(12) INTERNATIONAL APPLICATION PUBLISHED UNDER THE PATENT COOPERATION TREATY (PCT)

(19) World Intellectual Property Organization
International Bureau

(43) International Publication Date
7 February 2008 (07.02.2008)

PCT

(10) International Publication Number
WO 2008/017032 A2

(51) International Patent Classification:
H04Q 7/20 (2006.01)

(21) International Application Number:
PCT/US2007/075082

(22) International Filing Date: 2 August 2007 (02.08.2007)

(25) Filing Language: English

(26) Publication Language: English

(30) Priority Data:
60/821,378 3 August 2006 (03.08.2006) US
11/832,547 1 August 2007 (01.08.2007) US

(63) Related by continuation (CON) or continuation-in-part (CIP) to earlier application:
US 11/832,547 (CON)
Filed on 1 August 2007 (01.08.2007)

(71) Applicant *(for all designated States except US)*: **NTT DOCOMO INC.** [JP/JP]; Sanno Park Tower, 11-1, Nagata-cho, 2-chome, Chiyoda-Ku, Tokyo, 100-6150 (JP).

(72) Inventors; and
(75) Inventors/Applicants *(for US only)*: **GUVENC, Ismail** [TR/US]; 3614 Flora Vista Avenue, Apt. 270, Santa Clara, ca 95051 (US). **CHONG, Chia-chin** [MY/US]; 4048 Fitzpatrick Way, Santa Clara, CA 95054 (US).

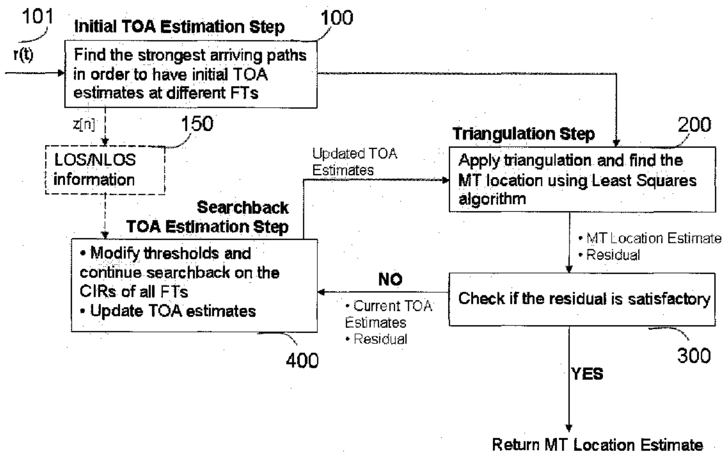
(74) Agent: **KWOK, Edward C.**; MacPherson Kwok Chen & Heid LLP, 2033 Gateway Place, Suite 400, San Jose, California 95110 (US).

(81) Designated States *(unless otherwise indicated, for every kind of national protection available)*: AE, AG, AL, AM, AT, AU, AZ, BA, BB, BG, BH, BR, BW, BY, BZ, CA, CH, CN, CO, CR, CU, CZ, DE, DK, DM, DO, DZ, EC, EE, EG, ES, FI, GB, GD, GE, GH, GM, GT, HN, HR, HU, ID, IL, IN, IS, JP, KE, KG, KM, KN, KP, KR, KZ, LA, LC, LK, LR, LS, LT, LU, LY, MA, MD, ME, MG, MK, MN, MW, MX, MY, MZ, NA, NG, NI, NO, NZ, OM, PG, PH, PL, PT, RO, RS, RU, SC, SD, SE, SG, SK, SL, SM, SV, SY, TJ, TM, TN, TR, TT, TZ, UA, UG, UZ, VC, VN, ZA, ZM, ZW.

(84) Designated States *(unless otherwise indicated, for every kind of regional protection available)*: ARIPO (BW, GH, GM, KE, LS, MW, MZ, NA, SD, SL, SZ, TZ, UG, ZM, ZW), Eurasian (AM, AZ, BY, KG, KZ, MD, RU, TJ, TM), European (AT, BE, BG, CH, CY, CZ, DE, DK, EE, ES, FI, FR, GB, GR, HU, IE, IS, IT, LT, LU, LV, MC, MT, NL, PL, PT, RO, SE, SI, SK, TR), OAPI (BF, BJ, CF, CG, CI, CM, GA, GN, GQ, GW, ML, MR, NE, SN, TD, TG).

Published:
— *without international search report and to be republished upon receipt of that report*

(54) Title: ITERATIVE METHOD FOR JOINTLY ESTIMATING TIME-OF-ARRIVAL OF RECEIVED SIGNALS AND TERMINAL LOCATION



(57) Abstract: A method for mitigating NLOS effects in a localization system uses both multipath channel characteristics and information from the mobile network. The method iteratively estimates the first arriving path of the received signals and the terminal location, with the estimate of the terminal location improving the estimate of the first arriving path, and vice versa. Initially, a peak selection method determines a rough time-of-arrival (TOA) for a signal received at each of a number of different fixed terminals (FTs). An estimate of the location of the mobile unit is then provided (e.g., based on a least-squares (LS) triangulation). If the residual error is unsatisfactory, the TOAs are refined, using a search-back algorithm, which searches back from the strongest paths of the received signals. The new TOAs are used to refine the estimate of the location of the mobile terminal. In addition, the parameters of the search-back algorithm (e.g., a search-back threshold) may be modified for greater accuracy in the estimated first path. The first arriving path estimate and the location estimate are iterated until convergence (e.g., the residuals are within a tolerance) or until a termination condition is reached, usually controlled by the thresholds setting.

