NLOS Signal Effect Cancellation Algorithm for TDOA Localization in Wireless Sensor Network

Chul-Gyu Kang, Hyun-Jae Lee and Chang-Heon Oh, *Member, KIMICS*

Abstract— **In this paper, the iteration localization algorithm that NLOS signal is iteratively removed to get the exact location in the wireless sensor network is proposed. To evaluate the performance of the proposed algorithm, TDOA location estimation method is used, and readers are located on every 150m intervals with rectangular shape in 300m× 300m searching field. In that searching field, the error distance is analyzed according to increasing the number of iteration, sub-blink and the estimated sensor node locations which are located in the iteration range.**

From simulation results, the error distance is diminished according to increasing the number of the sub-blink and iteration with the proposed location estimation algorithm in NLOS environment. Therefore, to get more accurate location information in wireless sensor network in NLOS environments, the proposed location estimation algorithm removing NLOS signal effects through iteration scheme is suitable.

Index Terms— **Localization algorithm, TDOA, TOA, AOA, Wireless Sensor Network, Sensor positioning.**

I. INTRODUCTION

UBIQUITOUS which is a new computing paradigm makes every device as an intelligent computer by inserting an unvisible computer into them, and can transmit and receive the information from the connected networks. There is a presupposition that every computer could be connectable to the networks, unvisible, usable anywhere and anytime and conversable in our life [1]. It is more developed computing environment than home networking or mobile computing which attracts the public attentions. Especially, the location information of a person or some objects in this computing environment is obtained and supported. Therefore, it could acquire the surrounding information and the perceptive information of the objects based on IT technology, as well as the localization technology which is able to acquire or manage the information via connecting to the network in real time is going to be raised as the most important part of the ubiquitous technology. Furthermore, the many research have been actively reported [2],[3].

The first step to support the ubiquitous service is finding the exact location. If we use a GPS (global positioning system) system, it is very easy to find a precise location. However, it economically enquires a lot of load economically to set up a GPS receiver to each sensor node and difficult to use GPS system in heavy rain forest or inside building where the GPS signal cannot be received. Therefore, we use TDOA (time difference of arrival), TOA (time of arrival), and TSOA (time sum of arrival) methods to estimate a node location in wireless sensor network. Fundamentally, it starts from this assumption that those methods use the received signal propagated through LOS (line of sight) path [4].

In real wireless sensor network, the precise location estimation is effected by many factors such as Gaussian noise and delayed signals propagated through NLOS (non-line of sight) path. The estimation error of Gaussian noise is an error occurred by the thermal noise at location estimation, but it can be overcome as a high SNR (signal to noise ratio). The estimation error of NLOS signal is happened by using the delayed signal which is blocked by many obstacles such as buildings and guideboards during the propagation. Between the both factors, the signal propagated through NLOS path brings the deep estimation errors. The research identifying NLOS signals has reported to reduce the estimation error. The idea is to find some distinct properties of NLOS signal distribution and develops hypothesis tests to segregate NLOS signals from LOS signals. Therefore, in this paper, we identify LOS signal and NLOS signal from all received signals, and search the method compensating the localization error by eliminating NLOS signals in NLOS environments. The searching area considered in this paper is 300m×300m.

The paper is organized as follows. Section II is devoted to introduce the system architecture and TDOA localization method. Section III explains the NLOS error model and simulation results, and conclusions are presented in section IV.

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II. TDOA AND NLOS SIGNAL DETECTION ALGORITHM

A. TDOA Algorithm

A sender node sends a signal that is received by readers to three different locations. Each reader notes the signal's time-of-arrival. The difference in arrival times at any pair of readers implies that the node was located somewhere on a known hyperbola. Using two reader pairs implies that the node resided at the intersection of two different hyperbolas. Fig. 1 illustrates this situation.

