Direction of Arrival Estimation of RF Signals Using Five-Port Technology and High Resolution Method

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Abstract: This paper presents a system based on five-port demodulator which measures DoA (directions-of-arrival) of radio frequency signals received on an antenna array in the azimuth plane. The receiver operating at 2.4 GHz is composed of four five-port demodulators connected to a ULA (uniform linear array) of four patch antennas. The DoA is estimated by measuring the phase difference of signals picked up by the elements of the array. Analytical and measurement results prove high integration, low-cost implementation and less sensibility to the phase and amplitude imbalances of the proposed demodulator. Moreover, the system presents good performance in terms of precision and resolution by using MUSIC (MUltiple SIgnal Classification) method in DoA estimation.

Key words: Direction of arrival, five-port demodulator, homodyne receiver, antenna array processing, MUSIC algorithm.

1. Introduction

DoA (Direction-of-arrival) estimation is required in many applications as in mobile communication systems, radar, satellite communications and so forth. This information is important for localization purposes and for radio channel modeling. Recently, measurement of DoA of RF (radio frequency) signals for radar, mobile and sonar system has been well investigated. The majority of DoA measurement systems are determined in baseband processing of the demodulated signal such as [1] and not on direct measurement of their phase. Heterodyne receivers were employed for decades, partly due to their excellent sensitivity and selectivity characteristics. However, because of their high cost, the IQ homodyne structure is preferred, which consists of fewer RF components allowing a high degree of integration and low power consumption. Nevertheless, this structure presents some disadvantages such as the drift of DC voltages (DC offset) and I/Q mismatch problems.

In this paper, another type of homodyne demodulator based on five-port circuit will be presented and it will be shown that this technique is able to overcome problems of the traditional IQ demodulators.

Originally conceived to measure the reflection coefficient of microwave network ports, the six-port reflect meter has been applied in many systems such as a frequency discriminator in radars [2] for example or a demodulator in homodyne receivers [3]. If the local oscillator, which is used as reference of phase and frequency, is stable enough so that its power can be assumed to be constant, one port of the reflect meter may be neglected and the applications previously
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mentioned may be well accomplished in five-port system [4].

Among the advantages of using the five-port technique is that the phase information is obtained by making only amplitude or power measurement of three different linear combinations of RF and local oscillator electromagnetic waves.

The five-port demodulator also performs a direct conversion but using a redundant mixer and a 120 degrees basis [5] instead of cartesian basis, which makes five-port system more robust to the phase and amplitude unbalance of the local oscillator. Other advantage of the present system is the reduction of the number of baseband circuits, which explains its low-cost compared to a conventional demodulator.

On the other hand, this system will be applied to estimate DoA using a ULA. The output of each element of this array is connected to a five-port demodulator in order to have responses of these elements in the baseband. Then MUSIC algorithm [6] will be used to estimate DoA of RF signals picked up by the ULA [7]. we treat here only non-coherent signals and we suppose that the channel parameters correspond to a real environment. Inspired by experimental models already studied [8], we have developed our own Matlab code to show the estimation results.

The rest of the paper is organized as follows. Five-port demodulator is presented in section 2 and measurement system is described in section 3. The DoA estimation procedure of signals is presented in section 4 followed by the simulation results and the main advantages of the detection system in section 5.

2. Five-Port Demodulator

We present in Fig. 1 the five-port demodulator that we have implemented in microstrip technology. This five-port demodulator is made up of a ring interferometer with five arms corresponding to 2 inputs and 3 outputs. RF and LO signals are injected into these inputs and each output is connected to a diode power detector used as a mixer and followed by a butterfly rejection filter and a low pass filter.

Power detector is based on Schottky diode to have response in baseband and the type of substrate used is the TMM4 which is characterized by $\varepsilon_r = 4.5$ and a thickness of 1.524 mm. More details on five-port demodulator components can be found in Ref. [9].

Fig. 2 shows the block diagram of a receiver based on five-port demodulator.

Each five-port output voltage is measured and digitized by an ADC (analog-to-digital converter). This system generates at the output of the DSP

![Five-port demodulator implemented in microstrip technology.](image)

Fig. 1  Five-port demodulator implemented in microstrip technology.
(digital signal processing) a signal $x(t)$ in temporal domain then representing the complex ratio between the two input RF and LO signals. This complex ratio is determined as a linear combination of the output voltage levels $V_3(t)$, $V_4(t)$ and $V_5(t)$ [5] and can be written as Eq. 1:

$$x(t) = I + jQ = aV_3(t) + \beta V_4(t) + \gamma V_5(t)$$  \hspace{1cm} (1)

where $I + jQ$ is the complex envelop; and $a$, $\beta$ and $\gamma$ are the complex calibration constants obtained by a calibration procedure presented in Ref. [9]. Besides, a linearization fitting of the power detectors is necessary to accomplish the power detection over a wide dynamic range.

