A Novel Location Finding System for 3GPP LTE

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Abstract—We propose a novel location finding system exploiting the downlink reference signal of the Long Term Evolution (LTE) because of the absence of an efficient location finding system for the LTE. The proposed system is based on the correlation method and Chan’s method for location sensing and positioning process, respectively. The conventional correlation method, however, is not matched to the LTE since the orthogonal gold sequence used for reference signal is assigned in frequency domain. Therefore, we estimate Time Difference Of Arrival (TDOA) data by cross-correlating the transmitted signal and received signal in the frequency domain. Simulation results show that the proposed system meets the Federal Communication Commission (FCC) requirement for typical Signal-to-Noise Ratio (SNR) region, and the performance can be further improved as more antennas are implemented in transmitter or receiver.

I. INTRODUCTION

Researches to find mobile’s location emerged since the Federal Communication Commission’s (FCC) required all wireless services providers to provide location information for Enhanced-911 (E-911) in 1996 [1]. Moreover, location-based services and applications such as location-sensitive billing, fraud detection, fleet management, and intelligent transportation systems have boosted research on location finding techniques [2]–[5]. The significant part of efforts for location finding have been focused on Code Division Multiple Access (CDMA)-based location [6], [7]. The spread spectrum employed in CDMA makes it more attractive since the accuracy of time based location finding techniques such as Time Of Arrival (TOA) and Time Difference Of Arrival (TDOA) can be improved because of a good correlation property of the Pseudo Noise (PN) of the spread spectrum.

Recently, a demand on packet data traffic has been tremendously increased, and results in exceeding voice data by the packet data traffic in the third Generation (3G) wireless communication systems [8]. As a result, the network providers have been pressured to increase the network capacity, and this motivates to evolve existing wireless communication standards towards fourth Generation (4G) for long term future. As a result, the Long Term Evolution (LTE) [10], [11] is standardized recently, within the Third Generation Partnership Project (3GPP). The LTE system (hereafter, called ‘LTE’) offers higher throughput, lower latency, and flexibility than formerly established standards.

Unfortunately, a research about a location finding system for the LTE is not progressed in the literatures, yet. The purpose of this paper is, therefore, to propose a location finding system for LTE and analyze the performance of the proposed system.

A location finding system can be implemented either in reverse mode or in direct mode [13]. In direct mode, a mobile determines the location by itself from the transmitted signal of at least three Base Stations (BSs). In contrast, a reverse mode location finding system calculates a mobile’s location by interaction of BSs from the signal transmitted by the mobile. In spite of advantages of the reverse mode, unnecessariness of additional devices and participation to mobile, it has a significant drawback that a signal from mobile may not be ‘hearable’ at one or more BSs due to a power allocation [13]. Considering those drawbacks, we propose a location finding system using direct mode for LTE.

In our proposed system, a mobile calculate the location by two procedures: a location sensing step and a positioning step. In location sensing step, several methods have been proposed to estimate different metrics such as TOA, TDOA, and Angle Of Arrival (AOA) [12]. The direct mode TOA estimation needs accurate synchronization between mobile and BSs, and the direct mode AOA estimation requires an antenna array in mobile, but the TDOA can be estimated without additional requirements. Accordingly, our location finding system adopts the TDOA in location sensing step.

To calculate a mobile’s position using TDOA, iterative and non-iterative positioning methods have been developed [14]–[20]. Since iterative methods are computationally complex, we apply a Chan’s method [20], which is a optimum non-iterative method, to our proposed system.

This paper will be organized as following. In section II, the general system model for location finding will be given, and section III describes detail procedures of our proposed system. Then, section IV shows simulation results and analysis, and lastly, conclusions will be given in section V.

Notation: A bold face letter denotes a vector or a matrix.

II. SYSTEM MODEL

A location finding system using TDOA should measures at least two TDOA data, which can be obtained from three different BSs. To make BSs distinguishable, different gold sequences are assigned for cell-specific reference signals of each BSs. The proposed location finding system, thus, utilizes the cell-specific reference signal to estimate TDOA.

