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A Practical 3-Dimensional Positioning Algorithm for 3GPP LTE System

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Abstract— **Mobile positioning enhancement has been an attractive standards issue to support high-quality location based services (LBS) in 3rd generation partnership project (3GPP) long term evolution (LTE) system. Especially for urban canyon environment with lots of tall skyscrapers, the necessity of 3-dimensional (3D) positioning has been raised to measure the altitude of user; however, the traditional method in LTE, time difference of arrival (TDOA) based positioning, only can estimate the horizontal position of user, not the vertical position of user in rectangular coordinate system. Several TDOA based methods for 3D positioning have been studied for decades; however, they still have practical limitations to be utilized in LTE. Therefore, in this paper, we propose a practical 3D positioning method based on 2D TDOA per each coordinate plane. Also, in order to improve the performance of 2D TDOA, we propose a new hyperbola equation derivation which provides more accurate 2D hyperbola equations by using pre-measured position information (PPI). In addition, we propose iterative TDOA algorithm which can provide PPI among 2D TDOAs. We verify that the proposed method can perform accurate 3D positioning with practical implementation.**

Keywords—local based service (LBS); time difference of arrival (TDOA); 3-dimensional positioning

I. INTRODUCTION

Mobile positioning techniques have received a considerable attention in telecommunication industry for decades. Although the trend has been triggered by safety requirements of government authorities in the U.S. federal communication commission, its commercial values for location based service (LBS) have become more attractive recently [1].

Most of mobile positioning techniques can be divided into two groups depending on the reference node type of received signals; global positioning system (GPS) based method and cellular based method. Though GPS based method guarantees the positioning with high accuracy, it can be unavailable in indoor environment [2]. For that reason, cellular based method can be an alternative by using signals from mobile communication infrastructure. Among them, received signal strength indication (RSSI) based positioning is well-known method mostly utilized in indoor environment [3]. Its accuracy is quite high; however, a considerable overhead is demanded for RSSI database construction [4]. Meanwhile, long term evolution (LTE) provides enhanced cell ID (E-CID) technology which utilizes ID of eNB and angle-of-arrival (AoA); however, it shows coarse positioning accuracy [2].

Trilateration based positioning that is based on time of arrival (TOA) and time difference of arrival (TDOA) can be one of the alternatives in LTE cellular network [5]. In TOA, the distances from three eNBs and their positions define three circles, and the intersection of the circles indicates the position of user equipment (UE). Nevertheless, the distance measurement from two eNBs, which are not serving eNB of UE, causes signaling overhead to UE in LTE. Therefore, 3rd generation partnership project (3GPP) adopted TDOA based positioning which uses time differences of downlink signals from three eNBs and finds the intersection of two hyperbola equations, as an optional method [2], [6].

Based on the TDOA positioning, LTE can support most cases of LBS; however, the necessity of measuring UE's altitude has been raised to provide more advanced LBS even in urban canyon environment where lots of tall buildings are positioned nearby. Following this trend, 3GPP started to discuss mobile positioning enhancement which can measure both horizontal and vertical positions of UE in rectangular coordinate system [7]. Although several 3-dimensional (3D) positioning methods already exist, they have some practical limitations in LTE cellular network.

Therefore, in this paper, we propose a novel 3D positioning method based on multiple 2D TDOA per coordinate plane. In this method, because a non-target axis cannot be considered in 2D hyperbola equations, positioning performance can be degraded in most of 2D TDOA cases. Nevertheless, the conventional 2D TDOA cannot apply the non-target axis information to 2D hyperbola equations. For that reason, we propose a new hyperbola equation derivation to revise 2D hyperbola equations for more accurate positioning. Then, for the acquisition of the non-target axis information, we propose pre-measured position information (PPI) based iterative TDOA algorithm which can mutually support the non-target axis information among 2D TDOAs of the proposed method.

II. SYSTEM MODEL

A. System Architecture

Figure 1 shows network elements for positioning in LTE system. First, enhanced serving mobile location centre (E-SMLC) manages the support of diverse location services for UE, including positioning of UE and delivery of assistance data to UE via serving eNB and mobile mobility entity (MME) [5].

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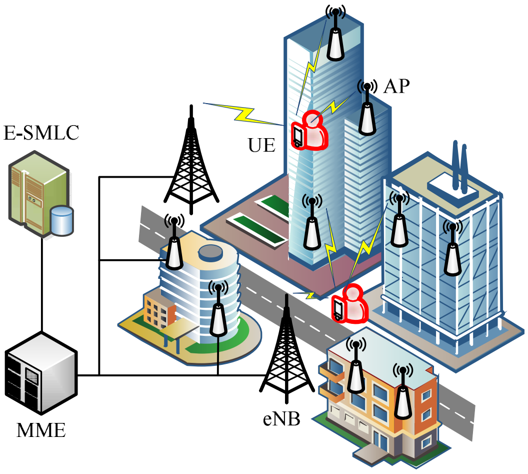

Fig. 1. LTE system model for positioning.

