

## Indoor Characterisation using High-Resolution Signal Processing Based on Five-Port Techniques for Signal Input Multiple Output Systems

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**Abstract: Problem statement:** The development of wideband mobile communication systems requires a deep knowledge of the characteristics of the indoor mobile radio channel. The characterization of the indoor multi-path propagation structure is important in developing antifading techniques for high-speed digital radio access. The high-resolution of the estimation of the Time of Arrival (ToA) and the Direction of Arrival (DoA) of multi-path signals in wireless communication involves locating a source of Radio Frequency (RF) waves and then directing the beam of antenna in the estimated direction. The time dispersion is relatively small and the frequency dispersion is rather low compared to those expected in outdoor environments. Those characteristics require a high resolution system. This improved the performance of communication system. **Approach:** The DoA was estimated by measuring the phase difference of signals detected by an antenna array while the estimation of ToA was based on the phase difference measured over two successive frequencies. Low cost and high-resolution were obtained by using five-port receivers and the MUSIC algorithm. The simulation of five ports junction was developed using Advanced Design System (ADS). It was used to optimize the parameters of the structure and the antennas. **Results:** We obtained the adapted ring with the desired functions, splitting the received power equally over the output branches with a dephasing of  $120^\circ$ . The corresponding output signals appear with an amplitude variation depending on the dephasing between the RF and OL signals. **Conclusion:** Simulation results, performed around the 2.4 GHz frequency, showed an excellent estimation of the ToA and DoA with a high resolution and a reduced errors in both the time and the direction of multi-path signals.

**Key words:** Five-port system, phase discriminator, channel sounder, MUSIC algorithm, time and direction of arrival

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### INTRODUCTION

The development of wideband mobile communication systems requires a deep knowledge of the characteristics of the mobile radio channel. A channel sounder can perform a multidimensional small-scale characterization of channels for communication system evaluation, such as allowable data rates. The aim of the present work is to study the sounding of Signal Input Multiple Output (SIMO) propagation channels in indoor environments. Some of the requirements of a channel sounder are resolution in the time delay, in the angular domain and in the fast measurement repetition rate<sup>[1,8]</sup>. Proposed channel sounder has a parallel receiver architecture reaching high-resolution capabilities by using the Multiple Signal Classification (MUSIC) algorithm both in the time and angular domain<sup>[2,3]</sup> for a non-coherent

Continuous Wave signal (CW). Using five port junction and a modified MUSIC algorithm we have a better precision on the estimation of ToA and DoA parameters. That is the advantage of this developed research.

Some simulation results on delay and angular estimation demonstrate the capability of the developed channel sounder. We treat in our case the non-coherent signals and we suppose that the parameters of the channel sounder are presented in a real environment and according to its parameters, inspired from experimental models already studied, we can develop Matlab codes showing the estimation results.

**Description and operating principle:** The five-port system shown in Fig. 1 consists of a five-access interferometer ring. Two accesses of the five-arm ring are the RF and local oscillator input ports and the three

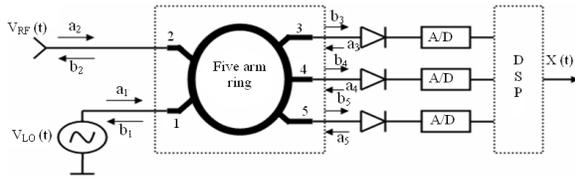


Fig.1: Receiver based on a Five-Port discriminator

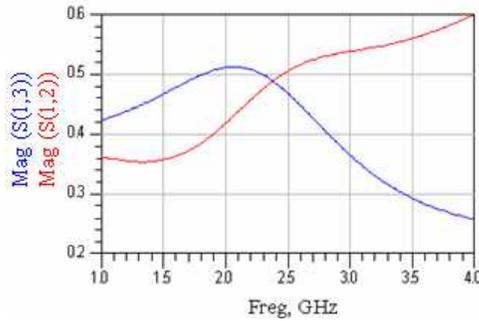


Fig. 2: The amplitude of  $S_{12}$  and  $S_{13}$  as a function of frequency

others are each connected to a diode power detector followed by a low-pass filter. This system has the purpose to generate a signal  $x(t)$  in temporal domain representing the complex ratio between the two input RF and LO signals as a linear combination of the three analogical voltages at the five-port discriminator outputs. This complex ratio is computed by digital signal processing (DSP) after A/D conversion of five-port output voltages  $v_3$ ,  $v_4$  and  $v_5$ .

