Source Localization using Reflection Omission in the Near-Field

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Abstract

Timing equations can be exploited to distinguish between LOS and reflected signals in an RF emitter location system. For this purpose, some algorithms will be given. The first algorithm extracts the group of the signals coming from the same source from all the first arrivals at the omni-directional sensors. This algorithm can be generalized for the directive sensors. Then an algorithm is given to distinguish between the transmitter and other located sources (reflectors). Finally a method is introduced to locate the transmitter when there are not enough LOS signals but at least four reflectors of the first type have been located in the first algorithm.

I. Introduction

Ranging and positioning are expected to play a main role in the advanced design of wireless communication networks in the coming years [1]. One of the advantages of Ultra-Wide-Band (UWB) technology, is having very short pulse widths. Therefore the multipath and interference issues can be resolved and precision location systems is a natural application of UWB signals.
Measurement error and Non-Line-of-Sight (NLOS) error are two major sources of localization error in location systems. Of these two sources of error, it has been remarked ([2] that NLOS error usually causes more degradation in localization accuracy and is quite common in all environments [2].
The previous works on hyperbolic positioning (which is based on Time Difference of Arrival (TDOA) measurement) have not focused on omitting or mitigating NLOS error in localization process.
In this paper, we address the problem of distinguishing between LOS and NLOS signals, for two techniques, TDOA and AOA, exploiting the timing relations between the arrivals and the estimated location. For the TDOA technique, there is one transmitter and n omni-directional receivers. The receivers are considered to be connected in order to have a common clock available. Only NLOS error is considered and all other kind of the errors are ignored here.

II. Determining the groups of the signals for an array of omni-directional antennas for 3-D

To locate every source in 3-D, there must be at least four source signals received by the sensors that are not coplanar. Therefore, to be able to locate the transmitter, the assumptions are
1. There is a transmitter in the area and there are at least four omni-directional receiving antennas around the area as the receivers (Fig. (1)).
2. All the first incoming signals to the receivers are LOS or first reflection signals.
3. All the sensors in the arrays are connected in order to have the same clock.
4. At least four non-coplanar receive LOS signal.
Assuming that (at least) four known signals are received from a source, it can be localized by the hyperbolic method. Thus, the propagation time t_p between the source, i.e. the transmitter or a reflector, and the receivers can be found as below

$$t_p = R/C. \tag{1}$$

in which R is the range of the source of the signal from the sensor obtained by the hyperbolic method and C is the propagation velocity.
If the located source is the transmitter, the difference between the clock of the transmitter and clock of the receivers can be easily obtained as below

$$t_{p_i} - t_{r_i} = \Delta t \quad i = 1, 2, ..., m, \tag{2}$$

in which t_{p_i} is the propagation time of the transmitter signal to the i^{th} sensor obtained by (1), and t_{r_i} is the signal relative receiving time to the receivers' clock. Fig. 1 shows a case in which four signals S1, S2, S3 and S4 from the transmitter are received by four sensors (non-coplanar), and signal S6, S7, S8, S9 and S11 are received from reflectors. Fig. 2 shows the timing diagram of the signals in Fig. 1. If the located source is a reflector (e.g. Ref1 in Fig. 1), the timing equation for signal $S6, S7, S8$ and $S9$ is

$$t_{p_i} + t_{mid} = t_{r_i} + \Delta t \quad i = 6, 7, 8, 9, \tag{3}$$

in which t_{p_i} is obtained from (1), t_{r_i} is available in the receiver and Δt and t_{mid} (the propagation time between the transmitter and the reflector) are unknown. Equation (3) can be rewritten as

$$t_{p_i} - t_{r_i} = \Delta t - t_{mid} \quad i = 6, 7, 8, 9. \tag{4}$$

As is evident from (2) and (4), for all the the signals in a group (i.e., coming from the same source) the difference between t_p and t_r is constant

$$t_{p_i} - t_{r_i} \approx K, \tag{5}$$

where K depends on the source location and not on i (the index of the signals in a group). There is an assumption here that the reflector behaves like a point source, and this approximation may be valid only in limited situation.
If a wrong location is obtained, forming the timing equations (4) does not provide a constant for all the signals in the group. This property can be exploited to determine the group of the signals coming from the same source. For this purpose, the signals in a group can be guessed and then the conjecture can be checked by forming the timing equations and checking (5). More details are given by the example shown in Fig. 1 in the next section.

