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Intelligent and Ubiquitous Positioning Framework in 5G Edge Computing Scenarios

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ABSTRACT The prosperity of artificial intelligence and 5G has continuously enhanced the capabilities of edge devices. Edge computing is one of the key technologies of 5G network in the future, and the positioning capabilities of edge devices can significantly expand application scenarios of edge computing. A series of new technologies introduced by 5G can not only meet the needs of communication but also improve the positioning accuracy and achieve ubiquitous positioning. However, 5G base stations and devices are far from popular, and the standards of 5G positioning has not fully formed. Thus, simulation is the main research method for studying 5G positioning. Accordingly, we propose a 5G positioning simulation experiment scheme. We mainly introduce the implementation ideas and the specific processes of the simulation experiment of three key parts including scene generation, signal propagation simulation and position estimation. Based on this, we conduct a preliminary study of integrated navigation of inertial measurement unit (IMU) and 5G positioning. Then, we verify the abilities of 5G simulation environment by experiments and discuss the results.

INDEX TERMS 5G, edge computing, location, simulation, channel modeling.

I. INTRODUCTION

In the 5G era, all smart terminals and sensing devices are connected to the network environment through edge computing [1], [2]. Positioning is one of the basic capabilities for almost all terminals. Thus, "ubiquitous positioning" must be considered in the development of edge computing [3]–[5]. Considering that traditional global navigation satellite system (GNSS) systems are difficult to apply to indoor environments, and WIFI and Bluetooth positioning are costly and not universal enough, many new technologies and features in 5G including high-frequency carrier and large bandwidth, massive multiple-input multiple-output (MIMO) and beamforming, ultra-dense network (UDN), device-to-device (D2D) [6] and others can be used for positioning and navigation. Therefore, 5G is an infrastructure for both communication and positioning and navigation. Achieving both precision and convenience through 5G networks, seamless positioning indoors and outdoors, will improve the basic computing capabilities of the entire 5G edge.

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There are two general ideas about 5G positioning. The first is to continue the evolution of the existing LTE-based auxiliary GNSS system (A-GNSS) and establish a 5G-based A-GNSS system [7]. The other is to treat the 5G network as a satellite positioning network on the ground. Each 5G base station which is like a pseudo-satellite [8], receives the GNSS signal for its own positioning, uses timing technology to obtain a high-precision time reference, and synchronizes the time reference - its accuracy can reach nanosecond level - with the base station [9]. Therefore, the positioning in this article is based on time synchronization. The base station can broadcast communication information and positioning information at the same time. It can locate the user by receiving and processing the positioning information and the known base station location, as shown in Fig. 1. Comparing with these two ideas, the first, a centralized system architecture follows the tradition, while the second coincides with edge computing.

Therefore, this paper adopts the second idea and proposes a 5G positioning simulation scheme with reference to the GNSS system. The scheme has the following advantages:

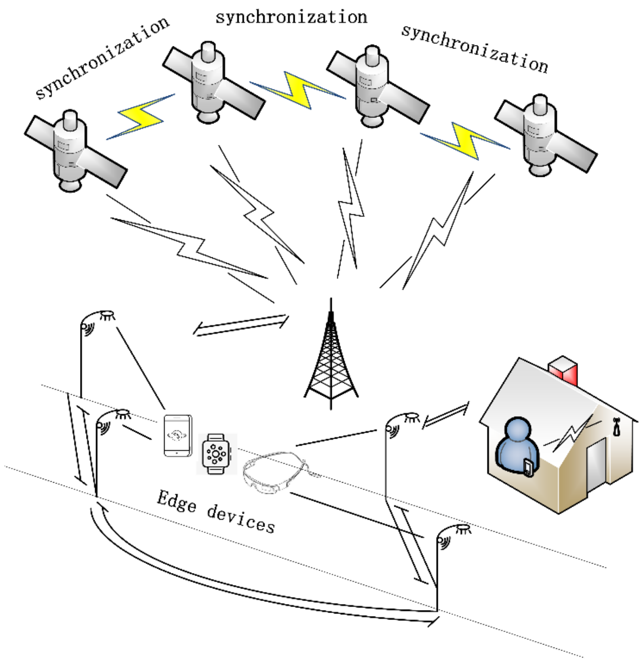

FIGURE 1. Edge computing and ubiquitous positioning of 5G.

(1) The scheme avoids the complex signal processing process. It has improved a mature channel simulator from the perspective of positioning, which makes the acquisition of observations easier and reduces the difficulty of simulation.

(2) The scheme has rich parameter/scene settings, making it convenient to study the impact of different factors on the positioning which mainly including the number of base stations using for positioning, the distribution of base station, line of sight(LOS), non-line-of-sight (NLOS), multipath, and carrier bandwidth.

(3) The scheme introduces the map of real world and will play a guiding role when deploying base stations.

(4) The scheme is able to learn from the rich research results in GNSS field to solve 5G positioning problems

II. RELATED WORK

A. DEVELOPMENT OF MOBILE LOCATION AND NEW FEATURES OF 5G

Researches on the use of mobile communication systems for positioning have increased since the enactment of the E911 Act in the United States, generating a variety of positioning technologies such as the cell ID (CID) positioning in the 2G era, and the Observed time difference of arrival (OTDOA) positioning in the 3G and 4G eras [10], [11]. The positioning effect of 5G is expected to make a breakthrough [10], [11] (see **Table 1**) cause the new technologies introduced. These key technologies are briefly described below.

1. High frequency carrier and large bandwidth can reduce the multipath effect due to the sparsity of high frequency carrier channel, and its large bandwidth can improve the resolution of time measurement and positioning accuracy. 2. MIMO and beamforming can enhance coverage and improve the accuracy of angle measurement. 3. The UDN structure of the base station improves the probability of LOS communication between the user and base stations, helping to achieve high precision positioning and indoor positioning. In addition, the newly-introduced device-to-device (D2D) communication through 5G standard makes it possible to achieve cooperative locating of equipment, which is helpful to solve the problem when it lacks reference station [12].

TABLE 1. Positioning effect comparison of communication standard in different generations.

Generations	Positioning error	Orientation estimation	Positioning delay
2G	>100m	none	>1s
3G	>50m	none	>1s
4G	<50m	none	>1s
5G(expected)	<0.1m	$<1^{\circ}$	<<1s

Based on these new features, the researchers conducted a series of studies on 5G positioning.

B. RESEARCH STATUS AND RELEVANT STANDARDS

Positioning is quite complex because there are a lot of problems to be solved such as frequency selection, waveform designing, channel modeling, the acquisition of observations and the derivation of localization algorithms [13], [14]. The research of 5G positioning also has many categories.

There are two main categories in terms of the overall structure of positioning. One is to establish a 5G-based A-GNSS system or similar system [7], and the other is to extend the 5G network into a pseudo-satellite system [8], using pseudo-range for positioning. As far as the current researches go, more studies have conducted based on the second structure (see Table 2).

TABLE 2. Major research directions of 5G positioning.

Directions	Content
Frequency band	Sub6 Ghz, Millimeter wave
Signal waveform	Common waveform/self-designed
Positioning strategy	Uplink signal of network side/downlink signal of user side
Time synchronization	Requirement, error source, solution
Channel Modeling	METIS、WINNER II、3GPP、NYU

In terms of frequency band for positioning, these two carrier frequencies (sub6Ghz and millimeter wave band) will coexist for a long time in 5G network due to the need of both coverage and rate. The two kinds of signals show different features in many aspects due to the differences in frequency, and thus different researches on the two frequency bands have been conducted. Koivisto M *et al.* made a detailed study on the architecture and positioning method of 5G positioning system in sub6Ghz frequency band. They deduced the theoretical performance of 5G positioning [15], and proposed the method of multi-layer filtering to gradually extract the observations and position [16]. They also considered the effect of synchronization. In the research of millimeter wave positioning, Wymeersch *et al.* [10] focused on vehicle positioning. They comprehensively analyzed the impact of 5G new features on positioning, summarized the relevant research directions of 5G positioning, and gave a theoretical positioning accuracy of the millimeter wave band. Shahmansoori *et al.* [17], [18] had a more detailed study. Under the carrier of 30Ghz, they derived the Cramer-Rao Lower Bound in 5G positioning under LOS/NLOS with TOA and DOA as observations.