The simulation of five port junction is developed using Advanced Design System (ADS) of Agilent technologies.

The magnitude of  $S_{12}$  and  $S_{13}$  are presented in Fig. 2 as a function of the frequency. We can see that  $S_{ij}$  ( $i \neq j$ ) has magnitude around 0.5 and we determine the phase difference between  $S_{12}$  and  $S_{13}$  magnitude is approximately  $120^\circ$  around 2.4 GHz.

We attain our purpose and we obtain the adapted ring with five arm functions like a power divider, splitting the power received in entry and distributing powers equal to each one of four other ways with dephasing  $\pm 120^\circ$ .

The five-arm ring performs three vectorial additions between the two input signals  $a_2$  and  $a_1$ . Using Fig. 1, we can write:

$$b_i = A_i a_1 + B_i a_2, \quad i \in \{3, 4, 5\} \quad (1)$$

where,  $A_i$  and  $B_i$  are the complex parameters depending on the S parameters of the circuit with 5 accesses. The output voltages after detection are:

$$v_i = K_i |b_i|^2 = K_i |A_i a_1 + B_i a_2|^2, \quad i \in \{3, 4, 5\} \quad (2)$$

The  $K_i$  factor ( $>0$ ) is defined by the sensitivity of the power detectors<sup>[5]</sup>.

By manipulating Eq. 2, it is possible to write the complex ratio between the input pseudo power waves as a linear combination of the voltages  $v_3$ ,  $v_4$  and  $v_5$  measured at the low-pass filter outputs:

$$x(t) = g_3 v_3 + g_4 v_4 + g_5 v_5 \quad (3)$$

where, the complex values  $g_3$ ,  $g_4$  and  $g_5$  are obtained using calibration measurements<sup>[4,5]</sup>.

**Five-port as a phase discriminator:** The output power on a matched load is proportional to  $|b_i|^2$ . It is noticed for each output, there is a dephasing between the two input signals  $\theta_{RF} - \theta_{OL}$ . If it is supposed that the detectors are identical ( $K_i = K$ ) and by taking account of the relations (3) we can write:

$$\begin{cases} V_3 = K \frac{|a|^2}{4} |1 - \exp(j\Delta\theta)|^2 = K |a|^2 \left| \sin\left(\frac{\Delta\theta}{2}\right) \right|^2 \\ V_4 = K \frac{|a|^2}{4} \left| 1 - \exp\left(j\left(\Delta\theta - \frac{2\pi}{3}\right)\right) \right|^2 = K |a|^2 \left| \sin\left(\frac{\Delta\theta - \frac{2\pi}{3}}{2}\right) \right|^2 \\ V_5 = K \frac{|a|^2}{4} \left| 1 - \exp\left(j\left(\Delta\theta + \frac{2\pi}{3}\right)\right) \right|^2 = K |a|^2 \left| \sin\left(\frac{\Delta\theta + \frac{2\pi}{3}}{2}\right) \right|^2 \end{cases} \quad (4)$$

To obtain a DC voltage variation on the output side of the power detectors, we carried out a simulation of the harmonic balancing of the complete circuit. Fig. 3 shows the three functions normalized to  $K |a|^2$  traced by Matlab.

We take the variation of the amplitudes  $v_3$ ,  $v_4$ ,  $v_5$  resulting from the dephasing between RF and OL. We note a complementary variation of the three voltages; each one has only one maximum or minimal value for a dephasing between the signal of reference OL and RF signal going from  $0-360^\circ$ . The five-port junction can be considered as phase discriminator. Each voltage  $v_i$  ( $i = 3...5$ ) is with periodicity of  $2\pi$  and the four minimal voltage values are separated by multiples of  $2\pi/3$ . This consideration is used to estimate the directional of arrival of multi-path signals by measuring the phase difference of detected signals. And, in the same time,

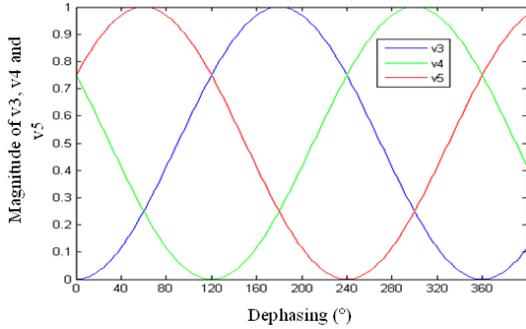


Fig. 3: DC outputs variation depending on dephasing between RF and OL

it is used to estimate the time of arrival by measuring the phase difference over two successive frequencies.

