US008068802B2

(12) **United States Patent**
Bhattacharya et al.

(10) **Patent No.: US 8,068,802 B2**
(45) **Date of Patent: *Nov. 29, 2011**

(54) **ESTIMATING THE LOCATION OF A WIRELESS TERMINAL BASED ON CALIBRATED SIGNAL-STRENGTH MEASUREMENTS**

(75) Inventors: **Tarun Kumar Bhattacharya**, San Jose, CA (US); **Martin Feuerstein**, Redmond, WA (US); **David Stevenson Spain, Jr.**, Portola Valley, CA (US)

(73) Assignee: **Polaris Wireless, Inc.**, Mountain View, CA (US)

(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 0 days.

This patent is subject to a terminal disclaimer.

(21) Appl. No.: **12/877,774**

(22) Filed: **Sep. 8, 2010**

(65) **Prior Publication Data**

US 2010/0329144 A1 Dec. 30, 2010

Related U.S. Application Data

(63) Continuation of application No. 11/080,861, filed on Mar. 15, 2005, now Pat. No. 7,796,966.

(51) **Int. Cl.**
H04B 7/00 (2006.01)

(52) **U.S. Cl.** **455/231**; 455/67.11; 455/67.13; 455/115.1

(58) **Field of Classification Search** 455/231, 455/67.11, 67.13, 115.1, 456, 67.14, 115.3, 455/456.1, 63.1
See application file for complete search history.

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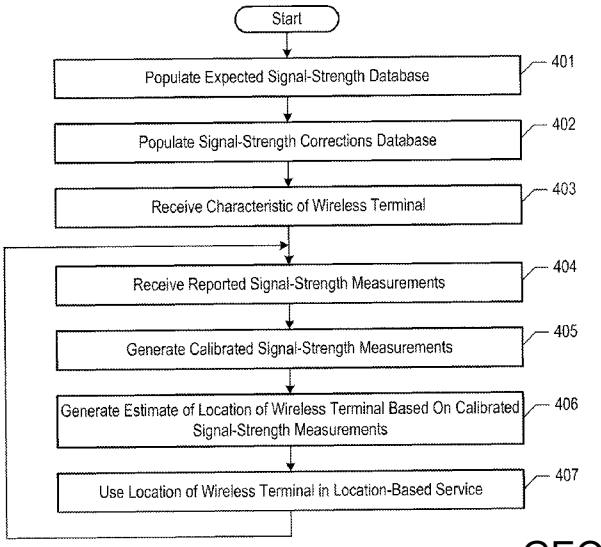
Primary Examiner — Minh D Dao
(74) *Attorney, Agent, or Firm* — DeMont & Breyer, LLC

(57) **ABSTRACT**

A process and machine for estimating the location of a wireless terminal is disclosed. The illustrative embodiment of the present invention is based on the observation that the signal strength of a signal from a transmitter is different at some locations, and, therefore, the location of a wireless terminal can be estimated by comparing the signal strength it currently observes against a map or database that correlates locations to signal strengths. In accordance with a first example, if a particular radio station is known to be received well at a first location and poorly at a second location, and a given wireless terminal at an unknown location is receiving the radio station poorly, it is more likely that the wireless terminal is at the second location than it is at the first location.

34 Claims, 23 Drawing Sheets



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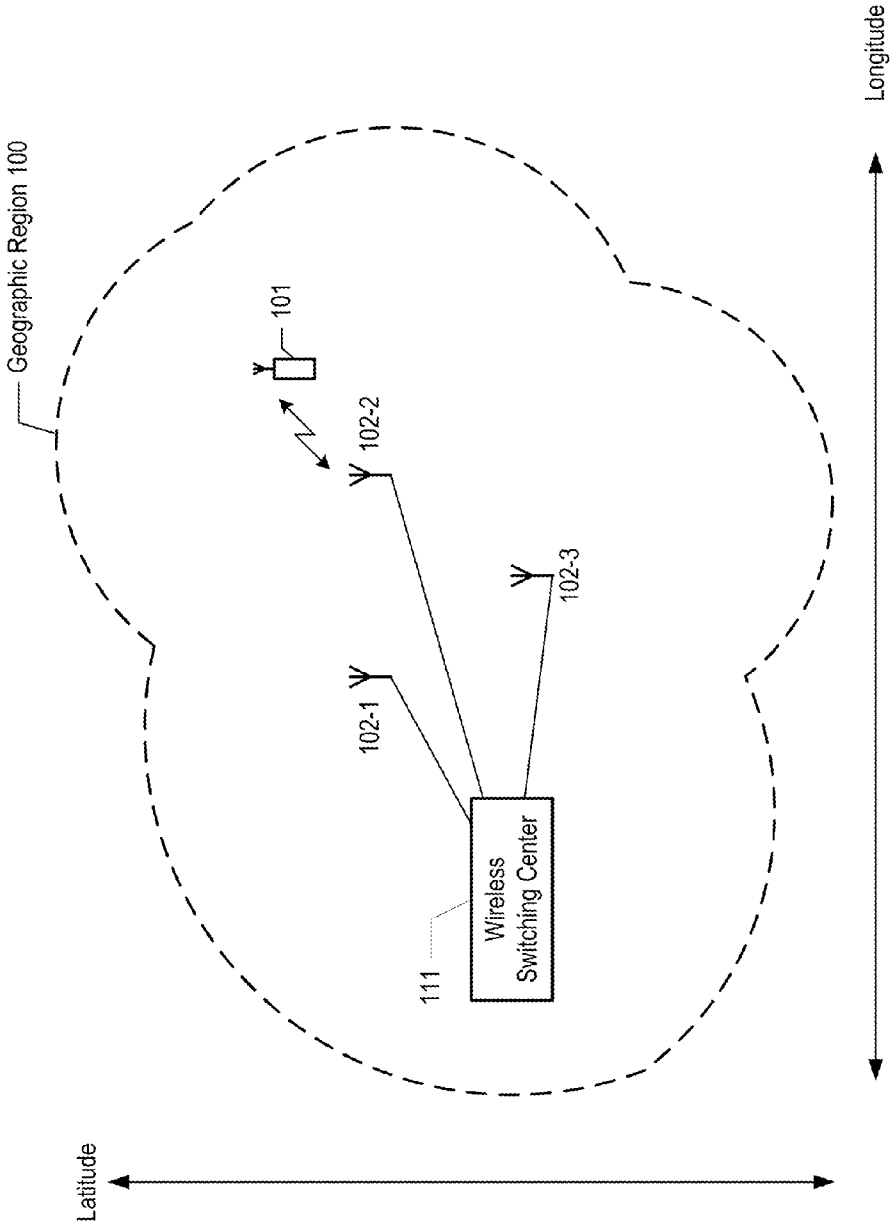


Figure 1 (Prior Art)

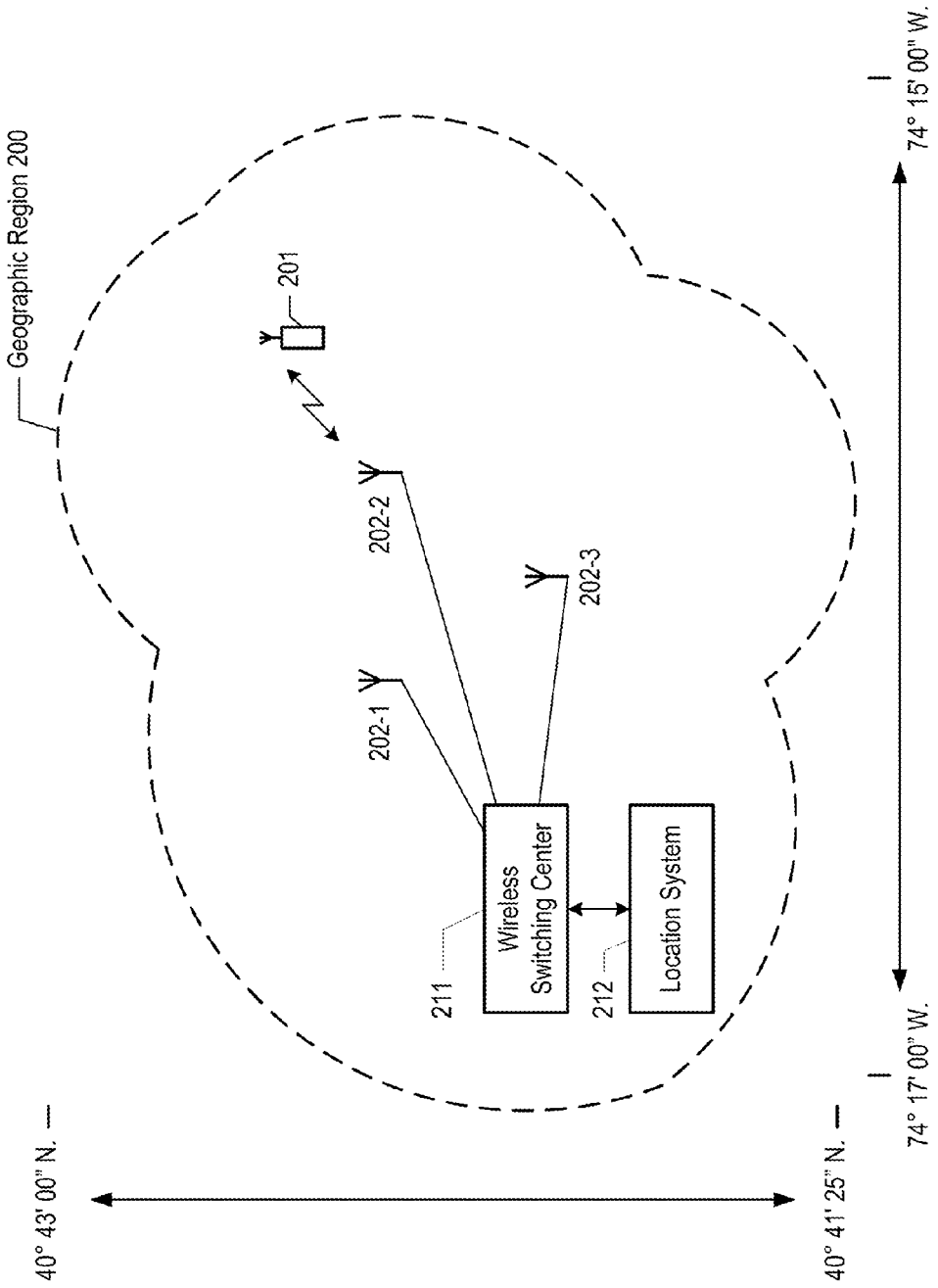

Geographic Region 200
201
202-1
202-2
202-3
Wireless Switching Center
Location System
211
212
40° 43' 00" N.
40° 41' 25" N.
74° 15' 00" W.
74° 17' 00" W.

Figure 2

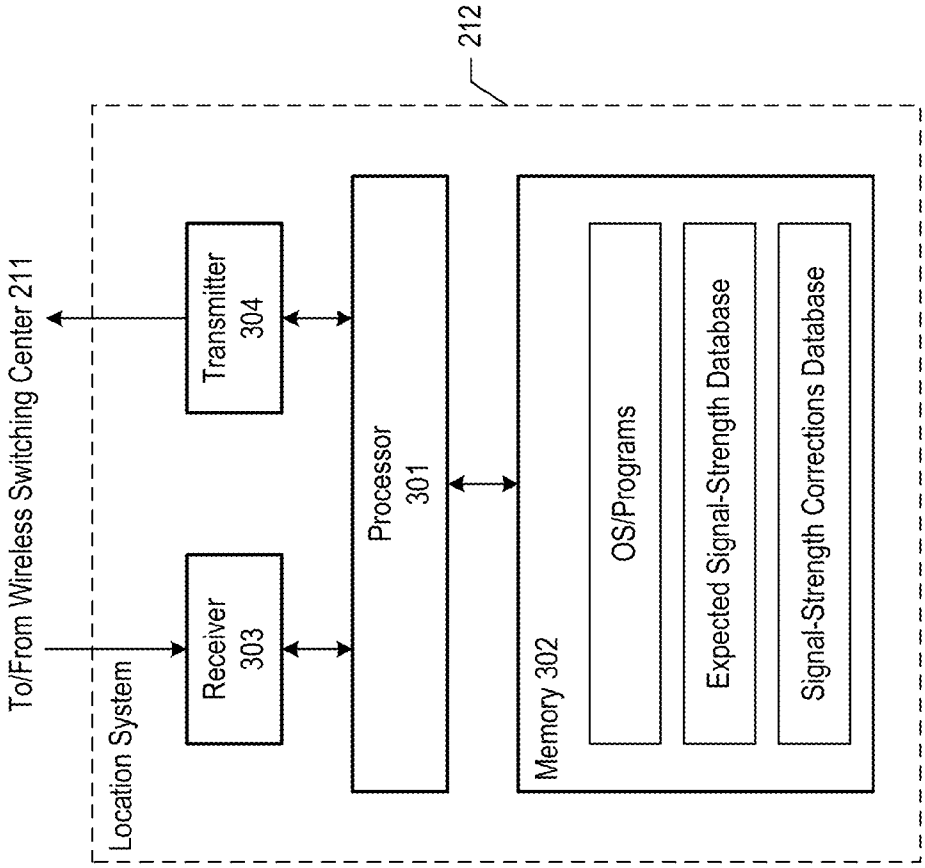

212
To/From Wireless Switching Center 211
Location System
Receiver 303
Transmitter 304
Processor 301
Memory 302
OS/Programs
Expected Signal-Strength Database
Signal-Strength Corrections Database

Figure 3

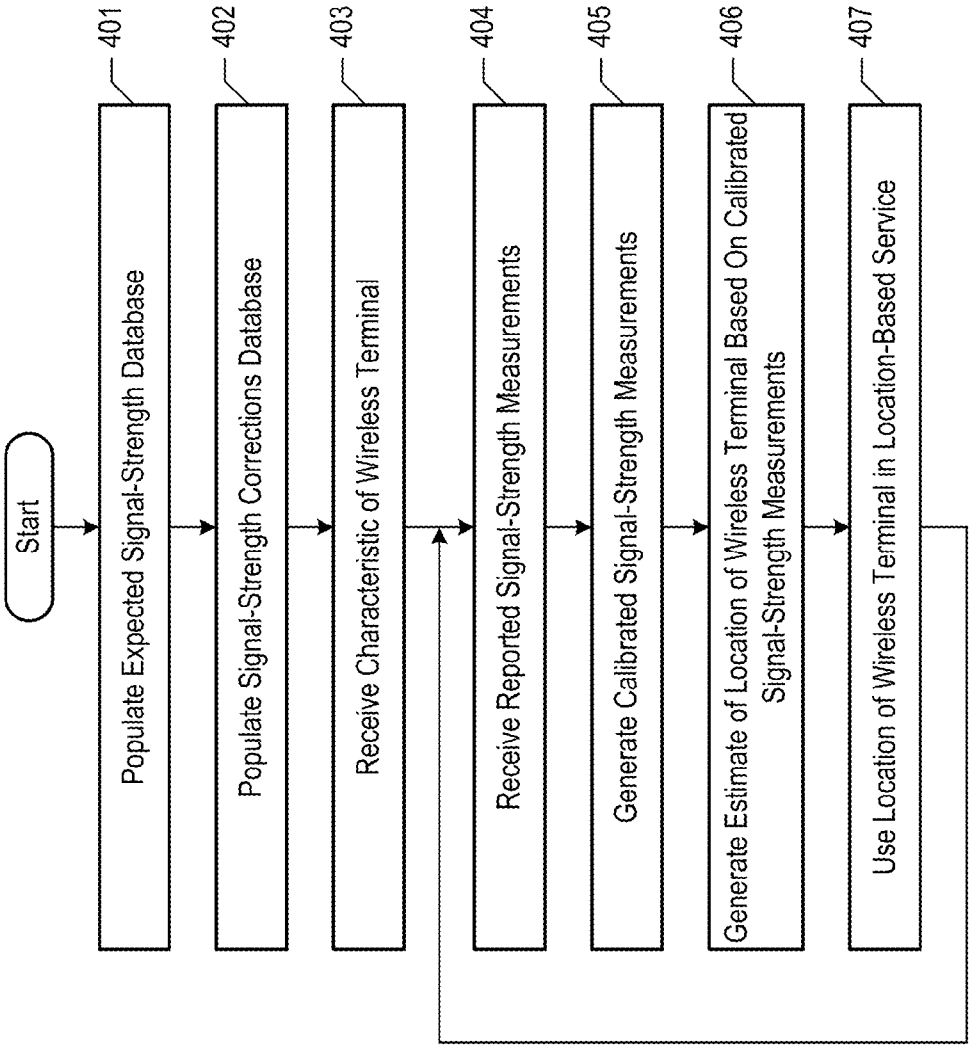

Start
401
Populate Expected Signal-Strength Database
402
Populate Signal-Strength Corrections Database
403
Receive Characteristic of Wireless Terminal
404
Receive Reported Signal-Strength Measurements
405
Generate Calibrated Signal-Strength Measurements
406
Generate Estimate of Location of Wireless Terminal Based On Calibrated Signal-Strength Measurements
407
Use Location of Wireless Terminal in Location-Based Service

Figure 4

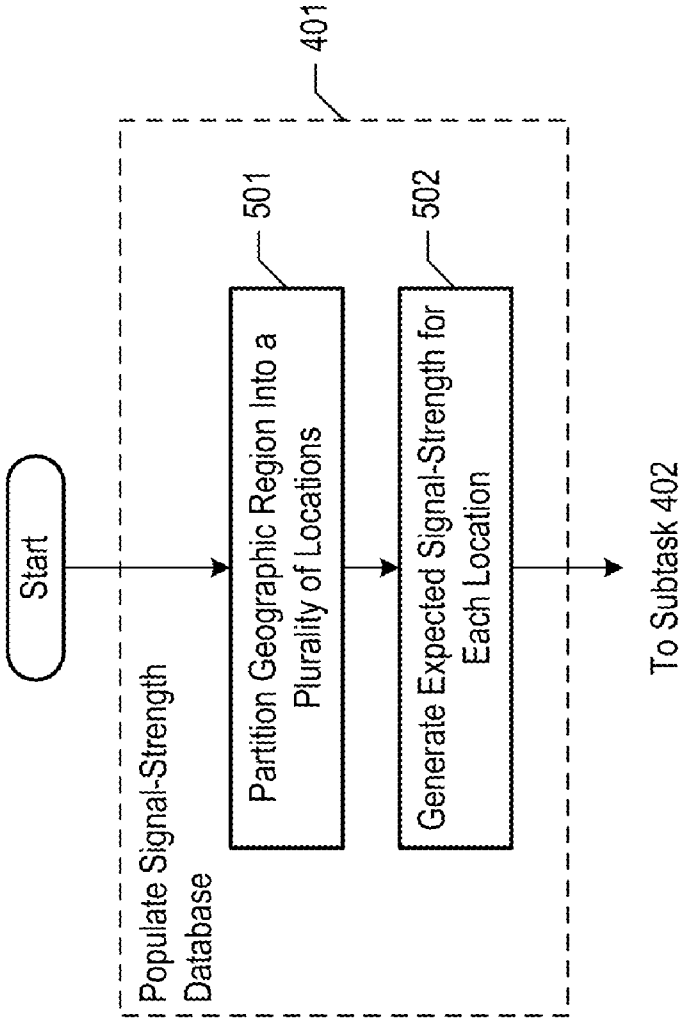

Start
Populate Signal-Strength Database
401
Partition Geographic Region Into a Plurality of Locations
501
Generate Expected Signal-Strength for Each Location
502
To Subtask 402

