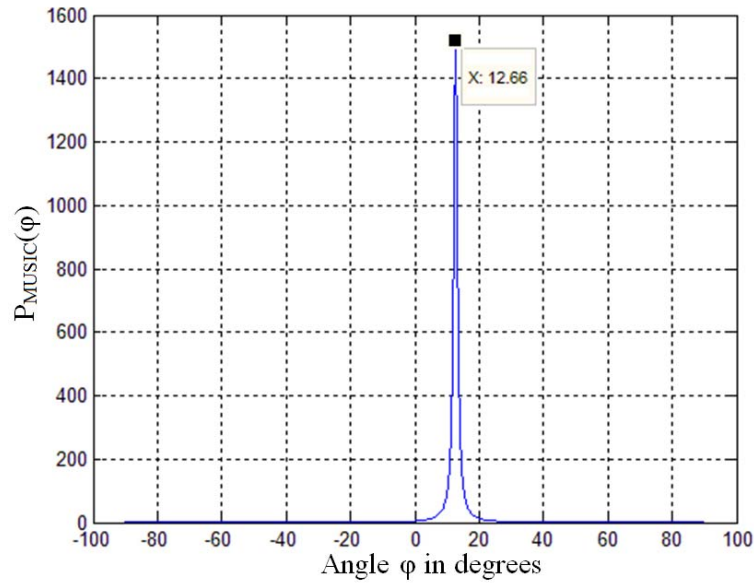


Fig. 7. Spatial pseudo-spectrum for an angle of 15 degrees between the target source direction and the normal to the antenna array

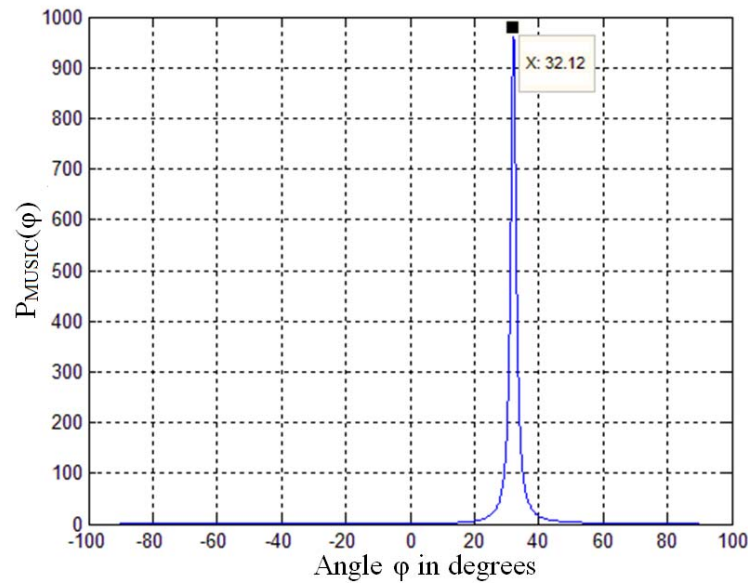


Fig. 8. Spatial pseudo-spectrum for an angle of 30 degrees between the target source direction and the normal to the antenna array

Table 1 summarizes the results issued from both methods, MUSIC and CSD. The relative error is calculated with the formula:

$$\text{Relative error [\%]} = \frac{\text{Estimated angle} - \text{True angle}}{\text{True angle}} \cdot 100 \% \quad (14)$$

Table 1

Comparison between MUSIC and CSD results

| True angle [degrees] | MUSIC | | CSD | |
|---------------------------|--------------------------------|-----------------------|--------------------------------|-----------------------|
| | Estimated angle [degrees] | Relative error [%] | Estimated angle [degrees] | Relative error [%] |
| -30 | -33.59 | 11.96 | -34 | 13.33 |
| -20 | -23.71 | 18,55 | -23.79 | 18,95 |
| -10 | -13 | 30,00 | -12.95 | 29,50 |
| 15 | 12.66 | -15,60 | 12.63 | -15,80 |
| 30 | 32.12 | 7,07 | 32.13 | 7,10 |

It can be noted that both methods, MUSIC and CSD, have the same overall accuracy in the conditions of this experiment.

MUSIC algorithm is expected to outperform CSD as the number of antennas in the array increases, in a single target source scenario [11].

Moreover, in the situation of multiple target sources MUSIC algorithm is the only choice, as CSD is not able to manage multiple sources.

5. Conclusions

In this paper we proposed a low-budget, two channels Software-Defined Radio approach for Direction Finding systems.

The mean absolute error of the localization is approximately 3 degrees. This value is higher compared to the 1 degree error produced by the 4 channels implementations in [5] and [6] but lower than the 10 degrees provided by the two channels system developed in [4].

From the economic point of view our system outperforms by far all the similar implementations presented in the scientific literature by reducing the cost to a value of 50% of the price for the implementation in [4] and less than 25% of the price of the implementations presented in [5] and [6].

For the future, we intend to implement a system capable of locating the target source in 2D using triangulation, integrating the results provided by two direction finding systems like the one described in this paper.

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