The cell-specific reference signals are transmitted in all downlink subframes on one or several antennas, maximum
four, and are defined as [11],

\[ X_{l}^{p,b}(k) = s_{l,n_{s}}(m') \]

where \( X \) is the cell-specific reference signal, \( s \) is the reference-signal sequence defined as the QPSK modulated length-31 gold sequence, \( p \) is the antenna port index, \( b \) is the BS index, \( k \) is the subcarrier index, \( m \) and \( m' \) denotes the index of the gold sequence, and \( l \) is the Orthogonal Frequency Division Multiplexing (OFDM) symbol number within the slot \( n_{s} \). The parameters, \( k \), \( l \), \( m \), and \( m' \), are defined like following,

\[
\begin{align*}
\k & = 6m + (v + v_{\text{shift}}) \mod 6 \\
\l & = \begin{cases} 
0, & N_{\text{symb}}^{\text{DL}} - 3 \text{ if } p \in \{0, 1\} \\
1 & \text{if } p \in \{2, 3\} 
\end{cases} \\
\m & = 0, 1, ..., 2 \cdot N_{\text{RB}}^{\text{DL}} - 1 \\
\m' & = m + N_{\text{RB}}^{\text{max,DL}} - N_{\text{RB}}^{\text{DL}}
\end{align*}
\]

where \( v \) and \( v_{\text{shift}} \) is the frequency shift reference signal for each antenna ports and BSs, \( N_{\text{symb}}^{\text{DL}} \) is the number of OFDM symbols within a resource block, \( N_{\text{RB}}^{\text{DL}} \) is the number of resource blocks in a slot, and \( N_{\text{RB}}^{\text{max,DL}} \) is maximum of \( N_{\text{RB}}^{\text{DL}} \). The variables \( v \) and \( v_{\text{shift}} \) are

\[
v = \begin{cases} 
0 & \text{if } p = 0 \text{ and } l = 0 \\
3 & \text{if } p = 0 \text{ and } l \neq 0 \\
3 & \text{if } p = 1 \text{ and } l = 0 \\
0 & \text{if } p = 1 \text{ and } l \neq 0 \\
3(n_{s} \mod 2) & \text{if } p = 2 \\
3 + 3(n_{s} \mod 2) & \text{if } p = 3 
\end{cases}
\]

\[
v_{\text{shift}} = N_{\text{ID}}^{\text{cell}} \mod 6.
\]

The reference signal generated in the frequency domain can be converted in the time domain by inverse Discrete Fourier Transform (IDFT).

\[
x_{l}^{p,b}(n) = \text{IDFT} \left[ X_{l}^{p,b}(k) \right] = \frac{1}{N} \sum_{k=0}^{N-1} X_{l}^{p,b}(k) e^{j\frac{2\pi}{N}kn}
\]

After this signal passes through the multipath channel, the received signal from BS\( b \), to mobile’s receive antenna \( q \) is represented as vector form like following,

\[
r_{l}^{q,b}(n) = \sum_{p=1}^{N_{t}} h_{pq}^{b} * x_{l}^{p,b}(n)
\]

Here, \( h_{pq}^{b} \) is the channel impulse response from transmit antenna \( p \) of BS\( b \) to mobile’s receive antenna \( q \), \( N_{t} \) is the number of transmit antennas, and * means the convolution operation.

Generally, all signals from different BSs arrives at receiver without distinction so the received signal considering all BSs becomes

\[
r_{l}^{q} (n) = \sum_{b=1}^{N_{b}} r_{l}^{q,b} (n - \tau_{b}) + w(n) \quad (1)
\]

where \( r_{l}^{q} (n) \) is time domain received signal of \( n \)-th sample, \( N_{b} \) is the number of BSs, \( \tau_{b} \) is propagation delay of signal transmitted from BS\( b \), and \( w(n) \) is the Additive White Gaussian Noise (AWGN).

