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SIGNAL SEPARATION OF INDOOR/PICO-CELL MULTIPATH WAVES USING FFT-MUSIC WITH TRIANGULAR ANTENNA ARRAY

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1. Introduction

There is a growing need for high-speed wireless indoor/pico-cell communication systems. The millimeter-wave band is considered to be promising for this application field because its vast frequency spectrum is available. To realize a system of high reliability we have to understand the details of signal parameters (propagation delay time (PDT), direction of arrival (DOA), strength and so on) of the multipath waves, and further delay time resolution for the multipath waves is required to be in the order of nanoseconds. To estimate the signal parameters the super resolution methods such as MUSIC[1] and ESPRIT[2] have been proposed, which are based on eigen-decomposition techniques. We show herein the method of estimating simultaneously the directions of arrival and propagation delay times of the multipath waves using the FFT-MUSIC algorithm with a triangular antenna array[3].

To classify the multipath waves in terms of propagation delay times, we need the frequency-domain data of the received signals. Therefore, the frequency sweeping has often been employed. However, it normally needs a cable to transmit a reference signal to the receiver. The FFT-MUSIC presented here is an alternative method without the frequency sweeping and allows the measurement to be cableless between the transmitter and receiver. It utilizes as the transmitted signal a carrier modulated by a PN sequence which is known at the receiver, and we obtain the sample data in the frequency domain through the FFT operation to the received data. Hence, it is expected that the presented method has high flexibility and capability of separating the multipath waves.

2. Estimation Method

Problem formulation

Figure 1 shows the geometry of triangular antenna array, in which three identical elements are placed at M_1, M_2, and M_3. The three antennas receive the multipath signals modulated by a PN sequence which is known at the receiver. After operating the FFT to the received data, we extract the finite number of sample data from the mainlobe in the frequency spectrum, as is shown in Fig.2. Let the sample data at the three antennas be represented by $U_l(f_n)$ $(l = 1, 2, 3; n = -K, -K+1, \cdots, K)$ where f_n's are the discrete frequencies and K is an integer number. On the other hand, we have a reference signal generated at the receiver, which is modulated by the same PN sequence as the transmitted one. Likewise, let the reference sample data in the frequency spectrum be represented by $V(f_n)$ ($n = -K, -K+1, \cdots, K$). Then, the normalized mainlobe sample data are given by

$$\begin{aligned} x_l(f_n) &= \frac{U_l(f_n)}{V(f_n)} \equiv x_l(n) \qquad (l = 1,2,3) \\ f_n &= f_o + n\Delta f \qquad (n = -K, -K+1, \cdots, K) \end{aligned} \tag{1}$$

where the frequencies are chosen with an equal separation Δf and f_o is the center frequency.

Now, under an environment that there are L multipath plane waves arriving, we can express $x_l(n)$ ($l = 1,2,3$; $n = -K, -K+1, \cdots, K$) in vector and matrix forms as follows:

$$\boldsymbol{X}_l = A\Phi_l \boldsymbol{F} + \boldsymbol{W}_l \qquad (l = 1,2,3) \tag{2}$$

where

$$\begin{aligned}
&\boldsymbol{X}_l = [x_l(-K), x_l(-K+1), \cdots, x_l(K)]^T \qquad (l = 1,2,3) \\
&A = [a(\tau_1), a(\tau_2), \cdots, a(\tau_L)] \\
&a(\tau_i) = [\exp(-j2\pi f_{-K}\tau_i), \exp(-j2\pi f_{-K+1}\tau_i), \cdots, \exp(-j2\pi f_K \tau_i)]^T \ (i = 1,2,\cdots,L) \\
&\boldsymbol{F} = [F_1, F_2, \cdots, F_L]^T \\
&\Phi_l = diag\left[\exp\left\{jkd\sin\theta_1\cos\left(\phi_1 - \frac{2\pi(l-1)}{3}\right)\right\}, \cdots,\right. \\
&\qquad\qquad \left.\exp\left\{jkd\sin\theta_L\cos\left(\phi_L - \frac{2\pi(l-1)}{3}\right)\right\}\right] \qquad (l = 1,2,3) \\
&\boldsymbol{W}_l = [w_l(-K), w_l(-K+1), \cdots, w_l(K)]^T \qquad (l = 1,2,3)
\end{aligned}$$