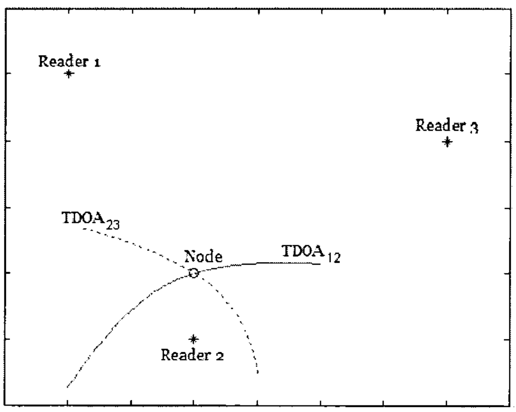

Fig. 1. Locating a tag through trilateration.

Fig. 1 and the equations to follow all pertain to a two-dimensional problem.

1) Mathematical location solution

Let t_i denote the time when the tag transmitted from location. The i-*th* sensor, at location (x_i, y_i), will detect the signal at time $toa_i = t_i + p_i$ where p_i denotes the time required for the signal to propagate from the node to the reader. This propagation time is equal to the node-to-reader separation divided by the speed of light, c as indicated in the equation below

$$p_i = \sqrt{(x-x_i)^2 + (y-y_i)^2} \Big/ c. \tag{1}$$

The unknown transmission time becomes unimportant when considering the difference in arrival time at two readers.

$$\begin{aligned} TDOA_{ji} &= TOA_j - TOA_i \\ &= \sqrt{(x-x_j)^2 + (y-y_j)^2} - \sqrt{(x-x_i)^2 + (y-y_i)^2} \Big/ c \end{aligned} \tag{2}$$

Equation (2) was used to generate the hyperbolic segments shown in Figure 1 for both $TDOA_{12}$ and $TDOA_{23}$. Equation pair (3) will produce two possible locations for this intersection, one real and the other extraneous. An extraneous solution will not satisfy the original pair of TDOA equations and may be recognized by this failure. Two possible solutions for the node location are given by the quadratic formula along with the linear equation.

$$\begin{aligned} x &= \frac{-b \pm \sqrt{b^2 - 4ac}}{2a} \\ y &= mx + b. \end{aligned} \tag{3}$$

The second solution is (almost always) extraneous, introduced by the squaring operation. It can be recognized by the fact that it will not match the observed time differences.

2) NLOS Signal Detection Algorithm

The estimated location of the sensor node is affected lots of factors. In those factors, NLOS signals give a deep effect to estimate a precise location. Therefore, the elimination is necessary to estimate a precise location. In this section, we estimate a node location with the all signals, LOS and NLOS signal, and then explain the decision mechanism of the final location of a node with LOS signals eliminating NLOS signal iteratively. If there is no information with respect to a NLOS sensor node, we can eliminate the estimated NLOS signals depicted in Fig. 2 that shows the deciding process of the proposed algorithm.

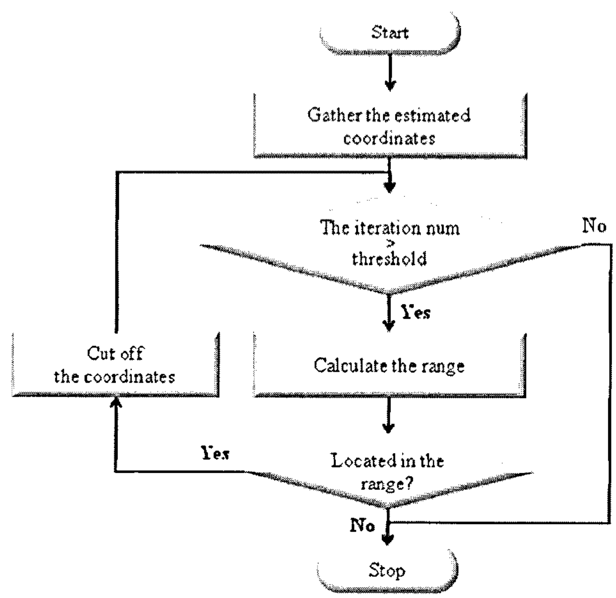

Fig. 2. The process of the proposed algorithm.