In proposed system, the TDOA is estimated in location sensing step using this received signal of LTE, and location of the mobile is calculated in positioning step. The proposed system model is described in Fig. 1, and in section III, detail procedures will be explained.

III. PROPOSED LOCATION FINDING SYSTEM

A. Location Sensing: TDOA estimation

In the location sensing step, the TDOA data are found by using signals from different BSs. Without loss of generality, we may let the nearest BS from the mobile to the BS\( 1 \), and then, the TDOA can be calculated from,

\[
\tau_{i,1} = \tau_{i} - \tau_{1} \quad (2)
\]

where \( \tau_{i,1} \) denotes the TDOA between BS\( i \) and BS\( 1 \), and \( \tau_{i} \) is the arrival time of signal from BS\( i \). Here, the conventional method to estimate \( \tau_{i} \) is correlation method. However, in the proposed system, the conventional correlation method cannot accurately find \( \tau_{i} \) since the transmitted PN sequences conveyed on the frequency domain are not orthogonal in the time domain. Instead of calculating the correlation in time domain, therefore, we estimate the TDOA by manipulating the received signal in the frequency domain.

For the simplicity, assume that the two by two Multiple-Input and Multiple-Output (MIMO) system, which is the minimum antenna configuration in LTE downlink, is used, and three BSs transmit the reference signals simultaneously. In addition, the BS is assumed to transmit reference signal at only the first OFDM symbol of the first slot. Then, the received signal described in eq. (1) is simplified as,

\[
r_{l}^{q} (n) = \sum_{b=1}^{3} r_{l}^{q,b} (n - \tau_{b}) + w(n)
\]

Fig. 1. Proposed location finding system
is cross-correlated with received signal as time shifts.

\[ C^b_x(t) = \sum_{n=-\infty}^{\infty} \tilde{r}^b(n-t)x^b(n) \]

\[ = \sum_{n=0}^{N-1} r^{a,b}(n-t)x^b(n) \]

where \( x^b \) is the transmitted signal from BS\(_i\) considering all transmit antenna ports, and \( C^b_x(t) \) is the cross-correlated output with \( x^b \). The TDOA is not accurately estimated by using this method directly since the orthogonality among \( x^b \) for BSs is broken. Accordingly, we multiply the delayed received signal and the given gold sequence in frequency domain as the delay shifts. That is,

\[ C^b_x(t) = \sum_{k=0}^{N} \tilde{R}^a_m(k)X^b(k) \]

where,

\[ \tilde{R}^b_m(k) = \sum_{n=1}^{N} \tilde{r}^b(n+\xi) e^{-j\frac{2\pi}{2\tau_1}kn} \]

\[ = \sum_{n=1}^{N} \left\{ \sum_{k=1}^{N} r^{a,b}(n+\xi - \tau_0) + w(n+\xi) \right\} e^{-j\frac{2\pi}{2\tau_1}kn} \]

\( \xi \) is the time shift index, and \( X^b(k) \) is the frequency domain representation of the transmitted signal \( x^b(n) \).

The orthogonality among reference signals preserver in frequency domain so the cross-correlated output has a peak value when \( m \) is equal to \( \tau_0 \). Hence, the propagation delay \( \tau_0 \) is estimated as tracking the peak of \( C^b_x(t) \), and the TDOA is calculated by eq. (2).

B. Positioning: Chan’s Method

After the TDOA data are estimated, they are converted to range differences between BSs by multiplying the velocity of the light. These range differences define hyperbolic equations with foci at BSs, on which the MS must be located. Since hyperbolic equations are non-linear, solving equations is not straightforward. Two approaches, an iterative positioning algorithm and a non-iterative positioning algorithm, have been proposed to solve equations.

