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Estimation method of DOA for DS-UWB signal

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Abstract Direction of arrival (DOA) estimation is one of the key technologies in smart antennas in the direct sequence ultra wideband (DS-UWB) system. Traditional DOA estimation methods based on narrow-band signals are not suitable for such system. Therefore, a fourth-order cumulant-based estimation method of DOA for DS-UWB signal is proposed. This method is set on the frequency domain model of DS-UWB array signal. Simulation results show that the algorithm is effective and can guarantee adequate estimation accuracy.

Keywords direction of arrival, direct sequence ultra wideband, fourth-order cumulant

1 Introduction

Ultra wideband (UWB) radio, unlike classic communications based on modulated sinusoidal carriers, uses a series of short duration pulses to convey information. After investigating research reports provided by many universities and companies, the Federal Communications Commission (FCC) in the United States first approved rules for the commercial utilization of UWB in February 2002. Direct sequence ultra wideband (DS-UWB) [1] has received wide attention and interest because of its higher data rates, low probability of interception and detection, low complexity and low cost.

Direction of arrival (DOA) estimation is one of the key technologies of smart antenna in DS-UWB system. The traditional DOA estimation methods such as MUSIC [2], ESPRIT [3] and high order statistics [4] based on narrow-band signals do not suit such system. Hence, a new method

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is proposed to estimate the DOA for DS-UWB signal utilizing ideas of eigenstructure of the spectral density matrix [5]. First, a frequency domain model of DS-UWB array signals is derived. Then the DOA for DS-UWB signal is estimated by the fourth-order cumulant matrices. Simulation results show that the method is effective.

2 Signal model

In a DS-UWB system [6] with K users, the transmitted signal can be described by:

$$s_k(t) = \sum_m a_k^m b_k(t - mT_s), \quad b_k(t) = \sum_{n=0}^{N-1} c_k^n w(t - nT_c), \quad (1)$$

where $\{a_k^m\}$ is the transmitted data sequence, T_s is the symbol interval, T_c is the chip period and $T_s = NT_c$. The sequence $\{c_k^n\}$ is the k th user's spread code and $w(t)$ is the basic pulse to convey information (referred to as monocycle).

As shown in Fig. 1, when these DS-UWB signals from different angles, $\theta_k, k = 1, 2, \dots, K$, arrive at a uniform linear array (ULA), the receiver signal of the p th antenna element is [7]:

$$x_p(t) = \sum_{k=1}^K \sum_{l=1}^{L_k} \alpha_{k,l} s_k(t - \tau_{k,l} - \tau_k^p) + n_p(t), \quad (2)$$
$$\tau_k^p = p \frac{d \sin \theta_k}{c},$$

where L_k is the total number of paths for the k th user, $\alpha_{k,l}$ is the multi-path gain coefficient, $\tau_{k,l}$ is the time delay of the l th path of the k th user, τ_k^p is the additional delay of the k th user associated with the p th antenna element. $n_p(t)$ is the additive white Gaussian noise (AWGN) for the p th antenna with two-sided power spectral density of $N_0/2$.

3 Estimation method of DOA for DS-UWB signal

From Eq. (2), we obtain the frequency modeling [5]:

$$X(f_i) = A(f_i)S(f_i) + N(f_i), \quad i = 1, 2, \dots, L', \quad (3a)$$

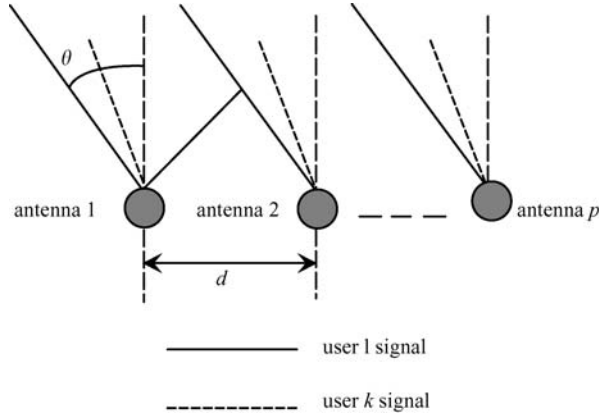


Fig. 1 Antenna array

where L' is the number of frequency bins. $\mathbf{X}(f_i)$ and $\mathbf{N}(f_i)$ are the $P \times 1$ vectors:

