Performance Evaluation of JADE-MUSIC Estimation for Indoor Environment

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Abstract: In this paper, the performance evaluation of the JADE-MUSIC estimation based on the indoor channel is presented. By means of the JADE-MUSIC algorithm, DOA and time delay can be obtained simultaneously. In the JADE-MUSIC method, the channel impulse response is first estimated from the received samples and then this impulse response is employed to estimate DOAs and time delays of multipath waves. Moreover, according to the JADE-MUSIC characteristics, it can work in cases when the number of impinging waves is more than the number of antenna elements, unlike the traditional parametric subspace-based method, such a case is not true. Therefore, we employ the JADE-MUSIC algorithm applying for the real indoor environment where is rich of the multipath propagation waves and can imply that the number of waves is very possibly higher than that of the array element. The experiment is carried out in our laboratory considered to be the real indoor environment. The performance of the JADE-MUSIC algorithm is evaluated in terms of the comparison between the simulation and experiment results by using the simulated channel model and the real indoor channel model, respectively. It is clear that the joint angle and delay estimation using the simulated channel model are in good agreement with the estimation using the real indoor channel model. Therefore, we can say that the JADE-MUSIC algorithm accomplishes the high performance to jointly estimate the angle and delay of the arriving signal for the indoor environment.

Keywords: JADE, MUSIC, DOA, Time delay, Indoor environment

1. INTRODUCTION

Recently, the source localization is one of the most interested issues among the researchers in signal processing. It generally involves the joint estimation of Doppler shifts, frequencies, direction-of-arrival and time/time-difference of arrival (TOA/TDOA), thereby it is the major issue in many radar and sonar applications. In addition, it can be applied for other applications such as emergency services and advance hand-over schemes in wireless communication systems as well as the source positioning or tracking for mobile robots. In the environment of multipath propagation, the source localization involves the estimation of the direction-of-arrival (DOA) and the time delay and their estimation is expected to be more effective and closely related to the physics of the propagating wave. To estimate the DOAs and delays of the signals arriving at the antenna array that is always in the receiving part, various approaches have been proposed in the literature [1]-[3].

This paper focuses on the joint estimation of angles and coincident delays of the multipath propagation signals spreaded from a single source and received by the antenna array by means of JADE (Joint Angle and Delay Estimation) algorithm [4]-[5]. Compared with the classical MUSIC (Multiple Signal Classification) technique [1], which can estimate the angle only, the estimation with JADE has an advantage in cases when multiple signals have almost same angles. Moreover, the estimation of DOAs with JADE can be solved when the number of waves exceeds the number of antennas [6]. Therefore, we employ the JADE-MUSIC algorithm applying for the real indoor environment where is rich of the multipath propagation waves. The experiment is carried out in our laboratory considered to be the real indoor environment. The eight-element array antenna is set as a receiving antenna and the microstrip-patch antenna is a transmitting antenna. The frequency transfer function between transmitting and receiving antenna is measured via Vector Network Analyzer (VNA). Then, the channel impulse response is post-processed from the measured transfer function and subsequently used to estimate the DOAs and corresponding time delays by means of the JADE-MUSIC algorithm. The performance of the JADE-MUSIC algorithm is evaluated in terms of the comparison between the simulation and experiment results by using the simulated channel model and the real indoor channel model, respectively.

2. DATA MODEL

In wireless communication systems, the radio channel is often characterized by a multipath propagation model. Assume that a digital sequence $\{s_k\}$ is transmitted over a channel. The received data at i^{th} element of an M-element antenna array is given by [4]-[5]

$$x_i(t) = \sum_{q=1}^{Q} a_i(\theta_q)\beta_q(t) r(t-\tau_q) + n_i(t), \qquad (1)$$

where Q is the number of multipath waves,

$a_i(\theta_q)$ is the response of the i^{th} receiving antenna to the q^{th} path arriving from angle θ_q,

β_q is the time-varying amplitude of the RF signal passing through the q^{th} path,