When UE requests positioning, E-SMLC decides on the positioning method to be used, commands UE to perform the positioning method via eNB. Then, after UE transmits the positioning information to E-SMLC via eNB, E-SMLC estimates UE's position based on a certain algorithm and notices the position information to UE.

Meanwhile, eNB is a network element of LTE system that performs measurements in response to requests from E-SMLC, makes measurements for UE, and provides measurement results to E-SMLC [5]. The role of eNB is an intermediary element between E-SMLC and UE for positioning. UE is a mobile user of LTE that requests positioning to eNB. After positioning grant from E-SMLC, it measures reference signals from eNBs or access points (AP), and transmits the positioning related information, such as physical cell ID and downlink reference signal time difference (RSTD), to E-SMLC via eNB.

B. *Network and Signal Model*

As described in Fig. 1, we assume urban environment with lots of tall buildings where numerous macro cells are outside of the buildings, and some small cells are inside of the buildings. In this environment, UE can be located on the ground or a certain floor of building. For that reason, UE can receive PRS from both eNB in macro cell and AP in small cell. For TDOA based positioning, UE needs to receive at least three downlink positioning reference signal (PRS) from eNB or AP.

In LTE release 9, PRS is newly defined for positioning. It is composed of pseudo random binary sequence (PRBS) which is already used in cell-specific reference signal (CRS) generation. In this paper, we assume that all eNBs (or APs) have mutually orthogonal PRS patterns and detection performance of UE is ideal. Also, PRS transmission time offset among eNBs can be compensated by E-SMLC in asynchronous network.

III. THE CONVENTIONAL METHOD

A. *TDOA based 2D Positioning*

In TDOA based positioning, E-SMLC estimates UE's position (x, y) by computing two hyperbola simultaneous equations based on two RSTD values, $r_{(n1,s)}$ and $r_{(n2,s)}$, and the positions of three eNBs, including a serving eNB (x_s, y_s) and two neighboring eNBs (x_{n1}, y_{n1}), (x_{n2}, y_{n2}), as described in Fig. 2. The hyperbola equations can be formulated as follows.

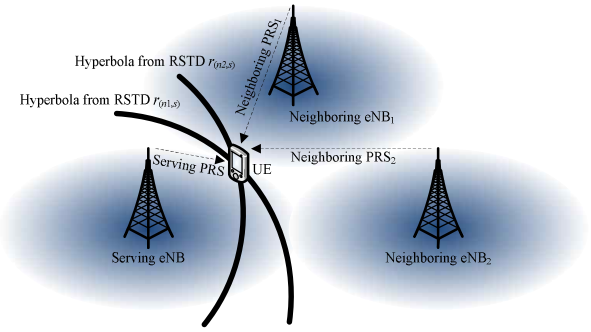

Fig. 2. TDOA based positioning.

$$r_{(n1,s)} = r_{n1} - r_s \tag{1}$$

$$\begin{aligned} r_{(n1,s)} &= \sqrt{(x-x_{n1})^2 + (y-y_{n1})^2} - \sqrt{(x-x_s)^2 + (y-y_s)^2} \\ r_{(n2,s)} &= \sqrt{(x-x_{n2})^2 + (y-y_{n2})^2} - \sqrt{(x-x_s)^2 + (y-y_s)^2} \end{aligned} \tag{2}$$

where r_{n1} is distance between neighboring eNB$_1$ and UE, r_s is distance between serving eNB and UE. Then, E-SMLC can estimate UE's position by solving the hyperbola simultaneous equations; however, the computation procedure of the non-linear equations is significantly complex. Therefore, in order to solve the non-linear equations, two location fixing algorithms are generally considered.

1) *Taylor Series (TS) based Algorithm*

This algorithm is based on iterative least square (LS) estimation to minimize deviation between actual value and estimated value [8]. It initiates UE's position as an arbitrary location (x_0, y_0), and transforms the non-linear equations (2) into an approximated linear equation by TS expansion.

$$\begin{aligned} r_{(i,j)}^{(x_0,y_0)} &= \sqrt{(x_0-x_i)^2 + (y_0-y_i)^2} - \sqrt{(x_0-x_j)^2 + (y_0-y_j)^2} \\ &= r_{(i,j)}^{(x_0,y_0)} + (\partial r_{(i,j)}^{(x_0,y_0)} / \partial x_0)\Delta x + (\partial r_{(i,j)}^{(x_0,y_0)} / \partial y_0)\Delta y + \cdots \\ &\cong r_{(i,j)}^{(x_0,y_0)} + (\partial r_{(i,j)}^{(x_0,y_0)} / \partial x_0)\Delta x + (\partial r_{(i,j)}^{(x_0,y_0)} / \partial y_0)\Delta y \end{aligned} \tag{3}$$

where (x_i, y_i) and (x_j, y_j) are the positions of eNB, Δx and Δy are the expected variation from (x, y) to (x_0, y_0). Then, two approximated equations can be expressed as a matrix equation such as (4), and it can estimate the next estimated position of UE (x_1, y_1) by performing transpose matrix operation $(\cdot)^{\mathbf{T}}$ and inverse matrix operation $(\cdot)^{-1}$ as follows.