WO 2008/017032 A2

ITERATIVE METHOD FOR JOINTLY ESTIMATING TIME-OF-ARRIVAL OF RECEIVED SIGNALS AND TERMINAL LOCATION

Ismail Guvenc
Chia-Chin Chong

CROSS REFERENCE TO RELATED APPLICATIONS

The present application relates to and claims priority of U.S. provisional patent application no. 60/821,378, filed August 3, 2006 and of U.S. patent application no. 11/832,547, filed August 1, 2007, both of which are incorporated herein by reference. For the US designation, the present application is a continuation of the aforementioned U.S. patent application no. 11/832,547.

BACKGROUND OF THE INVENTION

1. Field of the Invention

The present invention relates to wireless localization. More particularly, the present invention relates to estimating a terminal's position using a time-of-arrival (TOA) technique under non-line-of-sight (NLOS) conditions.

2. Discussion of the Related Art

Many location-based services are possible because of accurate wireless positioning and localization. Methods based on received signal strength (RSS), angle of arrival (AOA), time of arrival (TOA), and time difference of arrival (TDOA) are most commonly used approaches for estimating the position of a terminal.

NLOS conditions significantly affect the performance of mobile positioning techniques that are based on TOA. If the line-of-sight between a terminal and a base station (BS) is obstructed, a delay ("NLOS bias") is introduced into the received signal. Even a single or few NLOS base stations may significantly degrade localization accuracy, and thus mitigation of NLOS effects is important. One way to mitigate the effects of NLOS base stations is to identify them and to exclude them from the localization operation. However, when the number of base stations available for localization is limited, it may be impossible to exclude the NLOS base stations and still meet the requirements for localization. Localization typically requires three or more base stations for a two-dimensional (2-D) localization, and a minimum of four base stations for a three-dimensional (3-D) localization.

In addition to the NLOS biases, localization inaccuracy may result from poor or imperfect estimation of the first arriving path. Typically, to estimate a TOA, a search is initiated from the strongest path and continues backwards by testing samples against a pre-defined threshold. This search-back algorithm may lock onto a later path than the first path, and thus introduces additional bias. First-arriving-path estimation techniques are disclosed, for example, in (a) U.S. Patent Application Publication 2003/0174086, entitled "Determining a Time of Arrival of a Sent Signal," published on Sept. 18, 2003, (b) U.S. Patent 6,054,950, entitled "Ultra Wideband Precision Geolocation System," issued on Apr. 25, 2000; (c) U.S. Patent Application Publication 2006/0104387, entitled "Method for estimating time of arrival of received signals for ultra wide band impulse radio systems" filed on Nov. 15, 2004; (d) U.S. Patent Application Publication 2003/0025631, entitled "First-arriving-pulse detection apparatus and associated methods", filed on July 26, 2001; and in U.S. Patent Application Publication 2004/0235499, entitled "Ranging and positioning system, ranging and positioning method, and radio communications apparatus", filed on Feb. 18, 2004.

Once the TOAs of the received signals at different base stations are obtained, terminal location can be estimated using a well-known algorithm, such as the least square (LS) algorithm or the maximum likelihood (ML) algorithm. NLOS effects adversely affect the accuracy in the estimation of the terminal location. Numerous techniques have been developed that mitigate NLOS effects using information from the mobile network (and ignoring the channel statistics). If all the base stations are within line-of-sight, the residual location errors are small. However, even if only a single NLOS base station is present, the residual error may increase considerably, depending on the NLOS bias. Thus, the residual error may be used to detect the presence of NLOS base stations and to mitigate their effects. U.S. Patent Application Publication 2004/0127228, entitled "Method for Correcting NLOS Error in Wireless Positioning System", filed on Dec. 30, 2002, discloses NLOS effects and mitigation techniques using the mobile communication network.

The article "A Non-Line-of-Sight Error Mitigation Algorithm in Location Estimation", by P.Chen, published in *Proc. IEEE Wireless Commun. Networking Conf. New Orleans, LA*, pp. 316-320, vol. 1, Sept. 1999, discloses a technique for suppressing NLOS signals using the TOA information and the mobile network. The technique assumes that NLOS identification is not possible from the received multipath signal, and the number of base stations is greater than the minimum required. The article further discloses using different combinations of base stations to obtain location estimates, which are then weighted by the inverse of the corresponding residuals to obtain a final location estimate.

