Simulation and Analysis of Device Positioning in 5G Ultra-Dense Network

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***Abstract*—Device positioning has generally been recognized as an important service of LTE Advanced pro and the upcoming fifth generation (5G) mobile communication. The Observed Time Difference of Arrival (OTDoA) technique that utilizes cellular signals for positioning is considered as a promising candidate technology capable of meeting users' growing demands for high-precision and ubiquitous device positioning. The application of ultra-dense network (UDN) in 5G systems brings new opportunities and challenges to device positioning. However, existing researches mainly focus on the communication characteristics of UDN, while its positioning characteristics have not been analyzed thoroughly. In this study, a software simulation platform of OTDoA positioning in 5G UDN is first established based on the current 5G standards. Then, the performance of OTDoA technique in UDN and its influencing factors are comprehensively analyzed by heat map method over our simulation platform. The simulation results demonstrate that in 5G UDN, the unsatisfactory geometric distribution quality of base stations used for positioning and the non-line-of-sight (NLoS) propagation of cellular signals are the main factors that cause the performance degradation of OTDoA positioning. Moreover, based on the above analysis, we also provide some meaningful guidance for the development or improvement of OTDoA positioning technique used in 5G UDN.**

***Index Terms*—5G new radio (NR), LTE Advanced pro, 5G positioning, ultra-dense network (UDN)**

I. Introduction

With the rapid development of location-based services (LBS) like navigation and unmanned driving, high-precision device positioning has recently been considered as one of the essential ubiquitous service of LTE Advanced Pro and the upcoming 5G mobile communication systems. The acquisition of precise location information can also help 5G networks to enhance their communication performance, such as location-aware multimedia data transmission [1], location-based communication security [2], etc.

The existing Macro-cellular network will be unable to meet the increasing user demands for communication and ubiquitous service. Thus, UDN has been introduced into 5G wireless networks as a promising technology [3]. Compared with the conventional macro-cellular networks that only deploy macro cells, UDN are characterized by the additional dense deployment of low-power small cells. The densification of base stations increases both the probability of line-of-sight (LoS) transmission and the number of range measurements available to user devices, which brings new opportunities and challenges to device positioning [4]. Previous studies on UDN mainly focus on its communication characteristics [5], while its characteristics and performance of device positioning in UDN have not been comprehensively analyzed.

In this study, we analyze the characteristics and performance of OTDoA positioning technique in UDN by heat map method over our 5G UDN software simulation platform, which is established according to the current 5G standard [6], [7]. Based on the analysis results, the main factors influencing the performance of OTDoA technique in UDN are analyzed, and some meaningful guidance for the development or improvement of positioning technique used in 5G UDN are provided.

II. System Model

A. UDN Positioning Scenario

In this study, a dense urban scenario is used to simulate and analyze the characteristics and performance of OTDoA positioning in 5G UDN, which includes two kinds of base stations: Macro base station (UMa) and Micro base station (UMi). As shown in Fig. 1, Micro base stations are in a cluster deployment in the presence of a Macro-cellular network.

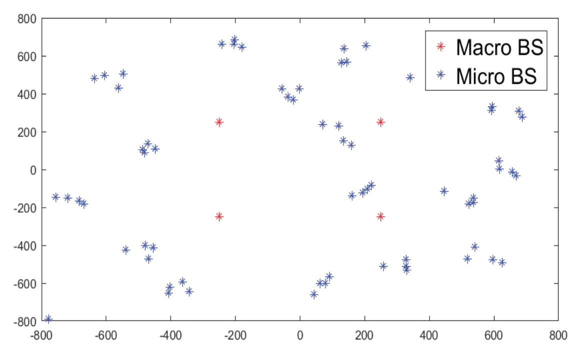

Fig. 1. 5G UDN Positioning Scenario.

The frequency allocation scheme implemented in the above scenario is as follows. The main frequencies of Macro base

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stations and Micro base stations are 2.5GHz and 3.5GHz, respectively, and the bandwidth for each base station is assumed to be 20 MHz by reusing Micro base stations' frequencies in different Micro base station clusters.

B. Model of LoS Probability

As mentioned in many existing researches, the NLoS propagation of the cellular signal is a major cause of performance degradation of OTDoA positioning. Thus, in our software simulation platform, the LoS/NLoS propagation status of the cellular signal between the user device and each base station needs to be determined before performing the OTDoA positioning. Without loss of generality, a probability model of LoS propagation proposed in [6] is used in our simulation platform to determine the signal propagation status. In this probability model, the probability of signal LoS propagation depends on the type of base station (Macro or Micro) and the propagation distance. For cellular signals transmitted by Macro base stations, the probability of LoS propagation can be calculated as follows:

$$p\left(d\right)=\left(\min\left(\frac{d_1}{d},1\right)\left(1-e^{-\frac{d}{d_2}}\right)+e^{-\frac{d}{d_2}}\right)^2, \quad (1)$$

where d is the two-dimensional distance between the user device and Macro base station, and the values of parameters d_1,d_2 are $d_1 = 20m$, $d_2 = 160m$.

