A Direction of Arrival Estimation System Using Five Ports Reflectometer

Ferid HARABI, Imen SFAR and Ali GHARSALLAH

Laboratoire de physique de la matière molle, Faculté des sciences de Tunis, TUNISIE
ferid.harabi@gmail.com
imen.sfar@voila.fr
ali.gharsallah@gmail.fr

Abstract: The estimation of directions of arrival (DOA) of RF signals in radar system domains, channel sounders and sonar, is an important topic of research since the last two decades. The directions of arrival estimation techniques have also an important impact on the spatial diversity study of the propagation channel (SDMA systems). In this paper, we propose a direction of arrival estimation system according to measures of phases achieved by five ports reflectometers that have the advantage to get the information of phase from measures of amplitude of three linear combinations of the RF waves and the local oscillator. Tension detection circuits are used to exits of the five ports to obtain baseband signals. A uniform linear array of four elements is used to receive RF signals at a frequency of 2 GHz. The estimation of directions of arrival is realised with the Extended-MUSIC algorithm. Performances of the system will be tested using ADS2002 and Matlab7.0.

Key words: DOA estimation, Extended-MUSIC, Five ports reflectometers, power detector.

INTRODUCTION

The technique for estimating the parameters of multiple waves provides a convenient tool for the analysis of multiple-waves fields and eventually for actual applications to mobile communications and the problem of estimating directions of arrival (DOAs) of multiple sources was the topic of several researches [Kre 89, Hua 91, Mar 93, Li 95, Wu 03, Liu 05]. The six ports and five ports reflectometers are usually used for the measurement of coefficients of reflection, frequency discriminator for radar applications and demodulator of RF signals [Eng 72, Mig 00, Nev 01]. In the channel sounder based on frequency technique the spectre of the channel is measured by step of frequency in a chosen frequency band [Cha 03, Kur 02]. Then, to apply the five ports systems to a channel sounder it is indispensable to calibrate the system in all the band of frequency.

It exist several methods of calibration [Nev 03, Fra 97, Sou 03]. In [Fra 97] a robust calibration method is presented but it asks for a lot of calculations because of its complexity. Another method based on training sequences has been presented in [Nev 03]. However, its inconvenience is the limit of the RF signal power (<-20 dBms). A new method that is based on the measure of differences of the three tensions phase in the out of the five ports has been presented [Sou 03]. Nevertheless it is applied for only one frequency.

In this paper, we present a system for the estimation of directions of arrival using an antennas array. The output of each element of the antennas array is connected at a five port reflectometer. The three outputs of each five ports reflectometer will be adjusted with a power detector based on Schottky diodes to have answers of these elements in the base band. Then we use the Exented-MUSIC algorithm, that we have presented in [har 07], for the estimation of directions of arrival of sources received on the antennas array. A uniform linear array of four elements is used to receive RF signals at a frequency of 2 GHz. The blocks diagram of the system is presented in figure1. The rest of the paper is organized as follow: section II describe the five ports reflectometer used in the system, section III shows a review of the Extend-MUSIC algorithm, section IV shows the simulation results and the principal advantages of the system of detection and section V makes conclusions.

1. The Five ports reflectometer

The five-port reflectometer presented in figure 2 is a linear passive circuit having two inputs and three outputs.
The five ports system consists of a five access interferometric ring implemented in microstrip technology. Two accesses of the five arm ring are the RF and local oscillator input ports and the three others are each connected to a diode power detector followed by a low-pass filter.

The complex envelope information when using the five ports technique is obtained by making only amplitude (or power) measurements of three different linear combinations of RF and local oscillator electromagnetic waves. This means that a five ports discriminator is in principle simply a passive linear circuit with two input ports and three output ports (hence its name). Indeed, the five ports discriminator is a constrained version of the six-ports which was originally designed to measure the reflection coefficient of microwave loads. Introduced by G. F. Engen and C. A. Hoer in 1972 [Eng 72], the six-port discriminator was widely used in metrological laboratories to perform precise RF circuit measurements. If the local oscillator (LO), used as reference of phase and frequency, is stable enough so that its power can be assumed to be constant, one of the six-port outputs may be neglected and the complex ratio between input signals may be well accomplished in five ports system.

This system has the purpose to generate a signal $x(k)$ in the digital domain representing the complex ratio between the two input RF and LO signals as a linear combination of the three analogic voltages at the power detectors outputs. After the calibration, this complex ratio is computed by digital signal processing (DSP) after A/D conversion of power detector output voltages $v_3$, $v_4$ and $v_5$.