Figure 5

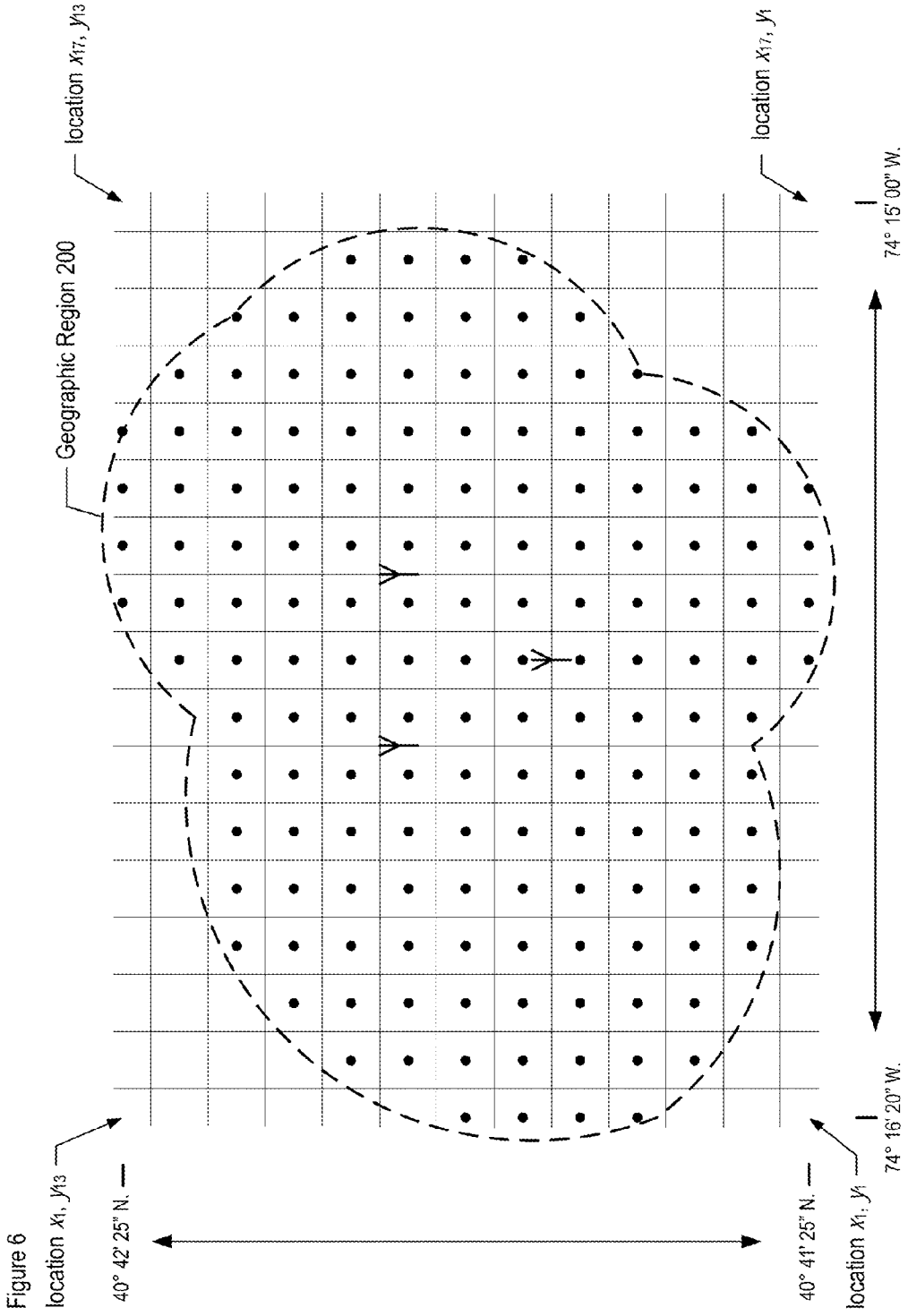

location x_{17}, y_{13}
location x_{17}, y_1
Geographic Region 200
74° 15' 00" W.
74° 16' 20" W.
location x_1, y_{13}
location x_1, y_1
40° 42' 25" N.
40° 41' 25" N.

Figure 6

Figure 7a

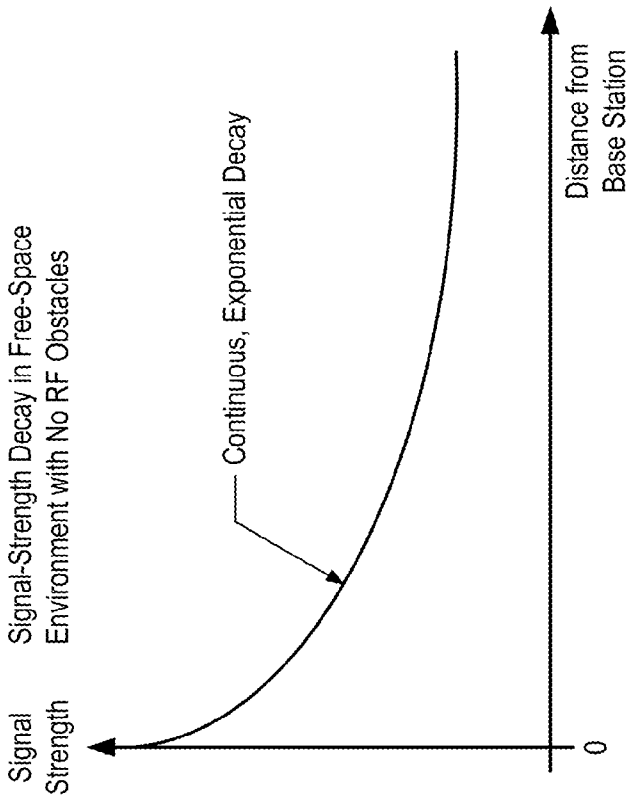


Figure 7b

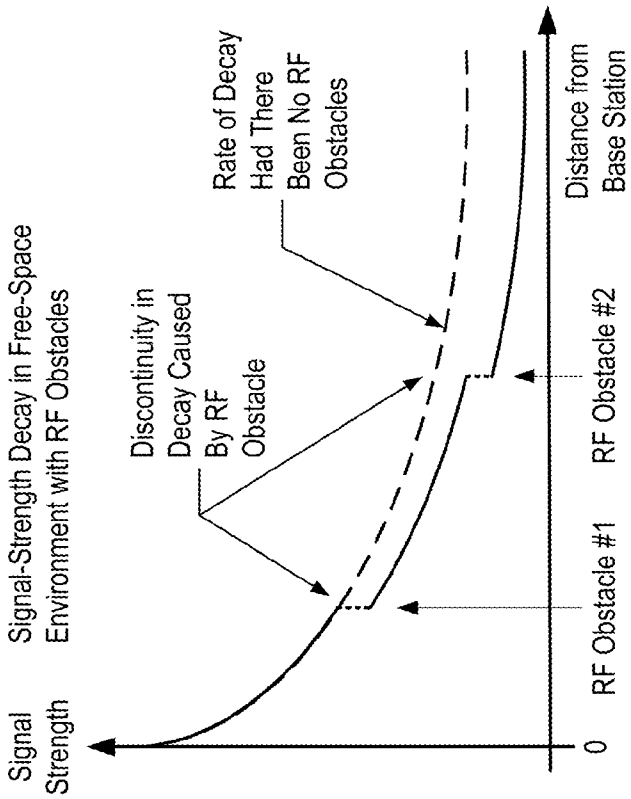


Figure 8

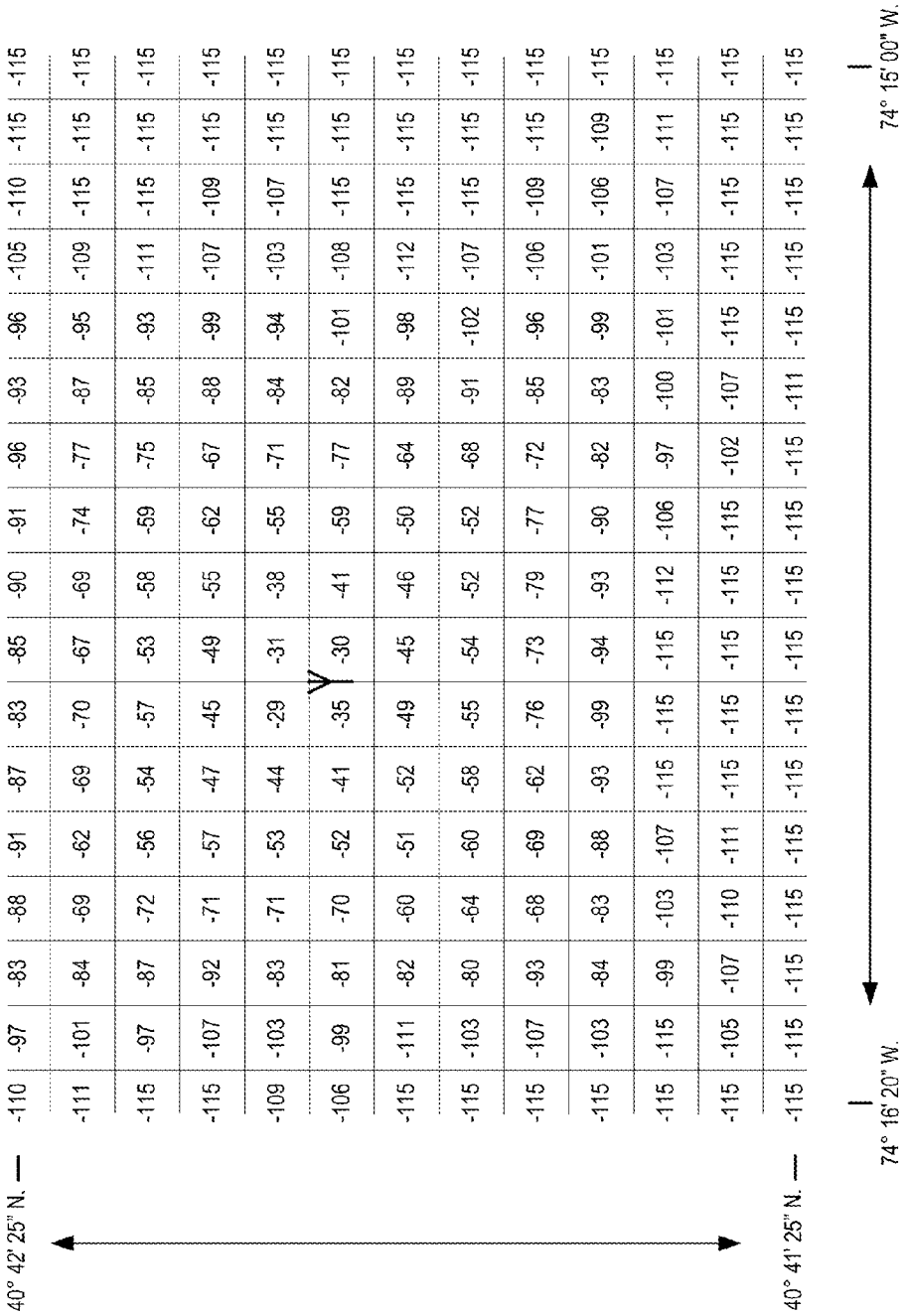

40° 42' 25" N.
40° 41' 25" N.
74° 16' 20" W.
74° 15' 00" W.
-110 -97 -83 -88 -91 -87 -83 -85 -90 -91 -96 -93 -96 -105 -110 -115 -115
-111 -101 -84 -69 -62 -69 -70 -67 -69 -74 -77 -87 -95 -109 -115 -115 -115
-115 -97 -87 -72 -56 -54 -57 -53 -58 -59 -75 -85 -93 -111 -115 -115 -115
-115 -107 -92 -71 -57 -47 -45 -49 -55 -62 -67 -88 -99 -107 -109 -115 -115
-109 -103 -83 -71 -53 -44 -29 -31 -38 -55 -71 -84 -94 -103 -107 -115 -115
-106 -99 -81 -70 -52 -41 -35 -30 -41 -59 -77 -82 -101 -108 -115 -115 -115
-115 -111 -82 -60 -51 -52 -49 -45 -46 -50 -64 -89 -98 -112 -115 -115 -115
-115 -103 -80 -64 -60 -58 -55 -54 -52 -52 -68 -91 -102 -107 -115 -115 -115
-115 -107 -93 -68 -69 -62 -76 -73 -79 -77 -72 -85 -96 -106 -109 -115 -115
-115 -103 -84 -83 -88 -93 -99 -94 -93 -90 -82 -83 -99 -101 -106 -109 -115
-115 -115 -99 -103 -107 -115 -115 -115 -112 -106 -97 -100 -101 -103 -107 -111 -115
-115 -105 -107 -110 -111 -115 -115 -115 -115 -115 -102 -107 -115 -115 -115 -115 -115
-115 -115 -115 -115 -115 -115 -115 -115 -115 -115 -115 -111 -115 -115 -115 -115 -115

Figure 9

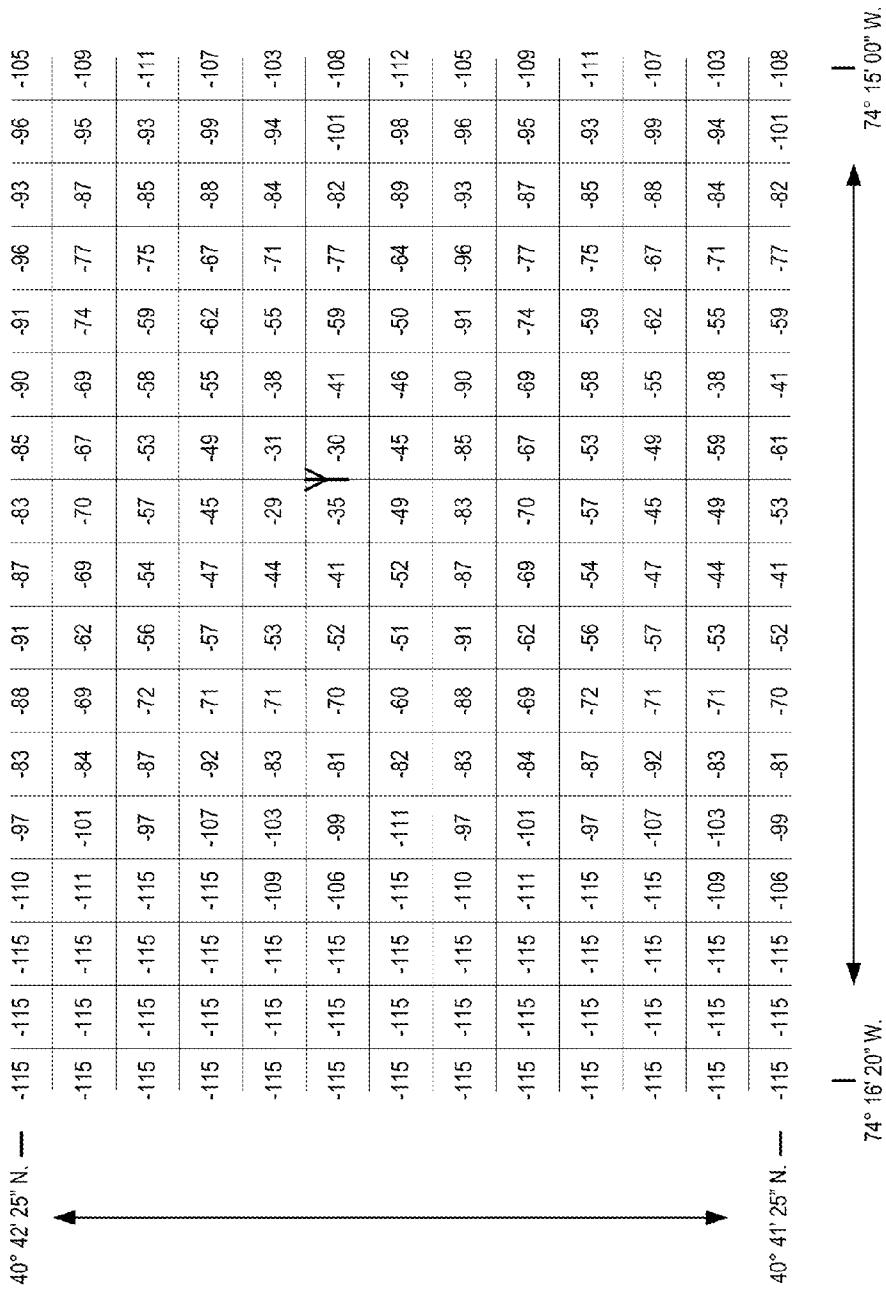

40° 42' 25" N.
40° 41' 25" N.
74° 16' 20" W.
74° 15' 00" W.
-115 -115 -115 -110 -97 -83 -88 -91 -87 -83 -85 -90 -91 -96 -93 -96 -105
-115 -115 -115 -111 -101 -84 -69 -62 -69 -70 -67 -69 -74 -77 -87 -95 -109
-115 -115 -115 -115 -97 -87 -72 -56 -54 -57 -53 -58 -59 -75 -85 -93 -111
-115 -115 -115 -115 -107 -92 -71 -57 -47 -45 -49 -55 -62 -67 -88 -99 -107
-115 -115 -115 -109 -103 -83 -71 -53 -44 -29 -31 -38 -55 -71 -84 -94 -103
-115 -115 -115 -106 -99 -81 -70 -52 -41 -35 -30 -41 -59 -77 -82 -101 -108
-115 -115 -115 -115 -111 -82 -60 -51 -52 -49 -45 -46 -50 -64 -89 -98 -112
-115 -115 -115 -110 -97 -83 -88 -91 -87 -83 -85 -90 -91 -96 -93 -96 -105
-115 -115 -115 -111 -101 -84 -69 -62 -69 -70 -67 -69 -74 -77 -87 -95 -109
-115 -115 -115 -115 -97 -87 -72 -56 -54 -57 -53 -58 -59 -75 -85 -93 -111
-115 -115 -115 -115 -107 -92 -71 -57 -47 -45 -49 -55 -62 -67 -88 -99 -107
-115 -115 -115 -109 -103 -83 -71 -53 -44 -49 -59 -38 -55 -71 -84 -94 -103
-115 -115 -115 -106 -99 -81 -70 -52 -41 -53 -61 -41 -59 -77 -82 -101 -108

Figure 10

40° 42' 25" N.	-115	-115	-115	-115	-115	-115	-115	-115	-115	-115	-115	-115	-115	-115	-115	-115	-115
	-115	-115	-115	-115	-115	-115	-115	-115	-115	-115	-115	-115	-115	-115	-115	-115	-115
	-115	-115	-115	-115	-115	-115	-115	-115	-115	-115	-115	-115	-115	-115	-115	-115	-115
	-115	108	-97	-83	-88	-91	-87	-83	-85	-90	-91	-96	-93	-96	-105	108	-115
	-115	-108	-101	-84	-69	-62	-69	-70	-67	-69	-74	-77	-87	-95	-109	-108	-115
	-115	-111	-97	-87	-72	-56	-54	-57	-53	-58	-59	-75	-85	-93	-103	-111	-115
	-115	-107	-107	-92	-71	-57	-47	-45	-49	-55	-62	-67	-88	-99	-105	-107	-115
	-115	-103	-103	-83	-71	-53	-44	-29	-31	-38	-55	-71	-84	-94	-103	-103	-115
	-115	-108	-99	-81	-70	-52	-41	-35	-30	-41	-59	-77	-82	-101	-108	-108	-115
	-115	-112	-111	-82	-60	-51	-52	-49	-45	-46	-51	-64	-89	-98	-112	-112	-115
	-115	-105	-97	-83	-88	-91	-87	-83	-85	-90	-91	-96	-93	-96	-105	-105	-115
	-115	-109	-101	-84	-69	-62	-69	-70	-67	-69	-74	-77	-87	-95	-109	-109	-115
40° 41' 25" N.	-115	-111	-97	-87	-72	-56	-54	-57	-53	-58	-59	-75	-85	-93	-111	-111	-115

74° 16' 20" W. 74° 15' 00" W.