τ_q is the time delay of q^{th} path,

n_i is the additive noise, and

$r(\cdot)$ is the transmitted signal which can be expressed as

$$r(t) = \sum_{i=1}^{N} s(i) g(t-iT), \qquad (2)$$

where $\{s_k\}$ is the sequence bit data,

$g(t)$ is the modulation pulse shape and

T is the symbol period

After sampling by the rate of T/P (P samples), the received signal during the n^{th} time burst can be written as

$$\mathbf{X}^{(\mathbf{n})}(t) = \sum_{l} s_l^{(n)} \mathbf{h}^{(\mathbf{n})}(t-lT) + \mathbf{n}^{(\mathbf{n})}(t), \qquad (3)$$

where $\mathbf{h}$ is the channel,

$$\mathbf{h}^{(\mathbf{n})}(t) = \sum_{q=1}^{Q} \mathbf{a}(\theta_q)\beta_q(n) g(t-\tau_q). \qquad (4)$$

It is reasonable to assume that $g(t)$ has finite support on $t \in [0, L_g T)$. With maximum delay $\tau_{\max}$ from all paths, the channel length is $LT = L_g T + \tau_{\max}$ so $h^{(n)}(t)$ is nonzero from $t \in [0, LT)$. If we stack each set of P samples of $x^{(n)}(\cdot)$ and collect the samples in Eq. (3), this leads to

$$\overline{\mathbf{X}}^{(n)} = \overline{\mathbf{H}}^{(n)}\overline{\mathbf{S}}^{(n)} + \overline{\mathbf{N}}^{(n)}, \qquad (5)$$

where $n = 1, \ldots, S$ slots,

$\overline{\mathbf{H}}^{(n)}$ is an $MP \times L$ matrix of samples of $h(\cdot)$ and

$\overline{\mathbf{S}}^{(n)}$ is an $L \times N$ Toeplitz matrix of the sequence bit data.

3. ESTIMATION ALGORITHMS

3.1 Joint Angle and Delay Estimation

In this paper, the radio channel from the mobile to the antenna array is time-slot modeled after the TDMA standard. Therefore, the channel $\mathbf{H}$ from the mobile to the antenna array can be assumed to be constant over each time slot from training sequence. Then a least-square estimate of $\overline{\mathbf{H}}^{(n)}$ can be obtained as $\overline{\mathbf{H}}_{est}^{(n)} = \overline{\mathbf{X}}^{(n)}\overline{\mathbf{S}}^{(n)\dagger}$, where $(\cdot)^{\dagger}$ is the pseudo-inverse operation. Thus, the noisy channel estimation is [7]

$$\overline{\mathbf{H}}_{est}^{(n)} = \overline{\mathbf{H}}^{(n)} + \overline{\mathbf{V}}_{est}^{(n)}, \qquad (6)$$

where $\overline{\mathbf{V}}_{est}^{(n)}$ is the estimated noise.

At this point, it will be convenient to rearrange the noisy channel estimation into $M \times PL$ matrix,

$$\mathbf{H}_{est}^{(n)} = \left[\mathbf{h}^{(n)}(0), \mathbf{h}^{(n)}\left(\frac{T}{P}\right), \ldots, \mathbf{h}^{(n)}\left(\left(L - \frac{T}{P}\right)T\right)\right]. \qquad (7)$$

From Eq. (3), the channel $\mathbf{H}$ can rewrite into

$$\mathbf{H}^{(n)} =: \mathbf{A}(\theta)\operatorname{diag}[\beta(n)]\mathbf{G}^T(\tau), \qquad (8)$$

where $\mathbf{A}(\theta) = [\mathbf{a}(\theta_1), \ldots, \mathbf{a}(\theta_q)]$,

$\beta(n) = [\beta_1(n), \ldots, \beta_q(n)]$ and

$\mathbf{G}(\tau) = [g(\tau_1), \ldots, g(\tau_q)]$.