$$\mathbf{H\delta} = \mathbf{Z}$$

$$\begin{bmatrix} \partial r_{(n1,s)}^{(x_0,y_0)} / \partial x_0 & \partial r_{(n1,s)}^{(x_0,y_0)} / \partial y_0 \\ \partial r_{(n2,s)}^{(x_0,y_0)} / \partial x_0 & \partial r_{(n2,s)}^{(x_0,y_0)} / \partial y_0 \end{bmatrix} \begin{bmatrix} \Delta x \\ \Delta y \end{bmatrix} = \begin{bmatrix} r_{(n1,s)}^{(x_0,y_0)} \\ r_{(n2,s)}^{(x_0,y_0)} \end{bmatrix} \tag{4}$$

$$\mathbf{\delta} = [\mathbf{H}^{\mathbf{T}}\mathbf{Q}^{-1}\mathbf{H}]^{-1}\mathbf{H}^{\mathbf{T}}\mathbf{Q}^{-1}\mathbf{Z} \tag{5}$$

$$\begin{bmatrix} x_1 \\ y_1 \end{bmatrix} = \begin{bmatrix} x_0 \\ y_0 \end{bmatrix} + \begin{bmatrix} \Delta x \\ \Delta y \end{bmatrix} \tag{6}$$

where **Q** is the covariance matrix of estimation error. The position estimation can be continually refined by iterating the above procedure until Δx and Δy got close to zero.

2) Fang's Algorithm

This algorithm is a kind of analytic solution introduced by Fang [9]. It simplifies (2) by parallel and rotary translation of eNBs' position in (x, y) coordinate plane as follows.

$$\begin{aligned} r_{(n1,s)} &= \sqrt{(x-x_{n1})^2+y^2}-\sqrt{x^2+y^2} \\ r_{(n2,s)} &= \sqrt{(x-x_{n2})^2+(y-y_{n2})^2}-\sqrt{x^2+y^2} \end{aligned} \tag{7}$$

Then, the two hyperbola equations are transformed into a linear equation (8), and a quadratic equation of x can be obtained from (7) and (8).

$$y = gx+h, \text{ where } \begin{cases} g = \{x_{n1}(r_{(n2,s)}/r_{(n1,s)})-x_{n2}\}/y_{n2} \\ h = \{K_2-r^2_{(n2,s)}+r_{(n2,s)}\cdot r_{(n1,s)}(1-(x_{n1}/r_{(n1,s)})^2)\}/2y_{n2} \end{cases} \tag{8}$$

$$dx^2+ex+f = 0, \text{ where } \begin{cases} d = -\{1-(x_{n1}/r_{(n1,s)})^2+g^2\} \\ e = x_{n1}\{1-(x_{n1}/r_{(n1,s)})^2\}-2gh \\ f = (r^2_{(n1,s)}/4)\{1-(x_{n1}/r_{(n1,s)})^2\}^2-h^2 \end{cases} \tag{9}$$

and $K_2 = x_{n2}^2+y_{n2}^2$. Finally, we can estimate UE's position by solving (9) and insert the result of (9) into (8). In this paper, we assume that the solution x is selected as the nearest one to the actual position of UE between two solutions.

B. TDOA based 3D Positioning

1) 3D-TS based Algorithm

This algorithm is an extended version of 2D-TS based algorithm. In this algorithm, three hyperbola equations should be formulated by using z-axis information of UE, 3D positions of four eNBs, and three RSTDs including $r_{(n3,s)}$. For that reason, the size of matrix **H** in (4) is changed into 3×3 [10].

Unfortunately, this algorithm has some practical problems to be utilized in LTE. First, TS based algorithm requires a proper initial position of UE for TS expansion. If the initial position is set to a wrong value far from the actual position of UE, the estimated position will be diverged. For practical application, the average value of eNBs' position can be used as the initial position [16]; however, it cannot guarantee an enough positioning performance in practical environment.

Besides, the 3D-TS based algorithm needs at least four eNBs; however, most of cell deployments in LTE system assume that UE can receive at most three downlink signals which guarantee the minimum signal-to-interference and noise power ratio (SINR) of PRS; for example, by using orthogonal PRS pattern and muting scheme. Also, additional complexity for PRS detection and RSTD feedback overhead are required to UE. For that reason, four eNBs based algorithm is not suitable for LTE environment.