In addition, some scholars have also done research on waveform, positioning strategy, time synchronization and other aspects. Cui *et al.* [12] and Dammann *et al.* [19] made a detailed comparative study separately to discuss the influence of different signal waveforms on the positioning effect. Abu-Shaban *et al.* explored the impact of using the uplink/downlink on the positioning effect [20]. Li *et al.* studied the requirements of time synchronization for 5G positioning [21], and explored the factors affecting synchronization and the degree of the effects.

The channel model plays an important role in 5G positioning. Firstly, the channel model contains the geometric relationship and propagation information between the observed value and the position to be estimated, and the accuracy of the position estimation is highly dependent on this information [13]. Secondly, the channel model can be used to derive positioning algorithms, and analyze the positioning performance [22], [23]. Finally, constructing a 5G positioning simulation environment also requires a channel model to provide observations. Therefore, articles or standards on 5G channel modeling are also introduced. At present, there is no unified standard for channel modeling of 5G. The commonly-used channel models include METIS [24], WINNER II [25], and related models of 3GPP [26]. It is worth mentioning that Rappaport T S *et al.* proposed a new channel models of 5G based on a large number of actual measurements and had compared performance with the 3GPP model [27], [28]. At the same time, they developed a channel simulator which was open soured [29].

Not only does the academic community care about 5G positioning, the industry also regards positioning as an important part of 5G in the future. The 3GPP has established a series of standards on positioning [30], [31]. The concept of 5G positioning has been extended in the standards, which is not a single method, but comprehensively adopts various current mainstream positioning methods, including A-GNSS, OTDOA, enhanced CID, Wi-Fi, Bluetooth, and air pressure positioning. It coincides with the current idea of multi-source integration, and it is also a major direction for future research.

In summary, there are three aspects can be studied in 5G positioning: (1) design aspects, including frequency selection, signal coding, and waveform designing; (2) interference, including multipath effect, LOS, NLOS and so on; (3) system requirements, including base station synchronization, the positioning strategy, and the solution of different requirements of locating and communicating such as base station distribution and base station-user interaction modes.

It can be noted that most of the articles are verified by simulation. Simulation is an important research method when 5G base stations and devices are not popular, and the standards of 5G positioning have not yet fully formed. However, only few article focus on the construction of 5G simulation environment. Therefore, how to establish an effective simulation environment may be a major obstacle. Based on this, this paper studies the system architecture of 5G positioning and proposes a simulation experiment scheme, and perform the implementation of simulation as verification, which will be significant references for researchers.

III. SCHEME OF THE SIMULATION EXPERIMENT

The flowchart of 5G positioning proposed in this paper is shown in **Fig. 2**. The thought was inspired by works [15], [16] of Koivisto M *et al.* The user moves in uniform motion along a certain track in a certain scene, and makes a positioning request at regular intervals. At this time, the channel simulator simulates the signal propagation process, and gives the observations, that is, the time of arrival (TOA) and the angle of arrival (AOA). After the observations have been imported, the positioning program estimates the user's position and sends it to the user, completing a circle of positioning. According to the above process, the simulation experiment of 5G positioning can be divided into three parts: scene generation, signal propagation simulation, and position estimation. Based on the above three core modules, we conducted more in-depth researches in two aspects: the theory of 5G positioning accuracy, and the possibility and effect of integrated navigation between IMU and 5G, providing richer simulation functions. The implementation steps are discussed below.

A. SCENE GENERATION

The scene for positioning is the basis of simulation experiment. Both authenticity and complexity need to be considered in scene generation. Referring to the scenes in the simulation guide provided by authoritative organizations not only can reduce the workload, but also improve the reliability of the simulation. The scene used in this paper refers to the map of Madrid in the simulation guide [24] provided by Metis.

Two methods are taken to generate scene in this paper. One is to generate scene randomly by the program, and the other is to import data from open source maps (such as Open Street Map) with appropriate modification. These two methods have the same positioning principles and processes. The introduction of the real map can increase the practical value of the simulation, for example, guiding the layout of

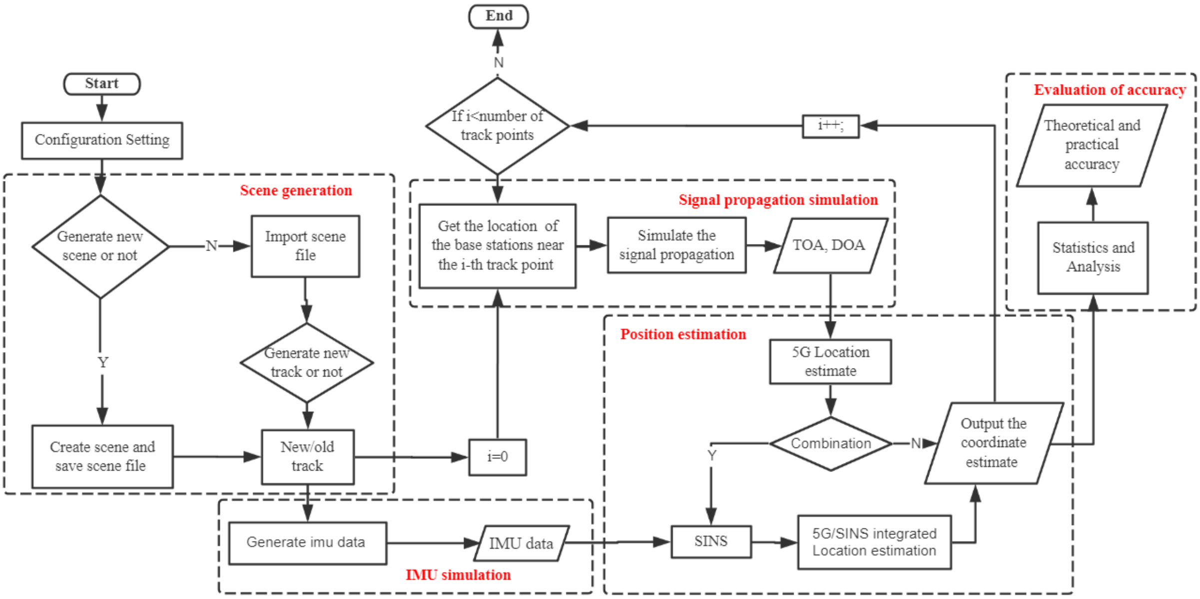

FIGURE 2. Flowchart of 5G simulation experiment.

the base station to obtain a better positioning effect, so we adopt these two methods.

