Hybrid GNSS + 5G Position and Rotation Estimation Algorithm Based on TOA and Unit Vector of Arrival in Urban Environment

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***Abstract*—Positioning methods that rely solely on global satellite navigation system (GNSS) measurements have significantly decreased reliability in urban environments and cannot meet the needs of industries, such as autonomous driving. This article introduces a novel fifth-generation (5G) joint time of arrival (TOA) and unit vector observation model that takes rotation into account, and evaluates its performance through multiple sets of simulated data. The results show that compared with the traditional joint TOA and angle of arrival (AOA) observation model, the proposed model can notably improve the positioning accuracy, and the effect is better after iteration. Furthermore, we conduct a new stochastic model for 5G measurements and investigate the impact of model coefficients on performance. The results reveal that inappropriate coefficients will lead to loss of observational information, highlighting the importance of stochastic models. In urban environments, the proposed 5G joint observation model can effectively assist GNSS and provide more accurate navigation services and rotation estimation, providing valuable insights for the future development of smart transportation.**

***Index Terms*—Fifth-generation (5G) joint model, global satellite navigation system (GNSS), rotation, time of arrival (TOA), unit vector.**

I. INTRODUCTION

A GLOBAL satellite navigation system (GNSS) is the main technology used in ground navigation systems, and the real-time positioning accuracy can reach centimeter level [1]. However, owing to the poor anti-interference of GNSS signals, it only denotes good performance in open environments [2], [3], [4]. As the autonomy of smart devices increases, the requirements on the reliability and availability of their navigation systems become more stringent [5]. Therefore, researchers are exploring other signals and sensors to improve the integrity of GNSS and overcome its severe signal attenuation in urban areas.

At this stage, technologies, such as Wi-Fi [6], Bluetooth, and [7] ultra-wideband (UWB) [8], have been extensively researched in assisting GNSS positioning. However, the additional construction and technical maintenance costs hinder the further promotion and application of the above positioning technology. In contrast, technologies, such as inertial navigation system (INS) [9], [10] and pedestrian dead reckoning (PDR) [11], suffer from error accumulation and cannot achieve long-term positioning. The fifth-generation (5G) communication system is known for its larger bandwidth and higher frequencies in communication [12], [13], [14], and it uses the existing communication base stations (BSs) without requiring additional equipment, which can significantly reduce costs. Its potential in high-precision positioning has attracted continued attention from researchers.

Currently, there are two types of observation information that 5G signals can provide: one is the distance information obtained through the signal propagation time: time of arrival (TOA), time difference of arrival (TDOA), and round-trip time (RTT); the other is the angle information: angle of arrival (AOA) and angle of departure (AOD). In the urban environment, the positioning method that combines 5G TOA and GNSS helps to achieve the full position availability [15], [16]. The 5G TDOA observation can eliminate clock errors between BSs and assist GNSS in achieving accurate positioning [17]. With the continuous development of technologies, such as autonomous driving, 5G distance observation alone cannot meet the needs of the public. The unit vector model based on AOD signal can effectively assist GNSS positioning in urban environments [18]; compared with relying solely on TOA-assisted GNSS, the positioning accuracy is improved by more than 40%. The AOD-based 5G positioning focuses on tracking signals from the server, while the AOA-based positioning model obtains observation information from the user, which is more conducive to improving system security.

Considering that in practical applications, user equipment (UE) is constantly moving, and the arrival direction of the AOA signal is constantly changing. Therefore, the posture of the equipment, especially the rotation within the plane, is particularly important for 5G positioning based on AOA [19]. In 5G network systems, AOA positioning can achieve sub-

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meter positioning accuracy [20], and using AOA to assist GNSS positioning can effectively improve the reliability of navigation solutions in urban environments [21]. However, the rotation of equipment is not taken into account in these studies. In [22], researchers assumed that the rotation is known, and combining TDOA and AOA can improve positioning accuracy and detect NLOS interference signals. In addition, the stochastic model is also an important factor affecting system performance. Most of the existing studies on hybrid GNSS + 5G systems focus on positioning algorithms and do not analyze the stochastic model. The equal-weighted model [23] and distance-based stochastic model [24] are commonly used to determine the weight of 5G observations. However, in most cases, the equal-weighted model is too simple to accurately reflect the data quality, and the distance-based model ignores the impact of elevation on 5G angle observations.