In the above expression, F_i, (θ_i, ϕ_i), and τ_i denote the complex amplitude, DOA, and PDT of the ith incident signal, respectively. c is the propagation velocity, d is the size of the array, and $k = 2\pi f_o/c$. $w_l(n)$ is the internal noise of the antenna M_l 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 over the mainlobe spectrum. In addition, we assume that $2\pi(f_K - f_{-K})(d/c)\sin\theta_i\cos\phi_i \ll 1$.

Estimation of PDT

We apply the MUSIC to the covariance matrix $S = \frac{1}{3}\sum_{l=1}^{3} E[\boldsymbol{X}_l\boldsymbol{X}_l^\dagger]$. It is performed with the spatial smoothing preprocessing (SSP)[4] for decorrelating the incoming multipath waves. As a result, we can obtain the estimates of PDTs : $\tau_1, \cdots, \tau_L$.

Estimation of DOA

We make the following cross-covariance matrices: $S_1 = E[\boldsymbol{X}_2\boldsymbol{X}_1^\dagger] = A\Phi_2 P\Phi_1^* A^\dagger$, $S_2 = E[\boldsymbol{X}_3\boldsymbol{X}_2^\dagger] = A\Phi_3 P\Phi_2^* A^\dagger$, and $S_3 = E[\boldsymbol{X}_1\boldsymbol{X}_3^\dagger] = A\Phi_1 P\Phi_3^* A^\dagger$ where $P = E[\boldsymbol{F}\boldsymbol{F}^\dagger]$ is a signal source covariance matrix. By applying the SSP and matrix inversion using the estimated PDTs to S_1 through S_3, we can have $\varphi_1(i)$, $\varphi_2(i)$ and $\varphi_3(i)$ ($i = 1,2,\cdots,L$) which are related to (θ_i, φ_i) as follows:

$$\varphi_1(i) = \sqrt{3}kd\sin\theta_i\sin\left(\varphi_i - \frac{\pi}{3}\right) \tag{3}$$

$$\varphi_2(i) = -\sqrt{3}kd\sin\theta_i\sin\phi_i \tag{4}$$

$$\varphi_3(i) = \sqrt{3}kd\sin\theta_i\sin\left(\phi_i + \frac{\pi}{3}\right) \tag{5}$$

Consequently we obtain the DOA estimates (θ_i, ϕ_i) ($i = 1,2,\cdots,L$) by solving eqs.(3), (4), (5) simultaneously.

3. Computer Simulation

To confirm the above estimation algorithm, we carried out computer simulation with a two-multipath model, whose conditions are given by

center frequency (f_o)	:	20GHz
modulation scheme	:	$\pi/4$-shifted DQPSK
modulation code	:	PN sequence (M-sequence code)
bit rate	:	200Mbps
DUR	:	5dB

The array size d is equal to 0.25 wavelength of the center frequency. In taking the sample data, we have $K = 21$.

In the simulation, particularly, we focused on the following key parameters:

- input SNR
- bandwidth extracted from the mainlobe spectrum
- frequency difference between transmitter and receiver
- number of snapshots in making the covariance matrices
- number of sampling points/symbol for FFT
- length of PN sequence

and we examined the influence of them on estimation errors.

Figure 3 shows the delay time resolution versus the SNR where the resolution is defined as the least delay time difference in which the two waves can be estimated with an error less than or equal to ± 0.5ns. From this figure, we can see that the highest resolution is attained when the extracted bandwidth is 80% to the mainlobe width. The relation of the delay time resolution to the frequency difference is depicted in Fig.4. In the simulation, the frequency difference is characterized by the zero-mean, Gaussian random process, and in the figure it is represented by the standard deviation of the ratio of the frequency difference to the center frequency. It is noted that the shorter PN sequence brings the robuster performance against the frequency difference and low SNR. Also, the shorter PN sequence surely lightens computational loads in the FFT process. Figure 5 provides the MSE in ϕ estimates of the first wave. If the SNR is higher than 10dB, we can estimate DOAs within the MSE of 5 deg. Further, it is confirmed that the larger number of snapshots reduces the MSE.