For cellular signals transmitted by Micro base stations, the probability of LoS propagation is given by:

$$p\left(d\right)=\min\left(\frac{d_1}{d},1\right)\left(1-e^{-\frac{d}{d_2}}\right)+e^{-\frac{d}{d_2}}, \quad (2)$$

where $d_1 = 20m$, and $d_2 = 39m$.

C. Path Loss Model

In addition to the NLoS propagation mentioned above, receiver noise and inter-cell interference are also sources of positioning errors. As will be mentioned in section 3.A, in the case of LoS propagation, the accuracy of ranging observations obtained in OTDoA positioning is directly related to the signal-to-interference-plus-noise ratio (SINR) of the received cellular signal. In this study, a close-in free space reference distance path loss model (CI model) proposed in [6] is utilized to model the path loss during the signal propagation, so as to calculate the power and SINR of the received signal. The CI model used in this study can be expressed as:

$$PL^{CI}\left[dB\right]=FSPL\left(f,1m\right)+10n\log_{10}\left(\frac{d}{1m}\right)+X_{SF}, \quad (3)$$

where f is the main frequency in Hz, n is the path loss exponent (PLE), d is the three-dimensional distance between the user device and base station, X_{SF} is the shadow fading (SF) term in dB. $FSPL\left(f,1m\right)$ is the free space path loss at $1m$, which can be expressed as:

$$FSPL\left(f,1m\right)=20\log_{10}\left(\frac{4\pi f}{c}\right), \quad (4)$$

where c is the speed of light. The values of parameters n and X_{SF} in CI path loss model for different scenarios are shown in Table I.

TABLE I
PARAMETERS OF CI MODEL FOR DIFFERENT SCENARIO

	Path Loss Exponent (n)	Shadow Fading Term (X_{SF})
UMa-LoS	2.0	4.1
UMa-NLoS	3.0	6.8
UMi-LoS	1.98	3.1
UMi-NLoS	3.19	8.2

III. OTDOA POSITIONING MODEL

A. OTDoA Positioning

The Observed Time Difference of Arrival (OTDoA) is a positioning technique that exists in the current long-term evolution (LTE) standards (3G and 4G) and is considered as a promising candidate technology for 5G positioning. In OTDoA positioning, the user device first measures the time of arrival (ToA) of a specific reference signal transmitted by multiple base stations, which can be Primary Synchronization Signals (PSS) or Secondary Synchronization Signals (SSS) in 5G standards [7]. Using $\mathcal{N}=\{1,\ldots,N\}$ to represent the set of base stations used for positioning, and without considering the NLoS propagation, the ToA observation corresponding to the i-th base station can be expressed as:

$$\hat{t}_i=\frac{r_i}{c}+\Delta\tau+\varepsilon_i, \quad (5)$$

where r_i is the Euclidean distance between the user device and i-th base station, $\Delta\tau$ is the clock error, ε_i is the timing error caused by noise and interference. For the OFDM signal used in 5G systems, the variance of ε_i can be calculated by [8]:

$$\sigma_i^2=\mathrm{var}\left(\varepsilon_i\right)=\frac{T_s^2}{8\pi^2\cdot SINR_i\cdot\sum\limits_{k\in\mathcal{N}_a}p_k^2\cdot k^2}, \quad (6)$$

where T_s is the OFDM symbol duration, $\mathcal{N}_a$ is the set of subcarriers used by the reference signal, p_k^2 is the relative power weight of the k-th subcarrier. The SINR of the received signal corresponding to the i-th base station is given by:

$$SINR_i=\frac{p_{t,i}/PL_i}{\sum\limits_{k\in\mathcal{J}_i,k\neq i}p_{t,k}/PL_k+p_{noise}}, \quad (7)$$

where $p_{t,i}$ is the transmitting power of i-th base station, PL_i is the path loss, p_{noise} is the power of receiver noise, $\mathcal{J}_i$ is the set of base stations that share the same communication resource with the i-th base station.

Then, the received signal time difference (RSTD) between every two base stations is calculated. By using $\mathbf{x}=[x,y]^T$ and $\mathbf{l}_i=[x_i,y_i]^T$ to represent the position of the user device and i-th base station respectively, the RSTD observation corresponding to the i-th and j-th base stations can be expressed as:

$$\Delta\hat{t}_{i,j} = \hat{t}_i - \hat{t}_j = \frac{1}{c}\cdot(\|\mathbf{I}_i - \mathbf{x}\| - \|\mathbf{I}_j - \mathbf{x}\|) + (\varepsilon_i - \varepsilon_j)\,, \quad (8)$$

It can be seen that the value of RSTD observation is directly related to the unknown position of user device. Thus, after obtaining RSTD observations corresponding to at least three base stations (two-dimensional positioning), iterative estimation methods like weighted least squares method [9] can be used to estimate the user's position.