Firstly, random scene generation is described. Four scene elements including buildings, roads, base stations and trajectories are finally selected after investigation [15], [16]. Random scene generation is based on buildings. And buildings with regular form are considered in this paper, which means the buildings are arranged in a square matrix, and the intervals between the buildings are equal and regarded as visual roads. The properties of the building include length, width, height and location information. The simulation guide [24] is the main reference for setting length, width and height, the length usually is 60m as well as the width, and the height is around 25m to 50m. while the location information can be set randomly, just make sure the calculation is convenient. Then, base stations need to be generated. Combining the reality and simplifying it, we assume that base stations are randomly distributed on edge of the buildings [24]. So the base stations can be generated after obtaining data of the buildings. Another issue is how to confirm the number and distribution of the base stations. According to the conclusions in [16], [32], [33], the user can perform line-of-sight communication with the base station in 80% of cases when the base station interval is not more than 50 meters. We use this as a basis to deploy the base station. After that, the data of roads need to be generated. This paper specifically designs the topology structure for the road network. The roads and the directions are represented by the connection relationship of the intersections, and the connection relationship between the roads is also generated. The coordinates of the intersection are generated based on the building coordinates.

Next, scene generation by importing an open source map is briefly described. The open source map that contains the buildings information and the topological information of the road is stored in Extensive Markup Language (XML) format. It is parsed by python script and saved separately as a text file of a specific format. By reading the text file can reproduce the buildings and the roads, then the base station is generated based on the similar principle as described above. The topological relationships between the roads are automatically generated based on the information contained in the XML file. Without additional processing, the generated map can be used in the subsequent experiments just like the random map.

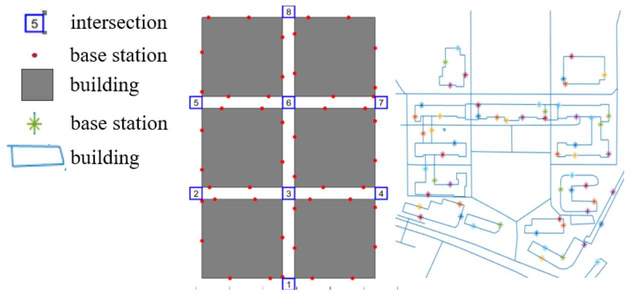

FIGURE 3. Scenes of positioning. The left is the scene generating randomly and the right is the scene generated according to Open Street Map (OSM).

At this point, the generated scenes can meet the needs of the experiment for 5G positioning, and the effect is shown in Fig.3. It is worth to note that Fig.3. is a top view of the scene, in fact the scene contains elevation information.

According to the positioning process, a track randomly generated on the simulation scene after the scene is generated. The trajectory generated in this paper is based on the road network. It includes two generation rules [15]: 1. when comes

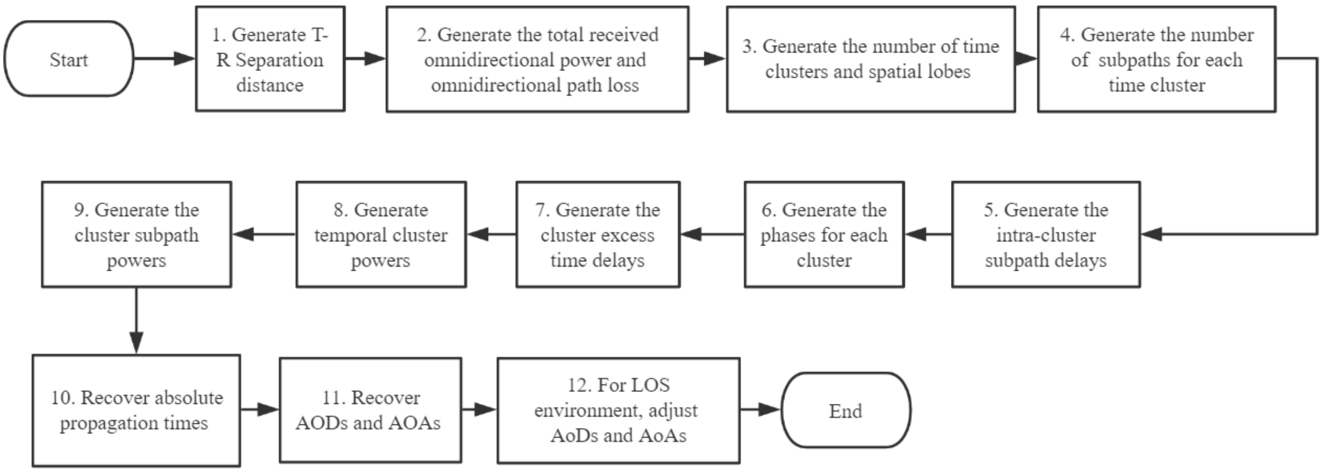

FIGURE 4. **The process of signal propagation simulation.**

across the intersection, it will randomly turn to the other three directions but cannot return the way it came from; 2. the trajectory is considered to be over after six turns or when it goes out of the map. It is easy to obtain the trajectory required for the experiment according to the above two generation rules and the road network data. The trajectory is represented by a series of road numbers, similar to the polyline. To achieve periodic positioning, the trajectory is split into a series of points based on a certain distance, and the coordinates of the points are recorded. The splitting can be realized from the point of vector or linear equation according to the line string of track and the known coordinates. The track point is the minimum unit of positioning in the simulation experiment.

B. SIGNAL PROPAGATION SIMULATION

The track points are taken out in turn from the obtained aggregate of points. Several base stations closest the track points are selected as the reference station for positioning. The standard of selection is the Euclidean distance, and the number of selected base stations can be set as needed. The signal propagation simulation can be conducted after the base stations being selected. The simulation experiment uses the channel simulator of New York University (NYU), an open source channel simulator of 5G developed by Rappaport *et al.* based on a large amount of measured data [29]. The simulator is simple and easy-to-use, and can provide plentiful parameters. And its simulation results improve compared with the commonly-used models such as WINNER and 3GPP [26]. Thanks to the open source of the software, the simulator after proper modification can be seamlessly integrated with the scene of positioning. Then the operation and principle of the simulator will be briefly introduced.

The simulator conducts signal propagation simulation in 12 steps as shown in Fig. 4. It finally gives the key values required for channel modeling, mainly including power distribution of the angle of departure, power distribution of the angle of arrival, omnidirectional power delay profiles, directional power delay profiles and small-scale power delay profiles. The path loss model and how multipath been simulated are described below.

(1) Path loss model [29]. The path loss model adopted by NYU satisfies the following formula:

$$P_L = 20\lg\left(4\pi\frac{d_0}{\lambda}\right) + n10\lg\left(\frac{d_{ist}}{d_0}\right) + d_{ist}\times aF_A + \Delta \quad (1)$$

P_L represents the path loss; $d_0 = 1\text{m}$ is the reference distance of free space; λ is the carrier wavelength; $n = 2$ is the path loss index; d_{ist} is the distance between the base station and the user; aF_A is the atmospheric attenuation factor and Δ is the shadow fading, which satisfies the normal distribution with a mean value of 0 and standard deviation of 4 dB. It is worth noting that the values of n and the distribution of Δ are different as parameters are different in different scene and environment.

(2) Simulation of multipath delay and angle

Two concepts time cluster and lobe are introduced to simulate the distribution of multipath signals in time and space dimensions, respectively in order to simulate the multipath in a more real way [34]. The time cluster refers to the multipath signal reaching the receiving end intensively in a certain period of time, and the lobe describes the spatial aggregation of the multipath signal. These two concepts are not firstly proposed in this simulator, but in previous models or literature the multipath signals of the same time cluster belong to the same lobe by default. However, Rappaport *et al.* had different research results [34]. This is also reflected in the simulator. Time clusters and lobes are generated separately with no binding between them.

According to the source code, the simulator completed the simulation of multipath in steps 3, 4, 5, 7, 10, and 11step by step. In step 3, the number of time clusters and lobes that occur during a signal propagation process is simulated.