Based on the above analysis, this study obtains observations from the user side and proposes a 5G joint TOA and unit vector positioning model, which takes user rotation into account, and introduces a new stochastic model to determine the weight of 5G observations. The structure of this article is as follows. Section II introduces the proposed model and localization algorithm. Section III evaluates the hybrid GNSS + 5G model performance experimentally. Finally, the conclusions are given in Section IV.

II. METHODOLOGY

We consider that a 5G system has at least four BSs. The location relationship between the BS and UE is shown in Fig. 1. Locations of the BS and UE are denoted by $\mathbf{p}_{\mathbf{BS,i}} = [x_i, y_i, z_i]^{\mathbf{T}}$ and $\mathbf{p}_{\mathbf{UE}} = [x, y, z]^{\mathbf{T}}$ with β denoting the rotation of the UE coordinate system.

The user's altitude change is not obvious in daily life, and only plane coordinates are estimated in subsequent experiments. The coordinates of BSs and z are assumed to be known, while the values of (x, y), β, and 5G clock bias τ are unknown.

A. 5G Joint TOA + AOA Observation Model

Traditionally, the angle measurements provided by the 5G system are in the local coordinate system, while the coordinates of the BS and the UE are in the global coordinate frame, so a rotation matrix is required for conversion. The observation model joint 5G TOA and AOA can be expressed by the following formula [20], [25]:

$$\mathbf{Z}_{\mathrm{TA}} = \begin{cases} d_{5\mathrm{G},i} = ||\mathbf{p}_{\mathbf{BS,i}} - \mathbf{p}_{\mathbf{UE}}|| + c \cdot \tau \\ \theta_i = \arccos\left(\dfrac{\left[\mathbf{R}^{\mathbf{T}}\left(\mathbf{p}_{\mathbf{BS,i}} - \mathbf{p}_{\mathbf{UE}}\right)\right]_z}{||\mathbf{p}_{\mathbf{BS,i}} - \mathbf{p}_{\mathbf{UE}}||}\right) \\ \alpha_i = \arctan\left(\dfrac{\left[\mathbf{R}^{\mathbf{T}}\left(\mathbf{p}_{\mathbf{BS,i}} - \mathbf{p}_{\mathbf{UE}}\right)\right]_y}{\left[\mathbf{R}^{\mathbf{T}}\left(\mathbf{p}_{\mathbf{BS,i}} - \mathbf{p}_{\mathbf{UE}}\right)\right]_x}\right) \end{cases} \tag{1}$$

where $||\cdot||$ is the geometric distance. c is the light propagation speed

$$\mathbf{R} = \begin{bmatrix} \cos\beta & -\sin\beta & 0 \\ \sin\beta & \cos\beta & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

denotes the rotation matrix. arccos and arctan are the inverse cosine and inverse tangent.

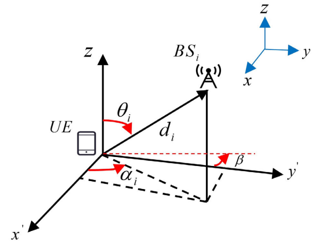

Fig. 1. Schematic of the location relationship between BS and UE. θ and α, respectively, represent the elevation and azimuth in local coordinate system, β is the rotation between the two systems, and d denotes the distance between BS and UE. The subscript i represents the BS identification number.

B. 5G Joint TOA + Unit Vector Observation Model

For 5G systems, nonlinear errors are a key factor affecting their performance. To solve this problem, we propose a unit vector observation model based on AOD measurements in [18] and verify its feasibility and performance. The unit vector model can also be extended to AOA observations, and the joint TOA and unit vector model is as follows:

$$\mathbf{Z}_{\mathrm{TU}} = \begin{cases} d_{5\mathrm{G},i} = ||\mathbf{p}_{\mathbf{BS,i}} - \mathbf{p}_{\mathbf{UE}}|| + c \cdot \tau \\ \sin\theta_i \cos\alpha_i = \dfrac{[\mathbf{R}^{\mathbf{T}}(\mathbf{p}_{\mathbf{BS,i}} - \mathbf{p}_{\mathbf{UE}})]_x}{||\mathbf{p}_{\mathbf{BS,i}} - \mathbf{p}_{\mathbf{UE}}||} \\ \sin\theta_i \sin\alpha_i = \dfrac{[\mathbf{R}^{\mathbf{T}}(\mathbf{p}_{\mathbf{BS,i}} - \mathbf{p}_{\mathbf{UE}})]_y}{||\mathbf{p}_{\mathbf{BS,i}} - \mathbf{p}_{\mathbf{UE}}||} \\ \cos\theta_i = \dfrac{[\mathbf{R}^{\mathbf{T}}(\mathbf{p}_{\mathbf{BS,i}} - \mathbf{p}_{\mathbf{UE}})]_z}{||\mathbf{p}_{\mathbf{BS,i}} - \mathbf{p}_{\mathbf{UE}}||}. \end{cases} \tag{2}$$

It is not difficult to find that compared with traditional AOA observations, the unit vector observation model is less affected by nonlinearization errors and theoretically has better positioning performance.