To estimate a location of the node, we need at least 3 readers (N≥3) receiving a signal from a node and sending the time information to the server, hence the number of the total estimated locations is decided according to the number of the total readers, N, and the number of readers participating in a location calculation. For instance, if the number of the total readers is 5, N=5, there are 16 eligible candidates. One could choose all 5 possible readers, or select 4 out of 5, or select 3 out of 5. That is,

1. Select 5 out of 5: $\binom{5}{5}$ 1 estimated location
2. Select 4 out of 5: $\binom{5}{4}$ 5 estimated locations
3. Select 3 out of 5: $\binom{5}{3}$ 10 estimated locations

In this paper, there are eight readers to estimate locations, and three readers participate in a location calculation at one time like table 1 is showing. Therefore, there are 56 estimated locations that among them, we identify the estimated locations which are the signal propagated through NLOS path.

TABLE I
READER COMBINATION

combination Number	1st Reader Num.	2nd Reader Num.	3rd Reader Num.
1	Reader 1	Reader 2	Reader 3
2	Reader 1	Reader 2	Reader 4
3	Reader 1	Reader 2	Reader 5
⋮	⋮	⋮	⋮
55	Reader 5	Reader 7	Reader 8
56	Reader 6	Reader 7	Reader 8

We need the central location to separate NLOS signals, so the central location is decided by equation (4).

$$\widetilde{x} = \arg\min \sum_{i\in S}^{all}\sum_{j\in S}^{all}\left(\left\|x_i - x_j\right\|\right)^2. \qquad (4)$$

$\|\cdot\|$: the norm operation over a vector

$\|x_i - x_j\|$: Euclidean distance between x_i and x_j

S: the nodes index set

x_i: i-*th* estimated location of the node

x_j: j-*th* estimated location of the node

$\widetilde{x}$: accumulated Euclidean distance

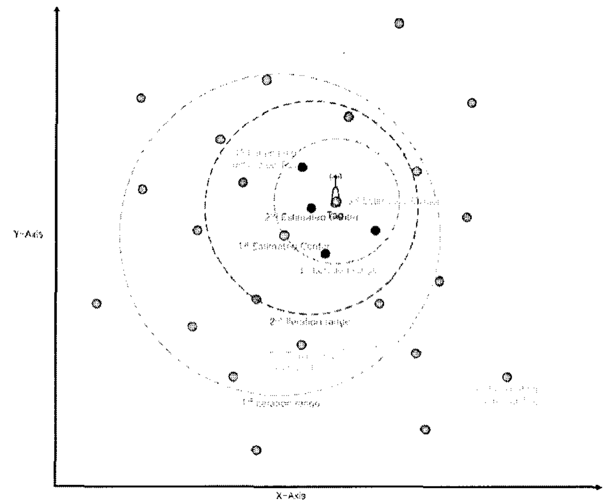

Fig. 3. Deciding process of the proposed algorithm.

After deciding the central location, we calculate the range from the decided central location to an estimated location which uses only LOS signals when it is estimated, to identify NLOS signals as equation (5). If the estimated locations pass over the range of equation (5), they are presumed that the estimated locations are used NLOS signals and eliminated from the next calculation, this range calculation is iteratively performed until an optimum threshold.

$$\widetilde{R} = \widetilde{x} + \frac{\arg\min \sum_{i\in S}^{all}\sum_{j\in S}^{all}\left(\left\|x_i - x_j\right\|\right)^2}{Size\ of\ S}. \qquad (5)$$

Fig. 3 shows the process of eliminating the estimated coordinates with NLOS signals via the explained algorithm. The total number of the estimated coordinates that have been mentioned before is 56 and, in Fig. 3, there are 3 iterations to eliminate the NLOS estimation coordinates.

III. NLOS ERROR MODEL AND SIMULATION RESULTS

A. NLOS Error Model

NLOS error depends on the propagation environment and changes from time to time, but at each time instance, NLOS can be considered as constant. We can estimate the value of NLOS error when there are enough readers available to determine the sensor node.

We write the TDOA hyperbolic equations as

$$Ct_i = R_i - R_1 + n_i + e_i. \qquad (6)$$

Where C is the speed of light, t_i is the measured TDOA time between reader i and 1, R_i is the distance between the sensor node and reader i, R_i is the distance between the sensor node and reader 1, n_i and e_i are the TDOA measurement noise and NLOS error, respectively. We assume that n_i is a Gaussian random variable with zero mean and variance σ_i. For NLOS readers, e_i is a positive random variable with mean μ_{nlos} and variance σ_{nlos}. We further assume that $\sigma_{nlos} > \sigma_i$, which is consistent with field test results.