With relation $\operatorname{vec}[\mathbf{A}\operatorname{diag}(b)\mathbf{C}] = (\mathbf{C}^T \circ \mathbf{A})b$ where $\circ$ is the Khatri-Rao product, which is a column-wise Kronecker product: $\mathbf{A} \circ \mathbf{B} = [\mathbf{a}_1 \otimes \mathbf{b}_1, \mathbf{a}_1 \otimes \mathbf{b}_1, \ldots]$ where $\otimes$ denotes the Kronecker product, we get

$$\operatorname{vec}\left[\mathbf{H}^{(n)}\right] = [\mathbf{G}(\tau) \circ \mathbf{A}(\theta)]\beta(n) = \mathbf{U}(\theta,\tau)\beta(n), \qquad (9)$$

where $\mathbf{U}(\theta,\tau)$ is called the space-time manifold matrix and is parameterized by the DOAs and the path delays.

Let $\mathbf{y}(n) = \operatorname{vec}\left[\overline{\mathbf{H}}_{est}^{(n)}\right]$ and $\mathbf{v}(n) = \operatorname{vec}\left[\overline{\mathbf{V}}_{est}^{(n)}\right]$ with Eq. (6), we get

$$\mathbf{y}(n) = \mathbf{U}(\theta,\tau)\beta(n) + \mathbf{v}(n), \qquad (10)$$

and let $\mathbf{Y} = [\mathbf{y}(1), \ldots, \mathbf{y}(S)]$, thus

$$\mathbf{Y} = \mathbf{U}(\theta,\tau)\mathbf{B} + \mathbf{V}. \qquad (11)$$

For given channel estimates $\mathbf{Y}$, the joint angle and delay estimation (JADE) problem is to find the angles θ and delays

τ using the model in Eq. (11). As an aside, not the resemblance of the JADE model to the familiar DOA model, which can be written as

$$\mathbf{X} = \mathbf{A}(\theta)\mathbf{S} + \mathbf{N}, \tag{12}$$

where $\mathbf{X}$ is the array output measurements,

$\mathbf{S}$ is the matrix of signal,

$\mathbf{N}$ is the additive noise.

The difference with Eq. (11) is that the data are the channel estimates and not the array outputs, the manifold matrix is parameterized by both angles and delays, and the path fadings play the part of the signals.

Therefore, the next and last steps of the method consist of jointly estimating parameters that satisfy the model Eq. (8). The well-known method MUSIC has been developed for the DOA, and model Eq. (12) are applicable to the JADE algorithm.

3.2 MUSIC

In terms of the signal model in Eq. (11), the $Q \times Q$ array output covariance matrix can be written as [8]-[9]

$$\mathbf{R} = E\left[\mathbf{x}(t)\mathbf{x}^H(t)\right] = \mathbf{A}\mathbf{P}\mathbf{A}^H + \sigma^2\mathbf{I}, \tag{13}$$

where $\mathbf{A}$ is the steering matrix,

$\mathbf{P}$ is the source covariance matix,

$(\cdot)^H$ is the complex conjugate, and

$\sigma^2\mathbf{I}$ is the noise covariance matrix that reflects the noise being uncorrelated among all sensors and having a common variance σ^2 at all sensors.

The structure of the covariance matrix with the spatial white noise assumption implies that its spectral decomposition can be expressed as

$$\mathbf{R} = \mathbf{U}_s\Lambda_s\mathbf{U}_s^H + \mathbf{U}_n\Lambda_n\mathbf{U}_n^H, \tag{14}$$

where $\mathbf{U}_s$ is the matrix containing the signal eigenvectors and

$\mathbf{U}_n$ is the matrix containing the noise eigenvectors.

Since the steering vectors corresponding to signal components are orthogonal to the noise subspace eigenvectors, namely,

$$\mathbf{U}_s^H\mathbf{a}(\theta) = \mathbf{0}, \tag{15}$$

where θ corresponds to the DOA of the multiple incident signals, then the DOA can be estimated by locating the peaks of the MUSIC spatial spectrum given by

$$\mathbf{P}_{MUSIC}(\theta) = \frac{1}{\left|\mathbf{a}^H(\theta)\mathbf{U}_n\right|^2}. \tag{16}$$

If there are Q signals impinged on the M-element array $(Q < M)$ from individual DOAs $\theta_1, \theta_2, \ldots \theta_q$, the Q largest peaks in the MUSIC spectrum corresponding to the directions of arrival of the signals impinged on the M-element array.