C. Stochastic Model of the 5G Joint Model

Moreover, the quality of measurement data at different locations varies. The existing research on hybrid GNSS + 5G positioning has not discussed the stochastic model of 5G observations. According to the 5G signal propagation model [26], we propose the following stochastic model:

$$\begin{aligned} \sigma^2_{d_{5\mathrm{G},i}} &= \left(\frac{d_{5\mathrm{G},i}}{b}\right)^2 \\ \sigma^2_{\theta_i} &= a \cdot \left(\frac{d_{5\mathrm{G},i}}{b}\right)^2 \cdot \left(\frac{1}{\cos^2\theta_i}\right) \\ \sigma^2_{\alpha_i} &= a \cdot \left(\frac{d_{5\mathrm{G},i}}{b}\right)^2 \cdot \left(\frac{1}{\sin^2\theta_i}\right) \end{aligned} \tag{3}$$

where a and b are the constants and σ is the standard deviation (STD). In the solution process, we consider that distance measurements are independent of each other, and their corresponding variance–covariance matrix is as follows:

$$\mathbf{Q}_{d_{5\mathrm{G}}} = \mathrm{diag}\left[\sigma^2_{d_{5\mathrm{G},1}}, \ldots, \sigma^2_{d_{5\mathrm{G},m}}\right] \tag{4}$$

where m is the number of BSs. According to the error propagation law, there is a mutual relationship between each measurement in unit vector model. We derived its variance and covariance matrix $\mathbf{Q}_{UV}$ in [18], and the stochastic model of the 5G joint model can be expressed as follows:

$$\mathbf{Q}_{\text{joint,5G}} = \begin{bmatrix} (\mathbf{Q}_{d_{5G}})_{m*m} & \\ & (\mathbf{Q}_{UV})_{3m*3m} \end{bmatrix}. \tag{5}$$

D. Hybrid GNSS + 5G Model

Typically, we express GNSS pseudorange measurements by the following formula:

$$P_j^s = \rho_j^s + c(dt_r - dt_s) + I + T \tag{6}$$

where $\rho = ((x_{s,j} - x)^2 + (y_{s,j} - y)^2 + (z_{s,j} - z)^2)^{1/2}$ is the geometric distance between the satellite and the receiver, and the subscripts s and j represent the satellite and their identification number, respectively. r is the receiver, and P represents the pseudorange. dt denotes the clock error. I and T represent the ionospheric delay error and the tropospheric delay error. According to (2) and (6), the observation model of the hybrid system can be represented by $\mathbf{Z}_{\text{GNSS,5G}} = [P_1^s, P_2^s, \ldots, P_n^s, Z_{\text{TOA}+UV,1}, \ldots, Z_{\text{TOA}+UV,m}]^{\mathbf{T}}$. n and m represent the number of satellites and the number of 5G BSs.

Furthermore, we consider that distance observations from different satellites are independent of each other, and their variance–covariance matrix can be expressed as follows:

$$\begin{aligned} \mathbf{Q}_{P_{\text{GNSS}}} &= \text{diag}\left[\sigma_{P,1}^2, \ldots, \sigma_{P,n}^2\right] \\ \sigma_{P,n}^2 &= k \cdot 10^{-(C/N_0)_n/10} + l \end{aligned} \tag{7}$$

where C/N_0 is the carrier-to-noise ratio. k and l are coefficient constants. Therefore, the variance–covariance matrix of the hybrid GNSS + 5G system is as follows:

$$\mathbf{Q}_{\text{GNSS,5G}} = \begin{bmatrix} (\mathbf{Q}_{P_{\text{GNSS}}})_{n*n} & \\ & (\mathbf{Q}_{\text{joint,5G}})_{4m*4m} \end{bmatrix}. \tag{8}$$

