Comparison of TDOA Positioning Solutions in 5G Network: Indoor and Outdoor Performance

Jiaqi Li, Seung-Hoon Hwang
Department of Electronics and Electrical Engineering
Dongguk University
Seoul, Korea
kikilee@dgu.ac.kr, shwang@dongguk.edu

***Abstract*— As 5G new radio (NR) networks continue to be deployed, indoor positioning has emerged as one of the most sought-after applications. However, achieving indoor positioning accuracy comparable to outdoor positioning using radio access network (RAT)-dependent technology remains a subject of extensive research and investigation. This paper delves into the investigation of the TDOA-based positioning architecture and presents the formulation of the DL-TDOA measurement methodology. Furthermore, the study examines three environmental settings: Line-of-Sight (LOS) propagation and random LOS propagation in the outdoor environment, as well as Non-Line-of-Sight (NLOS) propagation in the indoor environment. The study reveals that the UE position estimation errors remain consistent outdoors, but they are twice as large in the indoor environment compared to the outdoor scenario.**

Keywords—5G new radio (NR), Time Difference of Arrival (TDOA), Indoor positioning, Ranging estimation.

I. INTRODUCTION

Nowadays, the Global Navigation Satellite System (GNSS) has been widely used for outdoor positioning, with notable systems such as U.S. NAVASTAR GPS, the European Galileo, the Russian GLONASS, and the Chinese Bei-Dou being widely adopted [1]. Nevertheless, GNSS faces challenges regarding indoor positioning due to satellite signals encountering difficulty penetrating solid structures like walls and roofs. Signal attenuation and multipath effects result in inaccuracies in indoor positioning [2]. Specifically, GNSS signals may be completely blocked in deep indoor environments. With the increasing market demands for indoor positioning [3], various radio access network (RAT)-independent positioning, for example, Wi-Fi, ZigBee, Bluetooth (BLE), and ultra-wideband (UWB) [4], and RAT-dependent positioning, such as the 5th generation (5G) mobile networks and the long-term evolution (LTE), technologies have been developed to address the challenges involved.

The 5G mobile networks have been developing expeditiously. In 2019, Korea became the first country to launch commercial 5G networks worldwide, and by the end of 2022, the number of 5G users had reached over 28 million [5]. Compared to Wi-Fi-, BLE-, and UWB-based solutions, as indicated in Table I, 5G NR signals offer the advantages of covering larger areas, high capacity, and lower latency [6], thereby reducing the necessity for deploying dense infrastructure. Moreover, the support for 5G NR in modern mobile devices means that indoor positioning can be seamlessly incorporated into these devices without additional hardware or connectivity.

TABLE I. PERFORMANCE METRICS, TRADEOFFS, COMPARISONS [2]

Technology	**LTE**	**5G**	**BLE**
Positioning Accuracy (m)	50	10	< 1
Effective Range	Hundreds of metres	Hundreds of metres	Tens of metres
Technology	**Wi-Fi**	**UWB**	**GNSS**
Positioning Accuracy (m)	< 10	0.1 – 0.5	2 – 5
Effective Range	Tens of metres	Tens of metres	Kilometres

The beneficial characteristics of 5G for wireless positioning have been envisioned, leading the 3rd Generation Partnership Project (3GPP) to establish stringent requirements for indoor positioning accuracy. For instance, 3GPP Rel-16 aims to achieve high indoor positioning accuracy, encompassing both horizontal and vertical dimensions, with commercial use cases requiring precision within 3 m and latency below 1 s, while ensuring an 80% service availability [7]. Meanwhile, Rel-16 supports the following RAT-dependent positioning solutions: Downlink Time Difference of Arrival (DL-TDOA), Uplink Time Difference of Arrival (UL-TDOA), Multi-Cell Round Trip Time (Multi-RTT), Downlink Angle of Departure (DL-AoD), Uplink Angle of Arrival (UL-AoA), and Enhanced Cell ID (E-CID). The time-based positioning solutions of 5G mobile networks are regarded as promising techniques for indoor positioning due to their ability to yield moderate positioning errors and exhibit resilience against Non-Line-of-Sight (NLOS) propagation [8]. Hence, this paper is focused on the TDOA method.

The remainder of the paper is organised as follows. Section II provides an overview of the TDOA positioning technique. In Section III, the performance of the TDOA technique is analysed for both outdoor and indoor environments. Finally, the last section presents conclusions and outlines future work.

