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An AOA Estimation Algorithm for 5G Positioning Technology

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Abstract: Among the many positioning technologies, AOA (Angle of Arrival), as one of the most basic wireless positioning technologies, can be fused with other positioning technologies to achieve higher positioning accuracy. In this paper, the principle and implementation process of the MUSIC algorithm are studied according to the application requirements of AOA estimation, and the improved MUSIC algorithm and the maximum likelihood method are fused to achieve a higher-precision MUSIC algorithm. The simulation results show that the fused algorithm shows a positive correlation with the relevant parameters (number of array elements, number of snapshots, etc.), which proves the effectiveness of the algorithm.

Keywords: 5G, Positioning, AOA estimation, MUSIC algorithm.

1. Introduction

With the help of computer technology, wireless communication technology and even space technology, humans continue to explore ways to obtain location information more accurately and efficiently, and have never stopped trying and researching high-precision positioning technologies, methods and systems [1]. Nowadays, 5G technology is becoming increasingly mature. The 5G technical standard 3GPP Rel-16 standard has made a greater expansion on the Rel-15 standard, and added the downlink angle of departure (DL-AOD) to the original basis, uplink angle of arrival (UL-AOA) and other new 5G positioning technologies [2]. Among many positioning technologies, AOA (Angle of Arrival) is one of the most basic wireless positioning technologies. On the one hand, 5G uses high-frequency or millimeter-wave communication. Millimeter-wave communication has very good directivity and can achieve higher-precision angle measurement. On the other hand, 5G uses large-scale antenna technology and has higher-resolution beams. It can also achieve higher-precision angle measurement characteristics [3], and can also be integrated with other positioning technologies for positioning [4]. Therefore, in positioning technology for 5G, AOA-based positioning methods will have higher accuracy than 4G and before. The most typical existing AOA estimation algorithm is the MUSIC (Multiple Signal Classification) algorithm [5], which has the characteristics of high resolution, stable performance and high accuracy. Scholars have proposed many improvements based on the classic MUSIC algorithm. Methods, for example: Root -MUSIC algorithm uses a root-finding process instead of spectral search, which greatly reduces the amount of calculation [6]. The MUSIC algorithm based on spatial smoothing technology can also correctly distinguish coherent signals [7]. The improved MUSIC algorithm and modified MUSIC algorithm can not only distinguish coherent signals, but also correctly distinguish signals with small signal-to-noise ratios and small angular intervals [8]. Based on the improved MUSIC algorithm, this paper proposes fusion with the maximum likelihood method [9] to further improve the algorithm estimation performance.

2. Classic MUSIC Algorithm

The MUSIC algorithm, a multi-signal classification algorithm , was proposed by Schmidt et al. in 1979. The MUSIC algorithm is an algorithm based on subspace decomposition. It uses the orthogonality of the signal subspace and the noise subspace to construct a spatial spectrum function and estimate the parameters of the signal through spectrum peak search.

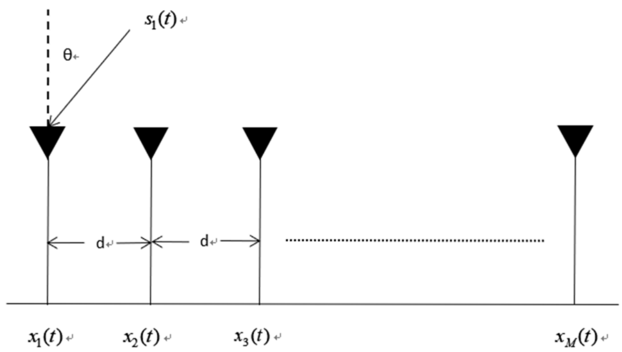

Figure 1. AOA estimated array signal model

Using the definition of a matrix, a more concise expression can be obtained:

$$x\ (t) = As(t) + n(t) \tag{1}$$

In the formula, A is the receiving array steering vector matrix, $s(t)$ is the signal vector, $n(t)$ and is the noise vector of each antenna element.