As linearizing equations lets the problem solvable, an iterative positioning algorithm [14], [15] exploits the Taylor series expansion to linearize equations iteratively, and then, calculate the position of mobile. The iterative positioning algorithm, however, has disadvantages, which are high computational complexity and convergence problem. Since the proposed system utilizes the direct mode location finding system, a mobile takes the computational burden. Hence, the proposed system adopts a non-iterative positioning algorithm considering long processing delay.

Several non-iterative methods are studied in the literatures [16]–[20]. Fang [16] proposed a method that gives an exact form solution only when the number of hyperbolic equations are equivalent to unknown coordinates. Thus, this method cannot use additional information though additional TDOA data are measured. The Spherical Interpolation (SI) [17]–[19] gives a closed-form solution for more general situation considering additional measurements, but the solution is suboptimal in the performance aspect. Chan’s method [20] provides the optimum estimate of mobile’s position, so the proposed location finding system applies Chan’s method as considering both complexity and performance.

The Chan’s method exploits the Least Square (LS) twice to obtain the position. Before applying the LS, the Chan’s method establishes an equation using the range difference and the range between BS and mobile.

The range difference between BSs with respect to BS\(_1\) is

\[ RD_{i,1} = c(\tau_i - \tau_1) = D_i - D_1 \]

\[ = \sqrt{(X_i - x)^2 + (Y_i - y)^2} - \sqrt{(X_1 - x)^2 + (Y_1 - y)^2} \]

where \( RD_{i,1} \) is the range difference between BS\(_i\) and BS\(_1\), \( c \) is the velocity of light, \( \tau_i \) is the propagation delay of the signal transmitted from BS\(_i\), \( D_i \) is the range between BS\(_1\) and mobile, \( X_i \) and \( Y_i \) are position of BS\(_i\), and \( x \) and \( y \) are the position of mobile. By rearranging eq. (3),

\[ D_i^2 = (RD_{i,1} + D_1)^2 \]

Since the range between BS\(_i\) and mobile is expressed as

\[ D_i = \sqrt{(X_i - x)^2 + (Y_i - y)^2} \]

\[ = \sqrt{X_i^2 + Y_i^2 - 2X_i x - 2Y_i y + x^2 + y^2} \]

the eq. (4) can be rewritten as substituting eq. (5) to eq. (4),

\[ RD_{i,1}^2 + 2RD_{i,1}D_1 = X_i^2 + Y_i^2 - 2X_i x - 2Y_i y - X_1^2 - Y_1^2 \]

where \( X_{i,1} \) and \( Y_{i,1} \) are equivalent to \( X_i - X_1 \) and \( Y_i - Y_1 \), respectively.

The vector representation of eq. (6) is

\[ \begin{bmatrix} RD_{2,1}^2 \\ RD_{3,1}^2 \end{bmatrix} + 2 \begin{bmatrix} RD_{2,1} \\ RD_{3,1} \end{bmatrix} D_1 = \begin{bmatrix} K_2 - K_1 \\ K_3 - K_1 \end{bmatrix} - 2 \begin{bmatrix} X_{2,1} & Y_{2,1} \\ X_{3,1} & Y_{3,1} \end{bmatrix} \begin{bmatrix} x \\ y \end{bmatrix} \]

where \( K_i = X_i^2 + Y_i^2 \). The least square solution for \( (x, y) \) for given \( D_1 \) is,

\[ \begin{bmatrix} x \\ y \end{bmatrix} = - \begin{bmatrix} X_{2,1} & Y_{2,1} \\ X_{3,1} & Y_{3,1} \end{bmatrix}^{-1} \begin{bmatrix} RD_{2,1} \\ RD_{3,1} \end{bmatrix} D_1 - 1/2 \begin{bmatrix} X_{2,1} & Y_{2,1} \\ X_{3,1} & Y_{3,1} \end{bmatrix}^{-1} \begin{bmatrix} RD_{2,1}^2 - K_2 + K_1 \\ RD_{3,1}^2 - K_3 + K_1 \end{bmatrix} \]