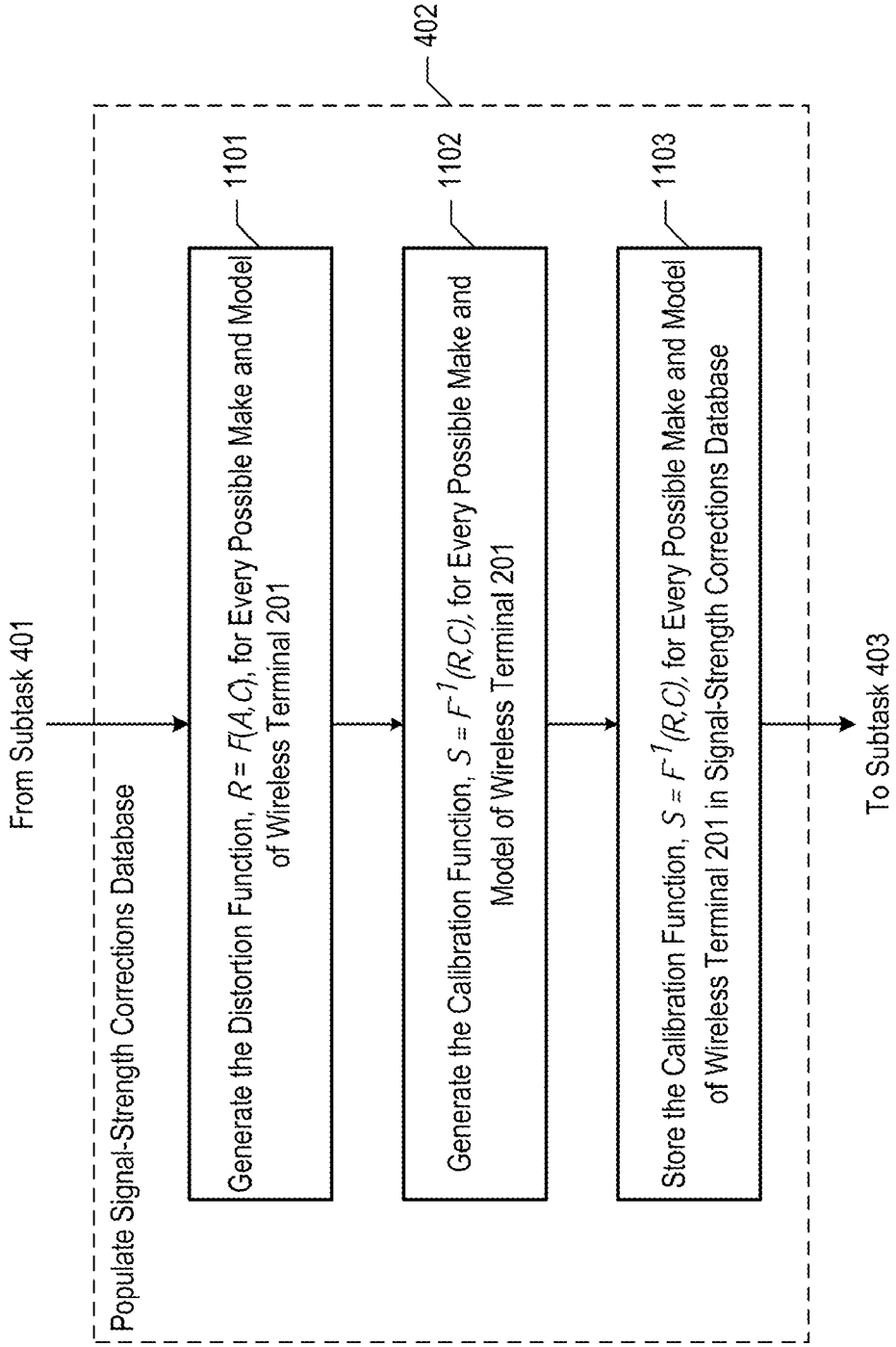

402
From Subtask 401
Populate Signal-Strength Corrections Database
1101
Generate the Distortion Function, $R = F(A,C)$, for Every Possible Make and Model of Wireless Terminal 201
1102
Generate the Calibration Function, $S = F^{-1}(R,C)$, for Every Possible Make and Model of Wireless Terminal 201
1103
Store the Calibration Function, $S = F^{-1}(R,C)$, for Every Possible Make and Model of Wireless Terminal 201 in Signal-Strength Corrections Database
To Subtask 403

Figure 11

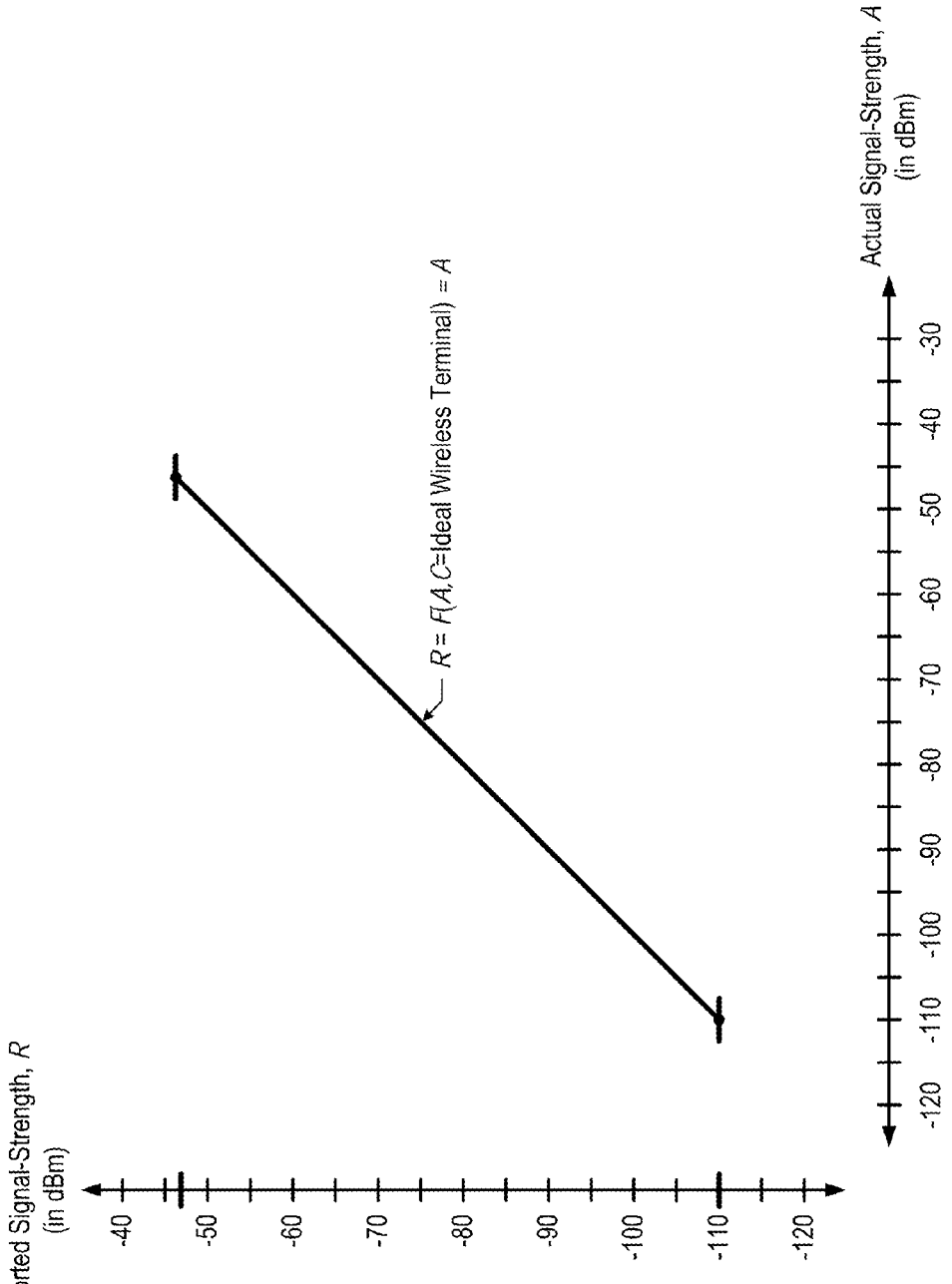
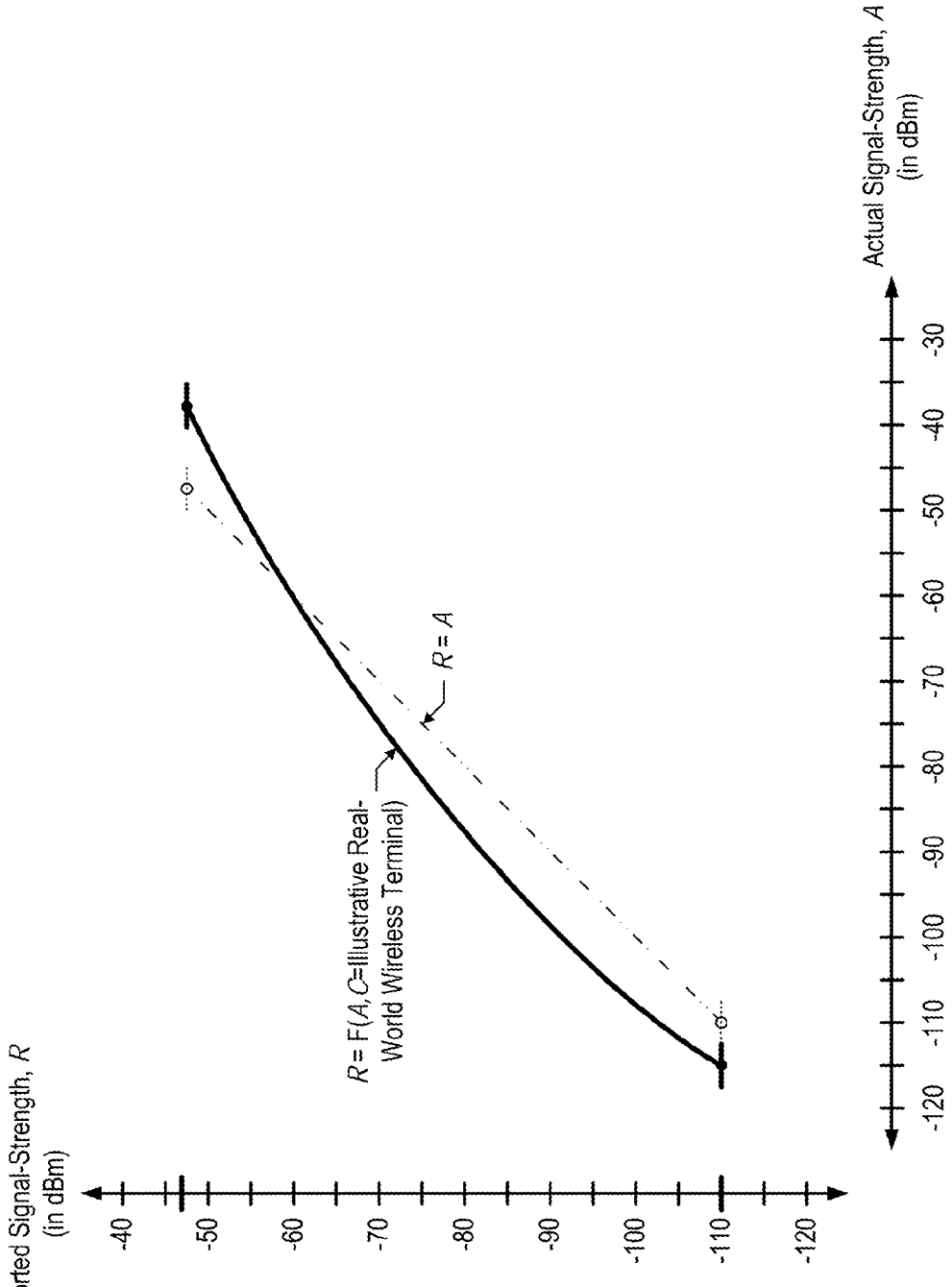

Reported Signal-Strength, R
(in dBm)
-40
-50
-60
-70
-80
-90
-100
-110
-120
R = F(A,C=Ideal Wireless Terminal) = A
Actual Signal-Strength, A
(in dBm)
-120
-110
-100
-90
-80
-70
-60
-50
-40
-30

Figure 12

Figure 13


Reported Signal-Strength, R
(in dBm)
-40
-50
-60
-70
-80
-90
-100
-110
-120
R = F(A,C=Illustrative Real-World Wireless Terminal)
R = A
Actual Signal-Strength, A
(in dBm)
-120
-110
-100
-90
-80
-70
-60
-50
-40
-30

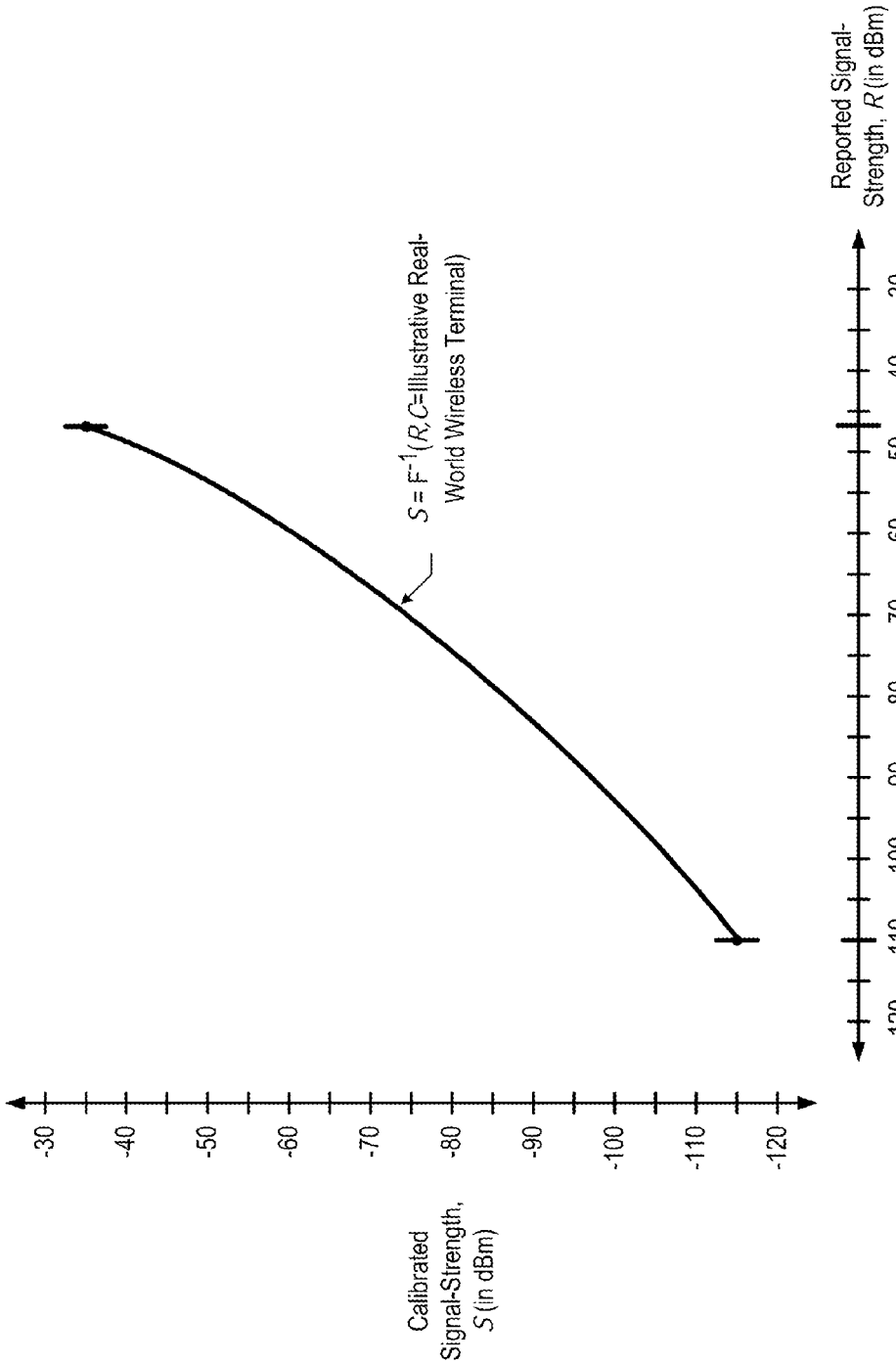

Calibrated Signal-Strength, S (in dBm)
-30
-40
-50
-60
-70
-80
-90
-100
-110
-120
S = F⁻¹(R,C=Illustrative Real-World Wireless Terminal)
Reported Signal-Strength, R (in dBm)
-120
-110
-100
-90
-80
-70
-60
-50
-40
-30