Assuming that the signal and noise are incoherent, the covariance matrix of the array input signal can be expressed as:

$$\begin{aligned} R_{xx} &= E\left[x(t)x^H(t)\right] \\ &= AE\left[s(t)s^H(t)\right]A^H + E\left[n(t)n^H(t)\right] \\ &= AR_{ss}A^H + R_{nn} \end{aligned} \tag{2}$$

In the formula, $R_{ss} = E[s(t)s^H(t)]$ is a K- order matrix, which represents the autocorrelation matrix of the incident signal; $R_{nn} = \sigma_n^2 I$ is an M- order matrix, which represents the autocorrelation matrix of the noise.

Assume that R_{xx} the eigenvalue of the matrix is $\{\lambda_1 \geq \lambda_2 \geq \cdots \geq \lambda_M\}$, and $AR_{ss}A^H$ the corresponding eigenvalue is $\{\nu_1 \geq \nu_2 \geq \cdots \geq \nu_M\}$. According to formula (2), we get:

$$\lambda_i = \nu_i + \sigma_n^2 \quad i = 1,2,\cdots,M \tag{3}$$

Assume that there are K signals incident on the array, K≤M, and all signals are independent and uncorrelated with each other, then the R_{ss} rank of is K, so $AR_{ss}A^H$ the rank of is also K, that is, there are K non-zero eigenvalues, so R_{xx} the eigenvalues of It can be expressed as:

$$\lambda_i = \{ \begin{array}{c} \nu_i + \sigma_n^2, i = 1,2,\cdots,K \\ \sigma_n^2, i = K+1,\cdots,M \end{array} \tag{4}$$

From this, the eigenvalues can be R_{xx} divided into two parts, namely the part corresponding to the signal and the part corresponding to the noise, and the eigenvector corresponding to the eigenvalue is also divided into two parts. Assuming R_{xx} that the eigenvector is $\{q_1, q_2, \cdots q_K, \cdots, q_M\}$, then these two parts are the signal subspace $V_S = [q_1, q_2, \cdots, q_K]_{M\times K}$ and the noise subspace respectively $V_n = [q_{K+1}, \cdots, q_M]_{M\times(M-K)}$.

According to the definitions of eigenvalues and eigenvectors, it can be seen that eigenvalues λ_i and their corresponding eigenvectors q_i satisfy the formula:

$$(R_{xx} - \lambda_i I)q_i = 0 \tag{5}$$

The MK minimum eigenvalues of the pair R_{xx} and their corresponding eigenvectors are:

$$\left(R_{xx} - \lambda_i I\right)q_i = AR_{ss}A^H q_i = 0 \qquad i = K+1,\cdots,M \tag{6}$$

Because A is of full rank and R_{ss} non-singular, we have:

$$A^H q_i = 0 \qquad i = K+1,\cdots,M \tag{7}$$

Therefore, R_{xx} the eigenvectors corresponding to the M-K minimum eigenvalues and the K guidance vectors that constitute A are orthogonal, that is:

$$\{a(\theta_1),\cdots, a(\theta_K)\} \perp \{q_{K+1},\cdots, q_M\} \tag{8}$$

This is the basic idea of the MUSIC method. The AOA of K incident signals is estimated from the peak value of the MUSIC spatial spectrum. The expression defining the MUSIC spatial spectrum is:

$$\hat{P}_{MUSIC}(\theta) = \frac{a^H(\theta)a(\theta)}{a^H(\theta)V_nV_n^H a(\theta)} \tag{9}$$

When it is the direction vector corresponding to the incident signal, it $a(\theta)$ is orthogonal $a^H(\theta)V_nV_n^H a(\theta)$ to the noise subspace, so V_n the value will be close to 0. At this time, the MUSIC space spectrum θ will produce a spectral peak at. The K maximum peaks in the MUSIC spectrum correspond to the arrival angles of signals incident on the array.

3. Improvement of MUSIC Algorithm

From the derivation process of the classic MUSIC algorithm, the conclusion that the signal subspace and the noise subspace are orthogonal comes from the full rank. Therefore, the prerequisite for the application of the classic MUSIC algorithm is that the incident signals are weakly coherent or incoherent, otherwise the accuracy of AOA estimation will be reduced. Based on the classic MUSIC algorithm, this paper conjugately reconstructs the data array and incorporates the idea of the maximum likelihood method into a new fusion MUSIC algorithm.