According to the measured data, the number of time clusters obeys a uniform distribution of 1-6, and the number of lobes of the transmitting and the receiving end satisfies the Poisson distribution. And the parameters are obtained from the measured data and built in the simulator. In step 4, the simulator simulates the number of multipath signals in each time cluster, which obeys a uniform distribution of 1-30. In step 5, the simulator simulates the appearance time of each multipath signal relative to the time cluster, it satisfies the formula derived from the measured data. In step 7, the simulator simulates the appearance time of each time cluster. The appearance of the time cluster obeys the exponential distribution. On this basis, the duration of the cluster and the correction of cluster spacing are added. In step 10, the simulator simulates the absolute propagation time of each signal, by sum up of the quotient obtained by dividing the distance by the speed of light, the result of step 5 and step 7. In step 11, the angle of arrival and the angle of the departure of the signal are simulated. The space is equally divided according to the number of lobes, and then an angle is randomly selected as the central angle in each aliquot. For each signal, first randomly select the interval in which it falls, then it will fall near the central angle of the interval, and the distribution of obedience is Gaussian or Laplacian, and the parameter is angle. The angle value and the specific distribution are obtained from the measured data and are built in the simulator.

The propagation delay and the angle of departure and arrival of 5G signals are gradually generated during the simulation process of the channel simulator, which are the observations required for positioning. But there is a contradiction between the original simulator and the experiment of positioning that is the distance and angle of signal propagation are randomly generated by the simulator but the positional relation between the user and the base station in the positioning scenario is fixed. The contradiction is a key issue to be solved in this paper. It is solved by modifying the simulator based on the in-depth study on the simulator code. The specific idea is to calculate the geometric position relationship between the user and each base station at each track point, including the distance and angle, and then input it as a parameter into the channel simulator. After that, the random generation of the channel simulator is changed to a semi-random generation based on the input parameters. The output is the delay and angle from the user to each base station. Therefore, the simulation of the signal propagation process and the acquisition of observations are completed.

C. POSITION ESTIMATION

Position estimation is the final process after completing the simulation of signal propagation and obtaining the TOA and DOA data. It is not difficult to make an observation equation based on the known geometric relationships. The result of position estimation can be obtained after the observation equation is linearized and solved iteratively by the least squares.

The observation equation is as follows:

$$\boldsymbol{Z_i}\left(\boldsymbol{k}\right) = \begin{bmatrix} AOD_{Azi} \\ AOD_{ele} \\ Ct \end{bmatrix} = \begin{bmatrix} \arctan \dfrac{y-y_s}{x-xs} \\ \arctan \dfrac{z-z_s}{\sqrt{(x_s-x)^2+(y_s-y)^2}} \\ \sqrt{(x_s-x)^2+(y_s-y)^2+(z_s-z)^2} \end{bmatrix} \tag{2}$$

$\boldsymbol{Z_i}(\boldsymbol{k})$ is the observation value of the i-th base station at time k; AOD_{Azi} is the angle of arrival in the horizontal direction; AOD_{ele} is the angle of arrival in the vertical direction; t is the propagation delay and $C = 3\times10^8 m/s$. (x_s, y_s, z_s) is the coordinates of the i-th base station closest to the user at time k; (x, y, z) is the coordinates of the user at time k.

Linearize the equation (2) at the approximate coordinate $\boldsymbol{X^0}(\boldsymbol{k})$ and gain:

$$\boldsymbol{Z_i}(\boldsymbol{k}) = \boldsymbol{H_i}(\boldsymbol{k})\,\boldsymbol{x}(\boldsymbol{k}) + \boldsymbol{Z_i^0}(\boldsymbol{k}) \tag{3}$$

where $\boldsymbol{H_i}(\boldsymbol{k})$ is the linearized Jacobian matrix; $\boldsymbol{Z_i^0}(\boldsymbol{k})$ is the approximate value of the observation at $\boldsymbol{X^0}(\boldsymbol{k})$ and $\boldsymbol{x}(\boldsymbol{k})$ is the difference between $\boldsymbol{X^0}(\boldsymbol{k})$ and the true position (x, y, z). The specific expressions are listed below:

$$\boldsymbol{x}(\boldsymbol{k}) = \begin{bmatrix} \Delta x \\ \Delta y \\ \Delta z \end{bmatrix} \boldsymbol{Z_i^0}(\boldsymbol{k}) = \begin{bmatrix} arctan\dfrac{y_0-y_s}{x_0-x_s} \\ arctan\dfrac{z_0-z_s}{\sqrt{d_3}} \\ \sqrt{d_2} \end{bmatrix}$$

d_2 represents the geometric distance from the base station to $\boldsymbol{X^0}(\boldsymbol{k})$ and d_3 represents the length of projection on the plane where $\boldsymbol{X^0}(\boldsymbol{k})$ lies.

$$d_2 = (x_s-x_0)^2 + (y_s-y_0)^2 \tag{4}$$
$$d_3 = (x_s-x_0)^2 + (y_s-y_0)^2 + (z_s-z_0)^2$$

$$\boldsymbol{H_i}(\boldsymbol{k}) = \begin{bmatrix} \dfrac{y_s-y_0}{d_2} & \dfrac{-(x_s-x_0)}{d_2} & 0 \\ \dfrac{(z_0-z_s)(x_s-x_0)}{d_2\sqrt{d_3}} & \dfrac{(z_0-z_s)(y_s-y_0)}{d_2\sqrt{d_3}} & \dfrac{\sqrt{d_3}}{d_2} \\ \dfrac{-(x_s-x_0)}{\sqrt{d_2}} & \dfrac{-(y_s-y_0)}{\sqrt{d_2}} & \dfrac{-(z_s-z_0)}{\sqrt{d_2}} \end{bmatrix} \tag{5}$$

In formula (3), let:

$$\boldsymbol{z}(\boldsymbol{k}) = \begin{bmatrix} \boldsymbol{Z_1}(\boldsymbol{k}) - \boldsymbol{Z_1^0}(\boldsymbol{k}) \\ \vdots \\ \boldsymbol{Z_i}(\boldsymbol{k}) - \boldsymbol{Z_i^0}(\boldsymbol{k}) \\ \vdots \end{bmatrix} \boldsymbol{H}(\boldsymbol{k}) = \begin{bmatrix} \boldsymbol{H_1}(\boldsymbol{k}) \\ \vdots \\ \boldsymbol{H_i}(\boldsymbol{k}) \\ \vdots \end{bmatrix}$$

Then:

$$\boldsymbol{z}(\boldsymbol{k}) = \boldsymbol{H}(\boldsymbol{k})\boldsymbol{x}(\boldsymbol{k}) \tag{6}$$

For equation (6), the least square solution is

$$\boldsymbol{x}(\boldsymbol{k}) = \left(\boldsymbol{H}^{T}(\boldsymbol{k})\boldsymbol{H}(\boldsymbol{k})\right)^{-1}\boldsymbol{H}^{T}(\boldsymbol{k})z(\boldsymbol{k}) \tag{7}$$

Then, the estimation of the user's location is:

$$\hat{X}(\boldsymbol{k}) = \boldsymbol{X}^{\mathbf{0}}(\boldsymbol{k}) + \boldsymbol{x}(\boldsymbol{k}) \tag{8}$$

The above is a complete process of position estimation. Usually, there are some requirements for the positioning accuracy. Thus, it is often difficult to meet this requirement by performing estimation only once. It is generally necessary to improve the accuracy by an iterative method.

The algorithm is as follows.