The $S$ matrix of the five ports reflectometer permits us to write:

$$b_i = \sum_{j=1}^{5} S_{ij} a_j \quad \text{pour} \ i \in \{1,2,3,4,5\} \quad (1)$$

with $a_i$ and $b_i$ are the inputs and outputs powers of the wave, respectively.

### 1.1. The Five-ports reflectometer Ring:

The ring with five branches (figure 3) is one of the simplest systems of five ports reflectometers with symmetrical accesses, we can see on figure 3 that two adjacent ports are connected by a transmission line of electric length $L$ and a characteristic impedance $Z$. we can prove that at a frequency equal to 2 GHz that:

$$L = 75.5^\circ \quad \text{and} \quad Z = \frac{\sqrt{3}}{2 \sin(L)} Z_l = \frac{2}{\sqrt{5}} Z_1 \quad (2)$$

with $Z_l$ is the line impedance in the five access points and it’s equal to 50 $\Omega$. $L$ is the angle between the access lines and $Z$ is the line impedance that construct the ring.

The ring dimensions are optimized by the ADS (Advanced Design System) software for a five ports system working around 2 GHz.

This optimization is performed by minimizing the reflection coefficient at the 5 accesses of the ring for frequencies around 2 GHz. The present ring is printed on an FR4 substrate with the following characteristics:

- **Dielectric features:**
  - epoxy;
  - width: $h = 1.59 \ mm$;
  - permittivity: $\varepsilon_r = 4.1$;
  - dielectric losses: $\tan(\varepsilon) = 0.02$.

- **Conductor features:**
  - copper on both sides of the substrate;
  - copper thickness, $e = 35 \ \mu m$. 

**Figure 1. The estimation system blocks diagram**

**Figure 2. The five ports reflectometer**
The optimized dimensions are as follows:

- Width of the access lines (50 ohms): 3.16 mm;
- Width of ring: 3.6 mm;
- Radius of the ring: 10.2 mm.

Figure 3. The symmetric ring five ports reflectometer

1.2. the power detectors circuit:

As illustrated in Figure 2, a Schottky diode is connected to each five arm ring output. The non linear and current-voltage characteristic of this kind of diode permits its use as a power detector with input voltages given by \( v_{in, i} \), \( i \in \{3, 4, 5\} \). An Agilent Schottky diode (HSMS2850) with reflection coefficient magnitude of about 0.6 at 2 GHz is used.

A Schottky diode and a low-pass filter (RCL) make up the power detector illustrated in Figure 4. The low-pass filter rejects the HF terms after diode mixing. Assuming that the power detectors are permanently connected at the five ports output ports, one may write:

\[
P_i = |b_i|^2 (1 - \Gamma_j^2), i=3, 4, 5
\]

By manipulating equations, it is possible to write the complex ratio between the input pseudo power waves as a linear combination of the voltages \( v_{out-3} \), \( v_{out-4} \) and \( v_{out-5} \) measured at the low-pass filter outputs after dc-offset cancellation

\[
x = a_3 v_{out-3} + b_3 v_{out-4} + y_3 v_{out-5}
\]

where the complex values \( a, b \) and \( y \) are three calibration constants and \( v_{out-3} \), \( v_{out-4} \) and \( v_{out-5} \) are proportional to \( P_3 \), \( P_4 \) and \( P_5 \). The calibration constants are determined by a calibration procedure such as the one presented in [nev 05].

2. The Extended-MUSIC Algorithm

In [har 07], we present a new subspace-based 2-D direction of arrival estimation method based on the properties of an extended covariance matrix developed by Horn and Johnson in [hor 94].

The correlation matrix of sensor observations \( X(t) \) is calculated:

\[
R = X(t).X(t)^H
\]

where \( H \) represents a conjugate transpose and \( X \) is a vector composed by the calibrated outputs of the power detectors. In practice, only a sample covariance matrix is available, i.e., an estimate of \( R \) based on a finite number \( P \) of data samples or snapshots

\[
\hat{R} = \frac{1}{P} \sum_{j=1}^{P} X(t_j).X(t_j)^H
\]

Then, obtain the eigenvalues decomposition \( \hat{R} = V \Lambda V^H \), \( V = [v_1, \ldots, v_N], \Lambda = \text{diag}[\gamma_1, \ldots, \gamma_N] \), where \( v_k \) is an eigenvector (N-dimensional column vector) and \( \gamma_k \) is the eigenvalues of \( v_k \) sorted as \( \gamma_1 \geq \gamma_2 \geq \cdots \geq \gamma_K \).