First, establish the transformation matrix J. The M- order inverse identity matrix can also be called the transformation matrix, that is:

$$J = \begin{bmatrix} 0 & \cdots & \cdots & 1 \\ \cdots & \cdots & 1 & \cdots \\ \cdots & \cdots & 0 & \cdots \\ 1 & \cdots & \cdots & 0 \end{bmatrix}_{M\times M} \tag{10}$$

Assume that $Y = JX^*$ the complex conjugate X^* in the formula is X, so another covariance matrix is obtained:

$$R_{yy} = E[YY^H] = JR_{xx}^* J \tag{11}$$

We add the two covariance matrices to get a new covariance matrix, which is expressed as follows:

$$R = R_{xx} + R_{yy} = AR_{ss}A^H + J[AR_{ss}A^H]^* J + 2\sigma^2 I \tag{12}$$

The analysis results show that R_{xx}, R_{yy} the noise subspaces of and are exactly the same to R.

Then the covariance matrix is eigenvalue decomposed and sorted to obtain the signal subspace $V_S = [q_1, q_2, \cdots, q_K]_{M\times K}$ and noise subspace $V_n = [q_{K+1}, \cdots, q_M]_{M\times(M-K)}$.

classic MUSIC algorithm is to $|a^H(\theta)V_n|^2$ minimize, while the idea of the maximum likelihood method is to $a^H(\theta)V_n$ maximize the likelihood value of the variable.

Finally, by integrating the maximum likelihood method [9], we get:

$$\hat{P}_{MUSIC}(\theta) = \frac{a^H(\theta)\hat{U}a(\theta)}{a^H(\theta)V_nV_n^H a(\theta)} \tag{13}$$

In the formula $\hat{U} = \sigma^2 \sum_{k=1}^{p} \frac{\lambda_k}{(\sigma^2-\lambda_k)^2} V_S V_S^H$, Vs is the signal subspace.

The steps to implement the fusion MUSIC algorithm are as follows:

1. First, use the L snapshot data received by the array to obtain an estimate of a covariance matrix of the data:

$$R_{xx} = \frac{1}{N}\sum_{n=1}^{N} x(n)x^H(n) \tag{14}$$

2. Perform matrix reconstruction, assuming $Y = JX^*$, so another covariance matrix is obtained:

$$R_{yy} = E[YY^H] = JR_{xx}^* J \tag{15}$$

3. Perform eigenvalue decomposition of the original matrix and the reconstructed matrix:

$$R = R_{xx} + R_{yy} = AR_{ss}A^H + J[AR_{ss}A^H]^* J + 2\sigma^2 I \tag{16}$$

4. Sort the eigenvalues according to the high and low, and filter out the required eigenvectors and noise vectors to obtain the eigenmatrix U:

$$\hat{U} = \sigma^2 \sum_{k=1}^{p} \frac{\lambda_k}{(\sigma^2 - \lambda_k)^2} V_S V_S^H \tag{17}$$

5. Make θ the change through the following formula:

$$\hat{P}_{MUSIC}(\theta) = \frac{a^H(\theta)\hat{U}a(\theta)}{a^H(\theta)V_n V_n^H a(\theta)} \tag{18}$$

Calculate the spectral function and obtain an estimate of the direction of arrival by finding the peak value.

4. MATLAB Simulation Analysis

4.1. Comparison between classic MUSIC algorithm and fused MUSIC algorithm

Use MATLAB 2021b software for simulation analysis. Assume that there are two independent narrowband signals, the signal incident angles are 20°,55°, the number of array elements is 10, the number of snapshots is 200, the array element spacing is $1/2$, and the signal-to-noise ratio is 20dB, the following are the classical MUSIC algorithm and fusion respectively MUSIC algorithm is used for simulation, and the results are shown in Figure 2:

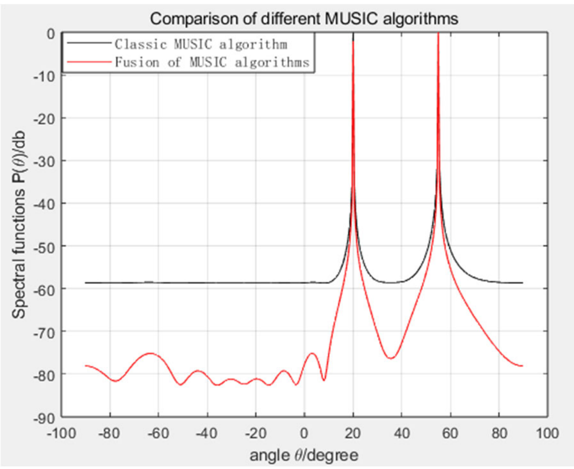

Figure 2. Comparison between classic MUSIC algorithm and fused MUSIC algorithm

The simulation results show that under the same conditions, the fused MUSIC algorithm is significantly better than the classic MUSIC algorithm, verifying the feasibility of the fused MUSIC algorithm proposed in this article.

Next, compare different parameters of the algorithm proposed in this article and analyze its impact.

4.2. The impact of different array element numbers on the fusion MUSIC algorithm

The incident angle, number of snapshots, and array element spacing remain unchanged, and the number of array elements is set to 10, 20, and 30 respectively. The impact of different numbers of array elements on the performance of the algorithm is analyzed. The simulation results are shown in Figure 3:

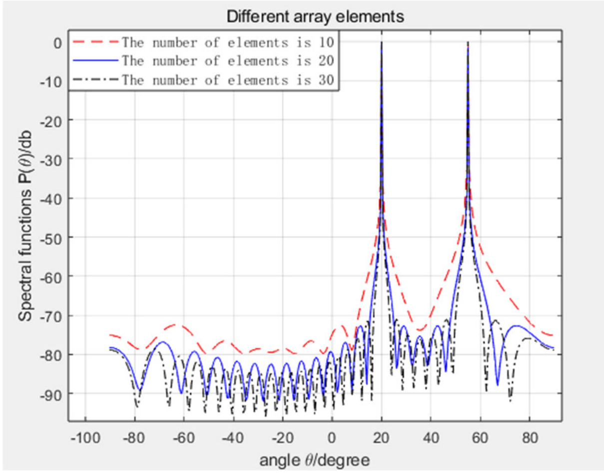

Figure 3. Fusion MUSIC algorithm when the number of array elements is different

It can be seen from Figure 3 that when only the number of array elements is changed and other conditions remain unchanged, increasing the number of array elements will narrow the beam width of the estimated spectrum and make the estimation result more accurate. Therefore, more accurate results can be obtained by increasing the number of array elements. the result of.

4.3. The impact of different array element spacing on the fusion MUSIC algorithm

Keeping other conditions unchanged, set the array element spacing to $d/4$, $d/2$, and respectively d to analyze the impact of different array element spacing on the algorithm performance. The simulation results are shown in Figure 4:

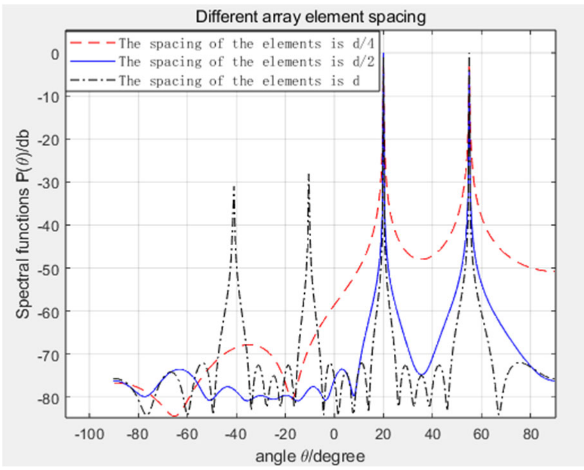

Figure 4. Fusion MUSIC algorithm when array element spacing is different

It can be seen from Figure 4 that when the array element spacing is $d/4$, its effect is obviously worse than $d/2$ that of the array element spacing, and the beam width of the estimated spectrum becomes wider. When the array element spacing is d, although the beam width of the same estimated spectrum will become narrower, false spectral peaks will appear, which cannot truly reflect the direction of the incident angle of the signal source.