**MATERIALS AND METHODS**

The general configuration of proposed measurement system is shown in Fig. 4. The CW signal from the generator is amplified and radiated by the transmitting antenna which is located at chosen angular and distance positions from the receiver. These angles and distances represent the DoA and the ToA that have to be determined using receiver block based on multi receiver antenna and five port junction. The inputs 1 and 2 of five-port are connected to LO and one to receiver antenna. The five-port detector's output is connected to a Sample and Hold circuit (S/H) which is used to treat the signals before performing A/D conversion by an A/D converter. Simultaneous measurements are very important for the phase discrimination of RF signals, so the synchronization between S/Hs is required. The three voltages at each five-port are measured at each frequency and stored for the post processing step as the estimation of time delay and the DoA in the azimuth and elevation plans using MUSIC algorithm.

**Processing for parameters estimation:**

**High-resolution estimation:** To overcome Fourier resolution limits, high-resolution algorithms exploit the a priori knowledge of the antenna array response. In our case, the chosen algorithm is MUSIC, which robustness and accuracy has already been demonstrated by many authors<sup>[2,6,7]</sup>. We will show how to use this algorithm in the case of estimation of the propagation delays and the directions of arrival.

**Delay estimation:** For time delay characterization, measurement system shown in Fig. 5 is used but only with one receiving antenna and one five-port.

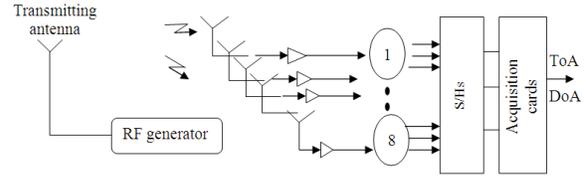


Fig.4. Measurement system

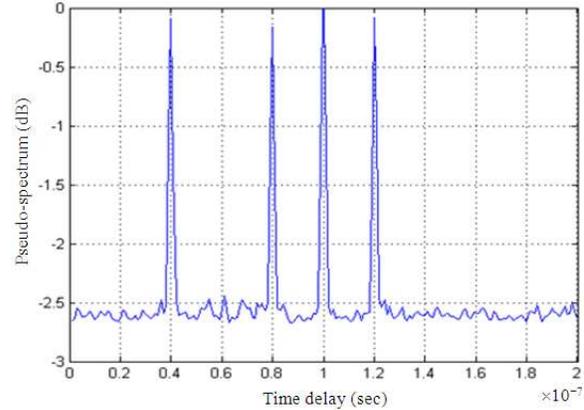


Fig. 5: Estimation of four paths by MUSIC algorithm

In the temporal field, a path with a delay  $\tau$  generates a dephasing of  $2\pi f\tau$  at the frequency  $f$ . In our case, we measured  $N$  points of frequency. If we suppose that there are  $K$  ways and that the emitted signal is with flat spectrum and that the channel is not selective in frequency, the signal measured at the frequency  $f_i$  is:

$$x_i(t) = \sum_{k=1}^K s_k(t) \exp(-j2\pi f_i \tau_k) + n_i(t) \tag{5}$$

$S_k(t)$  = The complex envelope of  $K^{\text{ième}}$  measured signal  
 $n_i(t)$  = The white Noise

By using the vectorial notation, we can state the expression (5) in the form:

$$X(t) = A.S(t) + N(t) \tag{6}$$

Where:

$$X(t) = [x_1(t) \ x_2(t) \dots x_n(t) \dots x_N(t)]^T \tag{7}$$

$$S(t) = [s_1(t) \ s_2(t) \dots s_k(t) \dots s_K(t)]^T \tag{8}$$

$$N(t) = [n_1(t) \ n_2(t) \dots n_n(t) \dots n_N(t)]^T \tag{9}$$

$A$  is the matrix of dimension  $N \times K$  of the mode vectors associated with  $K$  ways.

$$A = [a(\tau_1) \ a(\tau_2) \dots a(\tau_K)] \quad (10)$$

When  $f_i = f_1 + (i-1)\Delta f$  for  $i = 1 \dots N$ , The mode vector for a signal with a delay  $t$  is written:

$$a(\tau) = [e^{-j2\pi f_1 \tau} \ e^{-j2\pi f_2 \tau} \ \dots e^{-j2\pi f_n \tau} \ \dots e^{-j2\pi f_N \tau}] \quad (11)$$