U.S. Patent Application Publication 2006/0125695, entitled "System and Method for Enhancing the Accuracy of a Location Estimate", published on June 15, 2006, discloses a general framework for "enhancing the accuracy of a location estimate that modifies weights in a weight matrix associated with receiver station measurements in parallel with successive refinements of the location estimate". In one implementation, the weights are obtained from the residuals. Information from statistics on multipath received signals are not used.

Numerous papers disclose techniques for NLOS identification using the statistical distribution of the TOA of the received signal. Such techniques, which typically assume that the terminal is in motion, require a large number of measurements to accurately capture the necessary statistics for NLOS identification. For a static terminal, however, such techniques may not provide reliable identification, and multipath statistics of the received signal have to be used. NLOS identification using multipath received signals in a code division multiple access (CDMA) system is disclosed in European Patent Application Publication EP 1,469,685, entitled "a Method distinguishing line of sight (LOS) from non-line-of-sight (NLOS) in CDMA mobile communication system", filed on Dec. 29, 2002. In this patent application, a channel is identified as a LOS channel, if the power ratio of the maximum path to the local maximum path is greater than a pre-defined threshold and, simultaneously, the arrival time difference between the first path and the maximum path is less than a given time interval.

U.S. Patent Application Publication 2005/0281363, entitled "Wireless Positioning Approach Using Time Delay Estimates of Multipath Components", filed on Jun. 8, 2005, observes that, besides the first arriving signals, the second and later arriving signals, which are created due to NLOS propagation, also carry information regarding the position of interest. Therefore, all available multipath components may be processed, along with the first arriving ones, to improve the positioning accuracy.

These prior art techniques identify and mitigate NLOS effects either at the triangulation stage, using the mobile communication network, or directly from the received signal itself. Typically, triangulation is achieved in two independent steps; 1) TOAs are estimated from the multipath received signals corresponding to each terminal and base station link, and 2) based on the estimated TOAs, a least-square solution is obtained for the terminal's location. Note that, after estimation of the TOAs, information regarding the received signals is discarded, and only the TOA estimates are passed to the triangulation step. However, as stated in U.S. Patent Application Publication 2005/0281363, discussed above, the multipath components of the received signal also carry information regarding the LOS or NLOS characteristics of a terminal and base station link. When the *à priori* probability density function of NLOS induced path lengths is available, the probability density function may be used to obtain a maximum *à posteriori* (MAP) estimate of the terminal location. We are not aware of any technique in the prior art that uses information from both the mobile communication network and the received signal itself to iteratively mitigate NLOS effects.

Using information derived from multipath statistics of the received signal to mitigate NLOS effects may significantly improve the accuracy of localization systems, relative to techniques that rely only on the mobile network.

The prior art solutions often fail to consider the effects of an imperfect estimation of the first path arrival time. In addition to a bias between the actual first path and the TOA of the received signal due to NLOS effects, there may also be an offset between the actual first path and the estimated first path. The offset becomes more pronounced in extremely NLOS conditions where the delay between the first arriving path and the strongest path is large.

SUMMARY OF THE INVENTION

According to one embodiment of the present invention, a method is provided for estimating the location of a mobile unit based on signals received at various fixed terminals (FTs). The method includes determining times-of-arrival for the signals received at the FTs and, based on the times-of-arrival, providing an estimate of the location of the mobile unit. If the estimate of the location of the mobile unit is not accurate within a predetermined threshold, the method iteratively modifies the times-of-arrival, so as to repeat estimations of the location of the mobile unit, until an estimate fall within the accuracy criterion or criteria.

In one embodiment, the times-of-arrival are modified using a search-back algorithm. The search-back algorithm compares the signal strength of the received signal at each FT against a search-back parameter threshold. The search-back parameter threshold may depend on information derived from a determination of whether or not the signal received at the FT is line-of-sight. The search-back parameter threshold may also depend on the predetermined threshold used in determining the accuracy of the estimate of the location of the mobile unit.

According to one embodiment of the present invention, the method uses the times-of-arrivals of signals received at three or more FTs in the estimate of the location of the mobile unit. The successive estimates of the location of the mobile unit are provided using times-of-arrivals derived from different groups of FTs, each group having three or more FTs.

The present invention is better understood upon consideration of the detailed description below in conjunction with the accompanying drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

Figure 1(a) illustrates communication system in which time-of-arrival (TOA) estimation and wireless positioning operations may be performed based on signals received at different FTs under an NLOS environment.

Figure 1(b) illustrates the TOA estimation operations based on signals received at FTs 10, 20 and 30.

Figure 2 is a flowchart illustrating an iterative positioning algorithm, according to one embodiment of the present invention.

Figure 3 is a schematic block diagram showing in greater detail selecting a strongest arriving path in step 100 of the algorithm of Figure 2.

Figure 4 is a schematic block diagram showing in greater detail triangulation step 200 in the algorithm of Figure 2.

