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(12) **United States Patent**
Spain, Jr. et al.

(10) **Patent No.: US 7,257,414 B2**
(45) **Date of Patent: *Aug. 14, 2007**

(54) **ESTIMATING THE LOCATION OF A WIRELESS TERMINAL BASED ON NON-UNIFORM PROBABILITIES OF MOVEMENT**

(75) Inventors: **David Stevenson Spain, Jr.**, Portola Valley, CA (US); **Robert Morris Dressler**, Los Altos Hills, CA (US)

(73) Assignee: **Polaris Wireless, Inc.**, Santa Clara, 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.: **11/419,645**

(22) Filed: **May 22, 2006**

(65) **Prior Publication Data**

US 2006/0240842 A1 Oct. 26, 2006

Related U.S. Application Data

(63) Continuation-in-part of application No. 10/910,511, filed on Aug. 3, 2004, now Pat. No. 7,167,714, which is a continuation of application No. 10/128,128, filed on Apr. 22, 2002, now Pat. No. 6,782,265, which is a continuation of application No. 09/532,418, filed on Mar. 22, 2000, now Pat. No. 6,393,294, which is a continuation-in-part of application No. 09/158,296, filed on Sep. 22, 1998, now Pat. No. 6,269,246.

(51) **Int. Cl.**
H04Q 7/20 (2006.01)

(52) **U.S. Cl.** **455/456.1**; 455/456.5; 701/207; 342/357.01; 342/357.13; 342/450; 342/457

(58) **Field of Classification Search** 455/404.2, 455/414.2, 440, 456.1–456.6, 457; 342/457, 342/357.01, 357.06, 357.13, 450; 701/207, 701/213

See application file for complete search history.

(56) **References Cited**

U.S. PATENT DOCUMENTS

5,293,642 A 3/1994 Lo

(Continued)

FOREIGN PATENT DOCUMENTS

WO WO98/15149 A1 4/1998

OTHER PUBLICATIONS

Ingo Gaspard et al., Position Assignment in Digital Cellular Mobile Radio Networks (e.g., GSM) Derived from Measurements at the Protocol Interface, IEEE 1997, pp. 592-596.

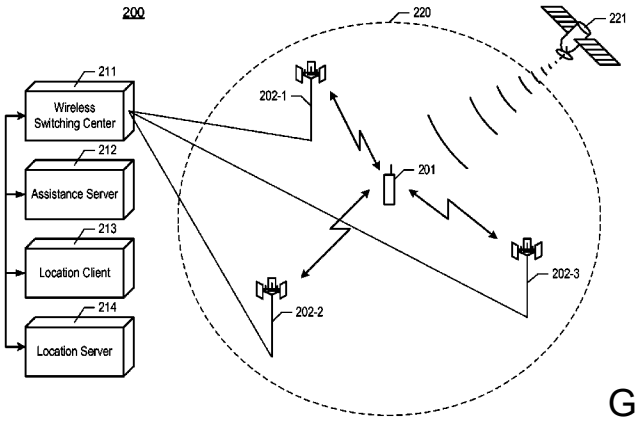
(Continued)

Primary Examiner—William Trost
Assistant Examiner—James D Ewart
(74) *Attorney, Agent, or Firm*—DeMont & Breyer LLC

(57) **ABSTRACT**

A technique for estimating the location of a wireless terminal at an unknown location in a geographic region is disclosed. The technique is based on the recognition that there are traits of electromagnetic signals that are dependent on topography, the receiver, the location of the transmitter, and other factors. For example, if a particular radio station is known to be received strongly at a first location and weakly at a second location, and a given wireless terminal at an unknown location is receiving the radio station weakly, it is more likely that the wireless terminal is at the second location than at the first location.