To derive the ML (maximum likelihood) estimator for the NLOS contaminated TDOA, we first derive the probability density function of the sum of the Gaussian noise n_i and the exponentially distributed NLOS error e_i with mean $1/\lambda$ given by

$$f_{n+e} = \frac{\lambda}{2} e^{-\lambda\left(x - \frac{\lambda\sigma_i^2}{2}\right)} \left[1 + erf\left(\frac{x - \lambda\sigma_i^2}{\sqrt{2}\sigma_i}\right)\right]. \quad (7)$$

Where $erf(\cdot)$ denotes the error function. Rewrite equation (7) and (8) in a matrix from

$$L = H + V. \quad (8)$$

where $H = R(R_2 - R_1, R_3 - R_1, \ldots, R_N - R_1)^T$, $L = C(t_2, t_3, \ldots, t_N)^T$, $V=(n_2 + e_2, n_3 + e_3, \ldots, n_N + e_N)^T$. Maximizing the conditional joint PDF

$$f(L \mid x) = f_v(L - H \mid x). \quad (9)$$

$$f_V(L - H|x) = \frac{\lambda}{2} e^{-\lambda\left(x - \frac{\lambda\sigma_i^2}{2}\right)} \left[1 + erf\left(\frac{x - \lambda\sigma_i^2}{\sqrt{2}\sigma_i}\right)\right] \cdot \prod_{i=2}^{N-1} \frac{1}{\sqrt{2\pi\sigma_i}} \exp\left(-\frac{(Ct_i - R_1 - R_2))}{2\sigma_i^2}\right). \quad (10)$$

Under the assumption that n_i and e_i are independent random variables, we derive equation (10).

B. Simulation Environments

We simulate the proposed algorithm with this parameters explained table 1. In NLOS environment, lots of information is needed to overcome NLOS signal errors to estimate the exact sensor location. Thus, 1 to 8 sub-blinks are used to get more information of the sensor coordinates.

TABLE II
SIMULATION PARAMETERS

Parameters	Values
Searching area	300 m×300 m
Localization method	TDOA
The number of readers	8
The number of NLOS signals	1 ~ 6
The number of sub-blink	1 ~ 8
The number of iteration	1 ~ 6
The error range of LOS signal	< 32.76 nsec
The error range of NLOS signal	< 500 nsec

In the real sensor network field, there is delay times which occurs by reflected signal due to several obstacles located on transmission path such as buildings, containers and so on. This delay time is a much bigger error source than measurement error. Delay time error is presented as a log-normally distributed probability density function toward the arriving time of LOS signal. In this simulation, delay time of NLOS signal is log-normally generated in 500 nsec (150 m / 3×10^8 m/s).

C. Results and Discussions

In this chapter, we analyze the localization error performance of the estimating sensor node location according to the number of iteration and sub-blink.

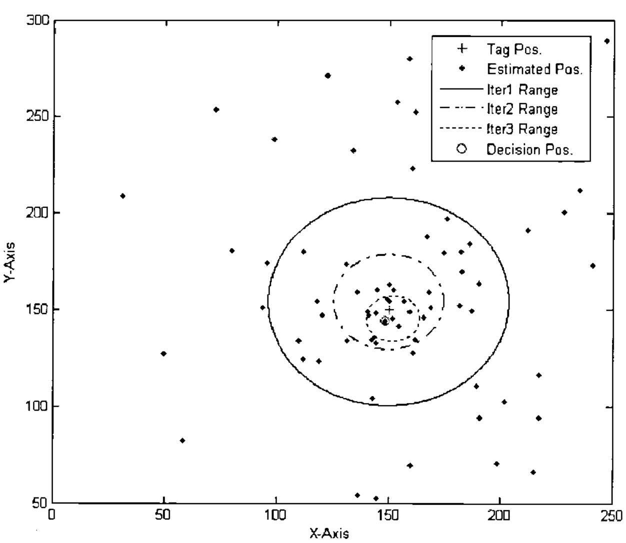

Fig. 4. Process of the iteration localization.