3.3 JADE-MUSIC Algorithm

From the channel estimation, we can find the covariance matrix according to Eq. (11), which is

$$\mathbf{R} = \mathrm{E}\left[\mathbf{Y}\mathbf{Y}^H\right]. \tag{17}$$

Assume that the noise estimate is the Additive White Gaussian Noise (AWGN) and orthogonal with the channel $\mathbf{H}$, hence

$$\mathbf{R} = \mathbf{U}(\theta,\tau)\mathbf{Z}\mathbf{U}^H(\theta,\tau) + \varsigma^2\mathbf{I}, \tag{18}$$

where $\mathbf{Z}$ is the complex fading covariance matrix and $\varsigma^2\mathbf{I}$ is the estimated noise covariance matrix. Like the conventional MUSIC, the steering vectors corresponding to signal components are orthogonal to the noise subspace eigenvectors, therefore

$$\mathbf{E}_n^H\mathbf{U}(\theta,\tau) = \mathbf{0}, \tag{19}$$

where θ corresponds to the DOA of the multiple arriving signal, we retrieve the noise subspace $\mathbf{E}_n$ from covariance matrix whose corresponding $MP - L$ smallest eigenvalues. We thus look for peaks in the two-dimension MUSIC spectrums from the JADE-MUSIC spatial spectrum given by

$$\mathbf{P}_{JADE-MUSIC}(\theta,\tau) = \frac{1}{\left|\mathbf{U}^H(\theta,\tau)\mathbf{E}_n\right|^2}. \tag{20}$$

4. EXPERIMENT SETUP

The experiment is carried out in our laboratory considered to be the real indoor environment, which can be shown in Fig. 1. The eight-element array antenna is set as the receiving antenna. For the transmitting antenna, we use two types of antenna, e.g. the microstrip-patch antenna and the sleeve dipole antenna. The frequency transfer function between transmitting and receiving antenna is measured via Vector Network Analyzer (VNA). Then, the channel impulse response is post-processed from the measured transfer function and subsequently used to estimate the DOAs and corresponding time delays by means of the JADE-MUSIC algorithm. The specification of the measurement system is demonstrated in Table 1.

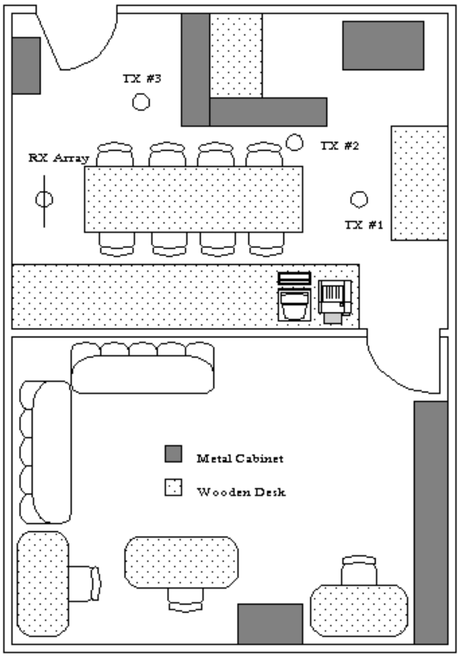

Fig. 1 Layout of a room indoor environment

Table 1. The specifications of the measurement system

Carrier frequency	2.45 GHz
Modulation type	BPSK
Number of samples	1,000
Sampling rate	25 samples/symbol
Type of the Rx antenna	The microstrip-array antenna
Number of the array element	8
Inter-element distance	$\lambda/2$
Type of the Tx antenna	The microstrip-array antenna And the sleeve dipole antenna
Height of the Rx antenna	2 m
Height of the Tx antenna	2 m
Distance between Rx and Tx#1	~ 3 m
Distance between Rx and Tx#2	~ 2.5 m
Distance between Rx and Tx#3	~ 1.5 m