4.4. The impact of different snapshot numbers on the fusion MUSIC algorithm

Keeping other conditions unchanged, set the number of snapshots to 5, 20, and 100 respectively to analyze the impact of different number of snapshots on the performance of the algorithm. The simulation results are shown in Figure 5:

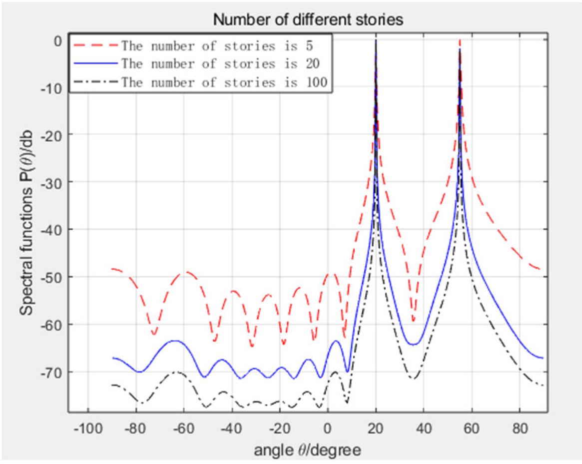

Figure 5. Fusion MUSIC algorithm when the number of snapshots is different

As can be seen from Figure 5, when other conditions are the same, the beam width of the estimated spectrum will become narrower as the number of snapshots increases, which increases the estimation accuracy. Therefore, the number of sampling snapshots can be increased to improve the accuracy of the algorithm.

4.5. The impact of different signal-to-noise ratios on the fusion MUSIC algorithm

Keeping other conditions unchanged, set the signal-to-noise ratio to -10 dB, 0 dB and 10 dB respectively to analyze the impact of different signal-to-noise ratios on the performance of the algorithm. The simulation results are shown in Figure 6:

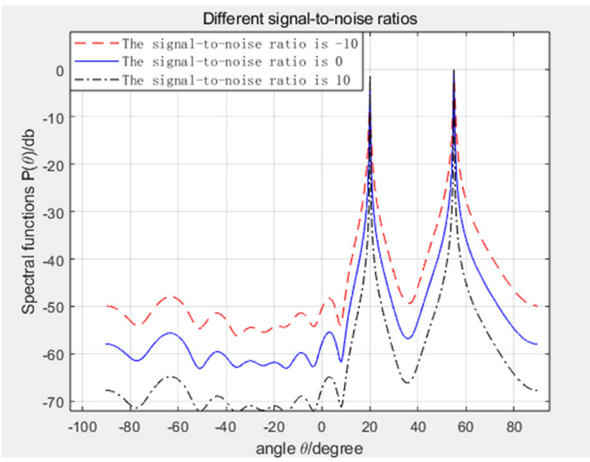

Figure 6. Fusion of MUSIC algorithm with different signal-to-noise ratios

It can be seen from Figure 6 that, under other conditions being the same, the performance of the algorithm will decrease rapidly when the signal-to-noise ratio is low, the beam width of the estimated spectrum will become narrower as the signal-to-noise ratio increases, and the estimation accuracy increases, so the signal-to-noise ratio can be increased to improve the accuracy of the algorithm.

5. Conclusion

Based on the classic MUSIC algorithm, this paper proposes a fused MUSIC algorithm in order to obtain a higher-precision algorithm. The essence of this algorithm is to integrate the ideas of the improved MUSIC algorithm and the maximum likelihood method, reconstruct the covariance matrix through the improved algorithm, and integrate the optimization matrix into it $\hat{P}_{MUSIC}(\theta)$. Finally, the algorithm proposed in this article is implemented through MATLAB software. Computer Simulation. The simulation results show that under the same conditions such as the number of array elements and the number of snapshots, the algorithm proposed in this article is better than the classic MUSIC algorithm, and the resolution of the fusion algorithm will increase with the number of array elements, number of snapshots and signal-noise. Increased as the ratio increases.

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