### 3. Measurement System

Fig. 3 shows the array of four rectangular patch antennas that we have printed in FR4 substrate with $\varepsilon_r = 4.5$ and a board thickness of 1.59 mm. The separation between consecutive elements is $\lambda/2 = 43.25$ mm in the horizontal axis, where $\lambda$ is the wavelength at 2.4 GHz frequency. The dimensions of the patch antennas were optimized to work around that frequency.

Simulation and measurement results of the input return loss for one of these patch antennas are shown in Fig. 4. We observe a good matching at the operating frequency with a measured value around -30 dB. The two curves are not superimposed because of the inaccuracy of the measuring instruments and the losses of the substrate. measurement system is illustrated in Fig. 5.

The CW signal provided by the generator is amplified and radiated by the transmitting antenna which is located at chosen angular and distance positions from the receiver. These angles represent the DoA that have to be determined by the receiver block.

![Homodyne receiver based on five-port demodulator](image)

![Receiving antenna array: (a) front view; (b) side view](image)

![Simulation and measured input return loss of a rectangular patch antenna](image)
Fig. 5 Measurement System.

On one side, the output of each antenna is connected to an input of five-port demodulator, the other input being connected to a reference signal (LO). On the other side, all outputs of the five-port are connected to a sample and hold circuit (S/H) which is used to freeze signals at the same time before performing the analog-to-digital conversion.

The three output voltages of each five-port demodulator are measured at each frequency and stored for the post processing step in order to estimate the DoA of signals in the azimuth plane.

4. DoA Estimation Procedure

MUSIC algorithm is chosen because its robustness and accuracy have already been demonstrated by many authors [6-10].

Let us review the procedure of this algorithm [6]. The correlation matrix of sensor observations \( x(t) \) is calculated according to Eq. (2):

\[
R = x(t) x(t)^H
\]

where \( H \) represents a conjugate transpose.

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:

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

\( x(t) \) is the response vector taken on the five-port demodulator outputs given in Eq. (1).

Then, we obtain the eigenvalues decomposition:

\[
\hat{R} = V \Lambda \Lambda^H, \ V = [v_1, ..., v_N], \ \Lambda = \text{diag} \ [y_1, ..., y_N]
\]

where \( v_k \) is an eigenvector (N-dimensional column vector) and \( y_k \) is the eigenvalue of \( v_k \) sorted as \( y_1 \geq \cdots \geq y_K \) the \( K \) points where the function:

\[
U(\theta) = \sum_{k=K+1}^{N} |v_k^H a(\theta)|^2
\]

approaches zero and corresponds to directions \( \theta_1, ..., \theta_K \) of the sources signals, and \( a(\theta) \) is the steering vector obtained with the ULA shown in Fig. 6 as:

\[
a_n(\theta) = \exp \left( -j \frac{2\pi}{\lambda} d(n-1) \sin \theta \right) \text{ with } n = 1, ..., N.
\]

where \( \lambda \) is the incoming signal wavelength and \( d \) is the distance between the sensor elements.

5. Results and Discussion

As noted above, we have realized four five-port demodulators and a ULA. The system generates a continuous wave signal whose power is divided into four equal powers through the use of power splitters.

Fig. 6 Plane wave model on a linear array antenna.
Fig. 7 Spectrogram of estimation of two non-coherent signals located at (75°, 120°) with 100 snapshots.

Fig. 8 Spectrogram of estimation of three non-coherent signals located at (20°, 60°, 75°) with 100 snapshots.

Fig. 9 Spectrogram of estimation of three non-coherent signals located at (20°, 60°, 75°) with 200 snapshots.

Fig. 7 presents spectrogram of estimation of two non-coherent signals located at (75°, 120°), respectively, receiving at the ULA. The angle of arrival is estimated by MUSIC method using 100 snapshots. The figure shows two peaks coinciding with the real DoA with a high precision, which proves the validity of the proposed system.

In Fig. 8 the system estimates three sources located at (20°, 60°, 75°), respectively. Only two sources are located. The third angle does not appear which indicates a certain failure of the system in some situations.

To solve this problem in our system, we need to increase the time of observations as shown in Fig. 9. It is clear in view of these figures that the non-coherent signals can be detected and the picks of the pseudo-spectrum MUSIC may well coincide with the true directions of arrival, which validates the objective of the system.

However, the disadvantage of employing MUSIC is that the number of signal measured must be smaller than the number of antenna elements.

There are other high resolution methods such as ESPRIT (estimation of signal parameters via rotational invariance techniques) [11] or ML (maximum likelihood) [12] that can be used to estimate DoA and may possibly be more appropriate.

6. Conclusions

Directions-of-arrival estimation results of non-coherent signals in azimuth plane are presented in this paper. The receiving system adopted is composed of four five-port demodulators and a uniform linear array composed of four rectangular patch antennas. The MUSIC method is used to estimate the DoA.

The obtained results show good consistency of the proposed measurement system and high precision for the DoA estimation. However, problems of estimation are remarked with a limited number of observations and a high number of sources. This inconvenient has
been solved by increasing the time of observations on the antenna array.

References