$$\mathbf{X}(f_i) = [X_1(f_i) \ X_2(f_i) \ \cdots \ X_P(f_i)]^T, \quad (3b)$$

$$\mathbf{N}(f_i) = [N_1(f_i) \ N_2(f_i) \ \cdots \ N_P(f_i)]^T. \quad (3c)$$

$\mathbf{S}(f_i)$ is the $K \times 1$ vector:

$$\mathbf{S}(f_i) = \left[S_1(f_i) \sum_{l=1}^{L_1} \alpha_{1,l} e^{-j2\pi f_i \tau_{1,l}} \ S_2(f_i) \sum_{l=1}^{L_2} \alpha_{2,l} e^{-j2\pi f_i \tau_{2,l}} \ \cdots \ S_K(f_i) \sum_{l=1}^{L_K} \alpha_{K,l} e^{-j2\pi f_i \tau_{K,l}} \right]^T. \quad (3d)$$

And $\mathbf{A}(f_i)$ is the $P \times K$ vector:

$$\mathbf{A}(f_i) = [\mathbf{a}(f_i, \theta_1) \ \mathbf{a}(f_i, \theta_2) \ \cdots \ \mathbf{a}(f_i, \theta_K)], \quad (3e)$$

$$\mathbf{a}(f_i, \theta_k) = \left[1 \ e^{-j2\pi f_i \frac{d \sin \theta_k}{c}} \ \cdots \ e^{-j2\pi f_i (P-1) \frac{d \sin \theta_k}{c}} \right]^T.$$

Note that each column of $\mathbf{A}(f_i)$ is associated with a different source. We shall denote these column vectors by $\mathbf{a}(f_i, \theta_k)$ and refer to them as the direction vectors of the sources.

Let $\mathbf{C}(f_i)$ be the matrix of the fourth-order cumulants of $\mathbf{X}(f_i)$, the rows of $\mathbf{C}(f_i)$ are indexed by $(k_1 - 1)P + k_2$, and the columns are indexed by $(k_3 - 1)P + k_4$, $k_1, k_2, k_3, k_4 \in \{1, 2, \dots, P\}$. The elements of $\mathbf{C}(f_i)$ is given by

$$\begin{aligned} & \text{cum}(X_{k_1}(f_i), X_{k_2}(f_i), X_{k_3}^*(f_i), X_{k_4}^*(f_i)) \\ &= E(X_{k_1}(f_i), X_{k_2}(f_i), X_{k_3}^*(f_i), X_{k_4}^*(f_i)) \\ & \quad - E(X_{k_1}(f_i) X_{k_3}^*(f_i)) E(X_{k_2}(f_i) X_{k_4}^*(f_i)) \\ & \quad - E(X_{k_1}(f_i) X_{k_4}^*(f_i)) E(X_{k_2}(f_i), X_{k_3}^*(f_i)), \end{aligned} \quad (4)$$

where $X_{k_1}(f_i)$ is the k_1 element in the vector $\mathbf{X}(f_i)$, and $*$ denotes the complex conjugate. The indices k_2, k_3, k_4 are similarly defined.

Thus, the cumulant matrix is given as

$$\begin{aligned} \mathbf{C}(f_i) &= E\left\{ (\mathbf{X}(f_i) \otimes \mathbf{X}^*(f_i)) (\mathbf{X}(f_i) \otimes \mathbf{X}^*(f_i))^H \right\} \\ & \quad - E\{ \mathbf{X}(f_i) \otimes \mathbf{X}^*(f_i) \} E\left\{ (\mathbf{X}(f_i) \otimes \mathbf{X}^*(f_i))^H \right\} \\ & \quad - E\{ \mathbf{X}(f_i) \mathbf{X}^H(f_i) \} \otimes E\left\{ (\mathbf{X}(f_i) \mathbf{X}^H(f_i))^* \right\}, \end{aligned} \quad (5)$$

where \otimes denotes the Kronecker product.

The matrix $\mathbf{C}(f_i)$ has K^2 signal eigenvalues and $P^2 - K^2$ noise eigenvalues. The eigenvectors corresponding to signal eigenvalues $\{\lambda_q(f_i), q = 1, 2, \dots, K^2\}$ span the signal subspace $\Omega_S(f_i) = \text{span}\{\mathbf{b}(f_i, \theta_1), \mathbf{b}(f_i, \theta_2), \dots, \mathbf{b}(f_i, \theta_K)\}$, where $\mathbf{b}(f_i, \theta) = \mathbf{a}(f_i, \theta) \otimes \mathbf{a}^*(f_i, \theta)$. The remaining $P^2 - K^2$ eigenvectors span the noise subspace $\Omega_N(f_i) = \{\mathbf{v}_{K^2+1}(f_i), \mathbf{v}_{K^2+2}(f_i), \dots, \mathbf{v}_{P^2}(f_i)\}$. Thus, the angular spectrum is:

$$\mathbf{P}(\theta) = \frac{1}{\frac{1}{L'} \sum_{i=1}^{L'} \sum_{k=K^2+1}^{P^2} \|\mathbf{b}^H(f_i, \theta) \mathbf{v}_k(f_i)\|^2}. \quad (6)$$

The angles of arrival are estimated by detecting the peaks in this angular spectrum.

