SIGNAL PARAMETER ESTIMATION OF INDOOR MULTIPATH WAVES WITH TRIANGULAR ANTENNA ARRAY

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1. Introduction

It is essential to grasp in detail the characteristics of indoor multipath propagation to realize the indoor radio communication systems with high reliability and flexibility. To understand the propagation circumstances, it is effective to know the direction of arrival (DOA), propagation delay time (PDT), and the strength of the respective incoming waves at receiving points.

So far, many array signal processing algorithms have been developed for estimating such signal parameters[1]-[3]. However, most of them estimate either DOAs or PDTs of the multipath waves. Therefore, we must use the different measurement systems to obtain both the DOAs and PDTs, and besides we have difficulty in making the DOA estimate correspond to the PDT estimate for each incident wave.

In this paper, we present the method of estimating simultaneously the DOAs and PDTs of the multipath waves using the ESPRIT[2] algorithm with triangular antenna array. The ESPRIT, which is one of the eigen-decomposition based algorithms, is known to be more effective because of its high resolution and computational efficiency[3]. Thus, it is expected that the presented method has great capability of classifying the multipath waves in terms of DOAs and PDTs.

2. Estimation Principle

Problem formulation

Figure 1 shows the geometry of triangular antenna array, in which three elements are settled at M_1, M_2, and M_3 in the xy plane and d denotes the distance between each element and the array center. Let us sweep the operating frequency discretely as follows:

$$f_n = f_o + n\Delta f \qquad (n = -K, -K+1, \cdots, K) \tag{1}$$

Then, under an environment that there are L multipath plane waves arriving, the receiving voltage of the antenna M_1 at the frequency of f_n can be expressed as

$$b_1(n) = \sum_{i=1}^{L} F_i \exp\left\{-j2\pi f_n \left(\tau_i - \frac{d}{c}\sin\theta_i \cos\phi_i\right)\right\} + w_1(n) \tag{2}$$

where F_i, $(\theta_i,\ \phi_i)$, and τ_i denote the complex amplitude, DOA, and PDT of the ith incident signal, respectively. c is the propagation velocity, and $w_1(n)$ is the internal noise of the antenna M_1 which is statistically independent of the incoming signals. In eq.(2), the receiving antennas are assumed to be isotropic and also to have the unvaried characteristics at the operating frequency band. In addition, assuming that the phase variation due to $(d/c)\sin\theta_i\cos\phi_i$ is very small over the operating frequency band, we obtain the following approximate expression of eq.(2):

$$b_1(n) = \sum_{i=1}^{L} F_i \exp(-j2\pi f_n \tau_i)\exp(jkd\sin\theta_i\cos\phi_i) + w_1(n) \tag{3}$$

where $k = 2\pi f_o/c$. Likewise, we obtain the receiving voltages of the antennas M_2, M_3 as follows:

$$b_2(n) = \sum_{i=1}^{L} F_i \exp(-j2\pi f_n \tau_i)\exp\left\{jkd\sin\theta_i\cos\left(\phi_i - \frac{2}{3}\pi\right)\right\} + w_2(n) \tag{4}$$

$$b_3(n) = \sum_{i=1}^{L} F_i \exp(-j2\pi f_n \tau_i)\exp\left\{jkd\sin\theta_i\cos\left(\phi_i + \frac{2}{3}\pi\right)\right\} + w_3(n) \tag{5}$$

Now, we express $b_1(n)$, $b_2(n)$, and $b_3(n)$ $(n = -K, -K+1, \cdots, K)$, respectively, in vector and matrix forms as follows:

$$\boldsymbol{B}_k = A\Phi_k\boldsymbol{F} + \boldsymbol{W}_k \qquad (k = 1, 2, 3) \tag{6}$$

where

$$\boldsymbol{B}_k = [b_k(-K), b_k(-K+1), \cdots, b_k(K)]^T \qquad (k = 1, 2, 3)$$
$$A = [\boldsymbol{a}(\tau_1), \boldsymbol{a}(\tau_2), \cdots, \boldsymbol{a}(\tau_L)]$$
$$\boldsymbol{a}(\tau_i) = [\exp(-j2\pi f_{-K}\tau_i), \exp(-j2\pi f_{-K+1}\tau_i), \cdots, \exp(-j2\pi f_K\tau_i)]^T \ (i = 1, 2, \cdots, L)$$
$$\boldsymbol{F} = [F_1, F_2, \cdots, F_L]^T$$
$$\Phi_1 = diag[\exp(jkd\sin\theta_1\cos\phi_1), \exp(jkd\sin\theta_2\cos\phi_2), \cdots, \exp(jkd\sin\theta_L\cos\phi_L)]$$
$$\Phi_2 = diag\left[\exp\left\{jkd\sin\theta_1\cos\left(\phi_1 - \frac{2}{3}\pi\right)\right\}, \cdots, \exp\left\{jkd\sin\theta_L\cos\left(\phi_L - \frac{2}{3}\pi\right)\right\}\right]$$
$$\Phi_3 = diag\left[\exp\left\{jkd\sin\theta_1\cos\left(\phi_1 + \frac{2}{3}\pi\right)\right\}, \cdots, \exp\left\{jkd\sin\theta_L\cos\left(\phi_L + \frac{2}{3}\pi\right)\right\}\right]$$
$$\boldsymbol{W}_k = [w_k(-K), w_k(-K+1), \cdots, w_k(K)]^T \qquad (k = 1, 2, 3)$$