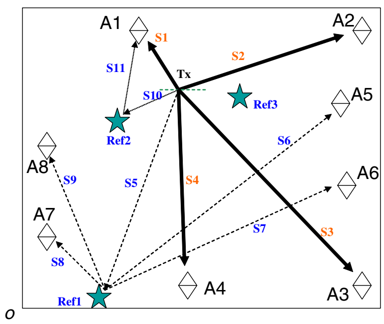

Fig. 1. Example 1: source localization with arrays of omni-directional sensors

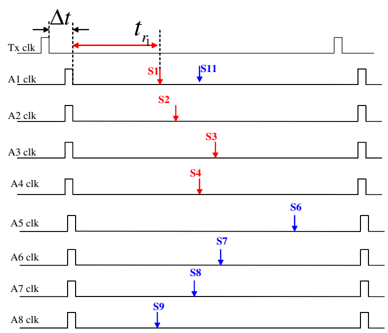

Fig. 2. Timing diagram of example 1

A. Algorithm

In this section the algorithm is described with the example shown in Fig. 1.

Step 1: Guessing the signals constructing a group

It is guessed that signals S1, S2, S3 and S4, that are the first coming signals to the sensors, are a group coming directly from the same source (that is a correct guess).

Step 2: Localization

The hyperbolic method is applied to the group signals in the above conjecture and the source location is found (If the localization process does not give any answer, the conjecture in *step*1 is wrong.).

Step 3: Checking the validity of Localization I

The validity of the source location solution (from *step* 2) in the accessible area is checked. If the guess is correct, the location is valid. (However if the conjecture is not correct, the source location may or may not be valid and the guess could be rejected or passed in this step.)

Step 4: Finding the propagation time

Then t_{p_i}s and K are obtained by (1) and (5).

Step 5: Constructing the timing matrix

In this step, matrix A is constructed as below

$$A = \begin{bmatrix} t_{p_1} & t_{p_2} & t_{p_3} & t_{p_4} \\ t_{r_1} & t_{r_2} & t_{r_3} & t_{r_4} \\ K & K & K & K \end{bmatrix}^T. \tag{6}$$

As seen, since a correct guess was made, all Ks are the same. Every row of this matrix is related to a signal in the group. The first column of the matrix is contained t_p , the second column is t_r and the third column is K obtained by (5).

Step 6: Checking the validity of Localization II

Now it is checked if the following equation is being held or not

$$A \begin{bmatrix} 1 & -1 & -1 \end{bmatrix}^T \approx 0. \quad (7)$$

With correct grouping, (7) holds, therefore, the signals in the group come from the same source (here the transmitter) and a correct location for the source has been obtained in *step*2.
It is shown (omitted here) that a wrong guess can not pass through *step* 6.
Because there is measurement noise in the real world, the right hand side (RHS) of (7) for a correct guess is not exactly a zero vector, but a vector with small elements close to zero (their statistical characteristics depend on the the noise). When a wrong guess passes through *step* 6, since a wrong location has been found for the source, RHS of (7) is a vector with non-zero elements that are far from each other. A rejection threshold test must be developed to make *step* 6 practical.
When there are $n \geq 8$ sensors in the area (Fig.1), multiple group signals may be distinguished in the algorithm. Therefore, multiple sources may be located in which one of them is the transmitter and the others are reflectors. Later, another algorithm will be introduced to distinguish between the transmitter and the reflectors in this situation.
Algorithms for separation of LOS signals from the reflections can be generalized to the directive sensors, but are omitted here.

III. An algorithm to distinguish between the transmitter and reflectors

To distinguish between the transmitter and the located reflectors when there are $L > 1$ sources located by the previous algorithms, once more the time equations can be used. Note that for the known and located transmitter and reflectors, the distance between the transmitter and the i^{th} reflector can be determined by

$$\overrightarrow{R}_{mid_i} = \overrightarrow{R}_x - \overrightarrow{R}_{ref_i} \quad i = 1, 2, ..., m-1, \quad (8)$$

in which R_x denotes the position vector of the transmitter, and R_{ref_i} is the the position vector of the i^{th} reflector in a global coordinate system. Therefore the propagation time between the transmitter and other sources are

$$t_{mid_i} = |\overrightarrow{R}_{mid_i}|/C \quad i = 1, 2, ..., L-1, \quad (9)$$

where C is the propagation velocity. The time equation for the reflectors signals is

$$t_{p_{i,j}} + t_{mid_{i,j}} - t_{r_{i,j}} - \Delta t = 0 \qquad \begin{matrix} i = 1, 2, ..., m \\ j = 1, 2, ..., L-1, \end{matrix} \quad (10)$$

where index i, j are related to the i^{th} signal in the group of the j^{th} reflector respectively. If the transmitter can be guessed, the conjecture can be checked by verifying the time equations. In the next section, the procedure is described by the example shown in Fig. 1.
Example
After applying the algorithm described in II-A, two sources *Source*1 and *Source*2, that is the transmitter and Ref1, are located. The groups related to these sources are S1, S2, S3, S4 and S6, S7, S8, S9, and their related timing equations are (2) and 10 (with $m = 3$, $L = 2$) respectively. The algorithm is described in the following.
Step 1: Guessing the transmitter
Assume that among two sources located in Fig. 1, it is guessed that *Source*1 is the transmitter. Therefore *Source*2 is the reflector (that is a correct guess).
Step 2: Obtaining Δt
By (2), Δt is obtained from one of the signals (e.g. S1) of the group signals of the assumed transmitter (that are signals S1, S2, S3 and S4). Thus Δt is obtained as below