We see that the Eq. 6 has the same form as in the case of a formulation of the problem to estimate the directions of arrival by a network of antennas. We can thus apply MUSIC algorithm for the estimation of the propagation's delays. We will suppose in the continuation that  $E\{N(t).N^H(t)\} = \sigma_0^2 I$ . We can not justify this assumption theoretically.  $\sigma_0^2$  is the power of the identical noise for all the frequencies and  $I$  is the identity matrix  $K \times K$ . By supposing that the noises are uncorrelated at the various moments and the different frequencies, for a series of  $T$  observations  $\{X(t_1), X(t_2), \dots, X(t_T)\}$ , the covariance matrix for the data vector is:

$$R_{xx} = E\{X(t).X^H(t)\} = \frac{1}{T} \sum_{t=1}^T X(t).X^H(t) = A.R_s.A^H + \sigma_0^2 I \quad (12)$$

$X^H(t)$  denotes a complex conjugate transpose of  $X(t)$ .  $R_s$  is the covariance matrix of the signal vector:

$$R_s = E\{S(t).S^H(t)\}$$

We define  $E_N$  like a matrix of dimensions  $N \times (N-K)$  whose columns are  $N-K$  Noise's eigenvectors. We can estimate the delays of propagation by seeking the positions of the peaks of the following function:

$$P_{MUSIC}(\tau) = \frac{a(\tau)^H a(\tau)}{a(\tau)^H . E_N . E_N^H a(\tau)} \quad (13)$$

**DoAs estimation in the azimuth plan:** In the general case, we suppose that there is  $K$  signals Passe band at the frequency  $f_0$ . These signals are collected by a network made up of  $M$  omnidirectional antennas with directions of arrival  $\varphi_k$  ( $k = 1, 2, \dots, K$ ). The received signal of the network is a superposition of all these signals and noise. Using the complex signal representation, we can express the data vector in base band  $X(t)$  received from the  $M$  antennas as follows:

$$X(t) = \sum_{k=1}^K a(\varphi_k) s_k(t) + N(t) \quad (14)$$

$a(\varphi_k)$  is the  $M \times 1$  steering or direction vector of the  $K^{i\text{ème}}$  signal:

$$a(\varphi_k) = \left[ 1 \ e^{-j\frac{2\pi d}{\lambda} \sin \varphi_k} \ , \dots \ , e^{-j\frac{2\pi d}{\lambda} (M-1) \sin \varphi_k} \right]^T \quad (15)$$

where,  $d$  represents the element spacing and  $\lambda$  is the wave length.

In matrix notation, the Eq. 14 becomes:

$$X(t) = A(\varphi).S(t) + N(t) \quad (16)$$

where,  $A(\varphi)$  is the  $M \times K$  matrix of the antennas array response vectors:

$$A(\varphi) = [a(\varphi_1) \ a(\varphi_2) \ \dots a(\varphi_k) \ \dots a(\varphi_K)] \quad (17)$$

$S(t)$  is the vector containing the complex envelopes of these  $K$  signals.

MUSIC exhibits peaks in the environs of the true DoAs by relating noise subspace to signal subspace. As shown in the references<sup>[7-9]</sup>, the subspace signal can be also generated by the direction vector and consequently, MUSIC estimation can be defined as:

$$P_{MUSIC}(\varphi) = \frac{a^H(\varphi).a(\varphi)}{a^H(\varphi).E_N.E_N^H a(\varphi)} \quad (18)$$

where,  $E_N$  represents the eigenvectors associated with the subspace noise.

**DoAs in the azimuth and elevation plans:** In an indoor environment, signals are reflected, diffused and arrive at the receiver not only in the azimuth plan but also in the elevation plan. The three-dimensional angular characterization of the channel is so important in this environment. We develop in this part the measurement of DoAs in these two plans. The signals are collected by An array made up of  $M$  omnidirectional antennas with directions of arrival  $(\varphi_k, \theta_k)$ , ( $k = 1, 2, \dots, K$ ).

The data vector in base band  $X(t)$  received from the  $M$  antennas is:

$$X(t) = \sum_{k=1}^K a(\varphi_k, \theta_k) . s_k(t) + N(t) \quad (19)$$

$a(\varphi_k, \theta_k)$  is the direction vector of the  $K^{i\text{ème}}$  signal.