2) Analytic Algorithm

Fang's algorithm can also consider the height of eNBs and UE z; however, it is available only in unusual case where the height of eNBs and UE are the same [9].

$$dx^2+ex+f = z^2 \tag{10}$$

Meanwhile, CH algorithm is introduced as another analytic solution to solve the non-linear equations for 3D positioning in satellite communication system. It also changes the non-linear equations into a linear equation using three RSTDs [11]. Although it does not require iterative procedure, CH algorithm is also based on four eNBs. Besides, LTE did not adopt the algorithm. For that reason, it can also provide a considerable calculation overhead to UE, eNB, and E-SMLC from the implementation point of view.

3) Two-Step based Algorithm

There are two algorithms which can estimate horizontal and vertical position of UE with different approach. The first algorithm estimates horizontal position of UE by 2D TDOA. The vertical position is detected by applying the horizontal position to a sphere equation and solving the equation. It is a geometric approach; however, it is available only in unusual deployment where the height of all eNBs is the same [12].

Another algorithm also obtains horizontal position of UE from 2D TDOA, while vertical position of UE is estimated by CID based method. It guesses UE's z-axis position on the basis of the nearest eNB's z-axis [13]. This algorithm has very simple implementation; however, it can be utilized where the height of eNBs is similar with that of UE.

IV. THE PROPOSED METHOD

A. 2D TDOA based 3D Positioning

The main characteristic of the proposed method is that it also estimates vertical position of UE using 2D TDOA. First, as y-axis variables of (2) are replaced to z-axis variables, (x, z) coordinate plane based 2D TDOA can be performed as follows.

$$\begin{aligned} r_{(n1,s)} &= \sqrt{(x-x_{n1})^2+(z-z_{n1})^2}-\sqrt{(x-x_s)^2+(z-z_s)^2} \\ r_{(n2,s)} &= \sqrt{(x-x_{n2})^2+(z-z_{n2})^2}-\sqrt{(x-x_s)^2+(z-z_s)^2} \end{aligned} \tag{11}$$

Then, the proposed method can obtain vertical position of UE. Also, 2D TDOA on the (y, z) coordinate plane is possible in the same way. Therefore, the proposed method can perform 3D positioning by using three 2D TDOAs on (x, y), (x, z), and (y, z) coordinate planes.

The first advantage of the proposed method is that it is possible to perform 3D positioning even when UE only can receive three PRSs, while the 3D-TS based algorithm and CH algorithm needs at least four PRSs. As described in Sect. III.B. 1), it is a valuable advantage in the implementation point of view. Also, it does not have to use TS based algorithm which has the initial value problem and high complexity due to the iterative process. Instead, the proposed method utilizes Fang's

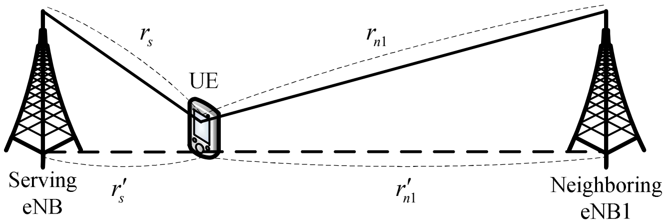

Fig. 3. An example of the hyperbola equation error.

algorithm which has simpler calculation than TS algorithm.

On the other hand, for more accurate positioning, the proposed method should eliminate its structural weakness as follows. In 2D TDOA, the hyperbola equations may have some errors due to the heights of eNB and UE. The reason is that the left hand side of (2), $r_{(n1,s)}$ and $r_{(n2,s)}$, is 3D value, while the right hand side of (2) is the 2D equations. In other words, the hyperbola equations do not utilize the height of eNB and UE. Figure 3 shows an example of the hyperbola equation error in 2D TDOA. In order to estimate the exact position of UE, 2D RSTD should be obtained from $(r'_{n1} - r'_s)$; however, the actual RSTD is 3D value like $(r_{n1} - r_s)$. Therefore, (2) may include RSTD error as much as $\left|(r_{n1} - r_s) - (r'_{n1} - r'_s)\right|$.

The effect of the hyperbola equation error is already verified in cellular network. As described in [8], the performance is degraded, as the height of eNBs increases. Therefore, a non-target axis, such as *z*-axis in (*x*, *y*) 2D TDOA, can lead to the performance loss. Especially in the proposed method, the same problem also occurs in both (*x*, *z*) and (*y*, *z*) 2D TDOA, and it can cause a considerable performance degradation to the proposed method.