The weight least squares method is used to estimate unknown parameters, and it can be constructed as follows:

$$Z_{\text{GNSS,5G}} = G(\mathbf{X}) + V. \tag{9}$$

$X = [x \;\; y \;\; \beta \;\; \tau]^T$ is the state vector, $G(X)$ is the modeled observation, and V is the residual of the observation. Taylor's first-order expansion is performed at the initial value X_0 to obtain the linearized error equation

$$V = -\mathbf{H} \cdot dX + L \tag{10}$$

where $\mathbf{H}$ is a coefficient matrix consisting of the partial derivatives of the observation equation with respect to the parameters. $L = Z_{\text{GNSS,5G}} - G(X_0)$ is the difference between the observed value and the modeled value, and $dX = [\Delta x \;\; \Delta y \;\; \Delta\beta \;\; \Delta\tau]^T$ is the correction for the parameters to be estimated. The solution for the hybrid GNSS + 5G system can be produced by using an iterative solution approach

$$\begin{aligned} X &= X_0 + dX \\ dX &= (\mathbf{H}^{\mathbf{T}}\mathbf{Q}_{\text{GNSS,5G}}\mathbf{H})^{-1}\mathbf{H}^{\mathbf{T}}\mathbf{Q}_{\text{GNSS,5G}}L \end{aligned} \tag{11}$$

where X_0 is the solution of the previous epoch and the meanings of the remaining parameters are the same as above.

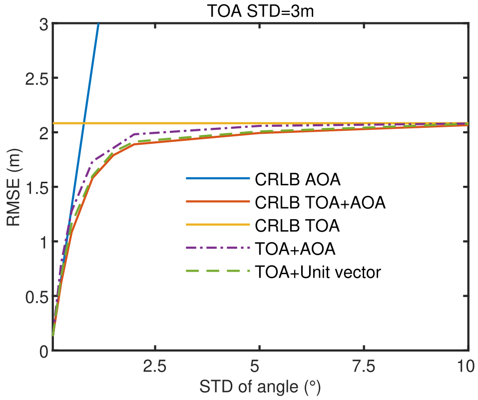

Fig. 2. Performance comparison of different joint models and CRLB of these methods. Note: STD of TOA measurements is 3 m.

III. Experimental Results and Discussion

In the 5G positioning process, the accuracy achieved by the TOA method can only meet the positioning requirements of some scenarios, and the impact of nonlinearization errors in the AOA method is nonnegligible. Therefore, we use the joint 5G TOA and unit vector model to conduct subsequent experiments and compare with other models.

A. Cramer–Rao Lower Bound of 5G Joint Model

To systematically and comprehensively verify the 5G joint model performance, we add different biases to the angle and distance measurements and analyze the Cramer–Rao lower bound (CRLB) of different methods [27].

The CRLB can be used to calculate the best estimation accuracy that can be obtained in unbiased estimation, and it is often used to evaluate the best performance of parameter estimation methods. To better simulate the urban observation environment, we fix the STD of TOA measurements to 3 m [24]. Fig. 2 shows the CRLB of different methods (solid lines) and the positioning root-mean-square error (RMSE) of two 5G joint models (dotted line) under different angle observation accuracies. It can be clearly seen that the 5G joint model has better CRLB than the single model, which also shows that more measurements can improve model performance to a certain extent. Comparing the positioning results, it can be found that the 5G joint TOA and unit vector model has a better performance and can provide accurate solutions. However, excessive angle measurement errors greatly reduce data availability, which results in the 5G joint model accuracy and CRLB being infinitely close to the CRLB of the TOA.

Likewise, we fix the STD for AOA measurement to 2° and display the results in Fig. 3. Analyze the relationship between the different positioning methods and the accuracy of distance measurement. We can draw the conclusion consistent with Fig. 2 that the 5G joint TOA and unit vector model performs better than the joint TOA and AOA model.

B. Simulation of 5G Joint Model

Section III-A analyzes the performance of different 5G positioning algorithms and theoretically verifies the superiority of 5G joint TOA and unit vector. Next, we quantitatively

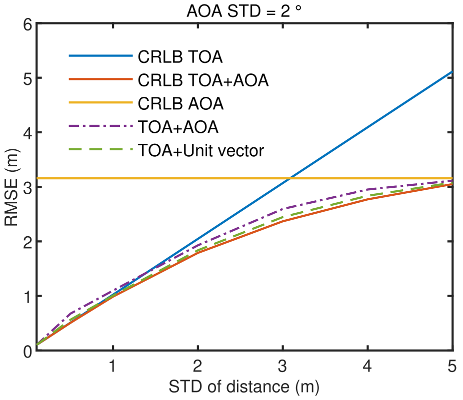

Fig. 3. Performance comparison of different joint models and CRLB of these methods. Note: STD of AOA measurements is 2°.