Figure 5 is a schematic block diagram showing in greater detail the search-back algorithm in step 400 of the algorithm of Figure 2.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

Figure 1(a) illustrates communication system in which time-of-arrival (TOA) estimation and wireless positioning operations may be performed based on signals received at different FTs under an NLOS environment. As shown in Figure 1, FTs 10, 20, and 30 each measure a TOA for their respective signals received from mobile terminal 5. The TOAs are forwarded to centralized processing unit 35 to estimate a location for terminal 5 by triangulation. Alternatively, terminal 5 may estimate its location using the measurements on the received signal at the FTs.

Figure 1(b) illustrates the TOA estimation operations based on signals received at FTs 10, 20 and 30. Typically, to measure a TOA, each receiver locks on the strongest path. In Figure 1(b) the respective strongest paths for FTs 10, 20 and 30 are each indicated by reference numeral 9. From the strongest path identified, each receiver searches backwards in time for the first arriving path. Under a LOS condition, the first arriving path (indicated by reference numerals 11 in Figure 1(b)) corresponds to the shortest distance between the transmitter and the receiver. However, under a NLOS condition (i.e., an obstruction exists between the transmitter and the receiver), the first arriving paths – indicated by reference numeral 7 in Figure 1(b) -- arrive later then LOS first arriving paths 11. A NLOS arriving path thus introduces a positive bias to the TOA estimate, even when the first arriving path is correctly identified. Also, a receiver typically sets a threshold value (indicated by reference numeral 8) that is used to qualify the first arriving path. When NLOS first arriving path 7 has signal strength less than the threshold value, the estimated first arriving path (indicated by reference numeral 12) has an even later value.

In a conventional system, the TOA of the received signal is estimated at each FT using selected thresholds. The TOA estimates are converted to distance estimates 31, 32 and 33. Then, using a least-squares approach, an estimate of the terminal location is provided by selecting the value of $\mathbf{x}$ which minimizes the sum of the squares of all residuals as follows:

$$\hat{\mathbf{x}} = \underset{\mathbf{x}}{\operatorname{argmin}} \sum_{i=1}^{N} \left[d_i - ||\mathbf{x} - \mathbf{x}_i|| \right]^2$$

where d_i is the distance between the ith base station and the terminal, x_i is the location of the ith FT, for N base stations available. The mean square residual error ("residual") for the estimated terminal location can be written as

$$\text{Residual} = \frac{1}{N} \sum_{i=1}^{N} \left[d_i - ||\hat{\mathbf{x}} - \mathbf{x}_i|| \right]^2$$

Under a LOS condition, the residual depends only on the measurement noise and the search-back errors. Search-back errors result from incorrect identifications of the first arriving path. Under a LOS condition, as a leading edge of a signal is easily identified, an accurate TOA estimate may be obtained for each FT. Consequently, under a LOS condition, the estimated terminal location is close to the actual terminal location (i.e., the residual is typically small, assuming sufficient averaging is performed to reduce noise variance.)

However, if a NLOS FT is included, the NLOS bias introduced creates a large residual. As discussed above, sources of NLOS bias include: 1) the delay between the LOS TOA and NLOS TOA, and 2) the delay between the estimated NLOS TOA and actual NLOS TOA. This invention aims to mitigate biases from both sources by iterating between the triangulation and TOA estimation steps. To minimize the second NLOS bias, an appropriate threshold should be selected. If the selected threshold is too high, the first arriving path may be missed, resulting in selecting a path that arrives later than the first arriving path. Conversely, setting a threshold too low may result in capturing a noise sample, rather than the first arriving path. The present invention selects a threshold using an iterative approach that uses information obtained from the triangulation step.

While the first type of bias (i.e., the delay between the LOS TOA and the NLOS TOA) cannot be dealt with directly at the search-back step, such bias can be handled in the triangulation step. Basically, the channel LOS or NLOS information can be obtained from multipath received signals (e.g., in the form of a likelihood weight). The multipath received signals can then be used in a triangulation step and in the search-back algorithm for identifying LOS base stations (as a termination condition).

Figure 2 is a flowchart illustrating an iterative positioning algorithm, according to one embodiment of the present invention. As shown in Figure 2, each FT obtains an initial TOA of the received signal 101 using peak selection step 100. Figure 3 is a schematic block diagram showing in greater detail selecting a strongest arriving path in step 100 of the algorithm of Figure 2. As shown in Figure 3, the received signal 101 is pre-filtered at step 102. At step 103, the filtered signal may be detected using an analog front-end processing unit, such as a matched filter or an energy detector 103. The output signal of the analog front-end processing unit may be sampled at step 104 and collected, at step 105, as vector z[n]. At step 106, a peak detector circuit then selects the strongest sample to provide an initial TOA estimate of the received signal.

Referring back to Figure 2, at step 200, the initial TOA estimates are used to estimate the terminal's location using least-squares, triangulation and minimization of residual techniques. Figure 4 is a schematic block diagram showing in greater detail triangulation step 200 in the algorithm of Figure 2. As shown in Figure 4, at steps 201-203, the TOA estimates from all the FTs are gathered. At step 204, a least-squares estimate of the terminal position is performed using the TOA estimates from the FTs and the corresponding known positions of the base stations. The residual is calculated using the estimated terminal position, as discussed above.