A solution for accurate hyperbola equation is to modify the hyperbola equations by considering the non-target axis. For example, 3D-TS based algorithm is possible to enter *z*-axis value into *z* variables of TS expanded equation; however, it still has the initial value problem. Meanwhile, Fang's algorithm can consider *z*-axis information in (*x*, *y*) TDOA; however, it is available only when all eNBs and UE have the same height.

B. A New Equation Derivattion for the Proposed Method

Therefore, we propose a new equation derivation which can apply the non-target axis information to the 2D hyperbola equations regardless of the height of eNBs and UE. First, for example in (*x*, *y*) 2D TDOA, new hyperbola equations can be expressed as follows.

$$\begin{aligned} r_{(n1,s)} &= \sqrt{(x-x_{n1})^2 + y^2 + (\hat{z}-z_{n1})^2} - \sqrt{x^2+y^2+\hat{z}^2} \\ r_{(n2,s)} &= \sqrt{(x-x_{n2})^2 + (y-y_{n2})^2 + (\hat{z}-z_{n2})^2} - \sqrt{x^2+y^2+\hat{z}^2} \end{aligned} \tag{12}$$

where $\hat{z}$ is *z*-axis PPI of UE which is obtained from the previous positioning process or an arbitrary initial value. As described in (12), therefore, the aforementioned hyperbola equation error can be removed because the *z*-axis information of UE and two neighboring eNBs are considered as a constant value. Then, we solve the square of hyperbola simultaneous equations (12) as follows.

$$\begin{aligned} r^2_{(n1,s)} - K'_1 + 2x_{n1}x + 2y_{n1}y &= -2r_{(n1,s)}\sqrt{x^2+y^2+\hat{z}^2} \\ r^2_{(n2,s)} - K'_2 + 2x_{n2}x + 2y_{n2}y + 2z_{n2}\hat{z} &= -2r_{(n2,s)}\sqrt{x^2+y^2+\hat{z}^2} \end{aligned} \tag{13}$$

where $K'_1 = x^2_{n1} + y^2_{n1}$ and $K'_2 = x^2_{n2} + y^2_{n2} + z^2_{n2}$. Next, we divide the first equation of (13) by the second equation of (13) as follows.

$$\frac{r^2_{(n1,s)} - K'_1 + 2x_{n1}x + 2y_{n1}y}{r^2_{(n2,s)} - K'_2 + 2x_{n2}x + 2y_{n2}y + 2z_{n2}\hat{z}} = \frac{2r_{(n1,s)}\sqrt{x^2+y^2+\hat{z}^2}}{2r_{(n2,s)}\sqrt{x^2+y^2+\hat{z}^2}} \tag{14}$$

After eliminating the equal term $\sqrt{x^2+y^2+\hat{z}^2}$ of (14), we can generate a new linear equation with a new coefficient h' .

$$y = gx + h', \text{ where}$$
$$\begin{cases} g = \{x_{n1}(r_{(n2,s)}/r_{(n1,s)}) - x_{n2}\}/y_{n2} \\ h' = \left.\begin{Bmatrix} K'_2 - r^2_{(n2,s)} + r_{(n2,s)} \cdot r_{(n1,s)}(1-(\sqrt{K'_1}/r_{(n1,s)})^2) \\ +2\hat{z}(z_{n1}(r_{(n2,s)}/r_{(n1,s)}) - z_{n2}) \end{Bmatrix}\right/ 2y_{n2} \end{cases} \tag{15}$$

where *g* is the same coefficient as Fang's algorithm. Then, as *y* of (12) is substituted for *y* of (15), the proposed method can obtain a quadratic equation of *x* which includes *z*-axis information of UE, $\hat{z}$, and two neighboring eNBs, z_{n1} and z_{n2}, with new coefficients e' , f' , *i*, and *j*.

$$dx^2 + e'x + f' + i\hat{z}^2 + j\hat{z} = 0, \text{ where}$$
$$\begin{cases} d = -\{1-(x_{n1}/r_{(n1,s)})^2 + g^2\} \\ e' = x_{n1}\{1-(\sqrt{K'_1}/r_{(n1,s)})^2 + 2\hat{z}(z_{n1}/r_{(n1,s)})\} - 2gh' \\ f' = (r^2_{(n1,s)}/4)\{1-(\sqrt{K'_1}/r_{(n1,s)})^2\}^2 - h'^2 \\ i = -\{1-(z_{n1}/r_{(n1,s)})^2\} \\ j = z_{n1}\{1-(\sqrt{K'_1}/r_{(n1,s)})^2\} \end{cases} \tag{16}$$

Through (15) and (16), we verify that the proposed method can utilize the non-target axis information such as $\hat{z}$, z_{n1}, and z_{n2} to (*x*, *y*) TDOA, while the conventional method cannot utilize every different height of eNBs and UE. Finally, by using quadratic formula, the proposed method can obtain (*x*, *y*) position of UEs, which can show higher positioning accuracy than the conventional method. 2D TDOA on other coordinate planes is also possible in a similar way from (12) to (16).