4. Conclusion

Via computer simulation, we have clarified the performance of the FFT-MUSIC with the triangular antenna array, and we have demonstrated that it is much useful in separating the indoor/pico-cell multipath waves in terms of their directions of arrival (azimuth and zenith angles) and propagation delay times.

References

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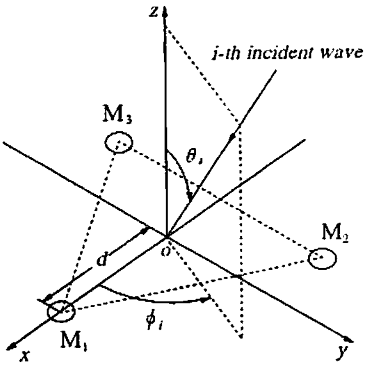

M_1, M_2, M_3 : measurement points

Figure 1: Geometry of triangular antenna array

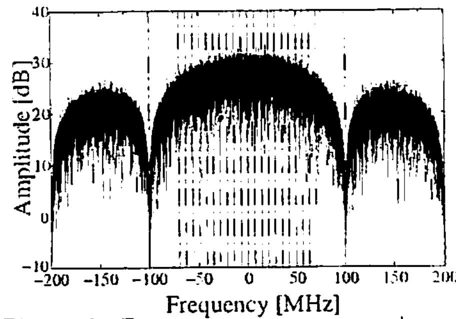

Figure 2: Frequency spectrum at baseband and data extraction

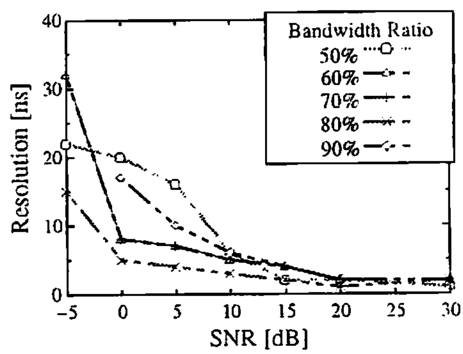

Figure 3: Delay time resolution vs. SNR

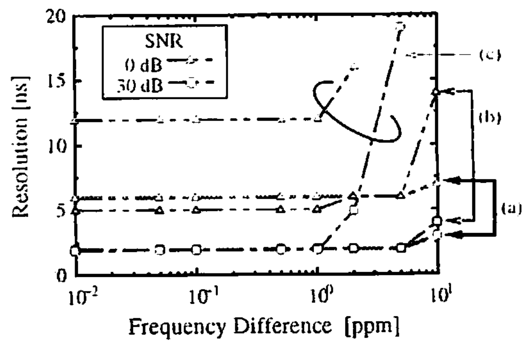

Figure 4: Delay time resolution vs. frequency difference: (a) 6-stage M sequence (64bit), (b) 7-stage M sequence (128bit), and (c) 9-stage M sequence (512bit)

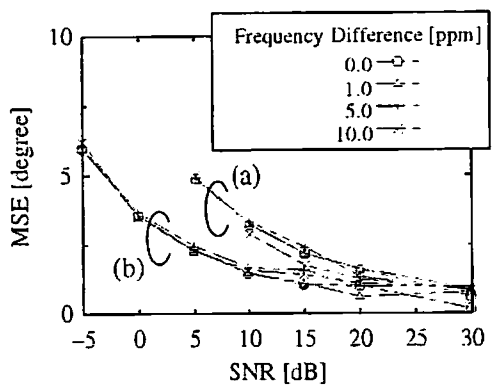

Figure 5: MSE in ϕ-estimates vs. SNR (first wave): (a) number of snapshots = 1, (b) number of snapshots = 6, where $(\theta_1, \phi_1) = (60°, 30°)$, $(\theta_2, \phi_2) = (80°, 160°)$, $\tau_1 = 20$ns, $\tau_2 = (21+\text{resolution})$ ns.