Once an initial estimate of a TOA is obtained, the residual is compared with a predetermined threshold value at step 300. If the residual is sufficiently small (e.g., when all base stations are LOS, and the first arriving path is the strongest path in all of them), the algorithm terminates and the location of the terminal is returned. Otherwise, the TOA estimation step is repeated (step 400) at each FT. Figure 5 is a schematic block diagram showing in greater detail the search-back algorithm in step 400 of the algorithm of Figure 2. The search-back algorithm uses the residual information and LOS or NLOS information to estimate the TOA. (The LOS and NLOS information is collected at step 150 of Figure 2, based on multipath received signals, as discussed above). One search-back algorithm that can be used is described in the article "Non-coherent TOA Estimation in IR-UWB Systems with Different Signal Waveforms", by I. Guvenc et al., published in *Proc. IEEE/CreateNet International Workshop on Ultrawideband Wireless Networking*, Boston, MA, Oct. 2005. In that algorithm, the samples prior in time to the strongest sample are searched. As shown in Figure 5, at step 403, each sample z[n], n = 1, …, W, is compared with a threshold ξ, beginning with z[W]. If sample value z[n] is greater than threshold ξ, and all the samples preceding z[n] are less than threshold ξ, then z[n] sample is selected as the first arriving path. The requirement that the samples preceding z[n] to be less than threshold ξ allows for the multiple clustering effects of UWB channels. Otherwise, the sample index is decremented (i.e., the immediately preceding sample of z[n] is next considered) and step 403 is repeated until the first arriving path is found.

When one or more FTs are NLOS, or when the search-back algorithm is not able to identify the leading edge path for all the FTs, the residual received from triangulation step 200 may be unsatisfactory. Under such circumstances, the search-back algorithm may be run after updating the parameters ξ (step 405), incorporating any LOS or NLOS information obtained from the received signals. A relatively large value may be selected for threshold ξ to avoid any false alarms in detecting the first path. One selection for threshold ξ may be, for example, half the strength of the strongest path. The threshold ξ may be decreased at fixed ratios for successive updates. Alternatively, threshold ξ may depend on the residual error.

Using the updated TOA estimates, steps 200 and 300 are repeated. Updating the TOA estimates and computing the terminal location estimates (i.e., steps 200 and 300) are repeated until the residual error is sufficiently small or until a stopping rule is satisfied.

Since the mean square residual error is normalized using the number of FTs, the mean square residual error is comparable with a mean square localization error. Simulations using basic settings indicate that the mean square residual error is usually smaller than the mean square localization error for all LOS FTs. However, when any base station is NLOS, the residual error increases considerably. Thus, the required threshold for the residual can be set based on the localization accuracy desired (e.g., 1 meter).

Note that the residual may not be satisfactory even if all the first paths are correctly identified. Then, a simple stopping rule which terminates the iteration if the change in the residual is not significant can be used.

The present invention has the advantage that the position of the terminal is determined by interrelated TOA estimation and triangulation steps. The present invention takes advantage of the information present in both the multipath signals and the mobile network to mitigate NLOS effects. Accordingly, localization accuracy is improved significantly, as compared to systems which use only the mobile network for NLOS mitigation. The present invention is applicable to cellular systems, wireless local area networks, wireless sensor networks, and any other related wireless system where localization is performed. The present invention is especially applicable to ultrawideband systems where identification of the first arrival path is more error-prone than narrowband systems.

The above detailed description is provided to illustrate specific embodiments of the present invention and is not intended to be limiting. Numerous variations and modifications within the scope of the present invention are possible. The present invention is set forth in the accompanying claims.

CLAIMS

We claim:

1. A method for estimating the location of a mobile unit based on signals received from a plurality of FTs, comprising:

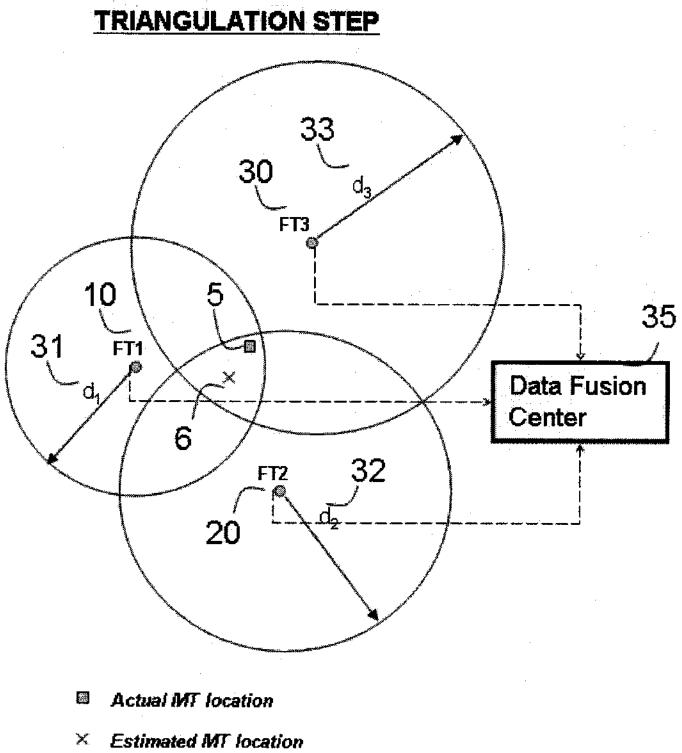
(a) at each FT, determining a time-of-arrival for the signal received at the FT;