Algorithm 1 FLeast Square

Input: $\boldsymbol{X}^{\mathbf{0}}(\boldsymbol{k})$, $\boldsymbol{Z}_i(\boldsymbol{k})$
Output: $\boldsymbol{X}^{\mathbf{0}}(\boldsymbol{k})$
1. While norm $(\boldsymbol{x}(\boldsymbol{k})) > 1\mathrm{e}-8$
2. Calculate $\boldsymbol{H}(\boldsymbol{k}), z(\boldsymbol{k})$;
3. $\boldsymbol{x}(\boldsymbol{k}) = \left(\boldsymbol{H}^{T}(\boldsymbol{k})\boldsymbol{H}(\boldsymbol{k})\right)^{-1}\boldsymbol{H}^{T}(\boldsymbol{k})z(\boldsymbol{k})$
4. $\boldsymbol{X}^{\mathbf{0}}(\boldsymbol{k}) = \boldsymbol{X}^{\mathbf{0}}(\boldsymbol{k}) + \boldsymbol{x}(\boldsymbol{k})$;
5. end

$\boldsymbol{X}^{\mathbf{0}}(\boldsymbol{k}) = [x_0, y_0, z_0]^T$ can be initially given by the user through GNSS, or can be assumed to be the center position of several nearby base stations. It is then iterated continuously according to the above algorithm until it meets the given accuracy requirements.

D. IMU AND INTEGRATED NAVIGATION ESTIMATION

This module uses the trajectory information in 5G position simulation to generate inertial navigation information, and then fuse IMU with 5G position for integrated navigation estimation. And the process is shown in Fig.5.

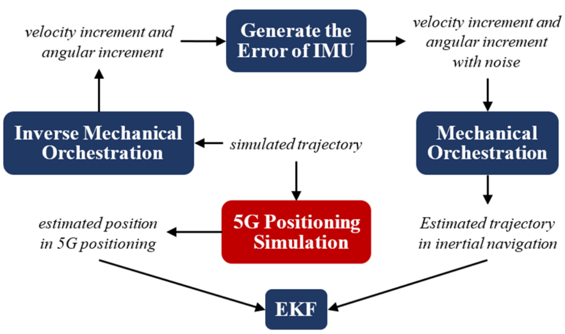

FIGURE 5. The progress of integrated navigation of 5G/SINS.

We implement integrated navigation in 4 steps, including inverse mechanical orchestration, generating IMU error, mechanical orchestration, and EKF.

First, we need to add the attitude information to the simulated trajectory (which only contains position information), and convert the newly-generated trajectory into angular increment and velocity increment of IMU at a certain sampling rate through inverse mechanical orchestration.

After that, IMU errors are modeled to generate the angular increment and velocity increment with noise, which are used as raw observations of the inertial navigation.

Then, raw observations of the inertial navigation are used to obtain the estimated position, velocity, and attitude results through mechanical orchestration.

Finally, the integrated position, velocity, and attitude are generated by fusing the inertial navigation estimation result with the position result in the 5G positioning simulation through EKF.

E. ACCURACY EVALUATION AND ANALYSIS

In order to evaluate the experimental results, it is necessary to obtain the accuracy of positioning experiments under different parameter settings. It is also conducive to in-depth research on the theory of 5G positioning accuracy. The accuracy evaluation and analysis module can perform statistics and analysis on the 5G positioning simulation results to meet the above requirements.

The implementation includes the following two aspects. The first is to conduct in-depth research on the 5G positioning model, find out the positioning influencing factors, derive the equations for positioning accuracy, and output the theoretical accuracy at different settings. The second is to conduct a statistical analysis of the simulation positioning experiment to give the actual experimental accuracy. Finally, the theoretical accuracy and actual accuracy are demonstrated by appropriate visualization methods.

IV. EXPERIMENT AND DISCUSSION

The 5G simulation environment can be built up based on the previous section, however, it needs to be verified whether it is effective or it can support further research. For this purpose, some important factors that will influence the positioning effect are found out. These factors are used in experiments as variable, and we can test the environment by observing whether the results change as expected or not. At the same time, there are many meaningful results in these experiments to be described. However, the reason is not the theme of this paper.

We get the positioning results from the observation equations (2). These important factors can be found by analyzing the observation equations (2). TOA and AOD finally decide the results, so each factor that affects TOA and AOD will influence the positioning effect. Considering the whole propagation process, such factors mainly include the number of base station, LOS/NLOS, multipath effect, and carrier frequency & bandwidth. Besides, in GNSS positioning, the distribution of base station will affect the Geometry dilution of position which has great influence in positioning result. The distribution may also have influences as our scheme is based on GNSS. In here, factors and experiments settings are listed in Table 3.

Experiments were conducted in the simulation environment according to the experimental settings described above. In addition to the basic experiments shown in the table3, this

TABLE 3. Settings of simulation experiments.

Scene and estimation method	Carrier frequency and bandwidth	Number of base stations	Base station distribution	LOS/NLOS	Multipath effect
Random map + least squares	3.5-100 28-400 77-800	1/2/3/4	None	None	None
Random map + least squares	3.5-100 28-400 77-800	1/2/3/4	Random/ Adjustment	None	None
OSM map + EKF	3.5-100 28-400 77-800	1/2/3/4	Random/ Adjustment	LOS/N LOS	Single/ multi

article also explores integrated navigation and theory of 5G positioning accuracy. In the above experiments, we only selected a few representative results to display and discuss as the results were numerous and somewhat repetitive.

A. THE INFLUENCE OF THE NUMBER OF BASE STATIONS FOR POSITIONING

The number of base station decides the number of observation. Each base station will offer three observations. As there are three unknowns to be solved, 1 base station is needed at least. Adding base stations can make positioning result get better. In this experiment, we test the simulation environment's ability of simulating the specific impact of the number of base stations on the positioning effect.

Positioning was performed using a 3.5Ghz-100Mhz signal on the random map. Under the condition the base stations were randomly set, the number of base stations used for positioning increased from one to four. The location estimation was performed by the least squares, and the positioning effects of different number of base stations are shown in Fig.6.

The results include the upper part and the lower part. The upper part shows the effect of the number of base stations on the Position Dilution of Precision (PDOP). PDOP characterizes the influence of measurement error on the final result of positioning. Generally speaking, the smaller the PDOP is, the better the observation condition is. The horizontal axis is the Track Point ID, represents different track points, and the vertical axis is the PDOP. The upper images show the PDOP value at each track point. The lower part shows the influence of the number of base stations on the positioning accuracy. Here, the horizontal axis is still the Track point ID, but the vertical axis is Δ, which represents the geometric distance in meters between the estimation result and the true value. The lower images show the positioning result on each track point. The later experimental results also conform to the above description.

There is no PDOP value when there is only one base station in Fig. 6 because there is no redundant observation with only one base station. When further analysis is carried out, it can be found that some outliers greatly affect the performance of

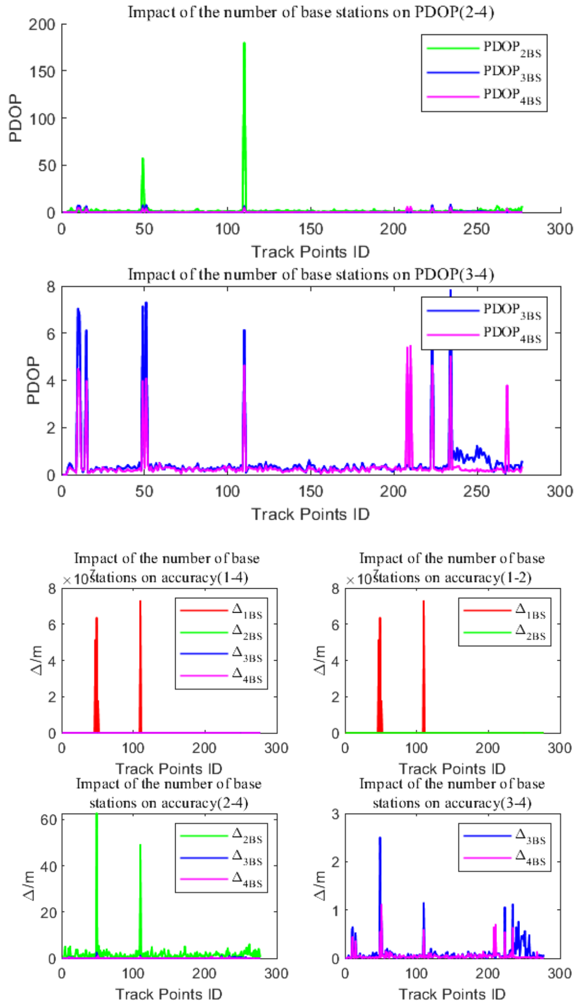

FIGURE 6. Results of influence of different number of base stations for positioning.