Figure 14

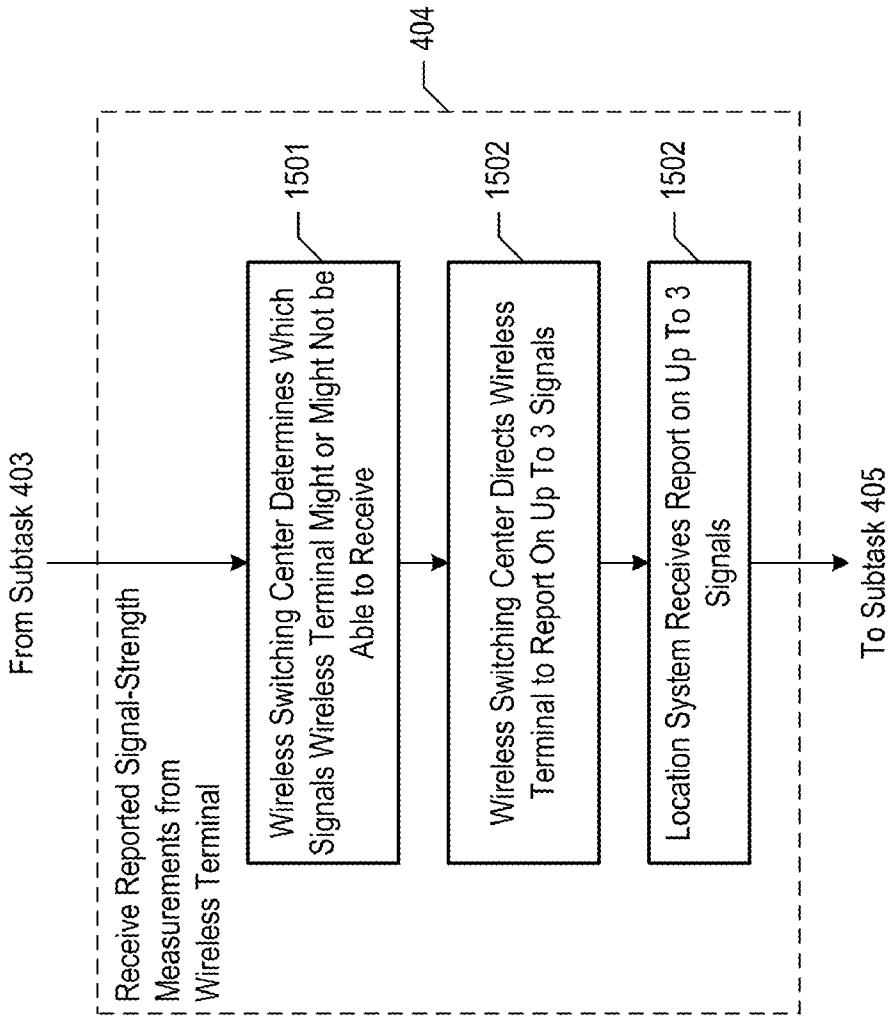

404
From Subtask 403
Receive Reported Signal-Strength Measurements from Wireless Terminal
1501
Wireless Switching Center Determines Which Signals Wireless Terminal Might or Might Not be Able to Receive
1502
Wireless Switching Center Directs Wireless Terminal to Report On Up To 3 Signals
1502
Location System Receives Report on Up To 3 Signals
To Subtask 405

Figure 15

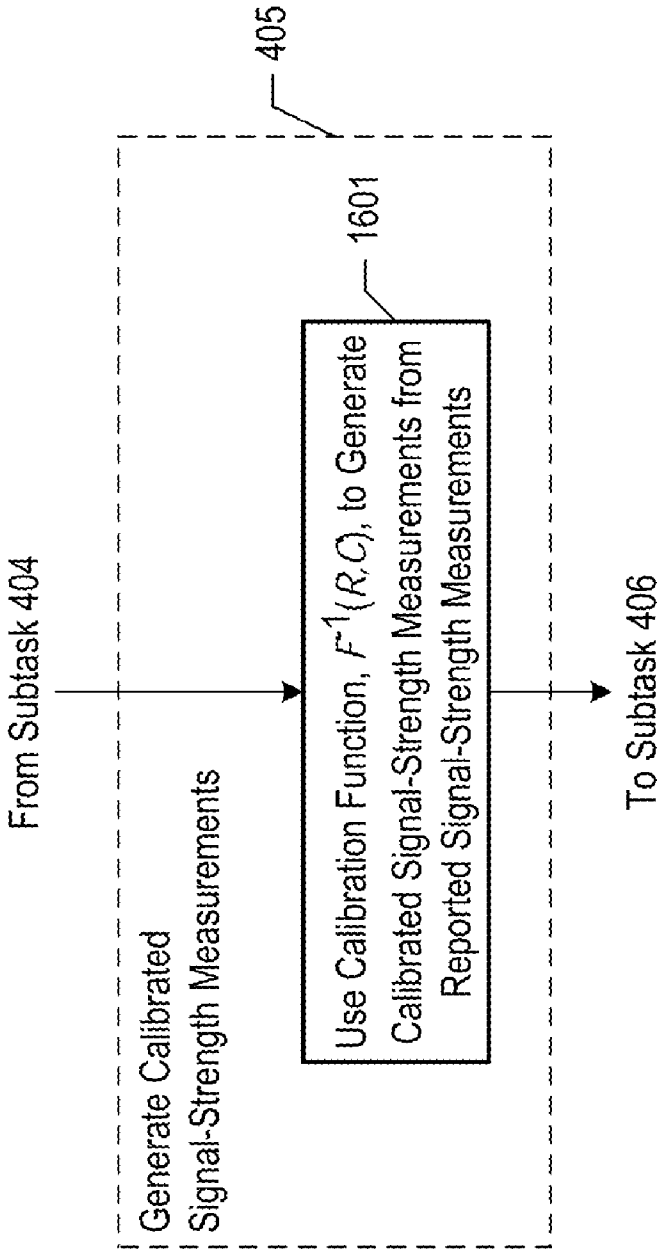

405
Generate Calibrated
Signal-Strength Measurements
From Subtask 404
1601
Use Calibration Function, $F^{-1}(R,C)$, to Generate
Calibrated Signal-Strength Measurements from
Reported Signal-Strength Measurements
To Subtask 406

Figure 16

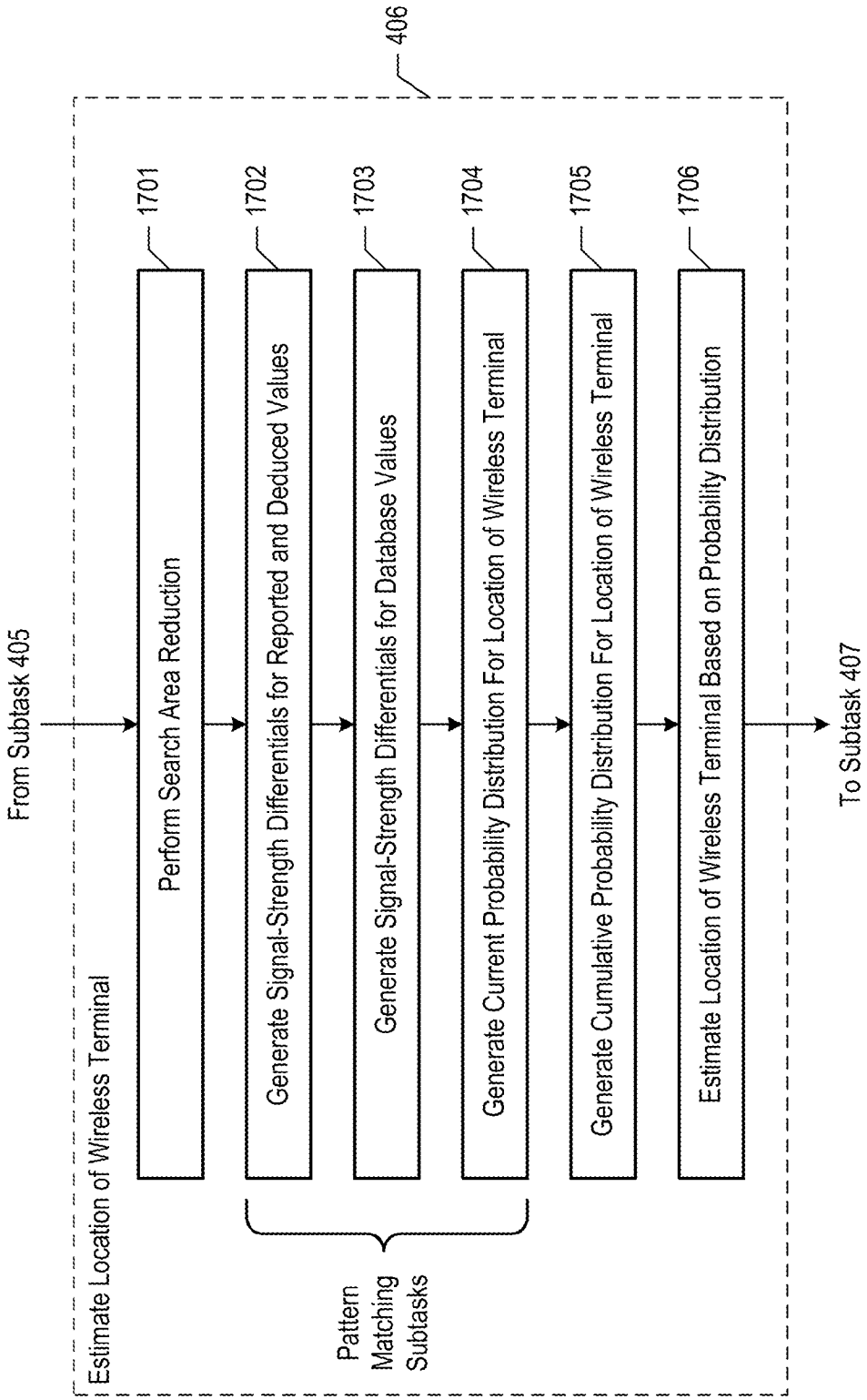

406
Estimate Location of Wireless Terminal
From Subtask 405
1701
Perform Search Area Reduction
1702
Generate Signal-Strength Differentials for Reported and Deduced Values
1703
Generate Signal-Strength Differentials for Database Values
1704
Generate Current Probability Distribution For Location of Wireless Terminal
1705
Generate Cumulative Probability Distribution For Location of Wireless Terminal
1706
Estimate Location of Wireless Terminal Based on Probability Distribution
Pattern Matching Subtasks
To Subtask 407

Figure 17

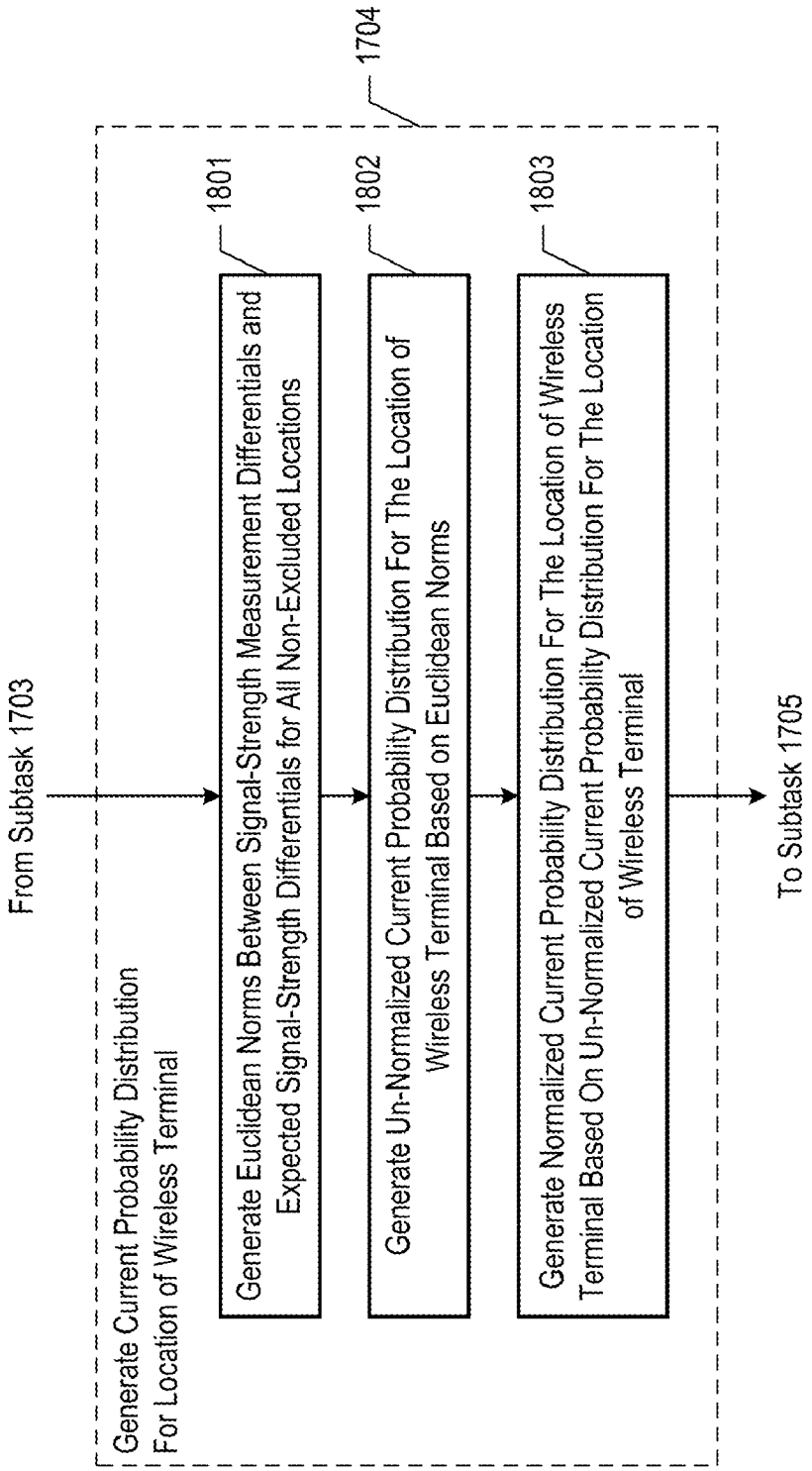

1704
Generate Current Probability Distribution For Location of Wireless Terminal
From Subtask 1703
1801
Generate Euclidean Norms Between Signal-Strength Measurement Differentials and Expected Signal-Strength Differentials for All Non-Excluded Locations
1802
Generate Un-Normalized Current Probability Distribution For The Location of Wireless Terminal Based on Euclidean Norms
1803
Generate Normalized Current Probability Distribution For The Location of Wireless Terminal Based On Un-Normalized Current Probability Distribution For The Location of Wireless Terminal
To Subtask 1705

Figure 18

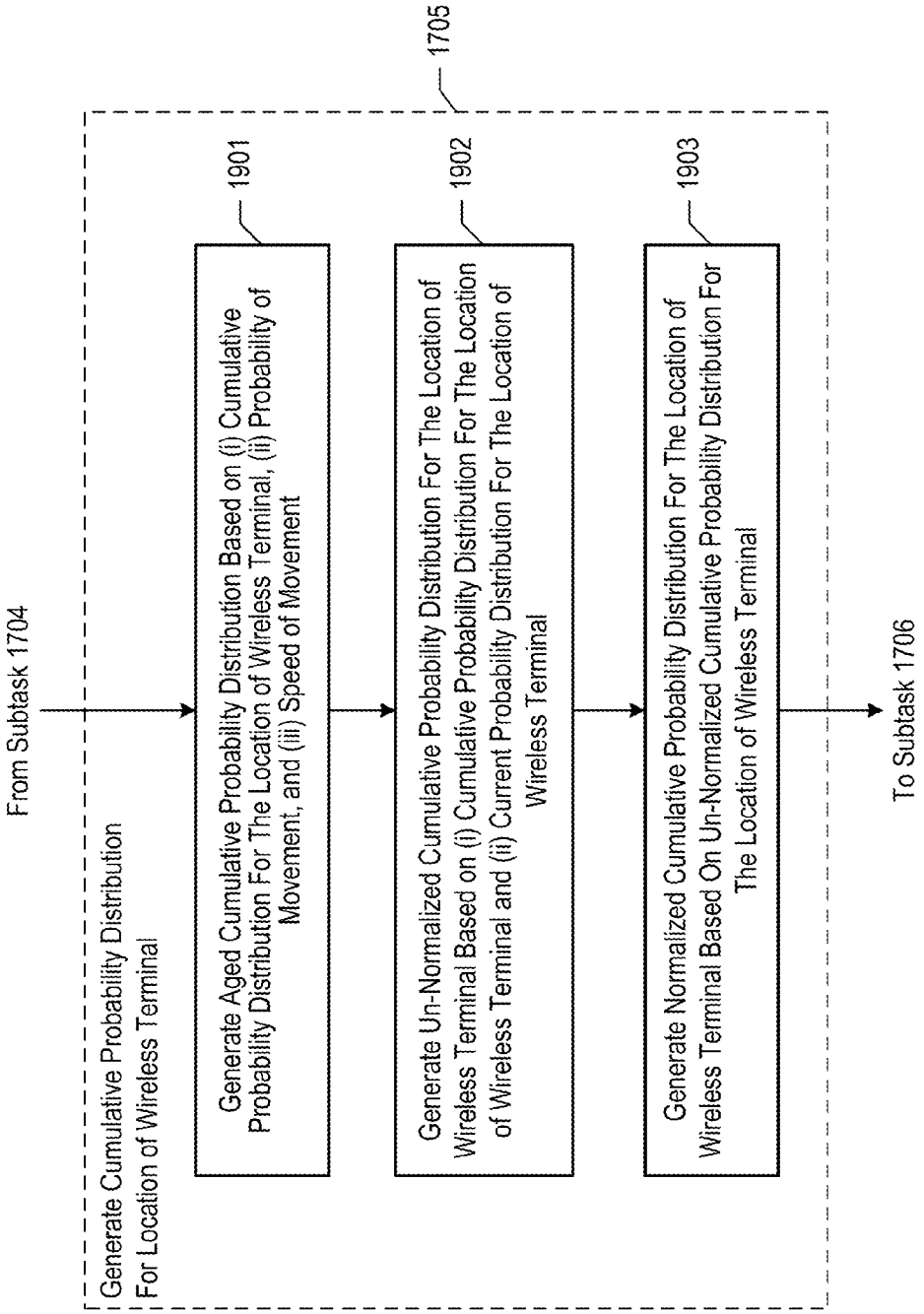

1705
From Subtask 1704
Generate Cumulative Probability Distribution For Location of Wireless Terminal
1901
Generate Aged Cumulative Probability Distribution Based on (i) Cumulative Probability Distribution For The Location of Wireless Terminal, (ii) Probability of Movement, and (iii) Speed of Movement
1902
Generate Un-Normalized Cumulative Probability Distribution For The Location of Wireless Terminal Based on (i) Cumulative Probability Distribution For The Location of Wireless Terminal and (ii) Current Probability Distribution For The Location of Wireless Terminal
1903
Generate Normalized Cumulative Probability Distribution For The Location of Wireless Terminal Based On Un-Normalized Cumulative Probability Distribution For The Location of Wireless Terminal
To Subtask 1706