(b) based on the times-of-arrival determined at the FTs, providing an estimate of the location of the mobile unit;

(c) determining if the estimate of the location of the mobile unit is accurate within a predetermined threshold, and

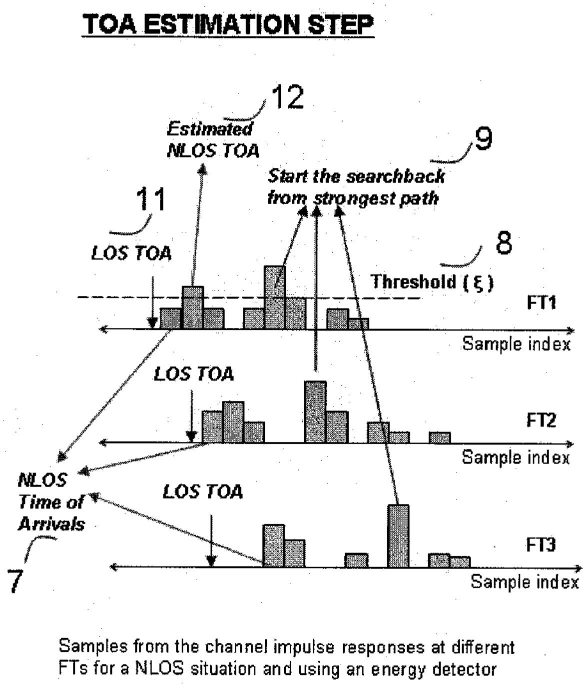
(i) when the estimate of the location of the mobile unit is accurate within the predetermined threshold, adopting the estimate of the location of the mobile unit; and

(ii) when the estimate of the location of the mobile unit is not accurate within the predetermined threshold, modifying the times-of-arrival, and repeating (b) and (c).



TRIANGULATION STEP
33
30
d3
FT3
10
5
35
31
FT1
d1
Data Fusion Center
6
FT2
32
20
d2
Actual MT location
Estimated MT location

FIG. 1(a)



TOA ESTIMATION STEP
12
Estimated NLOS TOA
9
Start the searchback from strongest path
11
LOS TOA
8
Threshold (ξ)
FT1
Sample index
LOS TOA
FT2
Sample index
NLOS Time of Arrivals
LOS TOA
FT3
7
Sample index
Samples from the channel impulse responses at different FTs for a NLOS situation and using an energy detector

Fig.1(b)

