Research on 5G positioning technology for urban canyon

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Abstract. Aiming at the problem of poor positioning accuracy of GNSS for urban canyon environment, this paper proposes a TDOA/AOA combined positioning technology based on 5G. Firstly, the AOA estimation algorithm based on conventional beam forming is compared with that based on MUSIC algorithm. Then, the weighted matrix is smoothed forward and backward. Finally, according to the measurement data of AOA and TDOA, Chan and Taylor combined localization algorithm is used to obtain the estimated location of the user.

1. Introduction
With the development of economy, urban building clusters gradually become dense, resulting in urban canyon, and the traditional GNSS positioning effect is not good. Cellular wireless Location service (LCS) can address such problems[1]. 5G positioning technology includes AOA (Angle of Arrival), TDOA (Time Difference of Arrival), RSSI (Received Signal Strength Indication)[2].

For the problem of signal interference, the traditional beam forming algorithm has low accuracy[3]. Schmidt et al. proposed the MUSIC algorithm[4]. Evans proposed a spatial smoothing algorithm to achieve decoherence[5]. Literature improves the spatial smoothing algorithm to deal with coherent sources more effectively[6-8]. In this paper, based on MUSIC algorithm and weighted forward and backward space smoothing algorithm, AOA estimation effect is better.

The positioning algorithm of TDOA will lead to more than one registration point in the case of fewer base stations or unreasonable distribution of base stations[9]. Common algorithms for TDOA position calculation include Fang algorithm[10], Chan algorithm and Taylor algorithm[11-12]. Fang algorithm can not use redundant information to improve location accuracy. Chan algorithm can improve its accuracy by increasing the number of base stations.

Many scholars have studied the combined positioning method based on the above algorithms[13]. In this paper, the improved MUSIC algorithm is used to complete AOA estimation. Combined with TDOA measurement data of 5G base station, TDOA/AOA combination positioning combined with Chan algorithm and Taylor algorithm is adopted to obtain more accurate THREE-DIMENSIONAL location information.

2. AOA Location

2.1. AOA positioning principle
The positioning algorithm of AOA (Angle of Arrival) uses the built-in antenna array at the receiving end of the base station to receive the azimuth of the electromagnetic wave sent by the user's equipment.
to construct the tangent function equation. The three-dimensional position principle of AOA in the urban environment is shown in Figure 1:

![Figure 1. AOA location principle](image)

According to the figure, the relationship between $\phi$, UE and $\text{BS}_i$ is:

$$\tan(\phi_i) = \frac{z_i - z}{\sqrt{(x_i - x)^2 + (y_i - y)^2}}$$  \hspace{1cm} (1)

Coordinate $[x, y, z]$ of UE can be achieved by combining three or more equations.

2.2. *AOA estimation by MUSIC algorithm*

The principle of MUSIC (Multiple Signal Classification) is to decompose the covariance matrix of the output data of any array by eigenvalue, and the eigenvectors of different eigenvalues form orthogonal signal subspace and noise subspace.

The auto correlation matrix can be expressed as:

$$R_x = E[x(t)x^H(t)] = AE[s(t)s^H(t)A^H + E[n(t)n^H(t)] = AR_nA^H + R_n$$  \hspace{1cm} (2)

Spatial spectrum of MUSIC algorithm $P_{\text{MUSIC}}(\theta)$:

$$P_{\text{MUSIC}}(\theta) = \frac{1}{a^H(\theta)E_nE_n^Ha(\theta)}$$  \hspace{1cm} (3)

2.3. *MUSIC algorithm for backward and forward space smoothing*

The forward space smoothing algorithm divides $M$ array signals into $L$ overlapping sub-arrays, as shown in the figure below.

![Figure 2. Schematic diagram of forward space smoothing algorithm](image)

Each sub-array has $N = M - L + 1$ elements. The spatial smoothing matrix of the $J$ sub array is:

$$R^H_n = A_jD_j^{-1}R_n(D_j^{-1})^H + \sigma^2I_N \hspace{1cm} j = 1, 2, ..., L$$ \hspace{1cm} (4)

The covariance moment after smoothing forward space can be obtained by averaging the covariance of all sub arrays, which can be expressed as:
The backward space smoothing algorithm smooths the covariance matrix of the backward sub array conjugate received data, and improves the number of smoothed sub arrays, as shown below.

\[
\hat{\mathbf{R}}^f = \frac{1}{L} \sum_{j=1}^{L} \mathbf{R}^{\hat{g}}_j
\]

(5)

The backward space smoothing algorithm smooths the covariance matrix of the backward sub array conjugate received data, and improves the number of smoothed sub arrays, as shown below.