Figure 19

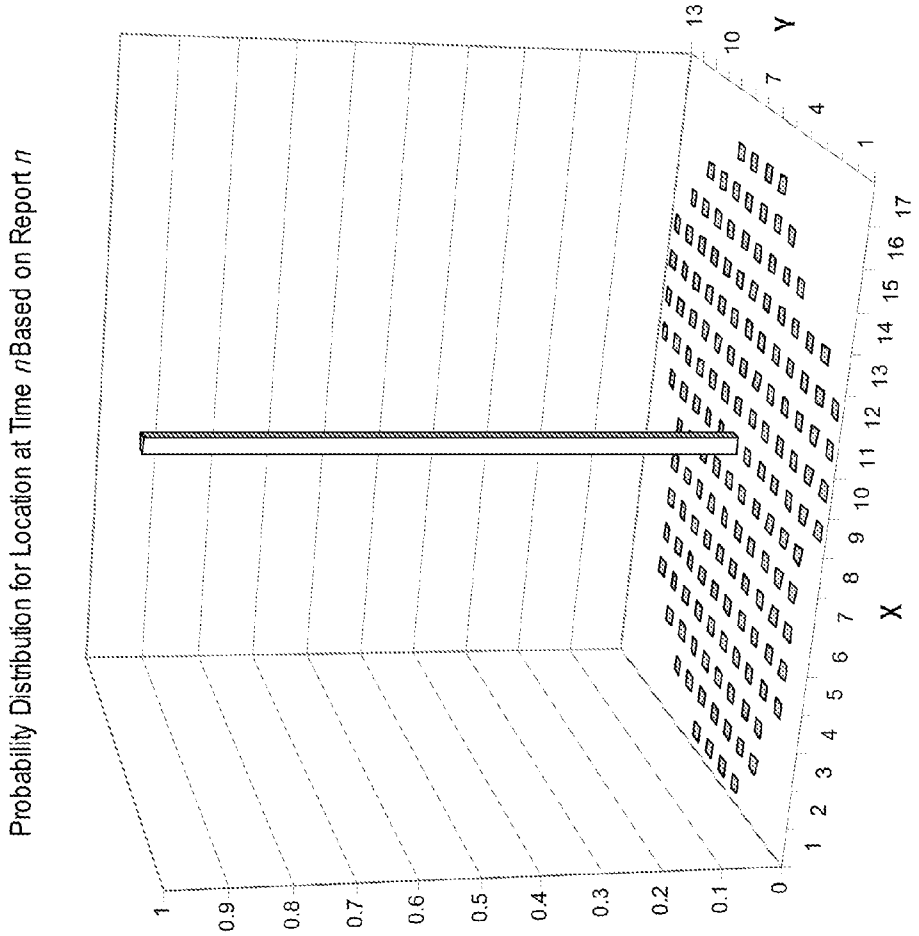

Probability Distribution for Location at Time nBased on Report n
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17
X
1 4 7 10 13
Y

Figure 20

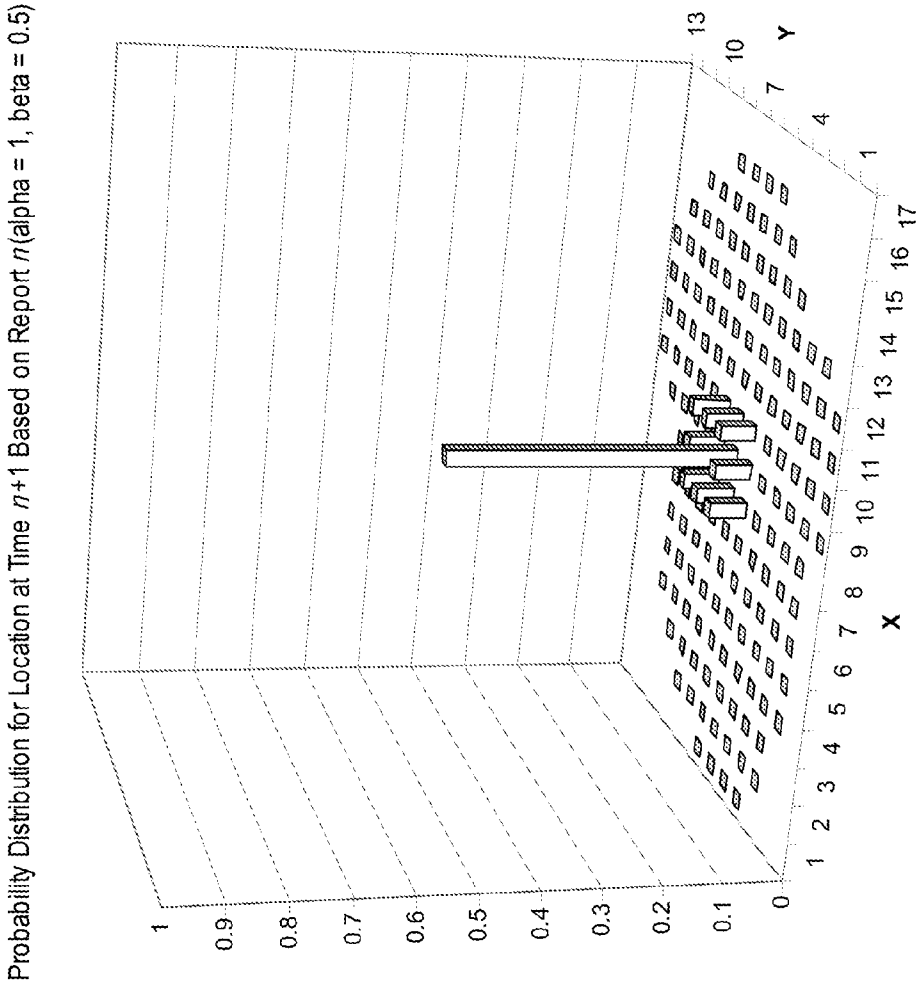

Probability Distribution for Location at Time n+1 Based on Report n(alpha = 1, beta = 0.5)
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17
X
1 4 7 10 13
Y

Figure 21

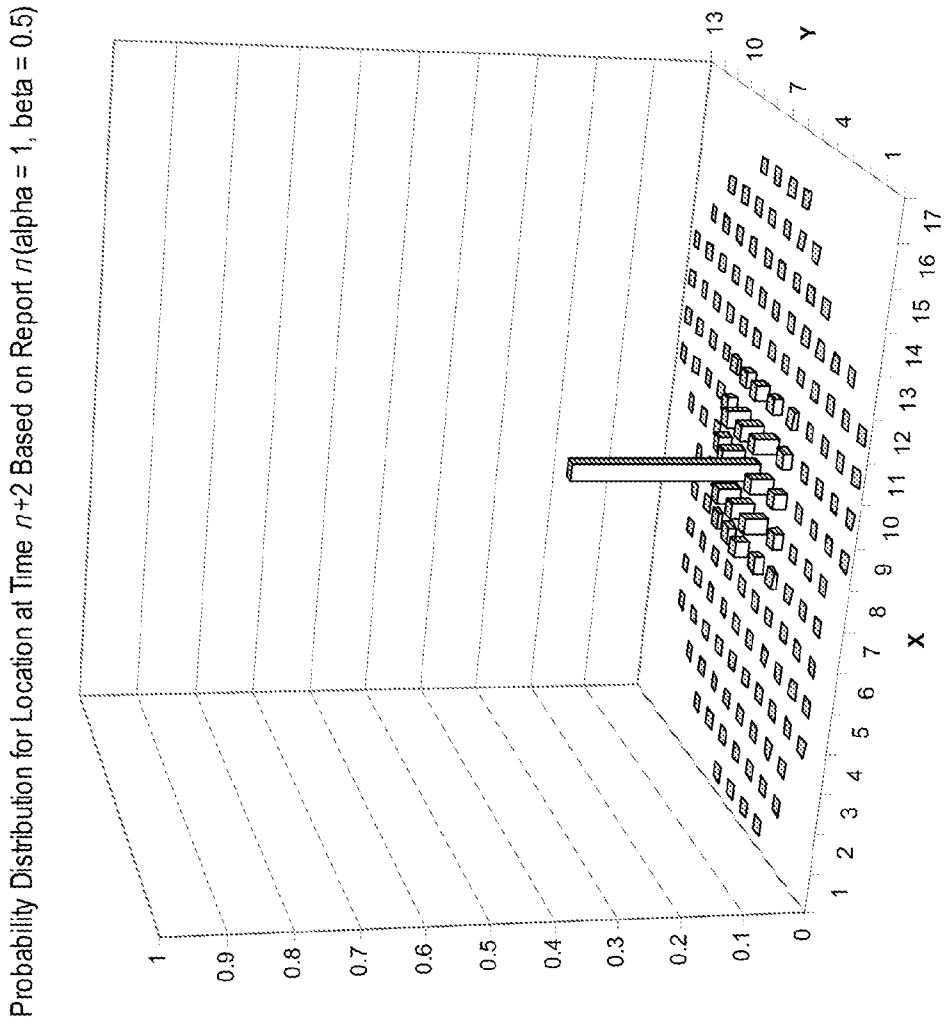

Probability Distribution for Location at Time n+2 Based on Report n(alpha = 1, beta = 0.5)
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17
X
1 4 7 10 13
Y

Figure 22

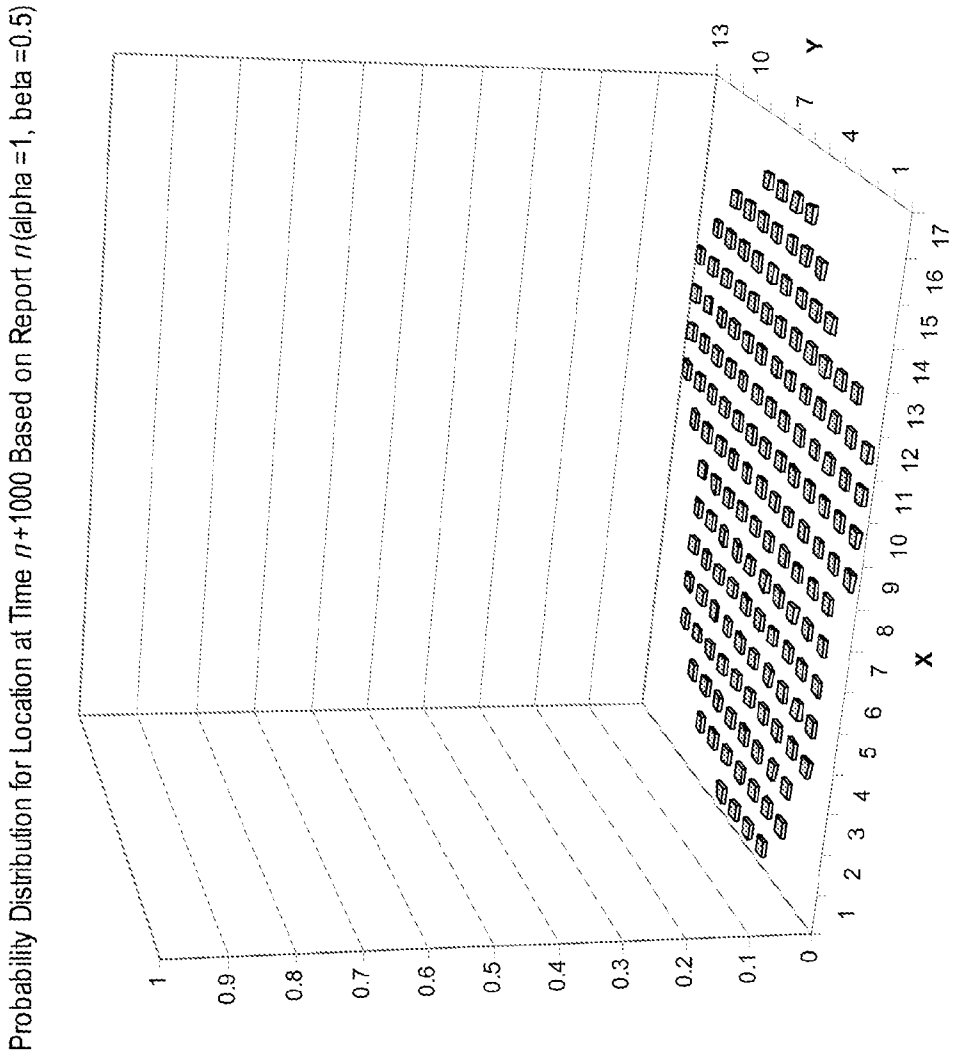

Probability Distribution for Location at Time n+1000 Based on Report n(alpha =1, beta =0.5)
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17
X
1 4 7 10 13
Y

Figure 23

ESTIMATING THE LOCATION OF A WIRELESS TERMINAL BASED ON CALIBRATED SIGNAL-STRENGTH MEASUREMENTS

CROSS REFERENCE TO RELATED APPLICATIONS

This application is a continuation of U.S. patent application Ser. No. 11/080,861, filed 15 Mar. 2005 which is incorporated by reference.

FIELD OF THE INVENTION

The present invention relates to telecommunications in general, and, more particularly, to a technique for estimating the location of a wireless terminal.

BACKGROUND

FIG. **1** depicts a map of a geographic region that is serviced by a wireless telecommunications system, which system provides wireless telecommunications service to wireless terminals (e.g., wireless terminal **101**) within the region. The heart of the telecommunications system is wireless switching center **110**, which might also be known as a mobile switching center ("MSC") or a mobile telephone switching office ("MTSO").

Typically, wireless switching center **111** is connected through a plurality of intermediate network elements (e.g., base station controllers, etc.) to a plurality of base stations (e.g., base stations **102-1**, **102-2**, and **102-3**), which are dispersed throughout the geographic area serviced by the system. As depicted in FIG. **1**, base station **102-2** serves wireless terminal **101**.

As is well known to those skilled in the art, wireless switching center **111** is responsible for, among other things, establishing and maintaining calls between wireless terminals and between a wireless terminal and a wireline terminal (which is connected to the system via the local and/or long-distance telephone networks and which are not shown in FIG. **1**).

The salient advantage of wireless telecommunications over wireline telecommunications is the mobility that is afforded to the users of the wireless telecommunications system. On the other hand, the salient disadvantage of wireless telecommunications lies in that fact that because the user is mobile, an interested party might not be able to readily ascertain the location of the user.

Such interested parties might include both the user of the wireless terminal and remote parties. There are a variety of reasons why the user of a wireless terminal might be interested in knowing his or her location. For example, the user might be interested in telling a remote party where he or she is.

There are a variety of reasons why a remote party might be interested in knowing the location of the user. For example, the recipient of a 911 emergency call from a wireless terminal might be interested in knowing the location of the wireless terminal so that emergency services vehicles can be dispatched to that location.

There are many techniques in the prior art for estimating the location of a wireless terminal.

In accordance with one technique, the location of a wireless terminal is estimated to be at the center of the cell in which the wireless terminal is located. This technique is advantageous in that it does not require that additional hardware be added to the wireless terminal or to the wireless telecommunications system, and, therefore, the first technique can be inexpensively implemented in legacy systems. The first technique is only accurate, however, to within a few kilometers, and, therefore, it is generally not acceptable for applications (e.g., emergency services dispatch, etc.) that require higher accuracy.

In accordance with a second technique, the location of a wireless terminal is estimated by triangulating the angle of arrival or the time of arrival of the signals transmitted by the wireless terminal to be located at various receivers. This technique is accurate to within a few hundreds of meters and is advantageous in that it can be used with legacy wireless terminals. It is disadvantageous, however, in that it generally requires that hardware be added to the telecommunication system's base stations. This causes the second technique to be very expensive.

In accordance with a third technique, the location of a wireless terminal is estimated by a radio navigation unit, such as, for example, a Global Positioning System (GPS) receiver, that is incorporated into the wireless terminal. This technique is accurate to within tens of meters and is advantageous in that it does not require that additional hardware be added to the telecommunication system's infrastructure. The third technique is disadvantageous, however, in that it cannot be used with legacy wireless terminals that do not comprise a radio navigation unit.

Therefore, the need exists for a technique for estimating the location of a wireless terminal with higher resolution than the first technique and that can be inexpensively implemented in legacy systems.

SUMMARY OF THE INVENTION

The present invention enables the estimation of the location of a wireless terminal without the addition of hardware to either the wireless terminal or to the telecommunication system's base stations. Some embodiments of the present invention are, therefore, ideally suited for use with legacy systems.

The illustrative embodiment of the present invention is based on the observation that the signal strength of a signal from a transmitter is different at some locations, and, therefore, the location of a wireless terminal can be estimated by comparing the signal strength it currently observes against a map or database that correlates locations to signal strengths. In accordance with a first example, if a particular radio station is known to be received well at a first location and poorly at a second location, and a given wireless terminal at an unknown location is receiving the radio station poorly, it is more likely that the wireless terminal is at the second location than it is at the first location.

When this same principal is applied to multiple transmitters and multiple signals, the location of a wireless terminal can be estimated with greater accuracy. A second example illustrates this point. A first radio station, Radio Station A, can be received well at Location **1** and Location **2**, but poorly at Location **3** and Location **4**, and a second radio station, Radio Station B, can be received well at Location **1** and Location **3**, but poorly at Location **2** and Location **4**. This information is summarized in the table below and forms the basis for a map or database that correlates location to expected signal strength.

TABLE 1

First Illustrative Expected Signal-Strength Database

	Radio Station A	Radio Station B
Location 1	Good Reception	Good Reception
Location 2	Good Reception	Poor Reception
Location 3	Poor Reception	Good Reception
Location 4	Poor Reception	Poor Reception

If a given wireless terminal at an unknown location can receive Radio Station A poorly and Radio Station B well, it is more likely that the wireless terminal is at Location **3** than it is at either Location **1**, **2**, or **4**.

The qualitative categorization of signal strengths is only useful when there are a small number of candidate locations for the wireless terminal and when no two locations have the same relative signal strength. For real-world applications—those in which there are hundreds or thousands of candidate locations—the estimated and measured signal strengths must be quantified.

In accordance with a third example, if a first radio station, Radio Station A, can be received at −56 dBm at Location **1**, −42 dBm at Location **2**, −63 dBm at Location **3**, and −61 dBm at Location **4**, and a second radio station, Radio Station B, can be received at −63 dBm at Location **1**, −56 dBm at Location **2**, −65 dBm at Location **3**, and −52 dBm at Location **4**. This information is summarized in the table below and forms the basis for a map or database that correlates location to expected signal strength.

TABLE 2

Second Illustrative Expected Signal-Strength Database

	Radio Station A	Radio Station B
Location 1	−56 dBm	−63 dBm
Location 2	−42 dBm	−56 dBm
Location 3	−63 dBm	−65 dBm
Location 4	−61 dBm	−52 dBm

If a given wireless terminal at an unknown location receives Radio Station A at −42 dBm and Radio Station B at −56 dBm, then the wireless terminal is more likely to be at Location **2** than it is at Location **1**, **3**, or **4**.