TABLE I

COORDINATES OF BASE STATIONS (m)

Base stations	X	Y	Z
1	100.000	100.000	32.543
2	-100.000	100.000	20.461
3	-100.000	-100.000	25.632
4	100.000	-100.000	27.856

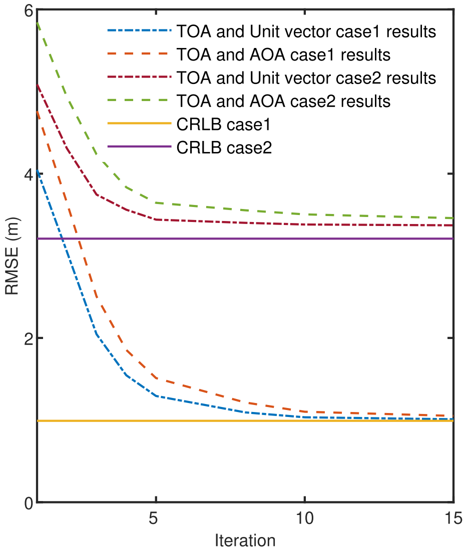

Fig. 4. Impact of coefficient selection and iteration on performance. The position of UE is (30, 40, 0).

verify the feasibility of the 5G joint model by simulating measurements, and the specific distribution of BSs is shown in Table I. To simulate measurements in urban environment, the STD of the 5G simulated distance and angle measurements are 3 m and 2° in the following experiments.

Appropriate stochastic models can exploit the full potential of measurements. In (3), we introduce the stochastic model used in this research. Typically, the distance between the UE and the nearest BS is set to b. After extensive simulation analysis, the value of a was selected as 0.05 (Case 1), and the value of a was enlarged 1000× (Case 2) to study the impact of the coefficient on the stochastic model. Meanwhile, we also analyze the impact of iterations on localization performance. The experimental results are shown in Fig. 4.

It can be found from Fig. 4 that the positioning results of the 5G joint model are more reliable when a is set to 0.05. This demonstrates that an excessively large coefficient will affect the utilization of observations. Also, the performance of the 5G joint TOA and unit vector model is better than that of the 5G joint TOA and AOA model under different coefficient settings, which reflects the superiority of the unit vector model. We also find that when Case 1 is used, the positioning results after iteration are closer to the CRLB. Moreover, we compared the impact of different iteration numbers on localization. The results prove that iteration can effectively improve the positioning accuracy, and when the number of iterations reaches 10, it is close to the best accuracy of the model. Therefore, we set a to 0.05 and the number of iterations to 10 in subsequent experiments.

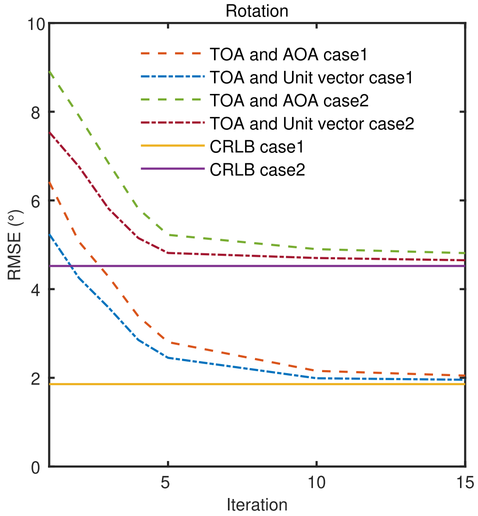

Fig. 5. Impact of coefficient selection and iteration on rotation estimation. The position of UE is (30, 40, 0).

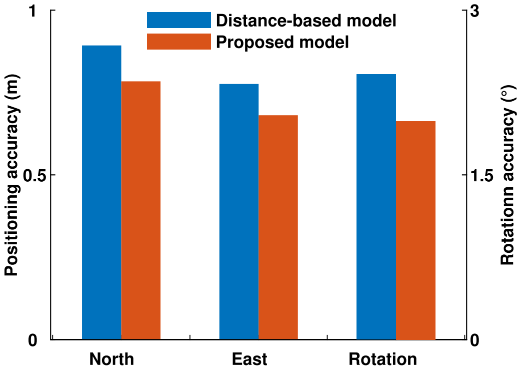

Fig. 6. Performance comparison of two stochastic models.

Fig. 5 illustrates the rotation accuracy of the two models under different policies. Similarly, both joint models show more reliable rotation calculation performance in Case 1. The rotation accuracy can reach 1.95° when more than ten times, while the optimal rotation accuracy is only 4.67° in Case 2.