If the \( x \) and \( y \) for given \( D_1 \) is substituted to eq. (6), the quadratic equations for \( D_1 \) is obtained in the form of,

\[ aD_1^2 + bD_1 + c = 0 \]

Although maximum two solutions exist by solving eq. (8), the following root is considered in cellular network. [21].

\[ D_1 = -b + \sqrt{b^2 - 4ac} \]

After substituting \( D_1 \) to eq. (8), the exact position of mobile is obtained.
IV. SIMULATION RESULTS

In this section, we desire to illustrate the validity of the proposed location finding system in terms of the positioning error. To evaluate the positioning performance of the proposed system, we use Monte-Carlo simulations in various environments of LTE. We introduce a positioning error \( \sqrt{(x - \hat{x})^2 + (y - \hat{y})^2} \), and a range difference error \( c|\tau_{i,1} - \hat{\tau}_{i,1}| \), where \( c \) is the velocity of light and \( \hat{\tau}_{i,1} \) denotes the estimated TDOA.

A BS covers up to 5 km with full performance in the LTE so we set a hexagonal cell having 5km coverage as illustrated in Fig.2. Also, a BS in the LTE can support from 1.25MHz to 20MHz bandwidth, but we assume that only one mobile exists in the BSs’ coverage and uses 20MHz, for the simplicity. According to [11], if a mobile uses 20MHz bandwidth, it samples the received signal with rate of 30.72 MHz, and transmits 220 resource blocks within one OFDM symbol symbol, and the Fast Fourier Transform (FFT) size is 2048. Also, the gold sequences having 220 symbols are transmitted because one symbol is assigned for each resource block. Note that, the range error about 9.765m is occurred whenever the TDOA estimation is missed by one sample.

Firstly, we consider the performance of the proposed system with changing the antenna configuration. The location of mobile is set to the equally distant point from three BSs (location A in the Fig.2), and the International Telecommunication Union (ITU) vehicular-A channel model is used. The Equal Gain Combining (EGC) is exploited when two receive antennas are used. The mean and variance of positioning error with different the number of antennas are evaluated in Fig.3. Fig.3 shows that both mean and variance of positioning error are decreased as the number of transmit or receive antennas increases. Note that, implementing more receive antennas leads more performance improvement than implementing more transmit antennas.

Also, the mean and variance of range difference error and positioning error compared in TABLE I. From the result, the positioning error decreases as the range difference error decreases. Hence, the main reason which causes positioning error is a range difference error, or equivalently, the TDOA error.

Secondly, the positioning error with respect to changing of the mobile’s location is compared in Fig.4. Here, only two by one system is considered, and a mobile is located at location A, B, and C, as illustrated in Fig.2. The location A is at equally distance from three BSs, and the location B makes the mobile biased toward BS1 so the distance from BS1 to a mobile becomes two third to that of location A. In location C, the location of mobile is more biased so that the distance from BS1 to the mobile is one third to that of location A. Fig.4 shows that mean and variance is decreased as Signal-to-Noise Ratio (SNR) increases, and a error floor is occurred in high SNR environment. As the mobile approaches a BS1 more, the error floor has larger value.

The FCC requirement is to locate the 67 percent of E-911 callers to within 125m of their actual location [1]. Throughout the simulations, the proposed system sufficiently satisfy the requirement in typical SNR region.

V. CONCLUSIONS

In this paper, the location finding system for the LTE has been studied. The proposed system uses the direct mode...
TDOA estimation and Chan’s method for location sensing and positioning, respectively. By considering the downlink reference signal of LTE, the conventional correlation method is modified to manipulate the received signal in frequency domain to obtain TDOA.

From the computer simulation, the proposed system is proved to show enough performance to satisfy the FCC requirement. Also, the accuracy and reliability of positioning can be improved by exploiting transmit and receive diversity, and especially, exploiting receive diversity provides more improvement than exploiting transmit diversity.

REFERENCES


Fig. 4. Positioning error with changing mobile’s position