C. PPI based Iterative TDOA Algorithm

Based on the proposed equation derivation, we also propose PPI based iterative TDOA algorithm. The main idea of the proposed algorithm is that estimation results from 2D TDOA on a certain coordinate plane can assist 2D TDOA on other coordinate plane as PPI.

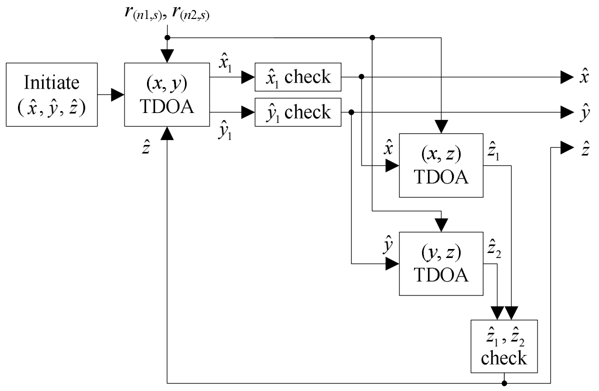

Fig. 4. A block diagram of the PPI based TDOA algorithm.

Figure 4 shows a block diagram of the proposed algorithm. The proposed algorithm is mainly composed of three 2D TDOA blocks. First, the proposed algorithm initiates $\hat{x}$, $\hat{y}$, and $\hat{z}$. If there is no PPI at initial stage, each value is configured as 0. On the other hand, if a reliable PPI exists, the proposed algorithm utilizes it as the initial value. Next, (x, y) TDOA is performed by using two RSTD values. After the (x, y) TDOA block obtains $\hat{x}$ and $\hat{y}$, each of them will be a PPI to (x, z) and (y, z) TDOA block and two TDOA blocks will provide two z-axis information such as $\hat{z}_1$ and $\hat{z}_2$.

In this stage, single z-axis value should be selected. Therefore, the proposed algorithm includes a distance based selection. For TDOA based positioning, UE should perform random access procedure for uplink synchronization and RSTD transmission to serving eNB. From this procedure, E-SMLC can obtain distance r_s between serving eNB and UE. Then, the proposed algorithm can compare r_s with $\hat{r}_{zi}$ which can be estimated from the sphere equation and the estimated position of UE ($\hat{x}$, $\hat{y}$, $\hat{z}_i$) as follows.

$$\hat{r}_{zi} = \sqrt{(\hat{x}-x_s)^2 + (\hat{y}-y_s)^2 + (\hat{z}_i - z_s)^2}, \text{ where } i = 1,\ 2 \quad (17)$$

Also, the proposed method should check the accuracy of $\hat{r}_{zi}$ because $\hat{z}$ with large estimation error can cause a considerable positioning error to the (x, y) TDOA. Therefore, the final value of $\hat{z}$ will be determined by the distance comparison and the accuracy checking conditions.

$$\hat{z} = \begin{cases} \hat{z}_1, & \text{if } |\hat{r}_{z1} - r_s| \le |\hat{r}_{z2} - r_s| \text{ and } |\hat{r}_{z1} - r_s| < \gamma \\ \hat{z}_2, & \text{else if } |\hat{r}_{z1} - r_s| > |\hat{r}_{z2} - r_s| \text{ and } |\hat{r}_{z2} - r_s| < \gamma \\ 0, & \text{elsewhere} \end{cases} \quad (18)$$

where γ is the accuracy threshold. If both $\hat{z}_1$ and $\hat{z}_2$ do not satisfy the conditions, the final value of $\hat{z}$ PPI is initiated as 0. For the same reason, the checking process can be applied after (x, y) TDOA block as follows.

$$\begin{aligned} \hat{r}_x &= \sqrt{(\hat{x}_1 - x_s)^2 + (\hat{y}-y_s)^2 + (\hat{z}-z_s)^2} \\ \hat{r}_y &= \sqrt{(\hat{x}-x_s)^2 + (\hat{y}_1 - y_s)^2 + (\hat{z}-z_s)^2} \end{aligned} \quad (19)$$