But if the design or manufacture of the wireless terminal is such that it does not measure signal strengths very accurately, the problem of matching signal-strength measurements to those at a location can become very difficult. A fourth example illustrates this point, if a given wireless terminal at an unknown location receives Radio Station A at −47 dBm and Radio Station B at −61 dBm, then it isn't at all readily apparent from Table 2 where the wireless terminal is most likely to be.

In accordance with the illustrative embodiment, the error in a wireless terminal's signal-strength measurements is compensated for based on some knowledge of how the wireless terminal incorrectly measures signal strength. For example, if one make and model of wireless terminal always measures a signal as 5 dBm less powerful than it actually is, the illustrative embodiment adds 5 dBm to the terminal's reported signal-strength measurements before it tries to match those measurements against the values in the expected signal-strength database. As a fifth example, if it is known that the wireless terminal in the fourth example above always measures a signal as 5 dBm less powerful than it actually is, then the reported measurements of −47 dBm and −61 dBm are calibrated to −42 dBm and −56 dBm, respectively. By using the calibrated signal-strength measurements, −42 dBm and −56 dBm, it is much more readily apparent that the wireless terminal is more likely to be at Location **2** than it is at Location **1**, **3**, or **4**.

This principal assumes, however, that the wireless terminal distorts the signal-strength measurements by a constant amount. In the real-world, however, this isn't generally so, and, therefore, the illustrative embodiment compensates for all kinds of distortions.

Wireless terminals of the same make and model can often report a different value for a signal's strength in the same location. This is due to various factors including the condition of the wireless terminal's antenna, the state of its battery, and whether the terminal is inside a vehicle.

The illustrative embodiment ameliorates the effects of these biases by pattern matching not the calibrated signal-strength measurements themselves to the predicted signal strengths themselves, but by pattern matching the pair-wise differentials of the calibrated signals strengths to the pair-wise differentials of the expected signal strengths.

TABLE 3

Third Illustrative Expected Signal-Strength Database

	Radio Station A	Radio Station B	Difference
Location 1	−56 dBm	−63 dBm	−7 dBm
Location 2	−42 dBm	−56 dBm	−14 dBm
Location 3	−63 dBm	−65 dBm	−2 dBm
Location 4	−61 dBm	−52 dBm	9 dBm

As a six example, if a given wireless terminal with a broken antenna and at an unknown location receives Radio Station A at −57 dBm and Radio Station B at −71 dBm, then it registers Radio Station A as 14 dBm stronger than Radio Station B. By matching the difference in the signal strengths between the two signals against their expected difference, this suggests that the wireless terminal is more likely to be at Location **2** than it is at Location **1**, **3**, or **4**. The illustrative embodiment also uses the differences in calibrated signal-strength measurements to estimate the location of a wireless terminal.

A disadvantage of this approach is that the common bias is eliminated at the expense of (1) doubling the variance of the random measurement noise, and (b) by reducing the number of data points to match by one. Furthermore, the pair-wise subtraction introduces correlation into the relative signal-strength measurement errors (i.e., all of the data points to be matched are statistically correlated). It will be clear to those skilled in the art how to account for this correlation in calculating the likelihood of the measurement report.

The illustrative embodiment comprises: receiving a first reported signal-strength measurement, R(1,n), from a wireless terminal; and generating a first calibrated signal-strength measurement, S(1,n), based on: (i) the first reported signal-strength measurement, R(1,n), and (ii) a characteristic, C, of the wireless terminal.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. **1** depicts a map of a portion of a wireless telecommunications system in the prior art.

FIG. **2** depicts a map of the illustrative embodiment of the present invention.

FIG. **3** depicts a block diagram of the salient components of location system **212** in accordance with the illustrative embodiment.

FIG. **4** depicts a broad overview of the salient tasks performed by the illustrative embodiment in estimating the location of wireless terminal **201** in geographic region **200**.

FIG. **5** depicts a flowchart of the salient subtasks performed as part of task **401**.

FIG. **6** depicts a map of how geographic region **200** is partitioned into 221 locations in accordance with the illustrative embodiment of the present invention.

FIG. **7***a* depicts a graph that illustrates how the signal strength of an electromagnetic signal decreases, in general, as a function of the distance from the transmitter and in an environment with no radio frequency obstacles.

FIG. **7***b* depicts a graph that illustrates how that the signal strength of an electromagnetic signal decreases, in general, as a function of the distance from the transmitter and in an environment with two radio frequency obstacles.

FIG. **8** depicts the expected signal strength, E(1,t=0), of Signal **1** at each location at one illustrative moment in time and under one set of atmospheric and meteorological conditions.

FIG. **9** depicts the expected signal strength, E(2,t=0), of Signal **2** at each location at one illustrative moment in time and under one set of atmospheric and meteorological conditions.

FIG. **10** depicts the expected signal strength, E(3,t=0), of Signal **3** at each location at one illustrative moment in time and under one set of atmospheric and meteorological conditions.

FIG. **11** depicts a flowchart of the salient subtasks performed as part of task **402**.

FIG. **12** depicts the distortion function F(A,C) for an ideal wireless terminal.

FIG. **13** depicts a graph of the relationship of reported signal-strength measurements as a function of actual signal strengths for an illustrative real-world wireless terminal.

FIG. **14** depicts a graph of the calibration function $F^{-1}(R, C)$ for the distortion function F(A,C) depicted in FIG. **13**.

FIG. **15** depicts a flowchart of the salient subtasks performed as part of task **404**.

FIG. **16** depicts a flowchart of the salient subtasks performed as part of task **405**.

FIG. **17** depicts a flowchart of the salient subtasks performed as part of task **406**.

FIG. **18** depicts a flowchart of the salient subtasks performed in subtask **1704**.

FIG. **19** depicts a flowchart of the salient subtasks performed in subtask **1705**.

FIG. **20** depicts a graph of the probability distribution for the location of wireless terminal **201** for the data depicted in Table 6.

FIG. **21** depicts a graph of the probability distribution for the location of wireless terminal **201** for the data depicted in Table 7.

FIG. **22** depicts a graph of the probability distribution for the location of wireless terminal **201** for the data depicted in Table 8.

FIG. **23** depicts a graph of the probability distribution for the location of wireless terminal **201** for the data depicted in Table 9.

DETAILED DESCRIPTION

FIG. **2** depicts a map of the illustrative embodiment of the present invention, which comprises: wireless switching center **211**, location system **212**, base stations **202-1**, **202-2**, and **202-3**, and wireless terminal **201**, which are interconnected as shown. The illustrative embodiment provides wireless telecommunications service to all of geographic region **200**, in well-known fashion, and is also capable of estimating the location of wireless terminal **201** within geographic region **200**, as described below.

The illustrative embodiment operates in accordance with the Global System for Mobile Communications (formerly known as the Groupe Speciale Mobile), which is ubiquitously known as "GSM," and the General Packet Radio Service, which is ubiquitously known as "GPRS." After reading this disclosure, however, it will be clear to those skilled in the art how to make and use alternative embodiments of the present invention that operate in accordance with other protocols, such as, for example, the Universal Mobile Telephone System ("UMTS"), CDMA-2000, IS-136 TDMA, Short Message Service, Circuit Switched Data, etc.

Wireless switching center **211** is a switching center as is well-known to those skilled in the art and is capable of relaying GPRS packet data back and forth between wireless terminal **201** and location system **212**. It will be clear to those skilled in the art how to make and use wireless switching center **211**. It will also be clear to those skilled in the art that wireless switching centers in the prior art are also known by other names, such as, for example, mobile switching center, mobile telephone switching offices, etc.

The illustrative embodiment comprises one wireless switching system, but after reading this disclosure it will be clear to those skilled in the art how to make and use alternative embodiments of the present invention that use two or more systems to obtain signal-strength measurements. Typically, this is useful when a wireless terminal is near the boundary of one or more systems. When two or more systems are used to obtain signal-strength measurements, one wireless switching center can use the IS-41 protocol messages HandoffMeasurementRequest and HandoffMeasurementRequest2 to elicit signal-strength measurements from another.

Base stations **202-1**, **202-2**, and **202-3** are well-known to those skilled in the art and communicate with wireless switching center **211** through cables and other equipment (e.g., base station controllers, etc.) that are not shown in FIG. **2**. As depicted in FIG. **2**, wireless terminal **201** is serviced by base station **202-2**. Although the illustrative embodiment comprises three base stations, it will be clear to those skilled in the art, after reading this disclosure, how to make and use alternative embodiments of the present invention that comprise any number of base stations.

Wireless terminal **201** is a GSM-compliant wireless terminal with GPRS packet data capability. After reading this disclosure, however, it will be clear to those skilled in the art how to make and use alternative embodiments of the present invention that operate in accordance with other protocols, such as, for example, the Universal Mobile Telephone System ("UMTS"), CDMA-2000, IS-136 TDMA, Short Message Service, and Circuit Switched Data, etc.

Wireless terminal **201** is equipped, in well-known fashion, with the hardware and software necessary to measure and report to wireless switching center **211** on the signal strength of signals from base stations **202-1**, **202-2**, and **202-3**. Furthermore, wireless terminal **201** is equipped with the software necessary to report to location system **212**, via GPRS packets, the characteristic, C, of wireless terminal **201**. The knowledge of the characteristic, C, is used by location system **212** to calibrate the reported signal-strength measurements transmitted by wireless terminal **201**. This is described in detail below and with respect to FIGS. **4**, **11**, and **16**. In accordance

with the illustrative embodiment, the characteristic, C, of wireless terminal **201** is the make and model of wireless terminal **201**.

In accordance with the illustrative embodiment of the present invention all of the specific portions of the radio frequency spectrum fall within the same band that wireless terminal **201** uses to communicate with base stations **202-1**, **202-2**, and **202-3**. In some alternative embodiments of the present invention, however, some or all of the signals measured and reported by wireless terminal **201** are outside the band that wireless terminal **201** uses to communicate with base stations **202-1**, **202-2**, and **202-3**. Those signals can be, for example, commercial television or radio signals, aviation navigation signals, etc. In any case, it will be clear to those skilled in the art, after reading this disclosure, how to make and use wireless terminal **201**.

Location system **212** is a data processing system that is capable of estimating the location of wireless terminal **201** in the manner described in detail below. Although the illustrative embodiment depicts location system **212** as estimating the location of only one wireless terminal—wireless terminal **201**—it will be clear to those skilled in the art, after reading this disclosure, how to make and use alternative embodiments of the present invention that are capable of estimating the location of any number of wireless terminals.

Location system **212** is capable of receiving reports from wireless switching center **211**, as described in detail below, which contain the reported signal-strength measurements from wireless terminal **201** for the base stations that are on wireless terminal **201**'s list of neighboring base stations. The reported signal-strength measurements in a report are made at substantially the same time, and the signal-strength measurements in different reports are made at substantially different times. It will be clear to those skilled in the art, however, after reading this disclosure, how to make and use alternative embodiments of the present invention in which a single report comprises reported signal-strength measurements made at substantially different, but documented, times.

Furthermore, although location system **212** is depicted in FIG. **2** as being physically distinct from wireless switching center **211**, it will be clear to those skilled in the art, after reading this disclosure, how to make and use alternative embodiments of the present invention in which location system **212** resides wholly or partially within wireless switching center **211**.

In accordance with the illustrative embodiment, location system **212** communicates with wireless switching center **211** via a local area network, but it will be clear to those skilled in the art, after reading this disclosure, how to make and use alternative embodiments of the present invention in which location system **212** communicates with wireless switching center **211** via a different network such as, for example, the Internet, the public telephone switched network, etc.

Furthermore, although wireless switching center **211**, location system **212**, and base stations **202-1**, **202-2**, and **202-3** are depicted in FIG. **2** as being within geographic region **200** (i.e., the region of candidate locations for wireless terminal **201**), this is not necessarily so, and it will be clear to those skilled in the art, after reading this disclosure, how to make and use alternative embodiments of the present invention in which some or all of these pieces of equipment are not within the region of location estimation.

FIG. **3** depicts a block diagram of the salient components of location system **212** in accordance with the illustrative embodiment. Location system **212** comprises: processor **301**, memory **302**, receiver **303**, and transmitter **304**, which are interconnected as shown.

Processor **301** is a general-purpose processor as is well-known in the art that is capable of executing the operating system and user programs in memory **302**, and of populating, amending, accessing, and generally managing the Expected Signal-Strength Database and the Signal-Strength Corrections Database in memory **302**. The user programs perform the tasks described below and with respect to FIGS. **4** through **18**. Processor **302** is also capable of receiving input from receiver **303** and sending output to transmitter **304** in well-known fashion.

Memory **302** is a non-volatile memory that stores:

i. the operating system and user programs for processor **301**,

ii. the Expected Signal-Strength Database, and

iii. the Signal-Strength Corrections Database,

as described below and with respect to FIGS. **4** through **18**.

Receiver **303** receives information from wireless switching center **211** and wireless terminal **201**, as disclosed below and with respect to FIG. **4**, and forwards this information to processor **302**.

Transmitter **304** receives output from processor **301** and transmits it to wireless switching center **211** and to wireless terminal **201** via wireless switching center **211** and GPRS.

Overview—FIG. **4** depicts a broad overview of the salient tasks performed by the illustrative embodiment in estimating the location of wireless terminal **201**. The overall process of estimating the location of wireless terminal **201** is described as comprising seven distinct tasks. It will be clear to those skilled in the art, however, after reading this disclosure, that the operations associated with some of these tasks can occur:

i. concurrently, or

ii. in a different order, or

iii. together in one task, or

iv. or any combination of i, ii, and iii.

The process of estimating the location of wireless terminal **201** comprises seven tasks:

i. populating the Expected Signal-Strength Database,

ii. populating the Signal-Strength Corrections Database,

iii. receiving the characteristic of wireless terminal **201**,

iv. receiving the reported signal-strength measurements from wireless terminal **201**,

v. generating the calibrated signal-strength measurements based on (1) the reported signal-strength measurements and (2) the characteristic of wireless terminal **201**,

vi. generating a current estimate of the location of wireless terminal **201** based on (1) the calibrated signal-strength measurements and (2) previous estimates of the location of wireless terminal **201**, and

vii. using the estimated location of wireless terminal **201** in a location-based service.

The details of each of these tasks are described briefly below and in detail afterwards with respect to FIGS. **4** though **17**.

At task **401**, the Expected Signal-Strength Database is populated with the expected signal strengths of three signals at each location in geographic region **200**. The three signals are Signal **1**, Signal **2**, and Signal **3**.

Signal **1** is the control channel broadcast by base station **202-1** and its expected signal strength at location x,y at time t is represented by the function E(1,x,y,t). Signal **2** is the overhead control channel broadcast by base station **202-2** and its expected signal strength at location x,y at time t is represented by the function E(2,x,y,t). Signal **3** is the overhead control channel broadcast by base station **202-2** and its expected signal strength at location x,y at time t is represented by the function E(3,x,y,t). For a given x,y location and time, these three functions together yield a 3-tuple of expected signal strengths designated as {E(1), E(2), E(3)}.

The control channels are used because they are broadcast at a constant power and because wireless terminal **201** can distinguish them from each other by their Base Station Identity Code. Task **401** is generally complex and potentially expensive, and it is, therefore, performed only when necessary. The details of task **401** are described in detail below and with respect to FIGS. **5** through **10**.

At task **402**, the Signal-Strength Corrections Database is populated with the calibration function for every possible make and model of wireless terminal **201**. The calibration function enables location system **212** to calibrate the reported signal-strength measurements from wireless terminal **201** based on the make and model of wireless terminal. The details of task **402** are described in detail below and with respect to FIGS. **11** through **14**.

At task **403**, location system **212** receives a characteristic, C, of wireless terminal **201**. In accordance with the illustrative embodiment, the characteristic, C, of wireless terminal **201** is the make and model of wireless terminal **201**, and the characteristic, C, are received by location system **212** via GPRS packet data from wireless terminal **201** in response to a query for it from location system **212**. It will be clear to those skilled in the art, after reading this disclosure, how to enable wireless terminal **201** to transmit and location system **212** to receive a characteristic, C, of wireless terminal **201**.

In some alternative embodiments of the present invention, location system **212** receives the characteristic, C, of wireless terminal **201** from another source than wireless terminal **201**. For example, location system **201** could be given the characteristic from the owner/operator of wireless switching center **211** when wireless terminal **201** is registered for service. This is advantageous in that it obviates the need for wireless terminal **201** to transmit the characteristic.

At task **404**, location system **212** periodically receives a Signal-Strength Measurement Report from wireless terminal **201** at discrete relative time n, wherein n is a non-negative integer. Signal-Strength Measurement Report n comprises:

i. a tuple of reported signal-strength measurements {R(1, n), R(2,n), R(3,n)},

ii. the real time, t, at which the signal-strength measurements were made, and

iii. a value of n, which indicates the relative order in which the signal-strength measurements are made.

R(1,n) is the nth reported signal-strength measurement of Signal **1** as measured by wireless terminal **201** at time t. Analogously, R(2,n) is the nth reported signal-strength measurement of Signal **2** as measured by wireless terminal **201** at time t, and R(3,n) is the nth reported signal-strength measurement of Signal **3** as measured by wireless terminal **201** at time t.

To facilitate this, wireless terminal **201** provides a temporal series (n, n+1, n+2, . . . , etc.) of Signal-Strength Measurement Reports to wireless switching center **211**, in well-known fashion, as part of the GSM protocol and the mobile-assisted hand-off process. Wireless switching center **211** then forwards the Reports to location system **212**. The details of task **404** are described in detail below and with respect to FIG. **16**.

In some alternative embodiments of the present invention, wireless terminal **201** provides the temporal series (n, n+1, n+2, . . . , etc.) of Signal-Strength Measurement Reports to location system **212** via GPRS packets.

At task **405**, location system **212** uses the reported signal-strength measurements {R(1,n), R(2,n), R(3,n)} from task **404** and the calibration function for the make and model of wireless terminal **201** to generate a tuple of calibrated signal-strength measurements {S(1,n), S(2,n), S(3,n)}. The purpose of task **405** is to correct—or compensate for—the signal-strength measurement errors made by wireless terminal **201**. The details of task **405** are described in detail below and with respect to FIG. **17**.

At task **406**, location system **212** generates a current estimate of the location of wireless terminal **201** based on:

i. the tuple of calibrated signal-strength measurements {S(1,n), S(2,n), S(3,n)},

ii. the expected signal-strength tuples for all locations {E(1,x,y,t), E(2,x,y,t), E(3,x,y,t)} at the time t when the measurements underlying {S(1,n), S(2,n), S(3,n)} were made, and

iii. the cumulative probability distribution for the location of wireless terminal **201**, NB(x,y,n−1), wherein NB(x, y,n−1) is an x by y array of normalized probabilities for the location of wireless terminal based on all of the Signal-Strength Measurement Reports up to and including Report n−1.

The details of task **406** are described in detail below and with respect to FIGS. **17** and **18**.