Fig. 4 shows the process of the iteration localization proposed in this paper. In Fig. 4, the 3 big circles are the iteration areas and that are used to divide the coordinates whether cutting off or not. Therefore, the final sensor location is decided using the survived coordinates.

1) The Error Distance According to Sub-blinks

There is a limit that if there is only one sub-blink, 56 estimated location coordinates are obtained. Therefore, to acquire more location information with respect to the sensor node, the number of sub-blinks should be increased, and we simulate on the error distance according to increasing the sub-blink. The simulation result is shown in Fig. 5. As shown on Fig. 5, the error distance is decreased according to increasing the number of sub-blink.

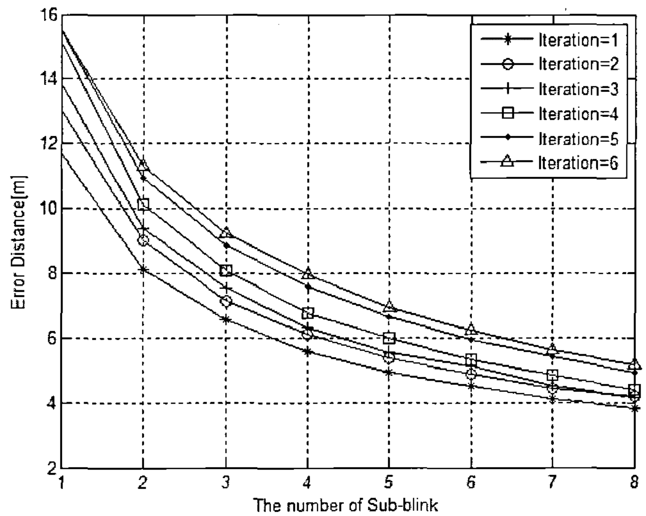

Fig. 5. Estimation error performance according to the number of sub-blink (LOS combination=1).

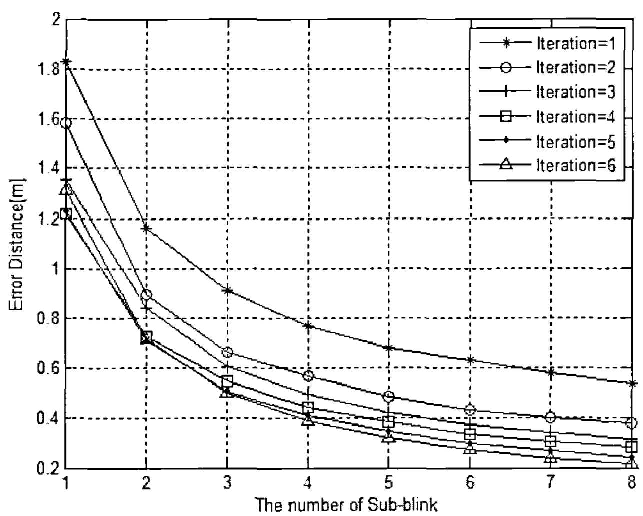

Fig. 6. Estimation error performance according to the number of sub-blink (LOS combination=18).

It is caused that when sub-blink is more than one, the number of estimated coordinates is increased from 56 to multiples of sub-blink, so if the number of coordinates estimated with NLOS is increased, the number of coordinates estimated LOS is relatively increased as well. The coordinates estimated with NLOS signals are removed iteratively in proposed algorithm. Therefore, LOS signals are used to decide the final location. In addition, when the number of reader combinations receiving LOS signal is 18 with 3 iterations, the localization error distance is corrected within 1m.

2) The Error Distance According to Iterations

Fig. 7 and Fig. 8 are shown the localization error distance of the sensor node according to iteration.