II. OVERVIEW OF THE TDOA POSITIONING TECHNIQUE

A. TDOA Positioning Technique

Unlike the time of arrival (TOA) method, which requires the user equipment (UE) to be precisely time-synchronised with the 5G mobile network to determine absolute distance, the TDOA method, a.k.a Observed Time Difference of Arrival (OTDOA), measures the difference in times of flight between the UE and a pair of fixed reference base stations. Therefore, clock synchronisation is only required between base stations rather than between UEs and base stations. By measuring two TDOAs with three different base stations, the location of UE can be determined at the intersection of the hyperbola formed by the two TDOAs. It is worth noting that at least four base stations are required to estimate the location of the UE in three-dimensional coordinates [9].

As depicted in Figure 1, the UE first receives the Positioning Reference Signal (PRS) from several gNBs in the

979-8-3503-1327-7/23/$31.00 ©2023 IEEE

case of the downlink or transmits the Sounding Reference Signal (SRS) to neighbouring gNBs in the case of the uplink and calculates the TOA for each PRS/SRS signal. A single TOA of one gNB is used as a reference to calculate the Reference Signal Time Difference (RSTD) or the Relative Time of Arrival (RTOA) for TOAs from the remaining gNBs [10]. In the downlink, the UE then sends the RSTD measurements to the core network to obtain the location of the UE by using the known geographical coordinates of the gNBs. Conversely, in the uplink, the RTOA is forwarded to location servers by the gNB. The 5G core network is composed of two key components, including the Location Management Function (LMF) and the Access and Mobility Management Function (AMF) [11]. LMF manages the location service resources and delivers the positioning-related assistance information, while AMF is responsible for handling the processing of location service requests and responses. Additionally, in 5G NR positioning, two protocols are utilised for exchanging location information: the extension of the LTE Positioning Protocol (LPP) and the NR Positioning Protocol Annex (NRPPa). LPP facilitates signalling between the UE and the LMF [12], while NRPPa defines procedures for transferring positioning-related information between gNBs and the LMF [13].

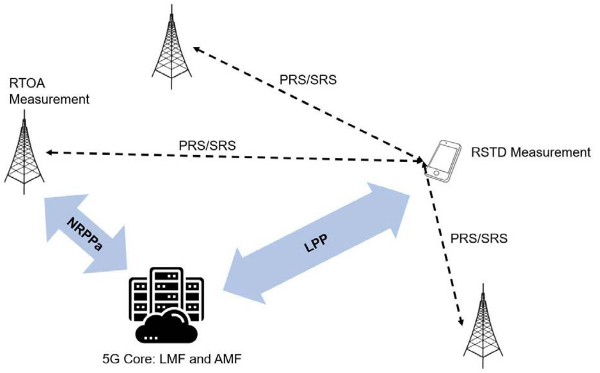

Figure 1. The general architecture of UE positioning in 5G NR.

B. TDOA Methodology

In the case of the downlink TDOA, the base station transmits the baseband signal, which can be expressed as [14]:

$$s(t) = \sum_{n=0}^{N_u} c_n \cdot e^{\frac{j2\pi nt}{N}} \tag{1}$$

where c_n denotes the modulated data, n is the subcarrier number, N is the total number of subcarriers transmitted in the 5G mobile network, and N_u represents the number of carriers at the central spectrum. j represents the imaginary unit of the complex number, where $j = \sqrt{-1}$. Furthermore, t is the transmission time duration which is constrained by:

$$0 \leq t \leq \frac{2^{-\mu}}{15000\,Hz} \tag{2}$$

where μ is the supported transmission numerlogy in [14].

The received signals at the UE from a couple of gNBs can be denoted as:

$$y_i(t) = s(t-\tau) + n_i \tag{3}$$

$$y_j(t) = \alpha \cdot s(t) + n_j \tag{4}$$

where n represents the additive white Gaussian noise which follows a complex Gaussian distribution with zero-mean and variance of σ^2, and α denotes relative amplitude. In addition, τ is the difference in the times of arrival whose value is to be estimated by utilising correlation analysis:

$$R_{i,j}(\tau) = \frac{1}{T-\tau}\int_{\tau}^{T} \alpha \cdot s(t-\tau) \cdot \widehat{s(t)}\, dt + \frac{1}{T-\tau}\int_{\tau}^{T} s(t-\tau) \cdot \widehat{n_j}\, dt + \frac{1}{T-\tau}\int_{\tau}^{T} \alpha \cdot s(t) \cdot \widehat{n_j}\, dt + \frac{1}{T-\tau}\int_{\tau}^{T} n_i \widehat{n_j}\, dt \tag{5}$$

where T represents the oberserved interval, and $\widehat{(\,)}$ signifies the comple conjugate. The TDOA value, i.e., τ, is aimed to maximise $R_{i,j}(\tau)$.