At task **407**, location system **212** transmits the location estimated in task **406** to another entity (not shown) for use in a location-based service (e.g., Emergency 911 Service, etc.). It is well known to those skilled in the art, after reading this disclosure, how to use the estimated location of a wireless terminal in a location-based service.

At this point, each of these seven tasks is described in detail.

Population of The Expected Signal-Strength Database—FIG. **5** depicts a flowchart of the salient subtasks performed as part of task **401**.

At subtask **501**, a rectangular grid of X by Y tessellated squares is overlaid onto geographic region **200** (see FIG. **6**) and the center of each square represents a location.

In accordance with the illustrative embodiment, the grid is 17 by 13 and, therefore, comprises 211 squares. Each square has an area of approximately 5 arc-seconds in length by 5 arc-seconds in width. Only 152 of the 211 locations are within geographic region **200**. In general, the size of the squares is chosen based on the following considerations.

First, the highest resolution with which wireless terminal **201** can be located is a function of the size of the squares. In particular, the wireless terminal can only be located to within one-half of the diagonal of a square or

$$\frac{\sqrt{2}}{4}$$

or ≈0.3535 times the width of the square.

Second, as the size of each square decreases and the resolution increases, the number of locations increases exponentially and so does the computational burden in subtasks **1702** through **1705**. This is discussed in detail below.

Third, as the size of each square decreases and the resolution increases, the likelihood increases that adjacent squares will have the identical or very similar signal-strength characteristics. In some embodiments of the present invention, this might cause the number of errors in estimating the location of wireless terminal **201** to increase.

With these considerations in mind, it will be clear to those skilled in the art, after reading this disclosure, how to make and use alternative embodiments of the present invention that operate with any number and size of squares. Furthermore, it will be clear to those skilled in the art, after reading this disclosure, how to make and use embodiments of the present

invention that overlay a grid of another tessellated shape (e.g., triangles, rectangles, hexagons, etc.).

At subtask **502**, the expected signal-strength functions E(1,x,y,t), E(2,x,y,t), and E(3,x,y,t) are generated, in well-known fashion.

In general, the signal strength of an electromagnetic signal decreases as a function of the distance from the transmitter, as is depicted in FIG. **7***a*, but the topography of the region and the presence of buildings, trees, and other radio-frequency obstacles severely alters this generalization, as is depicted in FIG. **7***b*. This is why the expected signal-strength functions are a function of x and y.

Furthermore, the expected signal strength at each location is dynamic and changes, for example, with time as the atmospheric and meteorological conditions change. This is why the expected signal-strength functions are a function of time.

In accordance with the illustrative embodiment, the expected signal-strength functions E(1,x,y,t), E(2,x,y,t), and E(3,x,y,t) are generated based on a combination of:

(i) a plurality of theoretical radio-frequency propagation models, and

(ii) a plurality of empirical signal-strength measurements.

It will be clear to those skilled in the art, after reading this disclosure, how to perform subtask **502**.

For example, one well-known modeling technique for outdoor radio-frequency signal propagation is adapted from the power-law decay model. The power-law decay model assumes that the base station's antenna is high above the ground and that there is line-of-sight propagation to the wireless terminal. In this case, the mean signal strength, P, received at the wireless terminal decays in inverse proportion to the square of the distance from the transmitter,

$$P \propto \frac{1}{r^2}, \quad \text{(Eq. 1)}$$

up to some break-point. Beyond that break-point, the mean power at the wireless terminal decays in inverse proportion to the fourth power of the distance from the transmitter:

$$P \propto \frac{1}{r^4} \quad \text{(Eq. 2)}$$

As is well-known to those skilled in the art, the location of the break-point is the location at which the ground bounce signal interferes with the line-of-sight signal.

In accordance with another well-known model, the expected signal strength at each location is generated by taking empirical measurements at various locations and by interpolating for the locations in between the sampled locations. This method is advantageous in that it does not require many empirical measurements to be made, but it is less accurate than taking measurements at every location and causes the square of the uncertainty in the modeling error, δ_E^2, to rise. The implications of this are discussed in detail below and with respect to FIG. **18**.

It will be clear to those skilled in the art, after reading this disclosure, how to generate the expected signal-strength functions for each location in the geographic region whether through:

i. one or more theoretical radio-frequency propagation models, or

ii. one or more empirical signal-strength measurements, or

iii. any combination of i and ii.

In accordance with the illustrative embodiment, FIG. **8** depicts the expected signal strength, E(1,t=0), of Signal **1** at each location at one illustrative moment in time and under one set of atmospheric and meteorological conditions. In general, Signal **1** is, in general, stronger near base station **202-1** and weaker far away from base station **202-1**.

In accordance with the illustrative embodiment, FIG. **9** depicts the expected signal strength, E(2,t=0), of Signal **2** at each location at one illustrative moment in time and under one set of atmospheric and meteorological conditions. Like Signal **1**, Signal **2** is, in general, stronger near base station **202-2** and weaker far away from base station **202-2**.

In accordance with the illustrative embodiment, FIG. **10** depicts the expected signal strength, E(3,t=0), of Signal **3** at each location at one illustrative moment in time and under one set of atmospheric and meteorological conditions. Like Signals **1** and **2**, Signal **3** is, in general, stronger near base station **202-3** and weaker far away from base station **202-3**.

In general, the illustrative embodiment of the present invention estimates the location of a wireless terminal by pattern matching the calibrated signal-strength measurements {S(1,n), S(2,n), S(3,n)} against the expected signal-strength functions E(1,x,y,t), E(2,x,y,t), and E(3,x,y,t) that correspond in time to when the signal-strength measurements underlying {R(1,n), R(2,n), R(3,n)} are based. This process is described in detail below and with respect to task **406**. From subtask **502**, control passes to task **402** in FIG. **4**.

Population of The Signal-Strength Corrections Database—FIG. **11** depicts a flowchart of the salient subtasks performed as part of task **402**.

At subtask **1101**, a distortion function F(A,C) is generated for every possible make and model, C, of wireless terminal **201**. In general, the distortion function F(A,C) is the relationship of the reported signal-strength measurement, R, as a function of each actual signal strength, A, and the characteristic C. This relationship is represented by equation 3:

$$R=F(A,C) \quad \text{(Eq. 3)}$$

F(A,C) is a function defined within the range of −110 dBm≦R≦−47 dBm because that, in accordance with the GSM protocol, is the allowable extent of reported signal-strength measurements.

In accordance with the GSM protocol, wireless terminal **201** is capable of reporting the signal strength of a signal as one of 64 levels between −47 dBm and −110 dBm. When wireless terminal **201** measures a signal with a strength of −46 dBm or stronger, wireless terminal **201** simply transmits a reported signal-strength measurement of −47 dBm for that signal. Similarly, wireless terminal **201** is incapable of transmitting a reported signal-strength measurement of −110 dBm or weaker, and, therefore, when wireless terminal **201** measures a signal with a strength of −110 dBm or weaker, wireless terminal **201** simply transmits a reported signal-strength measurement of −110 dBm for that signal.

It will be clear to those skilled in the art, after reading this disclosure, how to make and use alternative embodiments of the present invention in which the reported signal-strength measurements have a different range of reportable measurements or no range restriction at all.

In accordance with the illustrative embodiment, the distortion function F(A,C) is provided to the owner/operator of location system **212** by the wireless terminal manufacturer. It will be clear to those skilled in the art, after reading this disclosure, how to generate the distortion function F(A,C) for a wireless terminal.

An ideal wireless terminal perfectly measures and reports the signal strengths of the signals it receives and the distortion

function F(A,C) for an ideal wireless terminal is depicted in FIG. **12**. As can be seen from the graph in FIG. **12**, the salient characteristic of an ideal wireless terminal is that the reported signal-strength measurement, R, is exactly equal to the actual signal strength, A (i.e., there is no distortion).

In contrast, most real-world wireless terminals do not perfectly measure the signal strength of the signals they receive. For example, FIG. **13** depicts a graph of the relationship of reported signal-strength measurements as a function of actual signal strengths for an illustrative real-world wireless terminal. In this case, the reported signal-strength measurement is stronger than it should be between −110 dBm and −60 dBm, and the reported signal-strength measurement is weaker than it should be between −60 dBm and −47 dBm. Only at −60 dBm is the reported signal-strength measurement correct.

The magnitude of each of the errors in the reported signal-strength measurements is inherent in the distortion function F(A,C), and, therefore, knowledge of F(A,C) enables the measurement errors by wireless terminal **201** to be compensated for. In other words, when location system **212** knows exactly how a wireless terminal distorts a signal-strength measurement, it can correct—or calibrate—the reported signal-strength measurement with a calibration function to derive the actual signal strength. The calibration function is $F^{-1}(R,C)$, and it is generated in subtask **1102**.

In accordance with the illustrative embodiment, the distortion function F(A,C) is represented in tabular form, such as that shown in Table 4.

TABLE 4

The Distortion function F(A, C) in Tabular Form

	R = F(A, C)		
A	C = Motorola Model A008	. . .	C = Samsung Model A800
−110	−115	. . .	−107
−109	−114	. . .	−106
. . .	. . .	. . .	. . .
−48	−38	. . .	−50
−47	−37	. . .	−49

At subtask **1102**, the calibration function $F^{-1}(R,C)$ is generated for every possible make and model of wireless terminal **201**.

In general, the calibration function $F^{-1}(R,C)$ is the relationship of the calibrated signal-strength measurements, S, as a function of the reported signal-strength measurements, R. This relationship is represented by equation 4:

$$S=F^{-1}(R,C) \quad \text{(Eq. 4)}$$

$F^{-1}(R,C)$ is a function defined within the domain of −110 dBm≦R≦−47 dBm because that, in accordance with the GSM protocol, is the allowable extent of reported signal-strength measurements.

$F^{-1}(R,C)$ is the inverse of the distortion function F(A,C). In other words, the salient characteristic of the function $F^{-1}(R,C)$ is that it satisfies the equation 5:

$$S=F^{-1}(F(A,C),C) \quad \text{(Eq. 5)}$$

so that the calibrated signal-strength measurement, S, is what the reported signal-strength measurement, R, would have been had the wireless terminal making and reporting the measurement been ideal. It will be clear to those skilled in the art, after reading this disclosure, how to derive $F^{-1}(R,C)$ from F(A,C). FIG. **14** depicts a graph of the calibration function $F^{-1}(R,C)$ for the distortion function F(A,C) depicted in FIG. **13**.

In accordance with the illustrative embodiment, the function $F^{-1}(R,C)$ is represented in tabular form, such as that shown in Table 5.

TABLE 5

The Calibration Function $F^{1}(R, C)$ in Tabular Form

	S = $F^{1}(R, C)$		
R	C = Motorola Model A008	. . .	C = Samsung Model A800
−110	−115	. . .	−107
−109	−114	. . .	−106
. . .	. . .	. . .	. . .
−48	−38	. . .	−50
−47	−37	. . .	−49

At subtask **1103**, processor **301** stores the calibration function $F^{-1}(R,C)$ in the Signal-Strength Corrections Database.

The purpose of the characteristic, C, is to identify which calibration function should be used in calibrating the reported signal-strength measurements from wireless terminal **201**, and, therefore, the characteristic, C, should be as indicative of the actual distortion function for wireless terminal **201** as is economically reasonable.

For example, the characteristic, C, can be, but is not limited to:

i. the unique identity of wireless terminal **201** (e.g., its electronic serial number ("ESN"), its international mobile station identifier ("IMSI"), its temporary international mobile station identifier ("TIMSI"), mobile station identification ("MSID"), its directory number ("DN"), etc.); or

ii. the model of wireless terminal **201** (e.g., Timeport **210***c*, etc.); or

iii. the make (i.e., manufacturer) of wireless terminal **201** (e.g., Motorola, Samsung, Nokia, etc.); or

iv. the identity of the radio-frequency circuitry of wireless terminal **201** (e.g., Motorola RF circuit design **465**B, etc.); or

v. the identity of one or more components of wireless terminal **201** (e.g., the part number of the antenna, the part number of the signal-strength measuring component, etc.); or

vi. the distortion function, F(A,C), for wireless terminal **201**; or

vii. the calibration function, $F^{-1}(R,C)$, for wireless terminal **201**; or

viii. any combination of i, ii, iii, iv, v, vi, and vii.

The most accurate characteristic is probably the unique identity of wireless terminal **201** because that would enable location system **212** to use the calibration function generated for that very wireless terminal. It is unlikely, however, that this is economically feasible because it would require that every wireless terminal be tested to determine its own unique distortion function.

On the other hand, using only the make of wireless terminal **201** as the characteristic, C, is economically reasonable, but it is unlikely that a single calibration function for all of a manufacturer's wireless terminals would provide very accurate calibrated signal-strength measurements.

As a compromise, the illustrative embodiment uses the combination of make and model of wireless terminal **201** as the characteristic, C, because it is believed that the amount of variation between wireless terminals of the same model will be small enough that a single calibration function for that

model should provide acceptably accurate calibrated signal-strength measurements without having to test every individual terminal.

It will be clear to those skilled in the art, however, after reading this disclosure, how to make and use alternative embodiments of the present invention in which the characteristic, C, is something else.

From subtask **1103**, control passes to task **403** in FIG. **5**.

Receive Reported Signal-Strength Measurements from Wireless Terminal **201**—FIG. **15** depicts a flowchart of the salient subtasks performed as part of task **404**.

At subtask **1501**, wireless switching center **211** periodically determines, in well-known fashion, which signals wireless terminal **201** might or might not be able to receive. In accordance with the illustrative embodiment, wireless switching center **211** determines that wireless terminal **201** might be able to receive Signal **1**, Signal **2**, and Signal **3**.

At subtask **1502**, wireless switching center **211** periodically directs wireless terminal **201**, in well-known fashion, to attempt to receive the signals that it might be able to receive and to report back a signal-strength value for the signals that wireless terminal **201** is able to receive and distinguish. In accordance with the illustrative embodiment, wireless switching center **211** directs wireless terminal **211** to monitor Signal **1**, Signal **2**, and Signal **3** and to report on all of these signals.

At subtask **1503**, location system **212** receives, via wireless switching center **211**, a Signal-Strength Measurement Report from wireless terminal **201** on the signals that it was directed to monitor in subtask **1502**. Signal-Strength Measurement Report n from wireless terminal **201** comprises:

i. a tuple of reported signal-strength measurements {R(1,n), R(2,n), R(3,n)},

ii. the time, t, at which the signal-strength measurements were made, and

iii. a value of n, which indicates the relative order in which the signal-strength measurements are made.

In some alternative embodiments of the present invention, however, wireless terminal **201** provides the tuple of reported signal-strength measurements {R(1,n), R(2,n), R(3,n)}, the time t, and the value of n, to location system **212** as GPRS packet data and these reported signal-strength measurements are not be bounded by the −47 dBm to −110 dBm domain limitation imposed on GSM terminals in the prior art. This is advantageous because the quality of the estimate of the location of wireless terminal **201** is generally enhanced by the removal of the limitation on the dynamic range of the reported signal-strength measurements.

In some alternative embodiments of the present invention, wireless terminal **201** provides the signal-strength measurements on more than 3 signals to location system **212** as GPRS packet data as imposed on GSM terminals in the prior art either. This is advantageous because the quality of the estimate of the location of wireless terminal **201** is generally enhanced by increasing the number of reported signal-strength measurements given to location system **212**.

In some alternative embodiments of the present invention, wireless terminal **201** provides—in addition to or instead of {R(1,n), R(2,n), R(3,n)}—the signal-strength measurements for signals that have nothing to do with providing telecommunications service to wireless terminal **201**. Those signals can be, for example, commercial television or radio signals, aviation navigation signals, etc. The incorporation of signal-strength measurements for these kinds of signals can increase the quality of the estimate of the location of wireless terminal **201**.

It will be clear to those skilled in the art, after reading this disclosure, how to make and use embodiments of the present invention that perform task **404**. From subtask **1603**, control passes to task **405** in FIG. **4**.

Generate Calibrated Signal-Strength Measurements—FIG. **16** depicts a flowchart of the salient subtasks performed as part of task **405**.

At subtask **1601**, processor **301** uses the calibration function, $F^{-1}(R,C)$, for the make and model of terminal specified for wireless terminal **201** to generate the tuple of calibrated signal-strength measurements {S(1,n), S(2,n), S(3,n)} from the tuple of reported signal-strength measurements {R(1,n), R(2,n), R(3,n)}. It will be clear to those skilled in the art, after reading this disclosure, how to make and use embodiments of the present invention that perform task **1601**.

From subtask **1602**, control passes to task **406** in FIG. **4**.

Estimation of the Location of Wireless Terminal **201**—FIG. **17** depicts a flowchart of the salient subtasks performed as part of task **406**.

Estimation in General—Subtask **1701** begins with 152 candidate locations that must be considered as the location for wireless terminal **201**. Subtasks **1702** through **1705** can be computationally intense, and the computational burden increases markedly with the number of candidate locations that must be processed. Therefore, processor **301** attempts, at subtask **1701**, to reduce the number of candidate locations that must be processed.

To reduce the number of candidate locations that must be processed, processor **301** employs a technique called "search area reduction." In accordance with search area reduction, the probability that wireless terminal **201** is at some candidate locations is calculated to be very close to zero, and, therefore, that candidate location is excluded from consideration in subtasks **1702** through **1705**, but is considered in subtask **1706**. To the extent that search area reduction can exclude a location from consideration, the computational burden of subtasks **1702** through **1705** is reduced.

A candidate location is summarily excluded only when it is highly improbable that it is the actual location. A candidate location at x,y is excluded when, and only when, the following is true:

$$\forall i \in \{1,2,3\}, \forall j \in \{n-\Omega, n-\Omega+1, \ldots, n-2, n-1, n\} \, |E(i,x,y,t)-S(i,j)| \geqq \Psi \quad \text{(Eq. 6)}$$

wherein t corresponds in time to when the measurement underlying S(i,j) was taken, ψ is a positive real number, and Ω is a positive integer. In essence, the test excludes a candidate location only when the calibrated signal-strength measurements have been substantially different from the expected signal strengths at that location for the last Ω measurements.

In accordance with the illustrative embodiment, ψ=20 dBm. The value ψ=20 dBm is chosen for the illustrative embodiment because it is unlikely that a calibrated signal-strength measurement for a location will be more than 20 dBm different than the expected signal strength for the actual location of wireless terminal **201**. It will be clear to those skilled in the art, however, how to make and use alternative embodiments of the present invention that have a different value for ψ.

High values of ψ are advantageous in that they make the likelihood of erroneously eliminating from consideration the actual location of wireless terminal **201** small, but are disadvantageous in that they undermine most of the potential advantage of search area reduction. In contrast, low values of ψ are advantageous in that they eliminate the greatest number of candidate locations from consideration but are disadvantageous in that they increase the likelihood that search area reduction will erroneously eliminate from consideration the actual location of wireless terminal **201**.