TABLE 4. Success rate and number of base stations.

The number of base stations	1	2	3	4
The success rate of positioning	98.56%	98.56%	99.64%	100%

the graphics as shown in Fig. 6. These outliers are actually the points with large positioning error, for example, the iteration does not converge. By adding constraints to the program of position estimation, these points can be found and eliminated, and the success rate of positioning can be used to characterize this situation. The success rate of positioning is obtained by dividing the total number of experiments by the number of successful experiments under a certain condition of experiment. The success rate of positioning with different number of base stations is shown in the table below.

On the basis of the above, the following results are obtained by removing the outliers, as shown in Fig.7.

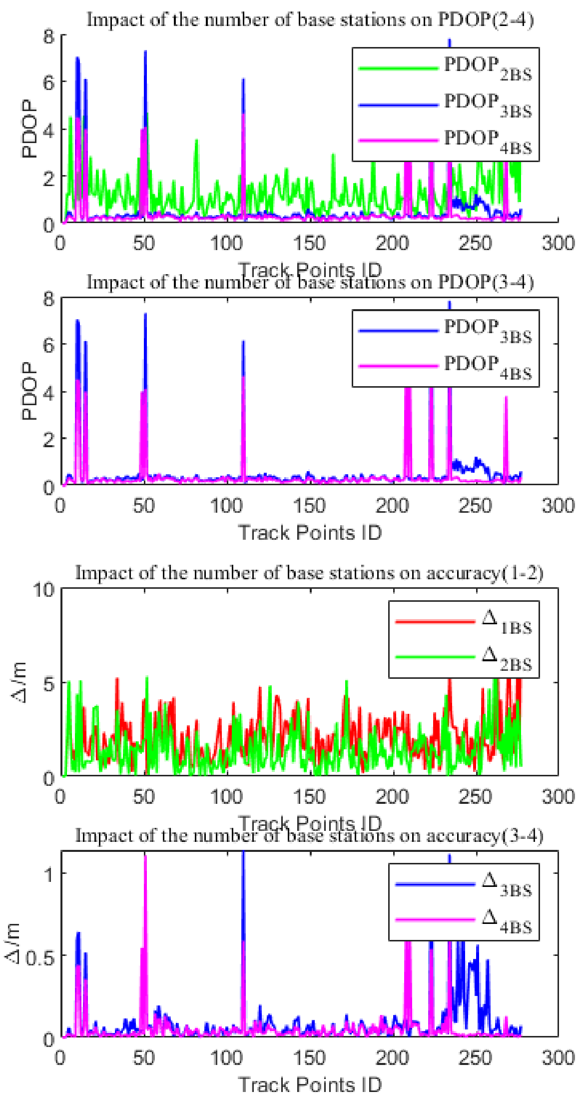

FIGURE 7. Result of influence of different number of base stations for positioning (without outliers).

From the perspective of PDOP, the PDOP values are different with different number of base stations. As a whole, the more the base stations there are, the smaller the PDOP is. Specifically, the PDOP becomes smaller in most points when the number of base stations increases from 2 to 3, and when the number increases from 3 to 4, only points with larger PDOP can become smaller. In addition, the PDOPs at different track points are different when the number of base stations is the same. It may be caused by different distribution of base stations. From the perspective of positioning accuracy, the results are similar to that of PDOP, that is the more the number of base stations there is, the higher the accuracy of positioning is. The positioning accuracy is about 2m when the number of base stations increases from 1 to 2, and it is about 0.1m when the number of base stations increases from 3 to 4, neither of them have obvious improvement. However, the positioning accuracy changes significantly when the number of base stations increases from 2 to 3. Additionally, the positioning accuracy is different on different track points. In general, the positioning accuracy is agreed with the curve of the PDOP. The positioning accuracy is low when the PDOP is large, and the positioning accuracy is high when the PDOP is small, which is similar with GNSS.

B. DISTRIBUTION INFLUENCE OF THE BASE STATION

In GNSS system, the geometrical distribution of satellites has a large impact on the results of positioning. It may also have influence in the proposed scheme. This experiment is used to test whether the environment can explore the influence of the geometrical distribution of base stations.

In the OSM map, the frequency of the signal used for positioning is set to 3.5Ghz-100Mhz; the number of base stations used for positioning is 4, and the estimation method of positioning is least squares. The geometric distribution of the base station and the final effect of positioning are shown in Fig. 8-Fig. 9.

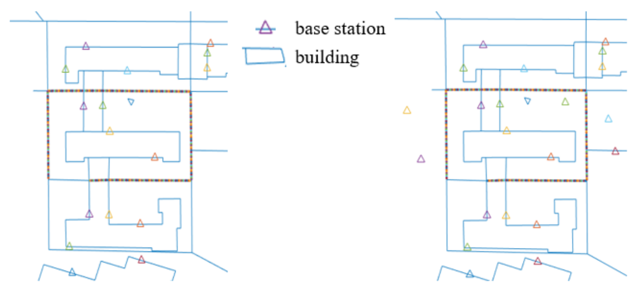

FIGURE 8. Base station in random and Base station with judgement.

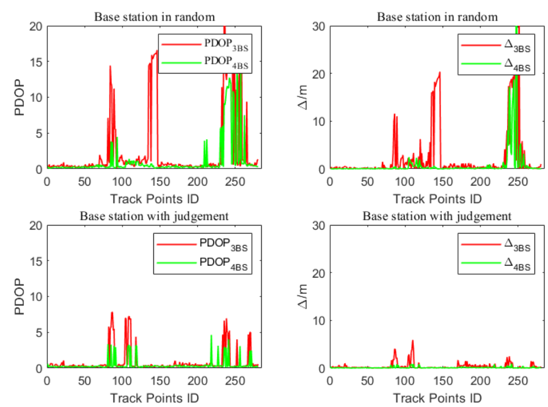

FIGURE 9. The influence of the arrangement of the base stations.

Comparing the scene graphs before and after the base station supplementation (the left and the right), it can be seen that two base stations are added on both sides of the scene, and a total of four base stations are added. It can be seen from the result graph (Fig.9.) that before the base station is supplemented, there are three regions in the trajectory with large PDOP, correspondingly, resulting in three regions with large errors of positioning. By supplementing the base station, it can be seen that the PDOP of the original three regions is greatly reduced, and the accuracy of positioning is improved. It can be seen that the arrangement of the base station has a great influence on the positioning accuracy.

The simulation program in this paper can represent the real-time positioning effect of the user in the scene in the form of error ellipse. It is also the basis for supplementing the base station, that is, supplementing the base stations in the area where the error ellipse is large. The experimental results show that supplementing a small number of base stations in key areas can greatly improve the effect of positioning. The simulation program in this paper helps to find these key areas.