In the case of a planar network in XOY plan with antenna 1 as a reference<sup>[3]</sup>:

$$a(\varphi_k, \theta_k) = \begin{bmatrix} 1 e^{-jk(\cos\theta_k \cdot \cos\varphi_k + \cos\theta_k \cdot \sin\varphi_k)} \dots \\ e^{-jk[(M_1-1)\cos\theta_k \cdot \cos\varphi_k + (M_2+1)\cos\theta_k \cdot \sin\varphi_k]} \end{bmatrix}^T \quad (20)$$

where,  $M_1$  and  $M_2$  are respectively the elements number for X and Y axis. In matrix notation, the Eq. 19 becomes:

$$X(t) = A(\varphi, \theta)S(t) + N(t) \quad (21)$$

$A(\varphi, \theta)$  is the  $M \times K$  matrix response of the antennas array:

$$A(\varphi, \theta) = [a(\varphi_1, \theta_1) \ a(\varphi_2, \theta_2) \dots a(\varphi_k, \theta_k) \dots a(\varphi_K, \theta_K)] \quad (22)$$

By applying the same estimation method in azimuth, MUSIC algorithm is used for the DoAs estimation:

$$P_{MUSIC}(\varphi, \theta) = \frac{a^H(\varphi, \theta) \cdot a(\varphi, \theta)}{a^H(\varphi, \theta) \cdot E_N \cdot E_N^H \cdot a(\varphi, \theta)} \quad (23)$$

### RESULTS

The proposed and simulated system generate a CW signal that sweeps covers the bandwidth from 2.2-2.6 GHz. The signal is sampled at a frequency of 1 KHz, thus the obtained data consists of 400 points with a frequency difference of 1 MHz between two consecutive samples. To validate the operation principle of the suggested system, we simulated it with Matlab and we treat the cases of uncorrelated signals.

**ToA results:** In this simulation, the propagation channel is represented by 4 ways of delays 40, 80, 100 and 120 ns. The results of simulation by using algorithm MUSIC are showed on Fig. 5.

In the case of the use of algorithm MUSIC for the three ways of 80 ns, 100 ns and 120 ns, we notice that they are correctly estimated as shown in Fig. 6.

**DoA results:** In this simulation, the DoAs are estimated by using the treatment presented above. Four uncorrelated signals with DoAs of  $-16^\circ$ ,  $-6.5^\circ$ ,  $6.5^\circ$  and  $16^\circ$  are simulated. The angles of arrival in azimuth estimated by MUSIC algorithm are shown in Fig. 7. Four paths with DoAs of  $-16.5^\circ$ ,  $-7^\circ$ ,  $7^\circ$  and  $16.5^\circ$  are detected with a maximum error of  $0.5^\circ$ . In the same way for three signals with DoAs of  $-30^\circ$ ,  $20^\circ$  and  $50^\circ$ , Fig. 8.