4 Simulation results

The performance of DOA estimation is evaluated using the channel model based on the indoor measurements in the 2–8 GHz frequency band proposed by the IEEE 802.15 Study Group 3a [8]. This model is similar to the Saleh-Valenzuela (S-V) model except that it employs a log normal distribution for the channel coefficients instead of a Rayleigh probability density. There are four different models, CM1, CM2, CM3 and CM4, corresponding to different channel characteristics. The number of the ULA antenna is four. We select the Gaussian monocycle pulse shape to be

$$w(t) = \left[1 - 16\pi \left(\frac{t - \frac{D_g}{2}}{D_g} \right)^2 \right] \exp \left[-8\pi \left(\frac{t - \frac{D_g}{2}}{D_g} \right)^2 \right]. \quad (7)$$

The parameters used in the simulation are set to $D_g = 0.2$ ns, $T_c = 1.6$ ns, $T_s = 49.6$ ns, $N = 31$.

Assume that there are three equal-power incoherent DS-UWB signals and their directions of arrival are fixed at 12° , 30° and 54° , respectively. As shown in Fig. 2, the method can accurately estimate DOA for DS-UWB signal. Figure 3 illustrates the mean square error for different signal-to-noise ratio (SNR). It is evident that the method has more estimation accuracy as SNR increases.

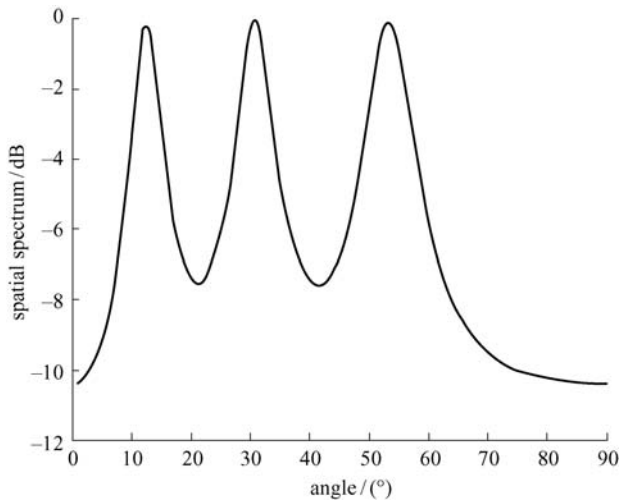


Fig. 2 Spatial spectrum

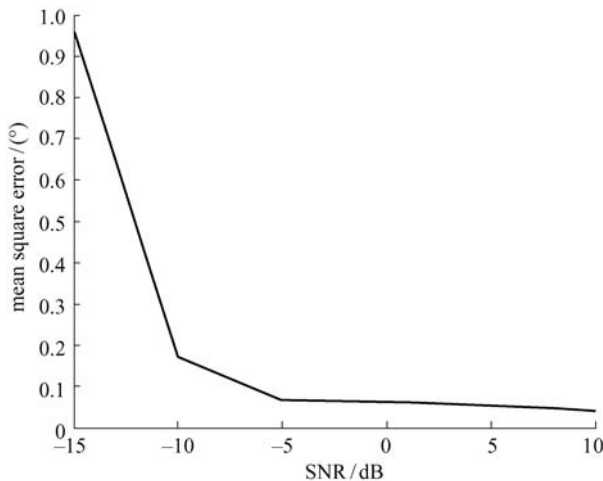


Fig. 3 Mean square error vs SNR

5 Conclusions

Ultra wideband radio is suitable for short range, high-speed wireless personal area network applications. Among various proposed UWB systems, DS-UWB takes the maximum advantage of what UWB has to offer. In a DS-UWB system, the application of smart antenna can improve performance, which requires accurate information of DOA. Thus, an estimation method of DOA for DS-UWB signal is presented. Simulation results show that the method is effective and can guarantee adequate estimation accuracy.

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