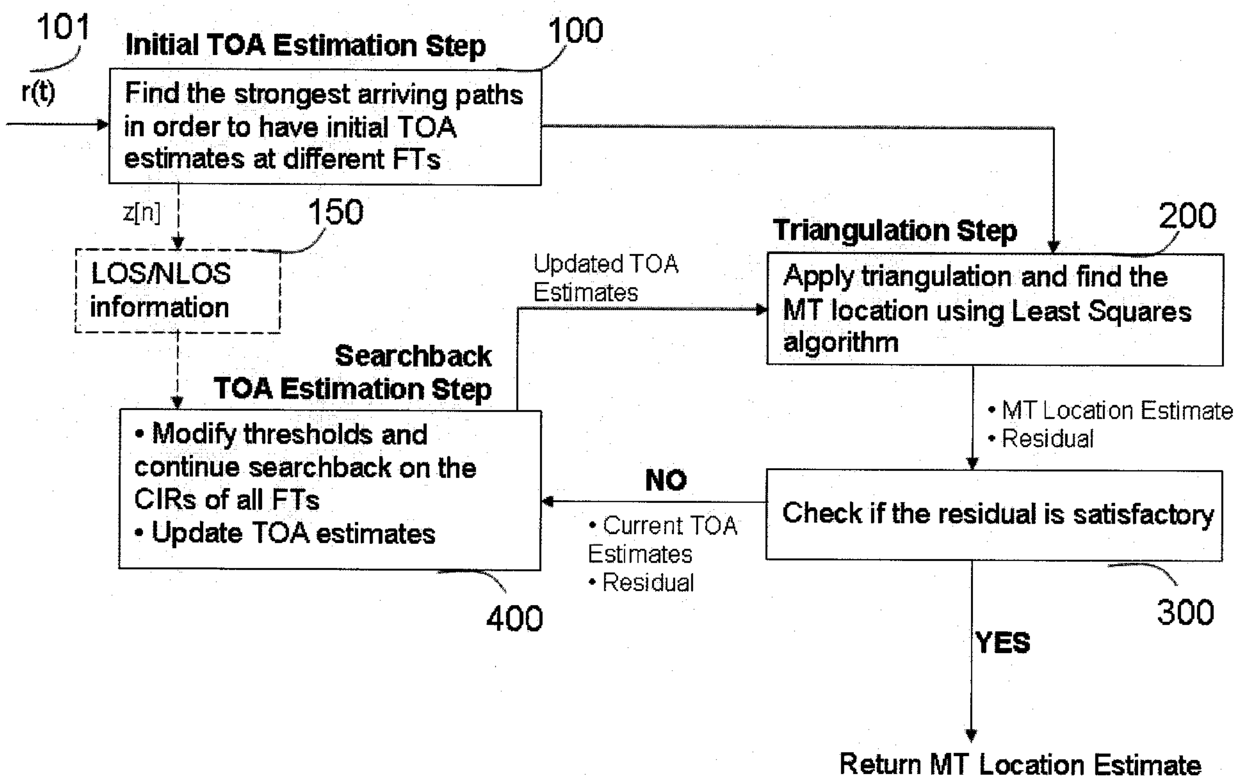

101
Initial TOA Estimation Step
100
r(t)
Find the strongest arriving paths in order to have initial TOA estimates at different FTs
z[n]
150
Triangulation Step
200
LOS/NLOS information
Updated TOA Estimates
Apply triangulation and find the MT location using Least Squares algorithm
Searchback TOA Estimation Step
• MT Location Estimate
• Residual
• Modify thresholds and continue searchback on the CIRs of all FTs
• Update TOA estimates
NO
Check if the residual is satisfactory
• Current TOA Estimates
• Residual
400
300
YES
Return MT Location Estimate

FIG. 2

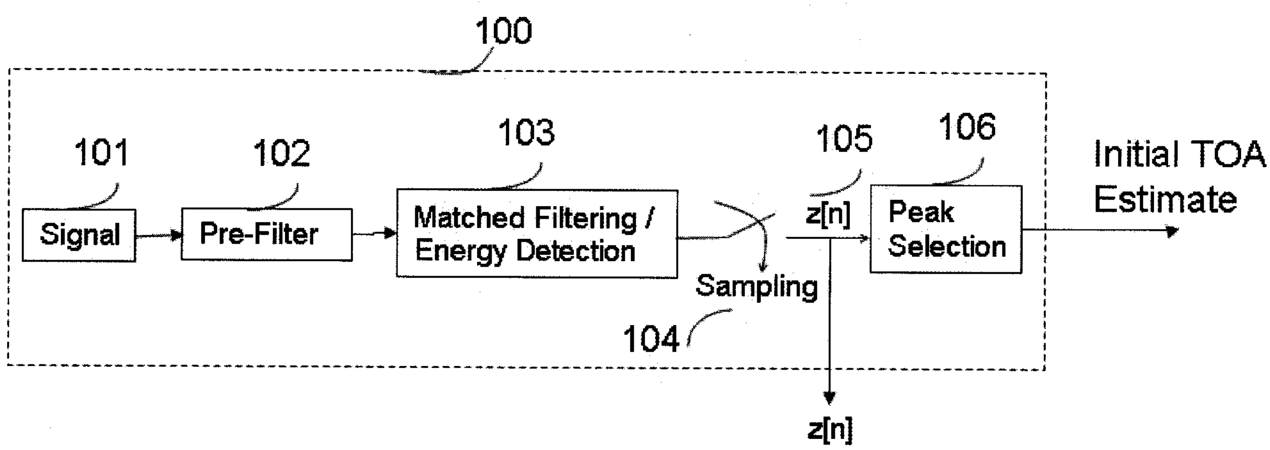

100
101
102
103
105
106
Initial TOA Estimate
Signal
Pre-Filter
Matched Filtering / Energy Detection
z[n]
Peak Selection
Sampling
104
z[n]