The hyperbola that defines the location of the UE can be expressed as:

$$\frac{x^2}{\frac{(\tau \cdot c)^2}{4}} - \frac{y^2}{\frac{D^2}{4} - \frac{(\tau \cdot c)^2}{4}} = 1 \tag{6}$$

where c is the speed of light, (x, y) represents the coordinates of the UE, and D denotes the distance of a pair of gNBs.

III. PERFORMANCE ANALYSIS

In this section, we demonstrate the performance analysis of TDOA-based positioning technology in both indoor and outdoor environments.

A. Environment Parameters

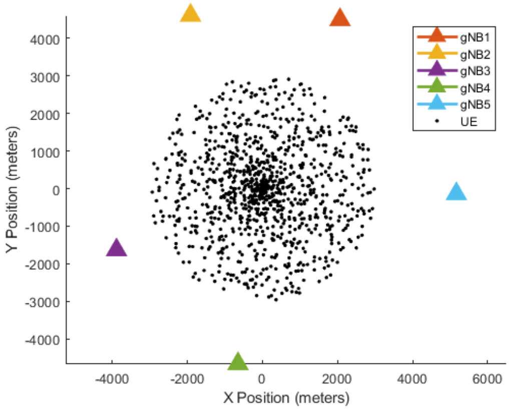

Figure 2. The locations of the UE and gNBs.

As illustrated in Figure 2, we begin by creating five random locations for base stations, marked as triangles. 1,000 UEs are positioned obeying a uniform distribution within the coverages of base stations. The UE correlates the incoming signal with reference PRS generated for each base station and then selects the three best cells based on the correlation outcomes. The base station is configured to transmit PRS on a 4.0 GHz carrier frequency with a bandwidth of 10 MHz.

In the deployment environment, 5G base stations are considered urban and deployment-dependent parameters are summarised in [15]. For the outdoor environment, we explore two design scenarios: 1) LOS conditions and 2) random LOS conditions. Scenario 1) assumes a scenario without any obstacles between base stations and the UE, whereas in scenario 2), channels are randomly configured as NLOS channels since LOS conditions are unpredictable in the real world. Additionally, for the indoor environment design, all channels are configured as NLOS conditions and modelled as Rayleigh fading.

B. Numerical Results

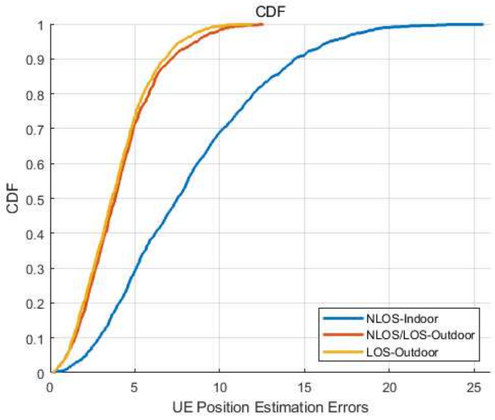

Figure 3. Performance analysis for indoor and outdoor positioning.

TABLE II. PERFORMANCE ANALYSIS

Scenario	LOS	LOS/NLOS	NLOS
Mean Positioning Accuracy (m)	3.8690	4.0847	8.1484

As expected and demonstrated in Table II, our proposed DL-TDOA-based positioning method achieves precise positioning. In the outdoor scenario, the mean UE position estimation errors for both scenarios 1) and 2) are observed to be 3.8690 m and 4.0847 m, respectively. In scenario 1), the rates of UE estimation errors less than or equal to 5 m reach 75%, while in scenario 2), this rate is observed to be 74.6%. This approaching performance, as shown in Figure 3, suggests that our DL-TDOA-based method is resilient to variations in line-of-sight conditions, maintaining its accuracy in diverse outdoor environments. The adaptability of the method can be attributed to the UE to compare received signals and select the best three cells for positioning, allowing it to consistently deliver reliable results across different design approaches and scenarios.

However, in the indoor environment, the mean UE position estimation error increases to 8.1484 m. Also, the rate of UE estimation error less than or equal to 5 m is only 34%. This is due to signals from base stations bouncing off walls, floors, and other obstacles, resulting in multipath effects. These reflections cause variations in the arrival time of signals at the UE, leading to inaccuracies in time-of-arrival measurements and, consequently, an increase in position estimation error. It is worth noting that in the real world, there are fewer base stations accessible to the UE indoors which limits the triangulation capabilities and potentially leads to increased estimation errors.