$$\Delta t = t_{p_1} - t_{r_1}. \quad (11)$$

Step 3: Finding the propagation time between the assumed transmitter and other sources
Assuming point o (Fig. 1) as the center of a global coordinate system, the distance between the assumed transmitter and Ref1 is found by

$$\overrightarrow{R}_{mid_1} = \overrightarrow{R_x} - \overrightarrow{R}_{ref_1} \quad (12)$$

in which R_x is the position vector of the assumed transmitter. Therefore the propagation time between the assumed transmitter and Ref1 is

$$t_{mid_1} = |\overrightarrow{R}_{mid_1}|/C. \quad (13)$$

Step 4: Constructing the timing matrix
Using the time equations (2) and (10), matrix B is constructed as below

$$B = \begin{bmatrix} t_{p_1} & t_{p_2} & t_{p_3} & t_{p_4} & t_{p_6} & t_{p_7} & t_{p_8} & t_{p_9} \\ 0 & 0 & 0 & 0 & t_{mid_1} & t_{mid_1} & t_{mid_1} & t_{mid_1} \\ t_{r_1} & t_{r_2} & t_{r_3} & t_{r_4} & t_{r_6} & t_{r_7} & t_{r_8} & t_{r_9} \\ \Delta t & \Delta t & \Delta t & \Delta t & \Delta t & \Delta t & \Delta t & \Delta t \end{bmatrix}^T . \quad (14)$$

Step 5: Check the guess
Now it is checked if the following equation is being held or not

$$B \begin{bmatrix} 1 & 1 & -1 & -1 \end{bmatrix}^T \approx 0. \quad (15)$$

With the conjecture in *Step 1*, (15) holds, and therefore it is a correct guess.
It is proved (omitted here) by contradiction that a wrong guess can not pass through *Step 5*.
If the last assumption in section II is not satisfied, some groups of signals may be distinguished in the algorithm of II-A, but the algorithm in III can not determine a transmitter since all the groups of signals are related to reflectors. However, if at least four reflectors are located (by the algorithm in II-A), the transmitter can still be localized. In the next section another algorithm is introduced to locate the transmitter in the case that there are insufficient LOS signals from the transmitter but at least four reflectors are located.

IV. Locating the transmitter without having LOS by at least four reflectors

Assuming that there are at least four first reflectors detected by the algorithms described in II-A, the timing equations introduced in (3) can be used to locate the transmitter even when there are not enough LOS signals from the transmitter (i.e., four and two LOS signals for omni-directional and directive sensors respectively). When the algorithm of section III can not determine the transmitter among the sources detected in section II-A, it implies that all the detected sources are reflectors. Assuming that the located sources are first reflectors, they can be considered as the known secondary sensors receiving LOS signals from the transmitter. Therefore, subtracting the propagation time t_p from the receiving time t_r for each reflector yields the difference of t_{mid}, that is the propagation time between the transmitter and these secondary sensors, and Δt.

$$t_{r_i} - t_{p_i} = t_{mid} - \Delta t \quad i = 1, 2, ... \quad (16)$$

This equation implies that the relative time difference between these secondary sensors and transmitter is available. Thus, the transmitter can be localized by the hyperbolic method regardless of the type of sensors (i.e. directive or omni- directional). The algorithm described here can be extended for this purpose.

V. Experimental Results

An experiment was done by UWB pulses with 1.6 nsec width and arrays of omni-directional antennas. The hyperbolic method described in [3] was applied to the group signals for localization. The correctness of part of the algorithm described in section III was verified.

VI. Conclusions

The study showed that the timing equation is a strong tool to distinguish between LOS and reflections. In transmitter localization applications, the timing equation can also be used to locate the transmitter even without LOS signals assuming that at least four reflectors can be located.

VII. Acknowledgements

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References

[1] Guerino Giancola Maria-Gabriella Di Benedetto, *Understanding Ultra Wide Band Radio Fundamentals*, Prentice Hall, June 2004.
[2] Pi-Chun Chen, "A non-line-of-sight error mitigation algorithm in location estimation," *Wireless Communications and Networking Conference, WCNC. IEEE*, vol. 1, pp. 316 – 320, Sept 1999.
[3] B.T. Fang, "Simple solutions for hyperbolic and related position fixes," *IEEE Transactions on Aerospace and Electronic Systems*, vol. 26, no. 5, pp. 748 – 753, Sept 1990.