We define the new correlation matrix as:

\[
G^p = \hat{R} + m a(\varphi) a(\varphi)^H
\]

where \( \hat{R} \) is given in (7), \( a(\varphi) \) is \( 1 \times N \) array response vector for direction \( \varphi \) and \( m \) is a positive scalar. The matrix \( G^p \) is also positive definite and if \( \mu_k \) and \( \epsilon^k \) denote eigenvalues and eigenvectors of \( G^p \) respectively, \( k=1, \ldots , N \),
Then it can be shown that while $m$ in (8) is a positive scalar we have [hor 94]:

$$
\mu_k \geq y_k \quad k=1,\ldots,N \quad \forall \varphi
$$

(9)

Another important property of $G^{\varphi}$ is that when $\varphi$ in (8) is set to one of the source directions, i.e., $\varphi = \theta_k$ for some $1 \leq k \leq K$, then it can be shown that

$$
\mu_k \geq y_k \quad k = 1,\ldots,K
$$

$$
\mu_k = y_k = \sigma_n^2 \quad k = K+1,\ldots,N
$$

(10)

We can note that except the actual source directions no other value of $\varphi$ have the properties showed in (9) and (10). The property stated in (10) does not depend on the value of scalar $m$ of (10) explicitly and will hold while $m$ is positive. Based on the above proprieties of the extended covariance matrix $G^{\varphi}$ an algorithm for estimating the direction of sources can be formed with the following steps:

1- From $P$ data samples compute $\hat{\mathbf{R}}$.

2- Compute $\hat{\mu}_k$, $k=1,\ldots,N$, the eigenvalues of $\hat{\mathbf{R}}$ that are in decreasing order.

3- Choose a positive $m$ and compute $G^{\varphi}$ for all possible values of $\varphi$.

4- For each value of $\varphi$, compute $\mu_k^{\varphi}$, $k=1,\ldots,N$ the eigenvalues of $G^{\varphi}$ and calculate the function $D(\varphi)$ as:

$$
D(\varphi) = \frac{1}{\sum_{k=1}^{N} (\mu_k^{\varphi} - \hat{\mu}_k)}
$$

(11)

5- Find all the values of $\varphi$ that maximize $D(\varphi)$. The azimuth angles of sources $\theta_1,\ldots,\theta_K$ are those values of $\varphi$ that correspond to $K$ largest maximums.

3. Simulation Results

Figure 5 illustrates simulation results of return loss at the RF input port of the five ports reflectometer. The curve shows that the circuit input is well matched ($S_{11} < -10$ dB) over a wide band of 1 GHz around 2 GHz. The circuit symmetry guarantees similar performance at the input port 2.

The magnitude of $S_{13}$ and $S_{14}$ and $S_{15}$ as a function of the frequency are presented in Figure 6. We can see that $S_{ij}$ ($i \neq j$) has magnitude around 0.5 at 2 GHz.

**Figure 5. The reflection coefficient of RF input port of the five port reflectometer**

At the output of the diode, the low frequency component of the signal generates a voltage ($v_{\text{out}-i}$, $i=3,4,5$) across the output resistor ($R$), which is a linear function of the RF signal power. Figure 4 shows a DC-block capacitor (CIN) and a 50-Ohm resistor used to match the power detector over a wide bandwidth. Its reflection coefficient simulated with ADS is illustrated in Figure 7 with the matching circuit and shows a good adaptation at 2 Ghz.

Figure 8 presents the spectrogram of estimation of a single source located at an azimuth angle 60° with the Extended-MUSIC method. The pick of the spectrogram coincide with the true direction of arrival that validate the objective of the system.

**Figure 6. The transmission coefficient between the RF input and the outputs of the five port reflectometer**
**Figure 7.** The input reflection coefficient of the power detector circuit

**Figure 8.** Spectrogram of estimation of a single source located at 60° with a SNR = 10dB and 10 snapshots

4. Conclusions

In this paper, we have presented a system for the detection of direction of arrival of sources using an antennas array. A demodulator based on five ports technology is used to obtain the signal in the base band form. The outputs of the demodulator are calibrated and introduced in the high resolution Extended-MUSIC algorithm to obtain an estimation of the azimuth angle of the source. The realization of this system after the simulation study will be our objective.

REFERENCES