IV. CONCLUSIONS

This paper has investigated the TDOA-based 5G NR positioning framework. We have developed a mathematical model to conduct a comparative study of the performance of DL-TDOA-based NR positioning in both outdoor and indoor environments. For the outdoor environment, we examine two scenarios: full LOS conditions and random LOS conditions. In contrast, for the indoor environment design, we considered full NLOS conditions. The results demonstrated that the UE position estimation errors remain consistent for the outdoor environment. However, the error for the indoor environment is twice as large as the outdoor scenario.

Compared to the indoor positioning accuracy defined in 3GPP Rel-16, our proposed method exhibits an obvious disparity. In further research, we will explore the incorporation of deep learning algorithms to enhance indoor positioning accuracy. Additionally, we plan to conduct comparisons with other 5G NR RAT-dependent positioning technologies to gain a comprehensive understanding of the performance of different technologies.

REFERENCES

[1] A. Bensky, “Satellite Positioning,” in *Wireless Positioning: Technologies and Applications*. Artech House, 2016, pp. 251–273.

[2] N. Samama, “Building Range Technologies: The Specific Case of Indoor GNSS,” in *Indoor Positioning: Technologies and Performance*. Wiley, 2019, pp. 191–216.

[3] “Indoor Location Market by Component (Hardware, Solutions, and Services), Technology (BLE, UWB, Wi-Fi, RFID), Application (Emergency Response Management, Remote Monitoring, Predictive Asset Maintenance), Vertical and Region – Global Forecast to 2028,” Markets and Markets, Rep. TC 2878, June 2023.

[4] F. Zafari, A. Gkelias and K. K. Leung, "A Survey of Indoor Localization Systems and Technologies," in IEEE Communications Surveys & Tutorials, vol. 21, no. 3, pp. 2568-2599, thirdquarter 2019, doi: 10.1109/COMST.2019.2911558.

[5] J. P. Tomás, “South Korea Ends 2022 with Over 28 Million 5G Subscribers,” RCR Wireless News, Feb. 7, 2023. Accessed on: Aug. 1, 2023. [Online]. Available: https://www.rcrwireless.com/20230207/5g/south-korea-ends-2022-over-28-million-5g-subscribers.

[6] M. Shafi et al., "5G: A Tutorial Overview of Standards, Trials, Challenges, Deployment, and Practice," in IEEE Journal on Selected Areas in Communications, vol. 35, no. 6, pp. 1201-1221, June 2017, doi: 10.1109/JSAC.2017.2692307.

[7] *Study on NR Positioning Support*, Release 16, 3GPP Technical Report 38.855, V16.0.0, Mar. 2019.

[8] S. Hara, D. Anzai, T. Yabu, K. Lee, T. Derham and R. Zemek, "A Perturbation Analysis on the Performance of TOA and TDOA Localization in Mixed LOS/NLOS Environments," in IEEE Transactions on Communications, vol. 61, no. 2, pp. 679-689, February 2013, doi: 10.1109/TCOMM.2013.012313.110509.

[9] Y. T. Chan, and K. C. Ho, “A Simple and Efficient Estimator for Hyperbolic Location,” IEEE Transactions on Signal Processing, Vol. 42, No. 8, August 1994. Accessed on Aug. 2, 2023. [Online]. Available: http://www.dei.unipd.it/~nil/lecturesPositionLocationNavigation/3_CellularNetworkPositioning/refs/ChanYT94.pdf.

[10] *Physical Layer Measurements*, Release 16, ETSI 3GPP TS 38.215, V16.2.0, July 2020.

[11] C. Yang, S. Mao, X. Wang, and M. Gong, “An Overview of 3GPP Positioning Standards,” Standards, GetMobile, Vol. 26, Issue 1, March 2022. Accessed on: Aug. 3, 2023. [Online]. Available: https://drive.google.com/file/d/1WgLYqT4g-XB4ZSAas-JnnDBlgFtk0Z7N/view?pli=1.

[12] *Evolved Universal Terrestrial Radio Access (E-UTRA); LTE Positioning Protocol (LPP)*, Release 15, 3GPP TS 36.355, V15.6.0. Jan. 2020.

[13] *NG-RAN; NR Positioning Protocol A (NRPPa)*, Release 16, 3GPP TS 38.455, V16.1.0. Nov. 2020.

[14] *NR; Physical Channels and Modulation*, Release 16, 3GPP TS 38.211, V16.2.0. July 2020.

[15] *Study on Channel Model for Frequencies from 0.5 to 100 GHz*, Release 16, 3GPP TR 38.901, V16.1.0. July 2020.