TABLE I. SIMULATION PARAMETERS

Parameter	Value
# of APs	4 per a floor
# of floors	4
Height of floor	3 m
AP deployment	Fixed position according to the cell layout[14]
UE distribution	Random distribution
Carrier frequency	2 GHz
Transmission power of AP	24 dBm
Pathloss & shadowing model	ITU InH model[21]
Multipath channel model	Single path
Antenna height of UE	$3(n_{fl}-1)+1.5$m, where $n_{fl} \in \{1,2,3,4\}$
Antenna height of AP	$3(n_{fl}-1)+12.5$m, where $n_{fl} \in \{1,2,3,4\}$
Network synchronization	Synchronous state
Initial value of TS algorithm	Average position of APs[16]
# of iteration for TS algorithm	10
# of iteration for the proposed algorithm	3, 5
Accuracy threshold (γ)	5 m, 10 m
PRS detection	Ideal performance
Sampling error by bandwidth	None (Ideal)

$$\hat{x} = \begin{cases} \hat{x}_1, & \text{if } |\hat{r}_x - r_s| < \gamma \\ 0, & \text{elsewhere} \end{cases}, \quad \hat{y} = \begin{cases} \hat{y}_1, & \text{if } |\hat{r}_y - r_s| < \gamma \\ 0, & \text{elsewhere} \end{cases} \quad (20)$$

In conclusion, the proposed method can be expected to improve the performance of both horizontal and vertical positioning with the revised 2D hyperbola equations.

V. SIMULATION AND ANALYSIS

In this section, we present various simulation results which compare the proposed method and the conventional methods in terms of both horizontal and vertical estimation error. In the simulation, we assume that a UE is randomly dropped in a four-story building which is based on 3GPP indoor cell layout [14]. As described in [14], each AP is located at the positions of 4 black dots, and UE selects APs based on signal-to-noise power ratio (SNR) of PRS. The main simulation parameters are based on LTE specifications and other major simulation parameters are listed in Table 1.

In TDOA based positioning, some estimation error can occur because RSTD is quantized due to the signal sampling at the receiver. For that reason, some solutions have been studied to solve the sampling error problem. In this paper, we assume no RSTD sampling error to clearly verify the performance gain caused by the proposed method.

Figure 5 shows cumulative distribution function (CDF) performance comparisons of horizontal estimation error. The horizontal estimation error means a root means square error (RMSE) in (x, y) coordinate plane. As shown in Fig. 5, the 3D-TS based algorithm, which utilizes four eNBs, shows inappropriate performance due to the initial value problem. On the other hand, all the performance of the proposed method, which is based on only three eNBs, shows high performance gain compared to the conventional 2D Fang's algorithm. First, the upper performance of the proposed method, which can utilize ideal PPI, guarantees almost perfect positioning performance. It means that the degradation effect of eNB's

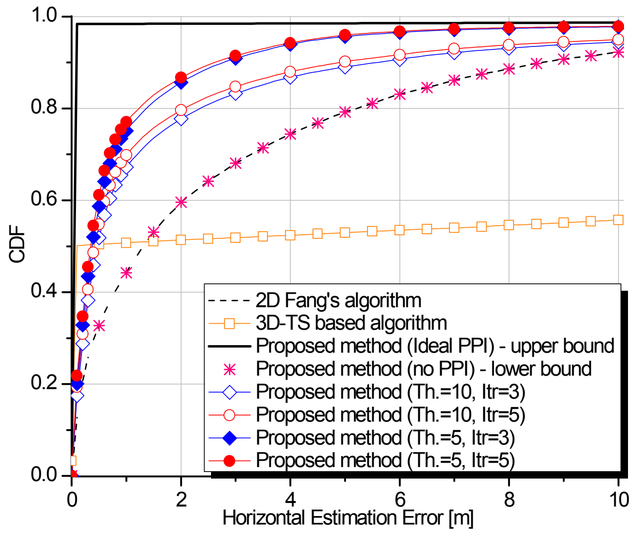

Fig. 5. CDF performance of horizontal estimation error.

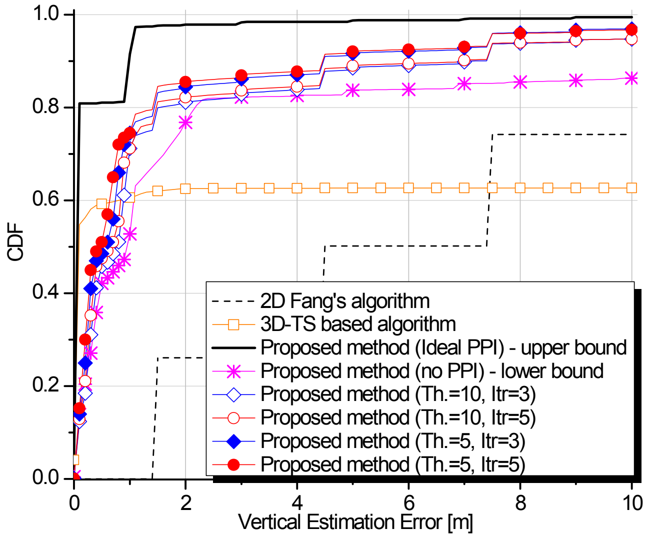

Fig. 6. CDF performance of verrical estimation error.

height can be efficiently removed by the proposed method. Also, the proposed method satisfies the positioning performance at least as much as the 2D Fang's algorithm. Meanwhile, between the upper bound and lower bound performance of the proposed method, the performance is improved, as the number of iterations of the proposed method increases. Also, we verify that smaller accuracy threshold can provide more improved positioning performance. In case of using 5 iterations and γ=5 m, the proposed method can show less than 0.59 m horizontal estimation error with 67%, and 4.35 m horizontal estimation error with 95% probability.