The above $\boldsymbol{B}_1$, $\boldsymbol{B}_2$ and $\boldsymbol{B}_3$ are available for the ESPRIT algorithm.

Estimation of PDT

We choose two overlapping subsets $\boldsymbol{X}$ and $\boldsymbol{Y}$ from $\boldsymbol{B}_1$ and further define $\boldsymbol{Z}$ as follows:

$$\boldsymbol{X} = [b_1(-K), b_1(-K+1), \cdots, b_1(K-1)]^T \tag{7}$$
$$\boldsymbol{Y} = [b_1(-K+1), b_1(-K+2), \cdots, b_1(K)]^T \tag{8}$$
$$\boldsymbol{Z} = [\mathbf{X}\ \mathbf{Y}]^T \tag{9}$$

Applying ESPRIT(TLS-ESPRIT) to the covariance matrix $S = E[\boldsymbol{Z}\boldsymbol{Z}^\dagger]$ together with the spatial smoothing technique[4] for decorrelating the incoming multipath waves, we can obtain the estimates of PDTs : τ_1, $\cdots$, τ_L.

Estimation of DOA

Using $\boldsymbol{B}_1$ and $\boldsymbol{B}_2$, we construct a new vector $\boldsymbol{Z}_1 = [\boldsymbol{B}_1\boldsymbol{B}_2]^T$ and also a covariance matrix $S_1 = E[\boldsymbol{Z}_1\boldsymbol{Z}_1^\dagger]$. In the same manner, we obtain $S_2 = E[\boldsymbol{Z}_2\boldsymbol{Z}_2^\dagger]$ from $\boldsymbol{Z}_2 =$

$[\boldsymbol{B}_2\boldsymbol{B}_3]^T$ and $S_3 = E[\boldsymbol{Z}_3\boldsymbol{Z}_3^\dagger]$ from $\boldsymbol{Z}_3 = [\boldsymbol{B}_3\boldsymbol{B}_1]^T$. Applying TLS-ESPRIT again to those covariance matrices S_1, S_2 and S_3 leads to $\varphi_1(i)$, $\varphi_2(i)$ and $\varphi_3(i)$ $(i = 1, 2, \cdots, L)$ which are expressed as follows:

$$\varphi_1(i) = \sqrt{3}kd\sin\theta_i\sin\left(\phi_i - \frac{\pi}{3}\right) \quad (10)$$

$$\varphi_2(i) = -\sqrt{3}kd\sin\theta_i\sin\phi_i \quad (11)$$

$$\varphi_3(i) = \sqrt{3}kd\sin\theta_i\sin\left(\phi_i + \frac{\pi}{3}\right) \quad (12)$$

We can obtain the DOA estimates (θ_i, ϕ_i) $(i = 1, 2, \cdots, L)$ by solving eqs.(10),(11),(12) simultaneously.

3. Estimation Experiment

We carried out an estimation experiment using the above method in the radio anechoic chamber. The conditions about the experiment are represented below:

center frequency (f_o)	:	1300 MHz
frequency bandwidth ($f_K - f_{-K}$)	:	100 MHz $((f_K - f_{-K})/f_o = 7.7\%)$
frequency separation (Δf)	:	5 MHz (21 samples)
polarization	:	vertical
transmitting antenna	:	a half-wavelength dipole
receiving antenna	:	discone antenna
size of triangular array	:	$d = 6$ cm (0.26λ for 1300MHz) [Fig.1]
S/N	:	35 dB

The experiment environment is shown in Fig.2. There are two transmitting antennas that are fed by a common signal generator. The lower antenna are fed through a delay line to transmit a wave with the longer propagation delay time. Thus, we establish a two-multipath model. Table 1 shows a scenario for estimation experiment and Table 2 the estimated results.