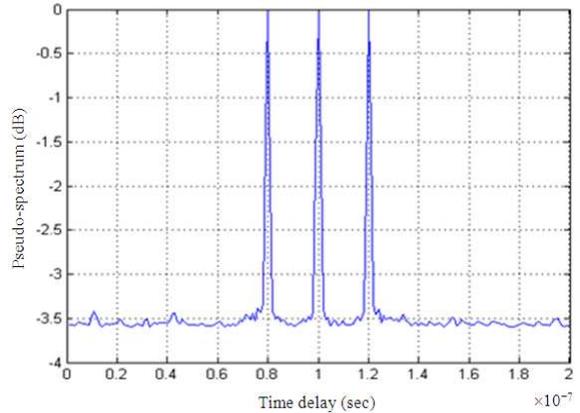


Fig. 6: Estimation of three paths by MUSIC algorithm

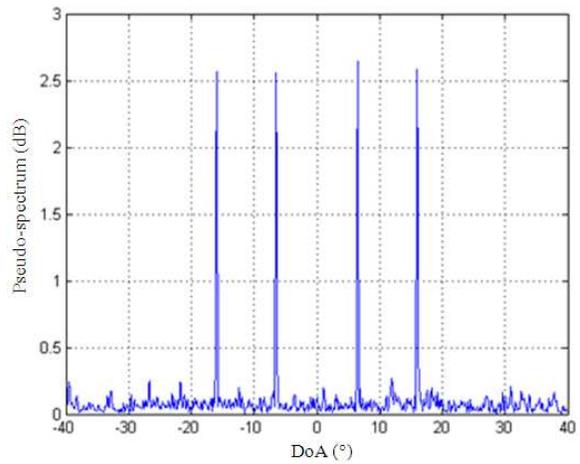


Fig. 7: Simulation results in the presence of four DoAs

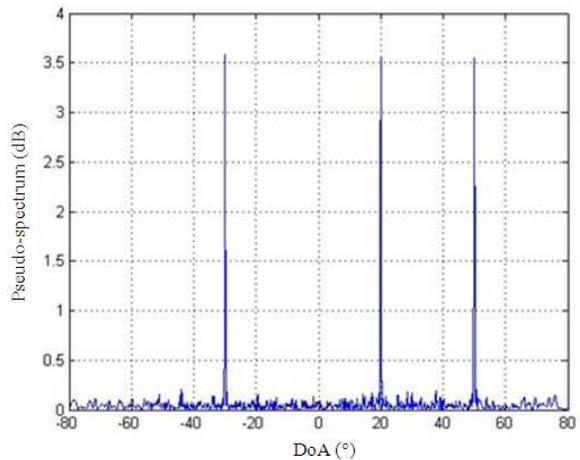


Fig. 8: Simulation results in the presence of three DoAs

The angles of arrival in azimuth and in elevation are also estimated by MUSIC algorithm. Figure 9 shows the simulation result of the system with an incidental signal in the direction  $(50^\circ, 50^\circ)$ . We can observe the signal in the direction  $(49.5^\circ, 50^\circ)$  is identified after treatment. The treatment made it possible to estimate the direction of arrival with a maximum of error of  $0.5^\circ$ .

To treat the case of detection of non coherent signals, we consider two non synchronized RF generators connected to two directing and transmitting antennas located in two different positions from the receivers.

Figure 10 shows the simulation result of the two signals with DoAs of  $(25^\circ, 40^\circ)$  and  $(70^\circ, 50^\circ)$ . These signals are identified  $(24^\circ, 39.5^\circ)$  and  $(71^\circ, 50^\circ)$  respectively with error of  $1^\circ$ .

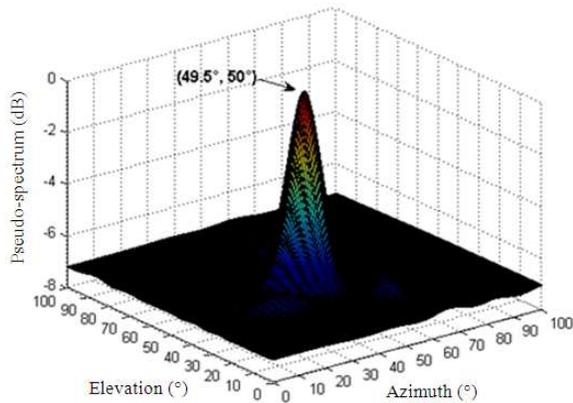


Fig. 9: Result with a theoretical signal  $\phi = 50^\circ$  and  $\theta = 50^\circ$

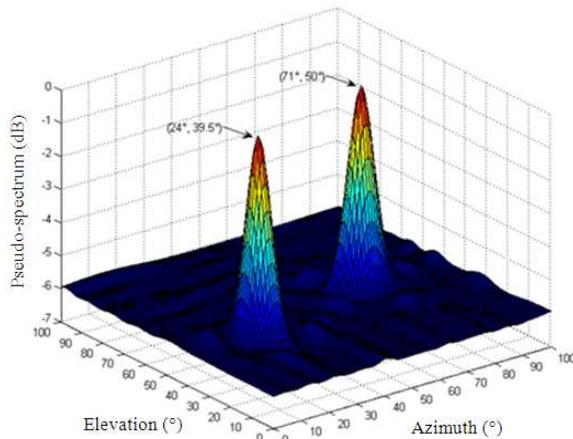


Fig. 10: Result with theoretical signals  $(25^\circ, 40^\circ)$  and  $(70^\circ, 50^\circ)$

## DISCUSSION

The accuracy given by 1 ns and  $0.5^\circ$  are enough sufficient for the estimation of the ToA and DoA, respectively. The proposed system is relatively simple from the realization point of view. The work can be extended to consider other type of signals such that those having variable time and frequency characteristics.

## CONCLUSION

In this research, we show the ToA and the DoA simulation results of non coherent signals in azimuth and in elevation plane by using a Matlab code. The simulation performed is based on the use of five-port circuit and with 2.4 GHz antenna array. The DoA is estimated by measuring the phase difference of the signals received by the antennas, the estimation of TOA is based on the phase difference measured at two successive frequencies in the used band. Using five port junction and modified MUSIC algorithm the estimation error was found to be not more than 1ns for time delay estimation and not more than  $0.5^\circ$  for directional of arrival. These results prove the compatibility of the proposed measurement system and the Music Algorithm for the estimation of the considered quantities.

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