Figure 6 represents CDF performance comparisons of vertical estimation error. It indicates RMSE in terms of z-axis. As shown in Fig. 6, the performance of the 3D-TS based algorithm is also diverged, and the 2D Fang's algorithm shows an odd graph like step curve. The reason is that the height of UE on each floor is based on the height of floor, and the 2D Fang's algorithm cannot estimate vertical position of UE. On the other hand, the vertical estimation of the proposed method shows similar performance with the horizontal estimation. As shown in Fig. 6, the proposed method can estimate the vertical position of UE with outstanding accuracy. When using 5 iterations and γ=5 m, the proposed method can show less than 0.73 m vertical estimation error with 67%, and 7.48 m vertical estimation error with 95% probability.

VI. CONCLUSION

This paper proposed a practical 3D positioning method which can support the practical implementation in 3GPP LTE system. The proposed method estimates both horizontal and vertical position of UE based on 2D TDOA. Also, in order to solve the non-target axis problem of 2D TDOA, we proposed a new equation derivation and PPI based iterative TDOA algorithm. Extensive simulation results verified that the proposed method can provide the considerable performance gain in terms of both horizontal and vertical positioning.

REFERENCES

[1] J. Borkowski, J. Niemelä, and J. Lempiäinen, "Location Techniques for UMTS Radio Networks," Mobile Venue Conference, May 2004.

[2] M. Thorpe, M. Kottkamp, A. Rössler, and J. Schütz, LTE Location Based Services, Rohde & Schwarz, Apr. 2013.

[3] M. Sugano, T. Kawazoe, Y. Ohta, and M. Murata, "Indoor Localization System using RSSI Measurement of Wireless Sensor Network Based on ZigBee Standard," IASTED Int. Conf. WSN, July 2006, pp. 1-6.

[4] B. Denby, Y. Oussar, and I. Ahriz, "Geolocalisation in Cellular Telephone Networks," NATO Science for Peace and Security Series – D: Information and Communication Security, IOS Press, vol. 19, June 2008, pp. 357-365.

[5] 3GPP TS 36.305 v12.2.0, "Evolved Universal Terrestrial Radio Access Network (E-UTRAN); Stage 2 Functional Specification of User Equipment (UE) Positioning in E-UTRAN (Release 12)," www.3gpp.org, Dec. 2014.

[6] S. Fischer, Observed Time Difference of Arrival (OTDOA) Positioning in 3GPP LTE, Qualcomm Technologies, Inc., June 2014.

[7] R1-151454, Final Report of 3GPP TSG RAN WG1 #80 v1.0.0, MCC Support, Feb. 2015.

[8] W. H. Foy, "Position-Location Solutions by Taylor-Series Estimation," IEEE Trans. Aerosp. Electron. Syst., vol. 12, no. 2, pp. 187-194, Mar. 1976.

[9] B. T. Fang, "Simple Solutions for Hyperbolic and Related Position Fixes," IEEE Trans. Aerosp. Electron. Syst., vol. 26, no. 5, pp. 748-753, Sept. 1990.

[10] G. Shen, R. Zetik, and R. S. Thoma, "Performance Comparison of TOA and TDOA Based Location Estimation Algorithms in LOS Environment," WPNC, Mar. 2008, pp. 71-78.

[11] K. C. Ho and Y. T. Chan, "Solution and Performance Analysis of Geolocation by TDOA," IEEE Trans. Aerosp. Electron. Syst., vol. 29, no. 4, pp. 1311-1322, Oct. 1993.

[12] H. W. Kang, D.-H. Hwang, and C. Park, "TDOA Measurement Based Taylor Series Design Method Considering Height Error for Real-Time Locating Systems," J. Inst. Cont., Robot. & Syst., vol. 16, no. 8, pp. 804-809, Aug. 2010.

[13] R1-144597, Discussion on the Simulation Methodology for Baseline Indoor Positioning Technologies, Huawei, HiSilicon, 3GPP TSG RAN WG1 Meeting #79, Nov. 2014.

[14] R1-145396, WF on Evaluation Scenarios and Assumptions for Indoor Positioning, LG Electronics et al., 3GPP TSG RAN WG1 Meeting #79, Nov. 2014.

[15] 3GPP TR 36.814 v9.0.0, "Further Advancements for E-UTRA Physical Layer Aspects," Mar. 2010.