To verify the correctness of the proposed stochastic model, we conduct a comparative experiment with the distance-based model, and the comparison results are shown in Fig. 6. It shows the plane positioning accuracy and the rotation estimation accuracy under the two stochastic models. The results demonstrate that the positioning errors in the north and east directions are 0.784 and 0.691 m after using the proposed stochastic model. Compared with the distance-based model,

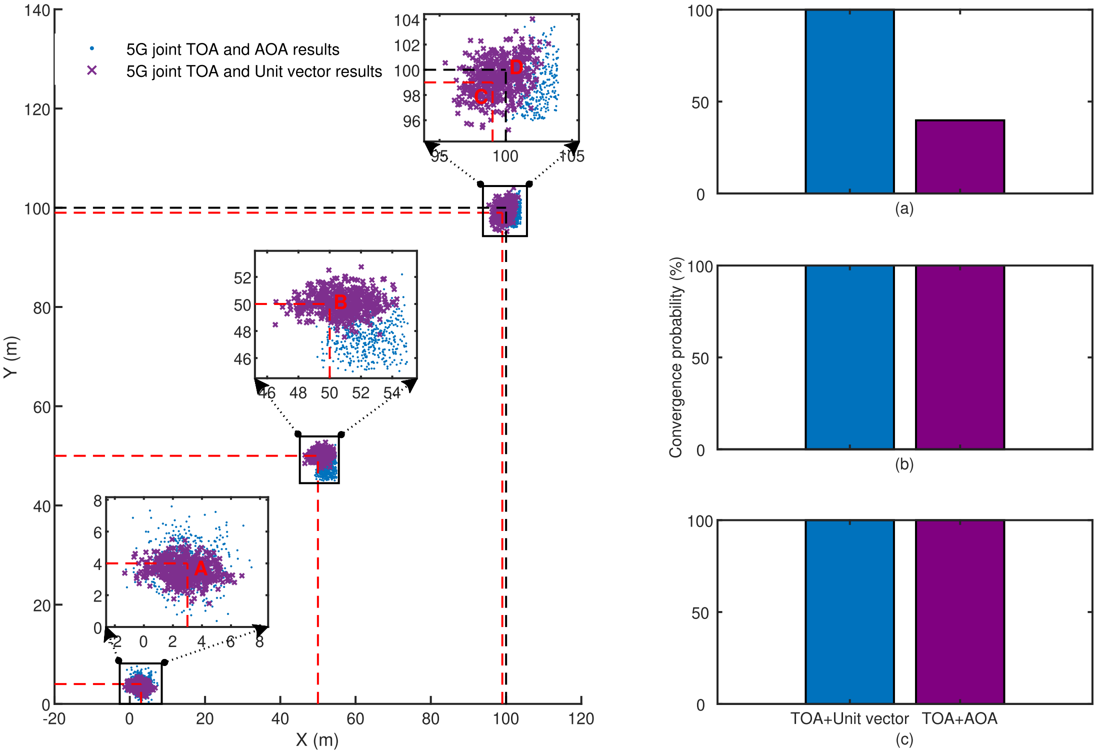

Fig. 7. Positioning results of two joint 5G models at different reference locations (left panel: positioning results of joint model and right panel: convergence probability of two joint models at different locations). (a) Point C. (b) Point B. (c) Point A.

the accuracy is improved by 12.2% and 10.9%, respectively. Similarly, the rotation estimation error also dropped from 2.42° to 1.99°.

As shown in Fig. 7, we also conduct experiments at different UE reference points to comprehensively compare the performance of the two models. The intersection of the red dotted lines represents the UE reference location A(3, 4, 0), B(50, 50, 0), and C(99, 99, 0), and the intersection of the black dotted lines represents the BS location D(100, 100, 32.543). Fig. 7 (left) manifests the positioning effects of the two joint models at different locations. Both joint models can maintain positioning accuracy within 1 m when the user is close to the central area, and the positioning results of the combined TOA and unit vector have a smaller error distribution range, while there is a significant gap in the performance of the two joint models, when the user is close to the BS. Fig. 7 (right) clearly displays that near the BS, the reliability of joint TOA and AOA model drops significantly. It is mainly due to the increase in the error range of the azimuth, while the joint TOA and unit vector model is less affected by azimuth errors and can still provide accurate solution. Furthermore, we show the location results between the BS and the center point for verification. The results also prove that the TOA and unit vector joint model has a better performance.