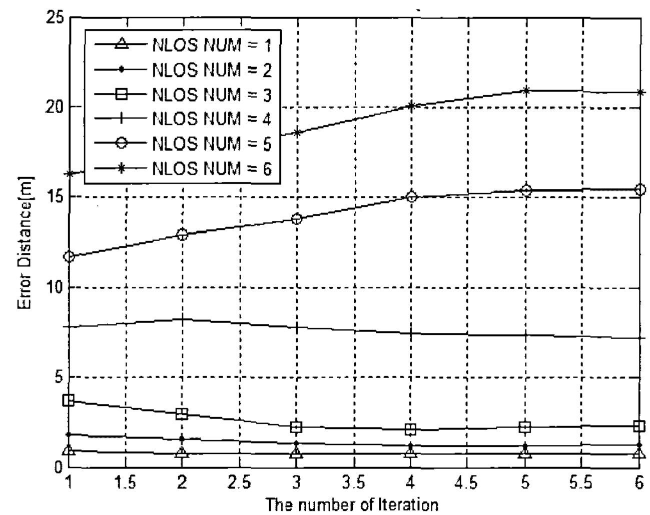

Fig. 7. Estimation error performance according to the number of iteration (sub-blink=1).

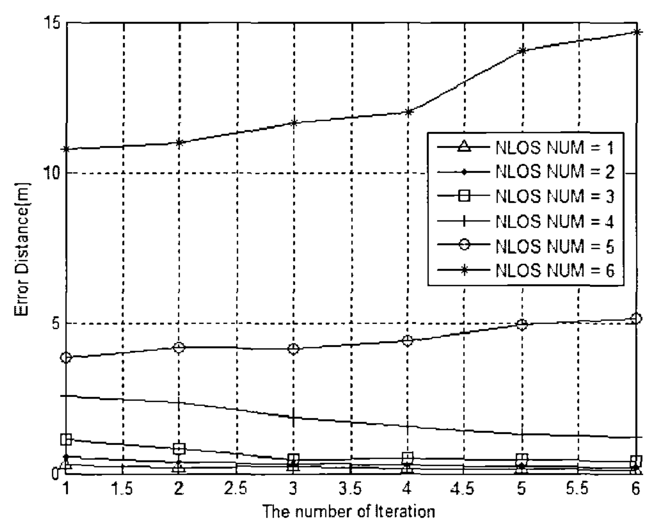

Fig. 8. Estimation error performance according to the number of iteration (sub-blink=8).

The estimation error distance is reduced according to increasing the number of iteration until 1 to 4 readers receiving NLOS signals by the proposed algorithm. However, the estimation error distance at 5 to 6 readers receiving NLOS signals is increased even though the number of iteration is increased.

It is caused that almost every reader combinations contain the readers receiving NLOS signals to calculate the sensor location in 5 to 6 NLOS environments, so the estimation information using NLOS signals is increased than the estimated location with LOS signals even though the total localization information is increased.

IV. CONCLUSIONS

In this paper, the iteration location estimation algorithm that NLOS signal is iteratively removed to get the exact location in the wireless sensor network is proposed. To evaluate the performance of the proposed algorithm, TDOA location estimation method is used, and readers are located on every 150m intervals with rectangular shape in 300m×300m searching field. In addition, the error distance is analyzed according to increasing the number of iteration, sub-blink and the estimated sensor node coordinates which are located in the iteration range.

From the simulation result, the error distance is diminished according to increasing the number of the sub-blink and iteration with the proposed location estimation algorithm in NLOS environments. The reason is that when the number of sub-blink is increased, the estimated location information of the sensor node is increased. Therefore, the error distance with respect to NLOS signal is getting more diminished. In addition, the estimated locations with NLOS signals are removed according to the iteration number. Therefore, the estimation error distance of the sensor node is decreased as the estimation locations with LOS signal is only used to decide the final location.

From these results, to get more exact location coordinate in wireless sensor network, the proposed location estimation scheme removing NLOS signal effects through iteration method is recommended.

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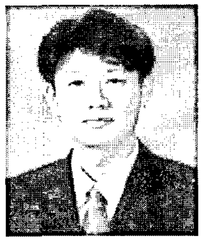

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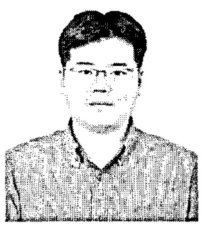

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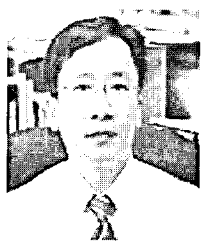

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