In accordance with the illustrative embodiment, Ω=25. The value Ω=25 is chosen for the illustrative embodiment because it is highly unlikely that all of the last Ω=25 calibrated signal-strength measurements for a location are more than ψ dBm different from the expected signal strength for the actual location of wireless terminal **201**. It will be clear to those skilled in the art, however, how to make and use alternative embodiments of the present invention that have a different value for Ω.

High values of Ω are advantageous in that they make the likelihood of erroneously eliminating from consideration the actual location of wireless terminal **201** small, but are disadvantageous in that they undermine most of the potential advantage of search area reduction. In contrast, low values of Ω are advantageous in that they eliminate the greatest number of candidate locations from consideration but are disadvantageous in that they increase the likelihood that search area reduction will erroneously eliminate from consideration the actual location of wireless terminal **201**.

At subtask **1702**, processor **301** computes the signal-strength differentials for all of the calibrated signal-strength measurements whose reported signal-strength measurements are not "saturated." A reported signal-strength measurement is "saturated" when the measurement is at one of the bounds of the range at which a measurement can be reported. In accordance with the illustrative embodiment, reported signal-strength measurements of −47 dBm and −110 dBm are saturated because they are the maximum and minimum reportable values, respectively.

The calibrated signal-strength measurements whose reported signal-strength measurements are saturated are used for search area reduction in subtask **1701**, but are not used in computing signal-strength differentials because their saturated nature prevents the true magnitude they represent from being known with enough certainty to be useful in computing signal-strength differentials.

When the tuple of calibrated signal-strength measurements {S(1,n), S(2,n), S(3,n)} comprises m measurements that are not saturated, an m-tuple of calibrated signal-strength measurements {N(1,n), . . . N(m,n)} is selected from the tuple of calibrated signal-strength measurements {S(1,n), S(2,n), S(3,n)}, wherein m is a non-negative integer and m≦n.

Then m−1 signal-strength measurement differentials are generated between different pairs of signal-strength measurements {N(1,n), . . . N(m,n)}. For example:

$$\Delta N(k,n)=N(k+1,n)-N(k,n) \quad \text{(Eq. 7)}$$

wherein k=1, 2, 3, . . . m−1, and ΔN(k,n) is the kth signal-strength measurement differential for Report n.

At the end of subtask **1702**, processor **301** will have generated m−1 signal-strength measurement differentials, {N(1,n), . . . N(m,n)}, for all of the candidate locations not excluded in subtask **1701**.

At subtask **1703**, processor **301** computes the expected signal-strength differentials:

i. for all of the locations not excluded from consideration in subtask **1701**,
ii. for only those signals that correspond to those used to compute ΔN(k,n), and
iii. that correspond in time to when the measurements underlying ΔN(k,n) were made.

The idea behind limitations (ii) and (iii) is, of course, to ensure that "apples are compared with apples" in subtask **1704** below. In particular, m−1 expected signal-strength differentials are generated where:

$$\Delta E(k,x,y,t)=E(k+1,x,y,t)-E(k,x,y,t) \quad \text{(Eq. 8)}$$

for k=1, 2, 3, . . . m−1, wherein ΔE(k,x,y,t) is the kth expected signal-strength differential for location x,y, and E(k,x,y,t) is the expected signal strength of the same signal as N(k,n) at location x,y at the time t when the measurements underlying ΔN(k,n) were made.

At the end of subtask **1703**, processor **301** will have generated m−1 expected signal-strength differentials, ΔE(1,x,y,t) through ΔE(m−1,x,y,t), for all of the candidate locations not excluded in subtask **1701**.

At subtask **1704**, processor **301** generates the "current probability distribution" for the location of wireless terminal **201** based on the most recently received reported signal-strength measurements (i.e., the data derived from {S(1,n), S(2,n), S(3,n)} only). In contrast, at subtask **1705**, processor **301** generates the "cumulative probability distribution" for the location of wireless terminal **201** based on all of the received reported signal-strength measurements (i.e., the data derived from {S(1,n), S(2,n), S(3,n)}, {S(1,n−1), S(2,n−1), S(3,n−1)}, {S(1,n−2), S(2,n−2), S(3,n−2)}, . . . etc.). This enables the illustrative embodiment to combine signal-strength measurements from different times to generate an estimate of the location of wireless terminal **201** that is more accurate than the estimate that is derivable from signal-strength measurements made at any one time alone.

FIG. **18** depicts a flowchart of the salient subtasks performed in subtask **1704**. At subtask **1704**, processor **301** compares the m−1 signal-strength measurement differentials, ΔN(1,n) through ΔN(m−1,n), to the m−1 expected signal-strength differentials, ΔE(1,x,y,t) through ΔE(m−1,x,y,t), for each location to generate a probability distribution that indicates the goodness of fit between the signal-strength measurement differentials, ΔN(1,n) through ΔN(m−1,n), and the expected signal-strength differentials, ΔE(1,x,y,t) through ΔE(m−1,x,y,t), at each location.

To accomplish this, at subtask **1801**, the Euclidean norm is generated between the signal-strength measurement differentials, ΔN(1,n) through ΔN(m−1,n), and the expected signal-strength differentials, ΔE(1,x,y,t) through ΔE(m−1,x,y,t), at each location. This is described in Equation 9:

$$\forall\, x,\, y V(x,\, y,\, n) = \sqrt{\sum_{2}^{m-1} (\Delta E(k,\, x,\, y,\, t) - \Delta N(k,\, n))^2} \quad \text{(Eq. 9)}$$

wherein V(x,y,n) is the Euclidean norm at location x,y based on the data derived from {S(1,n), S(2,n), S(3,n)} only.

At subtask **1802**, the Euclidean norms generated in Equation 9 are turned into un-normalized probabilities of the location of wireless terminal **201** by Equation 10.

$$UP(x,\, y,\, n) = e^{\left(\frac{-V^2(x,y,n)}{\delta^2}\right)} \quad \text{(Eq. 10)}$$

wherein UP(x,y,n) represents the un-normalized probability that wireless terminal **201** is at location x,y based on the data derived from {S(1,n), S(2,n), S(3,n)} only, and wherein δ^2 represents the amount of uncertainty in both ΔS(k,n) and ΔE(k,x,y,n) and equals:

$$\delta^2 = \delta_E^2 + \delta_M^2 \quad \text{(Eq. 11)}$$

wherein δ_E^2 is the square of the uncertainty in the error in the Expected Signal-Strength Database and δ_M^2 is the square of the uncertainty in the error in calibrated signal-strength measurements. It will be clear to those skilled in the art, after reading this disclosure, how to generate δ^2. Candidate locations that were summarily excluded from consideration in subtask **1701** are assigned a probability of zero (0) in subtask **1802**.

At subtask **1803**, the probabilities generated in subtask **1802** are normalized. This is described in Equation 12.

$$NP(x, y, n) = \frac{UP(x, y, n)}{\forall x, y \sum UP(x, y, n)} \quad \text{(Eq. 12)}$$

wherein NP(x,y,n) represents the normalized probability that wireless terminal **201** is at location x,y based on the data derived from {S(1,n), S(2,n), S(3,n)} only. In some alternative embodiments of the present invention, the location of wireless terminal **201** is estimated based on the geometric mean of NP(x,y,n) for all x and y, or the maximum likelihood function, but in accordance with the illustrative embodiment, the estimate is based on the cumulative normalized probability distribution generated in subtask **1705**.

From subtask **1803**, control passes to subtask **1705** in FIG. **17**.

At subtask **1705**, processor **301** generates the "cumulative probability distribution" for the location of wireless terminal **201** based on all of the received reported signal-strength measurements (i.e., the data derived from {S(1,n), S(2,n), S(3,n)}, {S(1,n−1), S(2,n−1), S(3,n−1)}, {S(1,n−2), S(2,n−2), S(3,n−2)}, . . . etc.). FIG. **19** depicts a flowchart of the salient subtasks performed in subtask **1705**.

At subtask **1901**, the cumulative probability distribution for the location of wireless terminal **201**, NB(x,y,n−1), is "aged" to compensate for the probable motion of wireless terminal **201** between the time when the measurements underlying {S(1,n), S(2,n), S(3,n)} and {S(1,n−1), S(2,n−1), S(3,n−1)} were made. The aging of the cumulative probability distribution enables "apples to be compared with apples" when the cumulative probability distribution is combined with the current probability distribution, NP(x,y,n).

The cumulative probability distribution is aged because it is not reasonable to combine the prior probability distribution with the most-recently generated probability distribution because they do not have the same value in estimating where the wireless terminal is at the time the most recent measurements were taken. But that does not mean that the prior probability distribution is worthless. On the contrary, the cumulative probability distribution, as compensated for the probable motion and likely speed of wireless terminal **201**, is very valuable.

There are two parameters that define the rate at which the cumulative probability distribution is aged: α and β. α is a positive integer and represents the average speed with which wireless terminal **201** is believed to move. In accordance with the illustrative embodiment, the dimensions of α are length/time and the units are locations per Signal-Strength Measurement Report. It will be clear to those skilled in the art, however, after reading this specification, how to make and use alternative embodiments of the present invention in which the units are something else (e.g., meter/second, miles/hour, etc.)

β is a normalized probability (i.e., $0 \leqq \beta \leqq 1$) that wireless terminal **201** does not change locations between successive Signal-Strength Measurement Reports.

In accordance with the illustrative embodiment, $\alpha=1$ and $\beta=0.5$, but it will be clear to those skilled in the art, after reading this disclosure, how to make and use alternative embodiments of the present invention in which α and β have different values. Typically, β will be between 0.30 and 0.80. In accordance with the illustrative embodiment, it is equally probable that wireless terminal **201** will move in any direction (i.e., the probability of moving is isotropic).

One way to visualize the aging of the cumulative probability distribution is to imagine melting a three-dimensional wax model of the cumulative probability distribution in which the probability dimension is depicted vertically. As heat is applied to the model and the wax begins to melt, the wax flows under the pull of gravity. At first, the model is only slightly distorted, but over time the wax flows until it is evenly distributed. In the metaphor of the melting wax model, α is analogous to the viscosity of the wax—higher values of α correspond to lower viscosity—and β is analogous to the rate at which the model melts—higher values of β correspond to slower melting.

An illustration of how one probability distribution ages over time is helpful in gaining an intuitive understanding of the aging process. In this example, FIG. **20** depicts a probability distribution based on Report n at time n, wherein the location of the wireless terminal is known with certainty to be at location X=9, Y=7. In this example, $\alpha=1$ and $\beta=0.5$.

After the time associated with one Signal-Strength Measurement Report has passed, the Probability Distribution in FIG. **20** ages into that depicted in FIG. **21**. After the time associated with another Report has passed, it ages into that depicted in FIG. **22**. And finally, after the time associated with another 1000 Reports has passed, it ages into that depicted in FIG. **23**. A probability distribution that is initially more complex ages in an analogously more complex manner, but it always ends up looking like the distribution in FIG. **32**. FIGS. **20** through **23** accurately reflect the common sense notion that a probability distribution loses value in estimating the location of wireless terminal **201** as time goes on.

The aging of the cumulative probability distribution for the location of wireless terminal **201** is described in Equation 13 (for $\alpha=1$).

$$\forall x, y\, AB(x, y, n-1) = \frac{(9\beta - 1)}{8} NB(x, y, n-1) + \frac{(1-\beta)}{8} \sum_{i=-1}^{+1} \sum_{j=-1}^{+1} NB(x+i, y+j, n-1) \quad \text{(Eq. 13)}$$

Wherein AB(x,y,n−1) is the aged cumulative probability distribution.

At subtask **1902**, the un-normalized cumulative probability distribution for the location of wireless terminal **201**, UB(x,y,n), is generated based on the aged cumulative probability distribution, AB(x,y,n−1), and the current normalized probability distribution, NP(x,y,n). This is described in Equation 14.

$$\forall x,y\; UB(x,y,n) = AB(x,y,n-1) \times NP(x,y,n) \quad \text{(Eq. 14)}$$

At subtask **1903**, the un-normalized cumulative probability distribution for the location of wireless terminal **201**, UB(x,y,n), is normalized to generate the normalized cumulative probability distribution for the location of wireless terminal **201**, NB(x,y,n). This is described in Equation 14.

$$NB(x, y, n) = \frac{UB(x, y, n)}{\forall x, y \sum UB(x, y, n)} \quad \text{(Eq. 15)}$$

From subtask **1902**, control passes to subtask **1706** in FIG. **17**.

At subtask **1706**, processor **302** estimates the location of wireless terminal **201** based on the normalized cumulative probability distribution for the location of wireless terminal **201**, NB(x,y,n), generated in subtask **1903**. In accordance with the illustrative embodiment, processor **302** estimates the location of wireless terminal **201** based on the geometric mean of the normalized cumulative probability distribution generated in subtask **1705**.

After reading this disclosure, however, it will be clear to those skilled in the art, after reading this disclosure, how to make and use alternative embodiments of the present invention that estimate the location of wireless terminal **201** based on another function of the normalized cumulative probability distribution, such as, for example, the maximum likelihood function.

From subtask **1706**, control passes to task **404** in FIG. **4**.

It is to be understood that the above-described embodiments are merely illustrative of the present invention and that many variations of the above-described embodiments can be devised by those skilled in the art without departing from the scope of the invention. It is therefore intended that such variations be included within the scope of the following claims and their equivalents.

What is claimed is:

1. A process comprising:

receiving a first reported signal-strength measurement, R(1,n), from a wireless terminal; and

generating a first calibrated signal-strength measurement, S(1,n), based on: (i) the first reported signal-strength measurement, R(1,n), and (ii) an identifying characteristic, C, of the wireless terminal;

wherein the first reported signal strength is for a first signal received by the wireless terminal; and

wherein the identifying characteristic, C, identifies the wireless terminal in comparison to another wireless terminal capable of receiving the first signal.

2. The process of claim **1** wherein the identifying characteristic, C, of the wireless terminal is the unique identity of the wireless terminal.

3. The process of claim **1** wherein the identifying characteristic, C, of the wireless terminal is the subscriber identity associated with the wireless terminal.

4. The process of claim **1** wherein the identifying characteristic, C, of the wireless terminal is the model of the wireless terminal.

5. The process of claim **1** wherein the identifying characteristic, C, of the wireless terminal comprises a feature of the radio-frequency circuitry of the wireless terminal.

6. The process of claim **1** wherein the identifying characteristic, C, of the wireless terminal is at least one component of the wireless terminal.

7. The process of claim **1** wherein the identifying characteristic, C, of the wireless terminal is the make of the wireless terminal.

8. The process of claim **1** further comprising receiving the identifying characteristic, C, of the wireless terminal from the wireless terminal.

9. The process of claim **1** further comprising estimating the location of the wireless terminal based on the first calibrated signal-strength measurement, S(1,n).

10. A machine comprising:

a receiver for receiving a first reported signal-strength measurement, R(1,n), from a wireless terminal; and

a processor for generating a first calibrated signal-strength measurement, S(1,n), based on: (i) the first reported signal-strength measurement, R(1,n), and (ii) an identifying characteristic, C, of the wireless terminal;

wherein the first reported signal strength is for a first signal received by the wireless terminal; and

wherein the identifying characteristic, C, identifies the wireless terminal in comparison to another wireless terminal capable of receiving the first signal.

11. The machine of claim **10** wherein the identifying characteristic, C, of the wireless terminal is the unique identity of the wireless terminal.

12. The machine of claim **10** wherein the identifying characteristic, C, of the wireless terminal is the subscriber identity associated with the wireless terminal.

13. The machine of claim **10** wherein the identifying characteristic, C, of the wireless terminal is the model of the wireless terminal.

14. The machine of claim **10** wherein the identifying characteristic, C, of the wireless terminal comprises a feature of the radio-frequency circuitry of the wireless terminal.

15. The machine of claim **10** wherein the identifying characteristic, C, of the wireless terminal is at least one component of the wireless terminal.

16. The machine of claim **10** wherein the identifying characteristic, C, of the wireless terminal is the make of the wireless terminal.

17. The machine of claim **10** wherein the receiver is also for receiving the identifying characteristic, C, of the wireless terminal from the wireless terminal.

18. The machine of claim **10** wherein the processor is also for estimating the location of the wireless terminal based on the first calibrated signal-strength measurement, S(1,n).

19. A process comprising:

generating a first calibrated signal-strength measurement, S(1,n), based on (i) a first reported signal-strength measurement, R(1,n), as made by a wireless terminal and (ii) an identifying characteristic, C, of the wireless terminal; and

estimating the location of the wireless terminal based on the first calibrated signal-strength measurement, S(1,n);

wherein the first reported signal strength is for a first signal received by the wireless terminal; and

wherein the identifying characteristic, C, identifies the wireless terminal in comparison to another wireless terminal capable of receiving the first signal.

20. The process of claim **19** wherein the identifying characteristic, C, of the wireless terminal is the unique identity of the wireless terminal.

21. The process of claim **19** wherein the identifying characteristic, C, of the wireless terminal is the subscriber identity associated with the wireless terminal.

22. The process of claim **19** wherein the identifying characteristic, C, of the wireless terminal is the model of the wireless terminal.

23. The process of claim **19** wherein the identifying characteristic, C, of the wireless terminal comprises a feature of the radio-frequency circuitry of the wireless terminal.

24. The process of claim **19** wherein the identifying characteristic, C, of the wireless terminal is at least one component of the wireless terminal.

25. The process of claim **19** wherein the identifying characteristic, C, of the wireless terminal is the make of the wireless terminal.

26. The process of claim **19** wherein the identifying characteristic, C, of the wireless terminal is provided by the wireless terminal.

27. A machine comprising:

a receiver for receiving a first reported signal-strength measurement, R(1,n), as made by a wireless terminal; and

a processor for:

generating a first calibrated signal-strength measurement, S(1,n), based on (i) the first reported signal-strength measurement, R(1,n), and (ii) a identifying characteristic, C, of the wireless terminal; and

estimating the location of the wireless terminal based on the first calibrated signal-strength measurement, S(1,n);

wherein the first reported signal strength is for a first signal received by the wireless terminal; and

wherein the identifying characteristic, C, identifies the wireless terminal in comparison to another wireless terminal capable of receiving the first signal.

28. The machine of claim **27** wherein the identifying characteristic, C, of the wireless terminal is the unique identity of the wireless terminal.

29. The machine of claim **27** wherein the identifying characteristic, C, of the wireless terminal is the subscriber identity associated with the wireless terminal.

30. The machine of claim **27** wherein the identifying characteristic, C, of the wireless terminal is the model of the wireless terminal.

31. The machine of claim **27** wherein the identifying characteristic, C, of the wireless terminal comprises a feature of the radio-frequency circuitry of the wireless terminal.

32. The machine of claim **27** wherein the identifying characteristic, C, of the wireless terminal is at least one component of the wireless terminal.

33. The machine of claim **27** wherein the identifying characteristic, C, of the wireless terminal is the make of the wireless terminal.

34. The machine of claim **27** wherein the receiver is also for receiving the identifying characteristic, C, of the wireless terminal as reported by the wireless terminal.

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