B. Horizontal Dilution of Precision (HDOP)

The geometry distribution of base stations relative to the user device can strongly affect the performance of OTDoA positioning. In this study, the geometric distribution quality of base stations in 5G UDN is evaluated by horizontal dilution of precision (HDOP) [10], whose value is negatively correlated with the positioning accuracy. The definition of HDOP is as follows:

$$HDOP = \sqrt{\mathrm{tr}\left\{(\mathbf{G}^T\mathbf{G})^{-1}\right\}}, \quad (9)$$

where $\mathbf{G}$ is the Jacobian matrix of ranging equation, and can be expressed as:

$$\mathbf{G} = \begin{bmatrix} \frac{x_1 - x}{\|\mathbf{I}_1 - \mathbf{x}\|} & \frac{y_1 - y}{\|\mathbf{I}_1 - \mathbf{x}\|} & -1 \\ \vdots & \vdots & \vdots \\ \frac{x_N - x}{\|\mathbf{I}_N - \mathbf{x}\|} & \frac{y_N - y}{\|\mathbf{I}_N - \mathbf{x}\|} & -1 \end{bmatrix}. \quad (10)$$

Due to its ability to reflect the geometric distribution quality of base stations, in this study, HDOP is used as one of the evaluation metrics to analyze the characteristics and performance of OTDoA technique in 5G UDN.

IV. SIMULATION PLATFORM

In this section, the characteristics and performance of OTDoA positioning technique in 5G UDN are numerically analyzed by heat map method over our 5G UDN software simulation platform. When implementing the heat map method, we first equally divide the area shown in Fig.1 into a number of small regions with the spatial resolution of $20m$, and then traverse each small region according to the steps illustrated in Fig.2 and calculate four evaluation metrics: Number of Available ToA Measurements, Number of LoS measurements, HDOP, Positioning errors.

As can be seen from Fig.2, in each small region, the heat map method first determines the signal propagation status between the user device and each base station according to the LoS probability model described in section 2.B. Then, the path loss corresponding to each base station is calculated according to the CI model mentioned in section 2.C. After that, the SINR of the received signal from each base station can be obtained by Eq. (7), and only those base station with $SINR \geq -15dB$ are considered to be available for OTDoA positioning. The ToA measurements corresponding to each available base station can be generated by Eq. (5) and Eq.

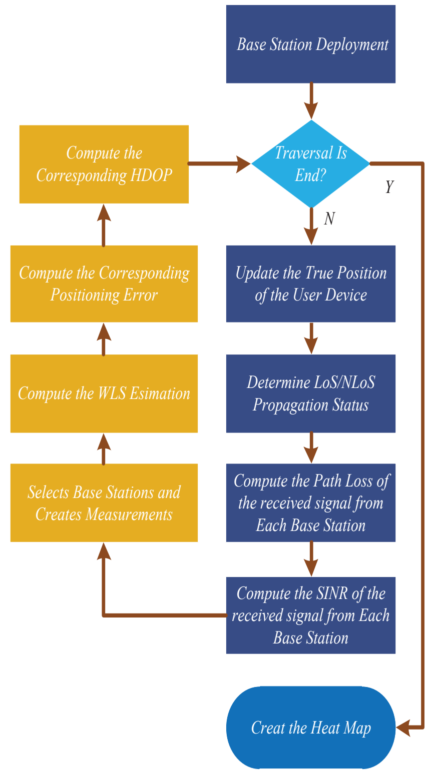


Fig. 2. Flowchart of the Heat Map Method.

(6). Finally, the four evaluation metrics corresponding to each small region are calculated and recorded.

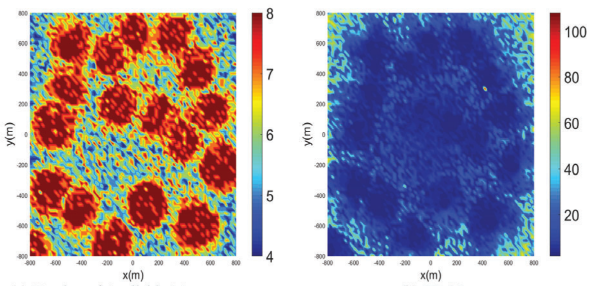
After the heat map method traverses all the small regions, several heat maps can be generated to analyze the characteristics and performance of OTDoA technique in 5G UDN. It is worth noting that for the case of NLoS propagation, additional power loss and time delay need to be introduced when calculating path loss and generating ToA measurements.