Each sub-array has \(L = M - P + 1\) elements. The relationship between backward space smooth covariance matrix \(\hat{\mathbf{R}}^b\) and forward space smooth covariance \(\hat{\mathbf{R}}^f\) is:

\[
\hat{\mathbf{R}}^b = J \ast \left( \hat{\mathbf{R}}^f \right)^\ast J
\]

(6)

The covariance after the forward and backward space smoothing is expressed as:

\[
\mathbf{R} = \frac{1}{2} \left( \hat{\mathbf{R}}^f + \hat{\mathbf{R}}^b \right)
\]

(7)

### 2.4. Weighted forward and backward space smoothing MUSIC algorithm

Weighted forward-backward space smoothing algorithm is a weighted average of forward-backward space smoothing and forward-backward space smoothing. The estimated value of the source \(\hat{\theta}_1, \hat{\theta}_2, \ldots, \hat{\theta}_K\) is obtained by using the forward-backward space smoothing MUSIC algorithm. A weighted matrix \(W\) can be expressed as:

\[
W = \left( B \cdot B^H \right)^{-1}
\]

(8)

The optimal weight matrix \(W_p\) is obtained by smoothing \(W\).

\[
W_p = \frac{1}{L} \sum_{j=1}^{L} F_k \cdot \left( W + J \cdot W^* \cdot J \right) \cdot F_k^T
\]

(9)

The weighted matrix \(W_p\) is combined with the covariance matrix of forward-backward space smoothing, and the obtained weighted forward-backward space smoothing covariance matrix is:

\[
\mathbf{R}^{\ast P} = \frac{1}{L} \sum_{j=1}^{L} \left( \mathbf{R}^{\hat{g}}_j + J \ast \left( \mathbf{R}^{\hat{g}}_j \right)^\ast J \right) \cdot W_p
\]

(10)

### 2.5. Simulation and analysis of improved MUSIC algorithm

The simulation uses a uniform linear array with 16 array elements and half wavelength spacing, and the two signal angles are \(\theta_s\) and \(\theta_1\) respectively. In the case of the SNR of -5dB, two groups of experiments are carried out on the forward-forward-backward space smoothing MUSIC algorithm and the improved weighted forward-forward-backward space smoothing MUSIC algorithm. The spatial spectrum obtained is shown in the figure below.
By analyzing the above simulation results and details, the weighted forward-backward space smoothing MUSIC algorithm is superior to the forward-backward space smoothing MUSIC algorithm under the condition of low SNR.

3. TDOA Location

TDOA (Time Difference of Arrival): To locate by measuring the Time Difference between user device signals and different base stations. The positioning principle of TDOA is shown in Figure 3-1. To determine a point in three-dimensional space, at least three distance differences and four base stations are required. The coordinate of the base station is \( BS_i = [x_i, y_i, z_i], i = 1, 2, 3, 4 \). Figure 3-1 shows the TDOA locating principle.

Figure 4. MUSIC algorithm and details of backward and forward space smoothing

Figure 5. Weighted forward-backward space smoothing MUSIC algorithm and its details

Figure 6. TDOA locating principle
Taking BS$_i$ as the reference base station, it is known that the time difference between the arrival of UE at each secondary station and the arrival of the main station is $\tau_{1i}(i = 2, 3\ldots)$. Assuming that the signal propagation velocity is the speed of light $c$, the distance difference between UE and the primary station and each secondary station is:

$$\Delta d_{1i} = c\tau_{1i}$$

(11)

Can also be expressed as:

$$\Delta d_{1i} = d_{j} - d_{i} = \sqrt{(x_{j} - x_{i})^2 + (y_{j} - y_{i})^2 + (z_{j} - z_{i})^2}$$

(12)

Set $q_{i}^2 = x_{i}^2 + y_{i}^2 + z_{i}^2$,

$$x(x_{j} - x_{i}) + y(y_{j} - y_{i}) + z(z_{j} - z_{i}) = \Delta d_{j}d_{i} + \frac{\Delta d_{1j}^2 + q_{j}^2 - q_{i}^2}{2}$$

(13)

The above equations should have three, which can be rewritten as a matrix:

$$\begin{bmatrix} x_{2} - x_{1} & y_{2} - y_{1} & z_{2} - z_{1} \\ x_{3} - x_{1} & y_{3} - y_{1} & z_{3} - z_{1} \\ x_{4} - x_{1} & y_{4} - y_{1} & z_{4} - z_{1} \end{bmatrix} \begin{bmatrix} x \\ y \\ z \end{bmatrix} = \begin{bmatrix} -\Delta d_{2} \\ -\Delta d_{3} \\ -\Delta d_{4} \end{bmatrix} \begin{bmatrix} d_{1} \\ l_{2} \\ l_{3} \end{bmatrix}$$

(14)

UE coordinate $[x, y, z]$ can be obtained.