5. RESULTS

The computer simulation result shown in Fig. 3 demonstrates the achievable performance of the JADE-MUSIC algorithm for the simultaneous estimation of DOAs and time delays of different arriving signals. Herein, we assume that the three different signals from three transmitting antennas impinging on the eight-element array antenna at the angles of 0, 45 and 60 degrees with their corresponding time delays of 1, 2 and 1 symbol periods, respectively. Compared to the traditional MUSIC algorithm, we can estimate only DOAs but cannot estimate the time delays simultaneously. Therefore, we cannot distinguish the different signals simultaneous arriving at the receiving antenna when their time delays are different by the traditional MUSIC algorithm while we can achieve this matter by using the JADE-MUSIC algorithm.

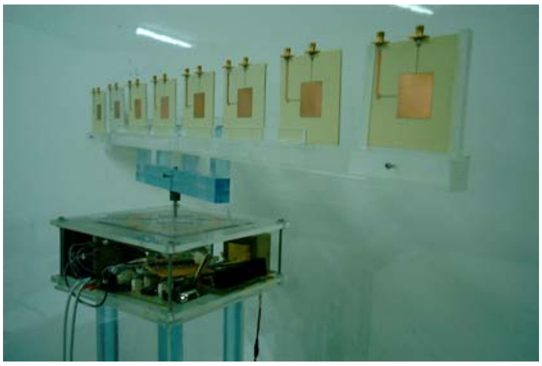

Fig. 2 The eight-element array antenna.

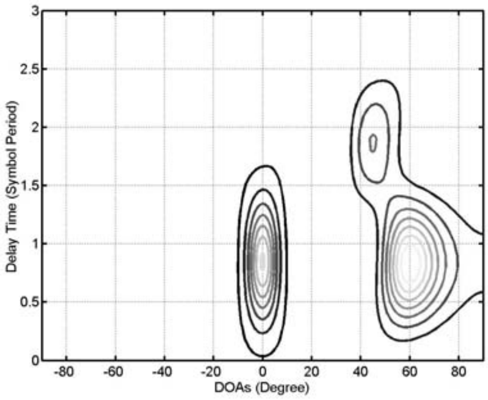

Fig. 3 The simulation result using JADE-MUSIC algorithm. Three signals arrive at the 8-element uniform linear array at angles of 0, 45 and 60 degrees corresponding to their time delays of 1, 2 and 1 symbol periods, respectively.

According to the experiment, the eight-element array antenna is set as the receiving antenna, as shown in Fig. 2, and the microstrip-patch antenna is the transmitting antenna. We employ the Vector Network Analyzer (VNA) to measure the transfer function between transmitting and receiving antenna. Then, the channel impulse response can be calculated from the measured transfer function and the real indoor channel model can be obtained. Therefore, we can simultaneously estimate the DOAs and time delays of the signals propagating through this real indoor channel model to the receiving antenna by applying the JADE-MUSIC algorithm. From Fig. 4, it is found that three signals arriving at the angle

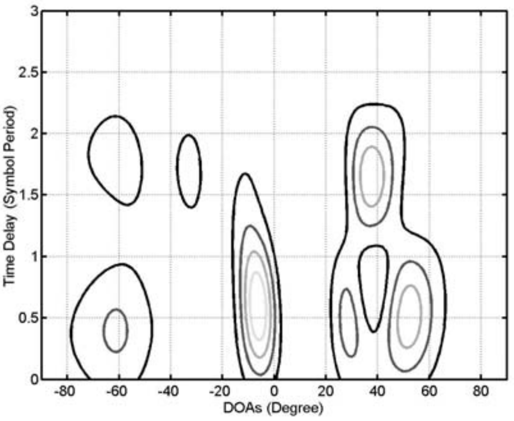

Fig. 4 The estimation result according to the real indoor channel model using JADE-MUSIC algorithm. Three signals arrive at the 8-element uniform linear array at angles of around 0, 45 and 60 degrees corresponding to their time delays of 1, 2 and 1 symbol periods, respectively.