V. SIMULATION RESULTS AND ANALYSIS

A. Characteristics of OTDoA Positioning in 5G UDN

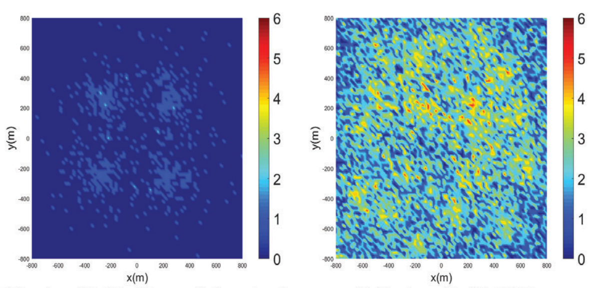
- **More Available Measurements**: For user device in the Macro-cellular network, the base stations available for positioning are just the 4 Macro base stations shown in Fig.1. The heat map of the number of available ToA measurements for user device in UDN is shown in Fig.3(a). It can be seen that the number of available ToA measurements in UDN is between 7 and 8 in the coverage of Micro base station clusters. In the areas between adjacent Micro base station clusters, the number of available range measurements is between 4 and 5, which does not increase much compared with the Macro-cellular network. This phenomenon is caused by the inter-cell interference and the low transmission power of Micro base stations. In general, the dense deployment of Micro base stations in UDN increases the available ToA and RSTD measurements for user device.

- **More LoS Measurements**: The heat maps of the number of available LoS measurements for user device in the Macro-cellular network and UDN are shown in Fig.4(a) and Fig.4(b), respectively. By comparing Fig.4(a) and Fig.4(b), it can be found that with the application of UDN, the number of LoS measurements increases significantly due to the smaller distance between the user device and base station. This characteristic of 5G UDN can help to reduce the impact of cellular signal NLoS propagation on the accuracy of OTDoA positioning.



(a) Number of Available Measurements (b) HDOP

Fig. 3. Number of Available Measurements and HDOP in 5G UDN.



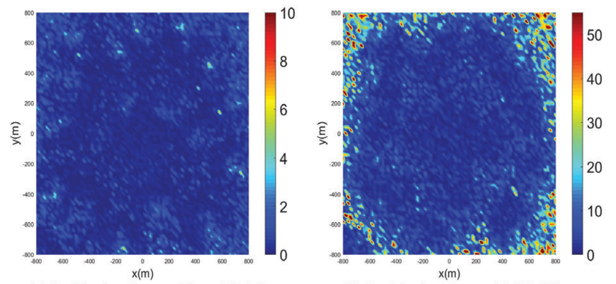
(a) Number of LoS in Macro-cellular network (b) Number of LoS in UDN

Fig. 4. Number of LoS Measurements in Macro-cellular network and 5G UDN.

B. Performance Analysis of OTDoA Positioning in 5G UDN

As mentioned above, the deployment of Micro base stations in 5G UDN increase the number of available measurements and LoS measurements. However, whether these characteristics could directly improve the positioning accuracy is questionable. Firstly, it can be seen from Fig.3(a) and Fig.4(b) that with the deployment of Micro base stations, the number of available measurements and LoS measurements increases almost simultaneously. This phenomenon means that in 5G UDN, a part of the ToA measurements obtained by user device still contain NLoS errors. If the user device do not filter the measurements before performing the OTDoA positioning, the positioning accuracy in 5G UDN will still be unsatisfactory.

Secondly, the performance of OTDoA positioning is also influenced by the geometric distribution quality of base stations. As mentioned in section 3.B, the geometric distribution quality of base stations can be evaluated by HDOP. The heat map of HDOP in 5G UDN is shown in Fig.3(b), which follows the same spatial distribution with the positioning error shown in Fig. 5(b). This phenomenon indicates that the distribution quality of base stations is also a non-negligible factor affecting the performance of OTDoA positioning in 5G UDN.



(a) Positioning Error without NLOS (b) Positioning Error with NLOS

Fig. 5. Positioning errors in 5G UDN.

C. Guidance For Improving Performance of OTDoA Positioning in 5G UDN

As discussed above, unsatisfactory geometric distribution of base stations and the NLoS propagation of cellular signals are the main factors that cause the performance degradation of OTDoA positioning in 5G UDN. By considering the above two factors comprehensively, some novel base station selection schemes could be proposed to improve the OTDoA positioning accuracy in 5G UDN.

VI. Conclusion

In this study, a software simulation platform of OTDoA positioning in 5G UDN is established based on the current 5G standards. The performance of OTDoA technique in UDN and its influencing factors are comprehensively analyzed by heat map method over our simulation platform. Moreover, based on the above analysis, we also provide some meaningful guidance for the development or improvement of OTDoA positioning technique used in 5G UDN.

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