C. MULTIPATH EFFECT

The multipath effect still exists in the 5G positioning, and this experiments is to test can it be studied through the simulation environment established in this paper. All path signals are weighted to calculate their observations according to the received intensity of signal, then the positioning under the multipath effect is simulated, and the positioning result of the first-path used as reference.

Localization was performed using a 3.5Ghz-100Mhz signal on the OSM map; the number of base stations used for positioning is 4 under the condition that the base stations are supplemented. The effect of positioning with EKF under the first path/multipath is as Fig.10.

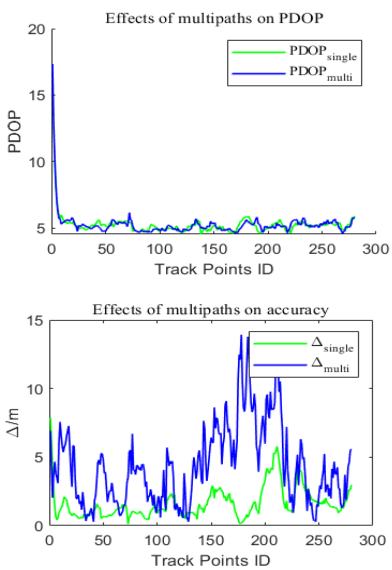

FIGURE 10. Multipath effect.

The accuracy of the first-path positioning by using the EKF method is lower than that obtained by using the least squares. The main reason is that there is no iteration in EKF code in this paper in order to improve efficiency.

The experimental results showed that the multipath and the first path have the same PDOP but quite different positioning effect. The main reason is that the multipath introduces large measurement error. Multipath effect in 5G positioning still has a great influence on the effect of positioning. It is a must to eliminate the impact of multipath in order to achieve high-precision positioning. It can be seen that most of the positioning errors are still in the range of 5m-10m in the multipath environment, which can meet the needs of most location services if the accuracy requirement is not very high.

D. LOS/NLOS

Choosing different LOS/NLOS parameters can simulate signal propagation in both LOS and NLOS environments. With this, the simulation environment of this paper may have ability in studying the influence of line-of-sight on the effect of positioning, and it is tested in this experiment.

In the channel simulator, the observations are different under LOS and NLOS conditions. While in the LOS condition the arrival angle of the first-path signal is corrected so that the difference between the arrival angle and the departure angle is maintained at 180°, then all the multipath are adjusted according to the corrected results, so that their characteristics satisfy the LOS condition better. And this correction is not conducted in the NLOS condition. In order to fully demonstrate the difference between LOS and NLOS, multipath position is used to compare the influence of LOS and NLOS on positioning.

Localization was performed using a 3.5Ghz-100Mhz signal on the OSM map; the number of base stations used for positioning is 4 under the condition that the base station is supplemented. The effect of positioning using EKF under LOS/NLOS shown in fig.11.

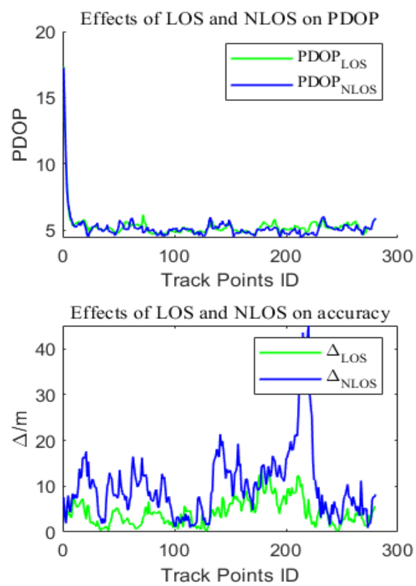

FIGURE 11. LOS/NLOS effect.

The results show that the positioning error in the NLOS condition is larger than that in the multipath effect, and the positioning error of about 5 m is expanded to nearly 20 m. Therefore, it is essential to ensure the LOS in order to achieve high-precision positioning. That is, a high-density base station network is the basis for high-precision 5G positioning.

E. INTEGRATED NAVIGATION OF 5G AND IMU

We can study the performance of 5G/IMU integrated navigation after adding IMU and integrated navigation estimation module to 5G simulation platform. The process of the experiment is as follows.

First, we establish a square base station grid with 50m spacing as shown in Fig.12.

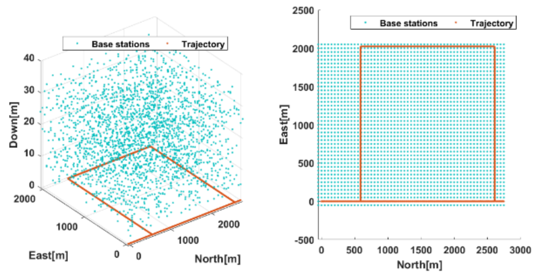

FIGURE 12. **Distribution of base stations.**

We assume that the elevation remains unchanged; roll and pitch angle stay zero; only the heading angle changes with the direction of movement. The trajectory simulates a moving vehicle at the speed of 36km/h, and the whole trajectory is about 18 minutes as shown in Fig.13.

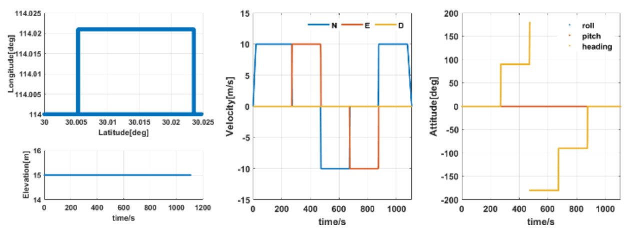

FIGURE 13. **The information of user's move track.**

Assuming three axes of IMU are equal, the simulated IMU is MEMS-level, with the parameter settings are as follows: angle random walk is 3deg/sqrt(h); velocity random walk is 0.12m/s/sqrt(h); correlation time, standard deviation of gyro bias and standard deviation of accelerometer bias in the first order Gauss-Markov process are 100s, 36deg/h, and 1000mGal, respectively.

We analyzed the accuracy of estimated position, velocity and attitude in 5G and IMU integrated navigation when the number of observed base stations varies, and compared with true trajectory. Then we calculated the standard deviation of the trajectory error. The RMS was obtained by averaging the standard deviation after repeating the experiment 10 times.

The following conclusions can be drawn from Fig.15:

1) When the number of base stations is 3 or more, the position accuracy improves significantly as the number of base stations increases, while the amount of increase is getting smaller; the velocity accuracy increases significantly as the number of base stations increases; the attitude accuracy remains unchanged as the number of base stations increases.
2) 5G and IMU integrated navigation can achieve sub-meter positioning accuracy.
3) The vertical velocity accuracy is better than the plane speed accuracy as the simulated vehicle trajectory is less dynamic in vertical direction.
4) The accuracy of heading angle is worse than roll and pitch angle, because heading angle is obtained through earth rotation, and the earth's rotation angular velocity is relatively small and is hard to extract from gyro observations with noise.