FIG. 3

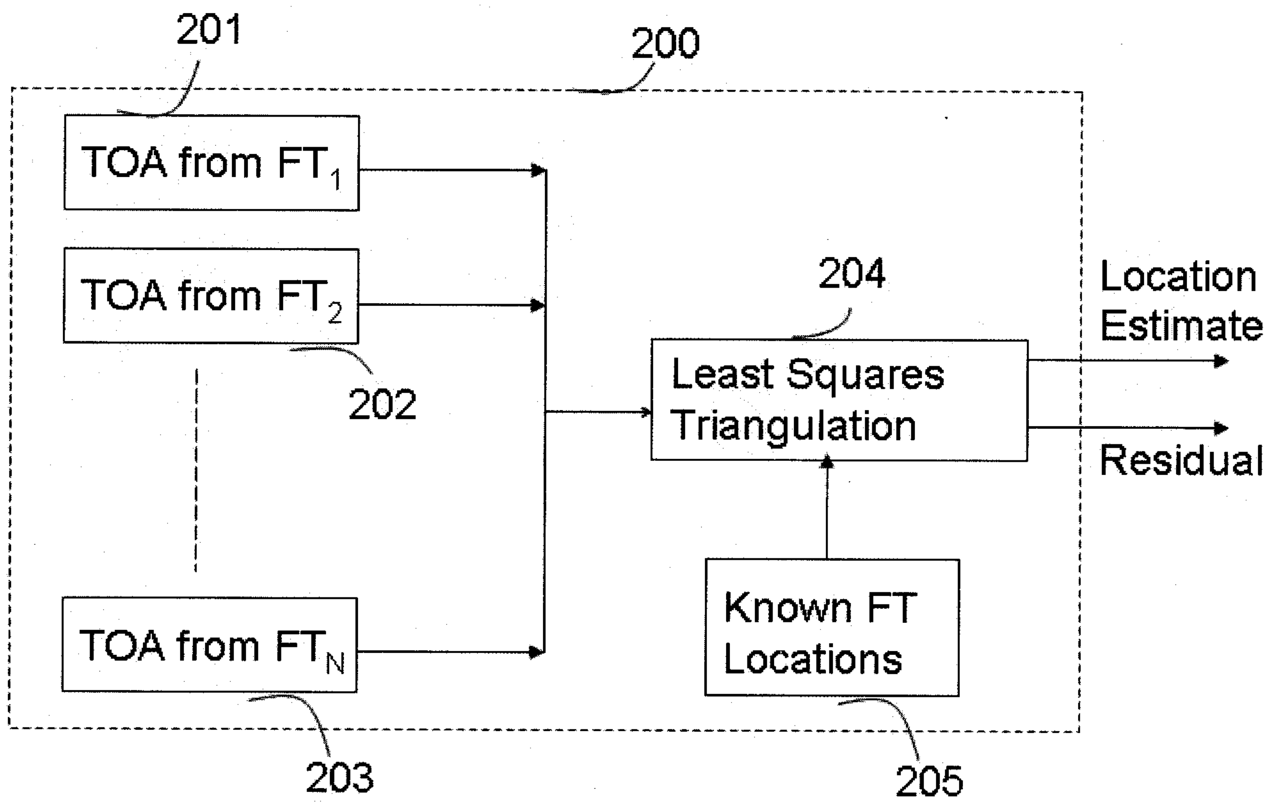

201
200
TOA from FT1
TOA from FT2
202
204
Location Estimate
Least Squares Triangulation
Residual
TOA from FTN
Known FT Locations
203
205

FIG. 4

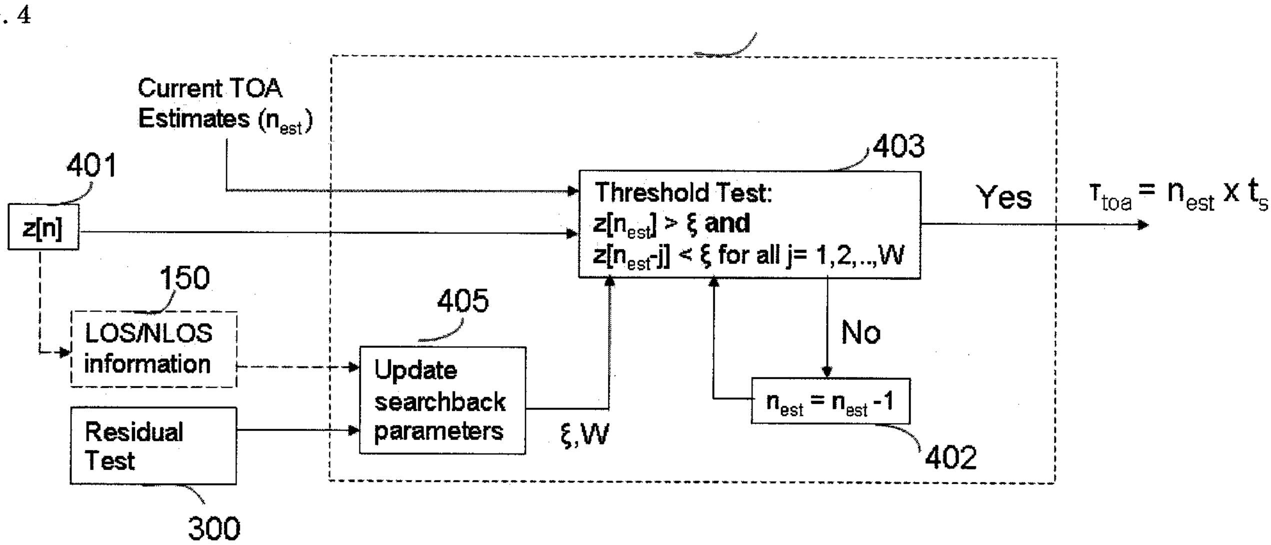

Current TOA Estimates (nest)
401
403
z[n]
Threshold Test:
z[nest] > ξ and
z[nest-j] < ξ for all j= 1,2,..,W
Yes
τtoa = nest x ts
150
405
LOS/NLOS information
No
Update searchback parameters
nest = nest -1
Residual Test
ξ,W
402
300

FIG. 5