4. TDOA/AOA combination localization

4.1. TDOA/AOA positioning principle

In this section, the positioning method combined with TDOA and AOA is adopted to establish a three-dimensional positioning system model by using the measured values of AOA and TDOA. Chan algorithm is a non-recursive positioning method based on TDOA positioning technology, and generally coordinates positioning with other algorithms to provide initial values for other algorithms. Chan algorithm was used to preliminary estimate the coordinates of $x$ and $y$ of UE, and then Taylor algorithm was used to iterate and revise the initial estimated value until it met a certain threshold value, and the position of UE was solved.

The relationship between $\phi_{i}$ and $d_{i}$ is:

$$\cos(\phi_{i}) = \frac{\sqrt{(x_{i} - x)^2 + (y_{i} - y)^2}}{d_{i}}$$

(15)

The $z$ coordinate of UE can be obtained from equation (1):

$$z = z_{i} - \tan(\phi_{i})\sqrt{(x_{i} - x)^2 + (y_{i} - y)^2}$$

(16)

The distance between UE and each base station can be expressed as:

$$d_{i} = \sqrt{(x_{i} - x)^2 + (y_{i} - y)^2 + (z_{i} - \tan(\phi_{i})\sqrt{(x_{i} - x)^2 + (y_{i} - y)^2})^2}$$

(17)

It can be obtained from the above formula:

$$y = ax + b$$

$$a = \frac{d_{21}x_{2} - d_{31}x_{3}}{d_{21}y_{1}}$$

$$b = \frac{(1 - \beta^2)d_{31}(d_{21} - d_{31})}{2y_{1}} - \frac{d_{21}x_{2}^2 - d_{31}(x_{2}^2 + y_{2}^2)}{2d_{21}y_{1}}$$

$$\beta = \sin(\phi_{i})$$

(18)
The obtained $[x, y]$ is used as the preliminary estimate of Taylor algorithm for the next iteration correction. The distance difference between UE and the reference base station and other base stations is $d_i = d_i - d_i$. The distance differences $g$ and $d$ are the form of the coordinates $x$ and $y$ of UE and are functions of $\phi_i$. Define $\rho = [x, y]^T$, and the cost function of about is expressed as $\rho$:

$$J(\rho) = \|g - d\|^2$$  \hspace{1cm} (19)

The objective function of $\rho$ estimation is:

$$\hat{\rho} = \arg\min_{\rho} J(\rho)$$  \hspace{1cm} (20)

The objective function of $\rho_{k+1}$ estimation is:

$$J(\rho_{k+1}) = \|g - H \rho_{k+1}\|^2$$  \hspace{1cm} (21)

The least squares solution of $x$ and $y$ can be obtained:

$$\rho_{k+1} = \rho_k + (H^TH)^{-1}H^T(g - d_k)$$  \hspace{1cm} (22)

If $|\rho_{k+1} - \rho_k| \leq \epsilon$, the estimated value of coordinates $x$ and $y$ can be determined by equation (18), and finally substituted into Equation (16) to obtain the position coordinate $[x, y, z]$ of UE.

4.2. Simulation and analysis
This section uses MATLAB simulation software to simulate and compare the improved AOA positioning algorithm, TDOA positioning algorithm and combined TDOA/AOA positioning algorithm in this paper. Assuming that four base stations are involved in positioning and the real positions of base stations and UE are known, the relationship between SNR and estimated standard deviation under different SNR is shown in figure 7.

![Figure. 7 Relationship between estimated standard deviation and SNR](image)

The simulation results show that the estimated standard deviation of the three methods decreases with the increase of SNR, but the TDOA/AOA positioning algorithm has the lowest estimated standard deviation and good stability.

5. Conclusion
In this paper, weighted spatial smoothing MUSIC algorithm is used to improve the AOA estimation accuracy. Chan algorithm was used to preliminary locate UE position, and Taylor algorithm was used for iterative correction, which effectively improved the positioning accuracy. 5G is a hot technology at
present. Next, we should make full use of the characteristics of 5G signal to improve positioning accuracy and make life more convenient for people in urban valleys in the future.

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