We notice from the results in Fig. 7 that the performance difference between the two joint models is obvious when UE is close to the BS. The positioning accuracy of the TOA and unit vector joint model has reached 3 m, while the maximum positioning error of TOA and AOA joint model reaches more than 6 m. We statistically calculate the convergence probabilities of the two model solutions when close to the BS. Among them, the convergence conditions are as follows: 1) the difference between the results of two adjacent iterations is less than 0.001 m and 2) the difference between the last iteration result and the reference coordinate is less than twice CRLB (5 m). The convergence results are shown in Fig. 8.

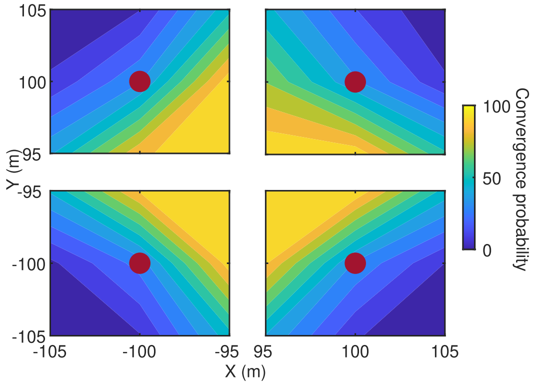

Fig. 8. Convergence probability heat map of the joint TOA and AOA model when the UE is located near the BS.

The results demonstrate that the joint TOA and unit vector model can still achieve convergence in all epochs, and only the convergence heat map of joint TOA and AOA model is shown in Fig. 8. The red dot indicates the location of the 5G BSs. Unlike all convergence in the central area, the convergence probability of the TOA and AOA model drops below 40% when the UE is close to the BS. In addition, we find that the convergence probabilities are different near different BSs, which is caused by the height of the BS affecting the geometric distribution [16].

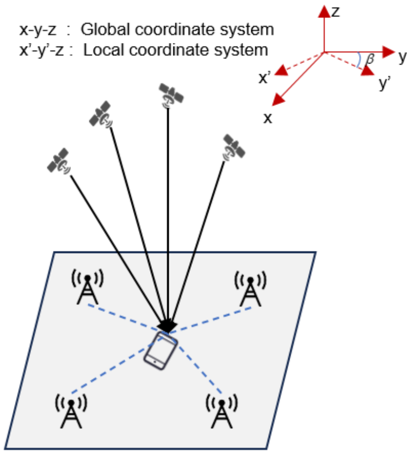

Fig. 9. Schematic of the hybrid GNSS + 5G positioning system.

Fig. 10. Schematic of the data collection point and its surrounding environment.

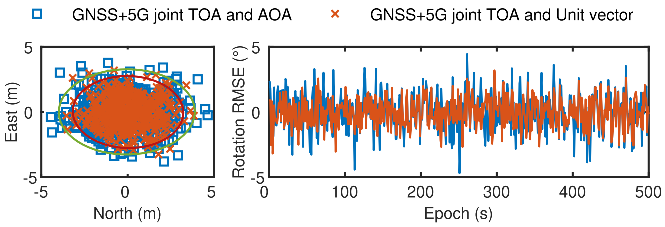

Fig. 11. Point error and rotation results of the hybrid GNSS + 5G model. Left: plane error distribution. Right: rotation accuracy.

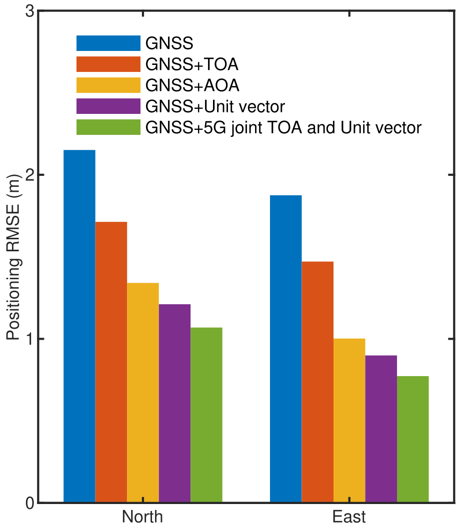

Fig. 12. Hybrid positioning performance of different 5G measurement models with GNSS measurements.

C. Hybrid GNSS + 5G Positioning Experiment

The GNSS measurements were collected by HUAWEI P40 smartphone at the Southeast University Jiulonghu Campus on Day 235 of 2023. HUAWEI P40 is equipped with the Kirin990 5G chipset, which supports receiving GPS ($L1/L5$), GALILEO ($E1/E5$a), BDS ($B1$), and GLONASS ($G1$) multisystem measurements.