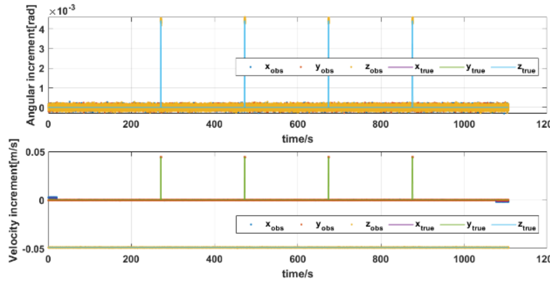

FIGURE 14. **Raw observations of IMU.**

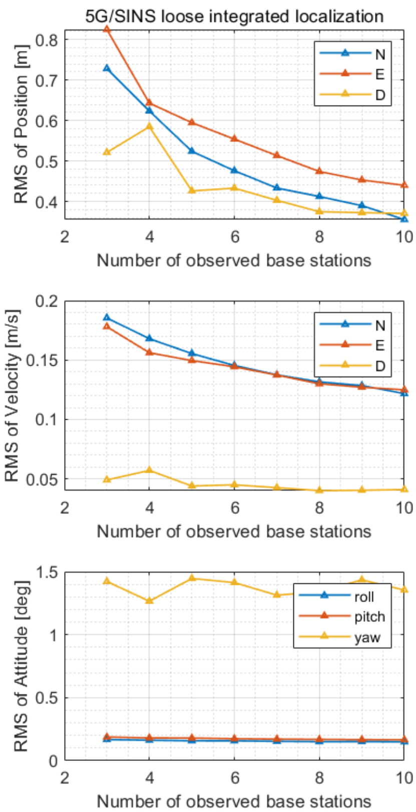

FIGURE 15. **Accuracy change with the number of observed base stations.**

We selected data with 5 observable base stations in above experiment to analyze the specific performance of 5G and IMU integrated navigation.

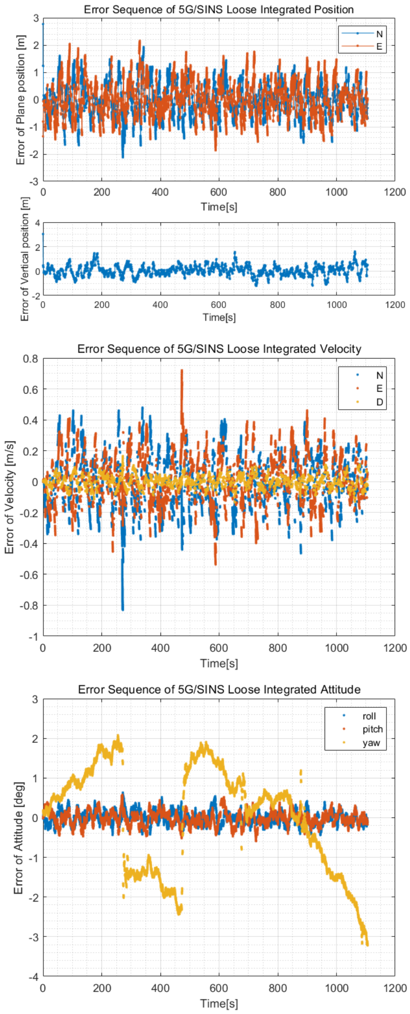

FIGURE 16. The accuracy of 5G / SINS integrated navigation.

As shown in Fig.16, position error ranges from −2.12 m to 2.77m in horizontal direction, and ranges from −1.23m to 3.03m in vertical direction; the mean deviation of position error in N, E, and D directions are −0.021m, 0.008m, and 0.044m, respectively, and the standard deviations of position error in N, E, and D directions are 0.55m, 0.60m, and 0.42m. The standard deviations of velocity error in N, E, and D directions are 0.55m, 0.60m, and 0.42m, respectively. In terms of attitude, roll angle ranges from −0.44° to 0.63°, and the standard deviation is 0.16°; pitch angle ranges from −0.59° to 0.58°, and the standard deviation is 0.18°; heading angle ranges from −3.22° to 2.08°, and the standard deviation is 1.32°.

The experiments show that 5G and SINS integrated navigation can achieve sub-meter positioning accuracy. Compared with 5G positioning, 5G and SINS integrated navigation can obtain velocity and attitude.

F. THE INFLUENCE OF PDOP ON POSITIONING ACCURACY

This simulation platform supports in-depth research related to 5G positioning accuracy. The 5G positioning accuracy-related theories will be introduced and analyzed in the future work. We selected positioning scenarios under different PDOP values to study the impact of PDOP on positioning results in this paper.

This experiment uses PDOP as the independent variable, ranging error as the parameter, and positioning error standard deviation as the dependent variable. PDOP takes interval values between 2 and 8. The ranging error includes four levels of 0.1m, 1m, 3m, and 5m. Assuming that the ranging error satisfies the normal distribution, we performed fifty experiments for each PDOP value and each error level to reduce occasional error interference. Results are shown in Fig.17.

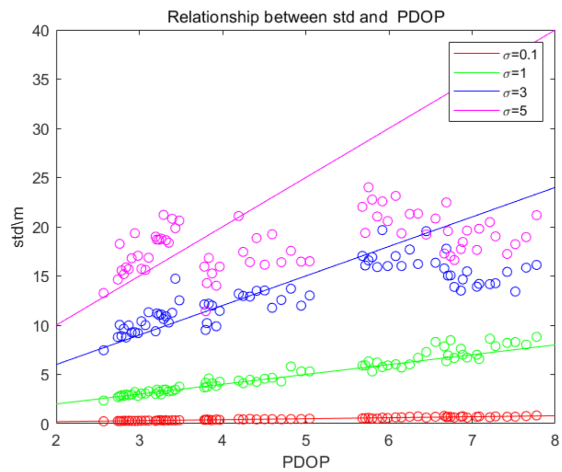

FIGURE 17. Relationship between std and PDOP.

In Fig.17, the abscissa is the value of PDOP and the ordinate is the standard deviation of the positioning error in meters. The ranging error is the parameter, and the results under different ranging errors are expressed in different colors. The solid line is the theoretical accuracy of positioning, and the scattered points are the actual accuracy of positioning. When the ranging error is 0.1m, the actual accuracy of positioning can match with the theoretical accuracy despite the increasing value of PDOP; when the ranging error is 1m, the actual and theoretical accuracy begin to deviate as the PDOP value increases. When the ranging error is 3m and 5m, the difference between actual accuracy and theoretical accuracy is more obvious. In general, the positioning error is positively correlated with PDOP. When the ranging error is small, the positioning error is directly proportional to PDOP, and the proportionality coefficient is the size of the ranging error.

V. CONCLUSION

As one of the most popular technologies, 5G can be used not only in the field of communication, but also in the field of positioning. When 5G positioning is truly implemented, first, it can bring people a better location service experience. Moreover, the positioning capability service can be provided to ubiquitous 5G terminals. Therefore, the combination of positioning capabilities and edge computing will bring huge benefits. In this article, new 5G technologies can help locating are introduced, including millimeter wave, MIMO and beamforming, and UDN. At the same time, the current research and standards related to 5G positioning are classified and explained, mainly include carrier frequency, waveform, positioning strategy, time synchronization, channel model and so on.

We have proposed a 5G positioning simulation experiment scheme and presented its flow chart. Then the implementation ideas and the specific processes of the three main parts of the simulation experiment including scene generation, signal propagation simulation and position estimation are introduced. After that, we have briefly introduced two senior research tools for accuracy evaluation and combination guidance. On this basis, we have carried out a lot of experiments by changing the system settings, and have obtained corresponding experimental results. The ability of the simulation environment established in this paper has been verified, and the factors affecting the effect of 5G positioning have been briefly analyzed such as the number of base stations, multipath effect. Furthermore, we have performed preliminary researches about the theory of 5G positioning accuracy and the integrated navigation of 5G and IMU.

Certainly, there are still some shortcomings in this article. We only use the channel simulator on a relatively basic level. We haven't fully utilized its powerful capabilities on simulation thus it is difficult to effectively simulate the impact of carrier bandwidth on positioning. Applying artificial intelligence to channel simulation should be able to obtain a more realistic simulation effect. We haven't optimized the algorithm used for positioning either. These are the aspects we will study in the future.

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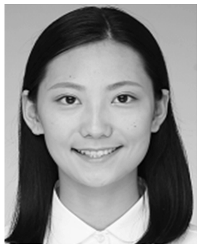

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