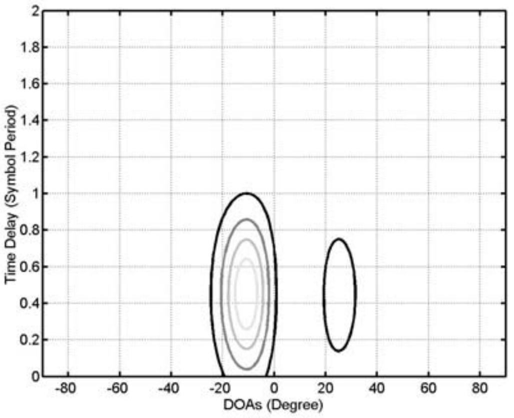

Fig. 5 One signal transmitted from the microstrip-patch antenna arrives at the 8-element array antenna at the angle of around –10 degree with its time delay of 0.5 symbol period.

approximately of 0, 45 and 60 degrees with corresponding to their time delays of around 1, 2 and 1 symbol periods can be distinguished. Nevertheless, a small amount of interference appears of the angles of around –60 and 30 degrees with their close time delays of around 0.5 symbol period. Compared to the simulation result in Fig. 3, it is clear that the joint angle and delay estimation using the simulated channel model are in good agreement with the estimation using the real indoor channel model.

Moreover, we employ two different types of transmitting antennas, namely, the sleeve dipole antenna and the microstrip-patch antenna to find the effect of the estimation result by using these different transmitting antennas. For the experiment, each of which is placed at the 0 degree associated with the receiving antenna. The estimation results corresponding to the microstrip-patch antenna and the sleeve dipole antenna are illustrated in Fig. 5 and Fig. 6, respectively. The expected angle-of-arrival is 0 degree; however, the signal arrives at the array antenna at the angle of around –10 degree when transmitted by the microstrip-patch antenna, shown in Fig. 5 and at the angle of around 5 degree when transmitted by the sleeve dipole antenna, shown in Fig. 6. Nonetheless, the DOAs of signals transmitted by both antennas are close to the expected angle, 0 degree. Therefore, we might use either the microstrip-patch antenna or the sleeve dipole antenna to transmit the signal.

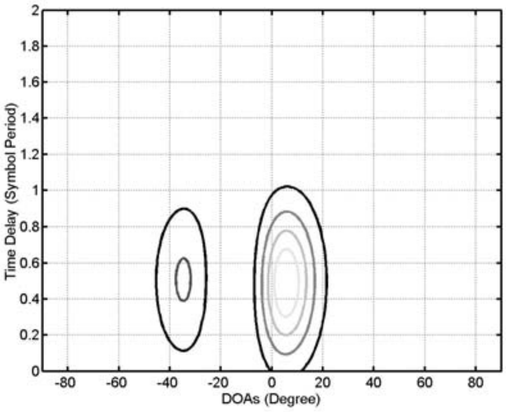

Fig. 6 One signal transmitted from the sleeve dipole antenna arrives at the 8-element array antenna at the angle approximately of 10 degree with its time delay of 0.5 symbol period and interference happens at the angle of around –30 degree.

6. CONCLUSIONS

In this paper, the performance evaluation of the JADE-MUSIC estimation based on the indoor channel is presented. By means of the JADE-MUSIC algorithm, DOA and time delay can be obtained simultaneously. The experiment is carried out in our laboratory considered to be the real indoor environment. From the results, it is clear that the joint angle and delay estimation using the simulated channel model are in good agreement with the estimation by the real indoor channel model. Therefore, we can say that the JADE-MUSIC algorithm accomplishes the high performance to jointly estimate the angle and delay of the arriving signal for the indoor environment. Additionally, it is found that either using the microstrip-patch antenna or the sleeve dipole antenna to transmit the signal, the estimation results of these antennas are consistent.

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