The schematic of the hybrid GNSS + 5G positioning system is shown in Fig. 9, x–y–z represents the global coordinate system, and x'–y'–z represents the local coordinate system of the device. This study only considers the rotation β of two coordinate systems on the plane. As shown in Fig. 10, there are tall buildings blocking at the GNSS data collection point, and relying solely on GNSS cannot provide a high-precision solution, and we integrate 5G measurements to improve positioning performance.

We integrate two 5G joint observation models with GNSS measurements, and the experimental results are manifested in Fig. 11. The blue square represents the positioning result of the hybrid GNSS + 5G joint TOA and AOA model, and the orange cross represents the positioning result of the hybrid GNSS + 5G joint TOA and unit vector model. It can be concluded from Fig. 11 that the error distribution of joint TOA and unit vector is more concentrated, and the positioning accuracy of fusion with GNSS is 1.516 m. The positioning accuracy is improved by 24.83% compared with the hybrid GNSS + 5G joint TOA and AOA model. Meanwhile, we also added 95% confidence ellipses (GNSS + 5G joint TOA and AOA is in green, and the GNSS + 5G joint unit vector is in red) to further display the improvement of GNSS performance between the two methods. It is not difficult to find that the hybrid model using unit vector has better stability and reliability. Also, the estimation of rotation is also more accurate after using unit vector measurements, which can be concluded in Fig. 11 (right). The rotation RMSE dropped from 1.46° to 1.03°, and the accuracy increased by nearly 30%.

Furthermore, we use another GNSS dataset collected on Day 270 of 2023 to analyze the hybrid positioning performance of the 5G joint TOA and unit vector model and other common 5G measurement model with GNSS measurements. Fig. 12 shows the positioning RMSE of hybrid models on the plane, and the numerical results are shown in Table II. The positioning accuracy using only GNSS measurements is 2.853 m, while the introduction of 5G measurement can indeed improve the positioning effect. The 5G AOA measurements improve GNSS positioning accuracy better than 5G TOA measurements, and unit vector has a more obvious hybrid positioning effect than TOA and AOA methods due to its low degree of nonlinearity.

TABLE II
HYBRID POSITIONING RESULTS OF DIFFERENT 5G MEASUREMENT MODELS WITH GNSS MEASUREMENTS (m)

	GNSS	GNSS +TOA	GNSS +AOA	GNSS +Unit vector	GNSS+ 5G joint TOA and Unit vector
N	2.151	1.717	1.344	1.243	1.069
E	1.875	1.473	1.002	0.899	0.773

The 5G joint TOA and unit vector model gives full play to the advantages of 5G measurements, and the point accuracy reaches 1.319 m.

IV. CONCLUSION

In this study, we propose a novel 5G joint TOA and unit vector model under the premise of considering rotation and analyze its performance theoretically. A hybrid GNSS + 5G positioning algorithm is developed based on the proposed model, and its feasibility is proved through experiments. Our approach involves several key components, summarized as follows.

1) We analyze the potential of 5G measurements in hybrid positioning systems and conduct an in-depth study of 5G models taking rotation into account. The proposed 5G joint model effectively decreases the degree of system nonlinearity and is compared with TOA, AOA, and their hybrid models through simulation experiments. The results show that the proposed joint TOA and unit vector model shows stronger stability and effectively improves the positioning accuracy of the 5G system.
2) Typically, iteration improves positioning accuracy. We verify the impact of the number of iterations on the system through simulation experiments and find that the coefficients of the stochastic model have a significant impact. In addition, the unit vector joint model can provide high-reliability positioning when the user is close to the BSs, while the accuracy and convergence probability of the AOA joint method will significantly decrease.
3) We combine the proposed 5G unit vector joint model with GNSS measurements to verify its effect in urban environments and compare it with other traditional methods. The results manifest that the hybrid GNSS + 5G joint TOA and unit vector model can still supply accurate navigation services and rotation estimation even in occlusion environments. Our proposed model has significant implications for the development of smart transportation.

In summary, our study demonstrates the great potential of 5G joint model in improving GNSS positioning accuracy and reliability. It can be used in fields, such as autonomous driving and smart transportation. Our next research focus is to combine 5G with other sensors to develop hybrid positioning algorithms suitable for dynamic environments. These studies will further enhance the practicality and effectiveness of the proposed model.

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