It is found that there is agreement between the scenario and the estimated values. It is also noted that there are some errors in the estimates of zenith angles compared with those of PDTs and azimuth angles. The reason is that the zenith angles are computed using the estimated values of azimuth angles and hence the estimation errors of azimuth angles are accumulated to those of zenith angles.

4. Conclusion

Via experiments, we have shown that the ESPRIT algorithm can be applied to the triangular antenna array for estimating both directions of arrival (azimuth and zenith angles) and propagation delay times of indoor multipath waves.

References

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[2] R.Roy and T.Kailath, "ESPRIT — Estimation of signal parameters via rotational invariance techniques," IEEE Trans., vol.ASSP-37, pp.984-995, July 1989.

[3] J.Lin and R.T.Compton,Jr., "Angle and polarization estimation using ESPRIT with a polarization sensitive array," IEEE Trans., vol.AP-39, pp.1376-1383, Sept. 1991.

[4] T.J.Shan, et al., "On spatial smoothing for direction-of-arrival estimation of coherent signals," IEEE Trans., vol.ASSP-33, pp.806-811, Aug. 1985.

Table 1: Scenario for estimation experiment

		1st wave	2nd wave
PDT	(ns)	0.0	5.0
azimuth angle	(deg)	62	62
zenith angle	(deg)	89	104
power	(dB)	0.0	-2.0

Table 2: Estimated results in experiment

		1st wave	2nd wave
PDT	(ns)	0.0	5.0
azimuth angle	(deg)	62	66
zenith angle	(deg)	77	111
power	(dB)	0.0	-0.3

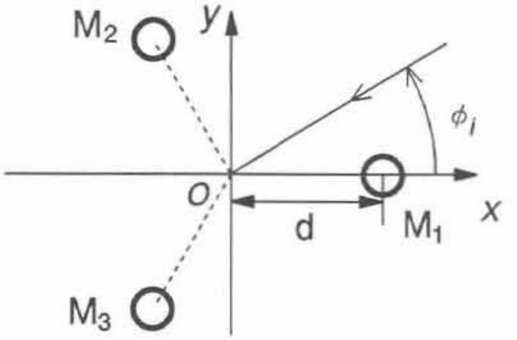

Figure 1: Geometry of triangular antenna array

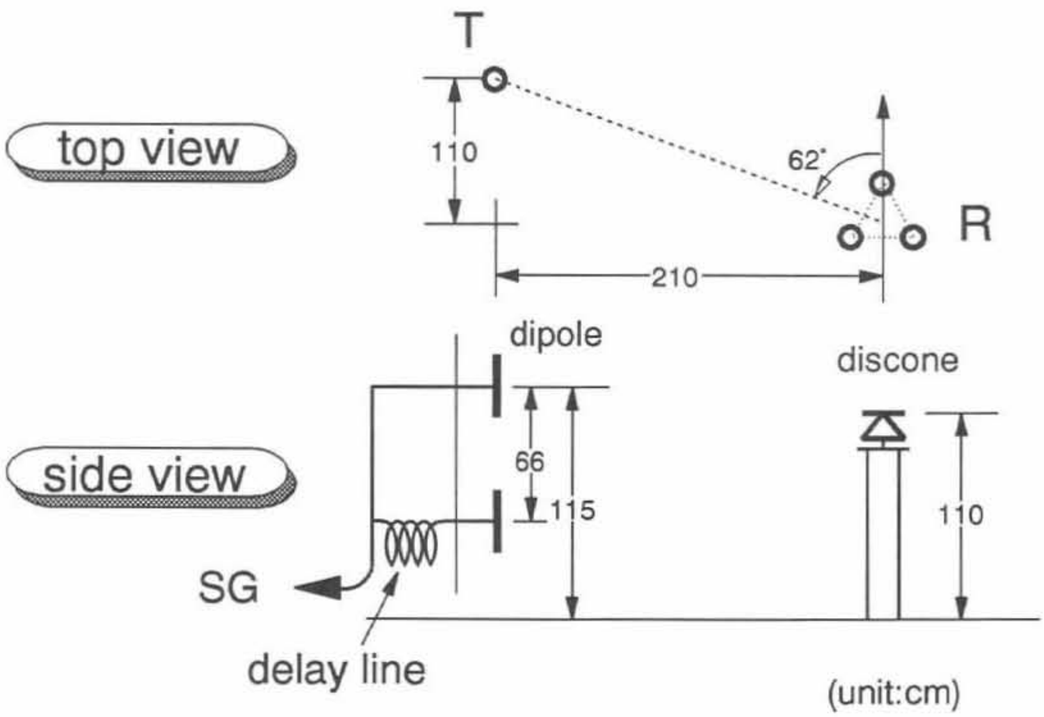

Figure 2: Experiment environment in radio anechoic chamber