23 Claims, 32 Drawing Sheets



GEOSCOPE EXHIBIT 2005
Apple v. Geoscope, IPR2024-00031

U.S. PATENT DOCUMENTS

5,404,376	A	4/1995	Dent	
5,564,079	A *	10/1996	Olsson	455/456.3
5,717,406	A	2/1998	Sanderford et al.	
6,026,304	A	2/2000	Hilsenrath et al.	
6,064,339	A *	5/2000	Wax et al.	342/417
6,134,448	A	10/2000	Shoji et al.	
6,236,365	B1	5/2001	LeBlance et al.	
6,236,849	B1	5/2001	Reudink et al.	
6,249,252	B1	6/2001	Dupray et al.	
6,263,208	B1	7/2001	Chang et al.	
6,362,783	B1	3/2002	Sugiura et al.	
6,496,701	B1	12/2002	Chen et al.	
6,564,065	B1	5/2003	Chang et al.	
6,674,403	B2	1/2004	Gray et al.	
6,704,651	B2	3/2004	van Diggelen	
6,782,262	B1	8/2004	Lundborg	
6,799,047	B1	9/2004	Bahl et al.	
6,873,852	B2	3/2005	Koorapaty et al.	
6,952,181	B2	10/2005	Karr et al.	
2003/0214397	A1 *	11/2003	Perkins et al.	340/524
2005/0270236	A1 *	12/2005	Krumm et al.	342/451

OTHER PUBLICATIONS

Martin Hellebrant et al., "Estimating Position and Velocity of Mobiles in a Cellular Radio Network," IEEE Transactions on Vehicular Technology, vol. 46, No. 1, Feb. 1997, pp. 65-71.

J. Jimenez et al., "Mobile Location Using Coverage Information: Theoretical Analysis and Results," Euro-Cost, Apr. 1999, pp. 1-9.

H. Koshima et al., "Personal Locator Services Emerge," IEEE Spectrum, Feb. 2000, pp. 41-48.

* cited by examiner

Figure 1 (Prior Art)

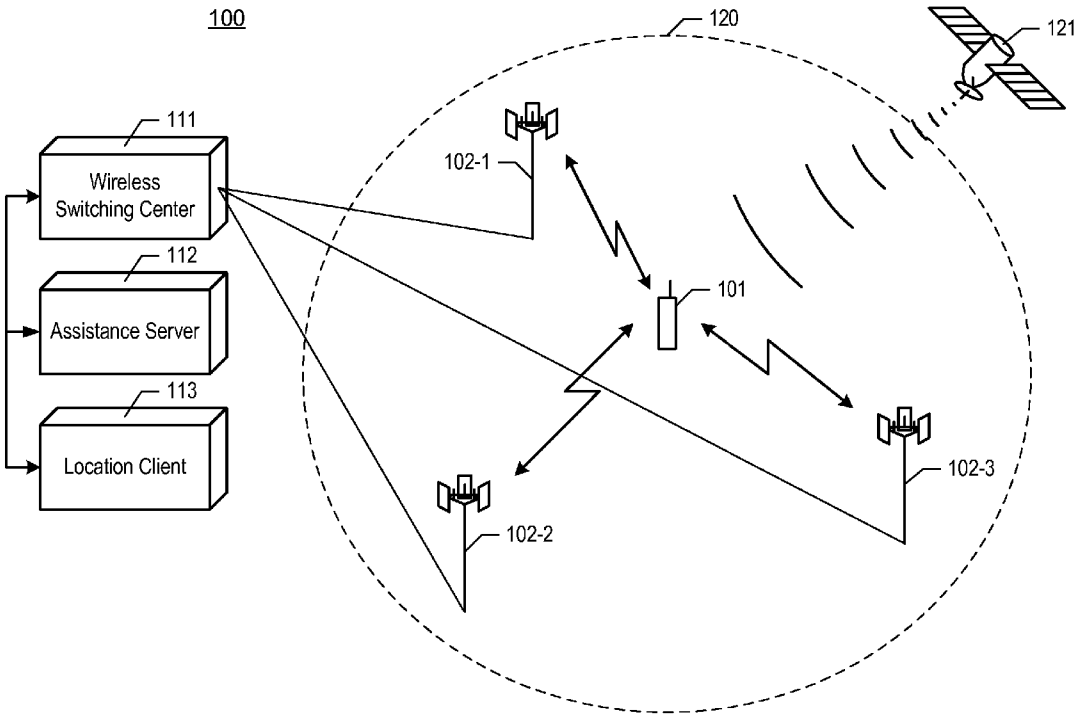


Figure 2

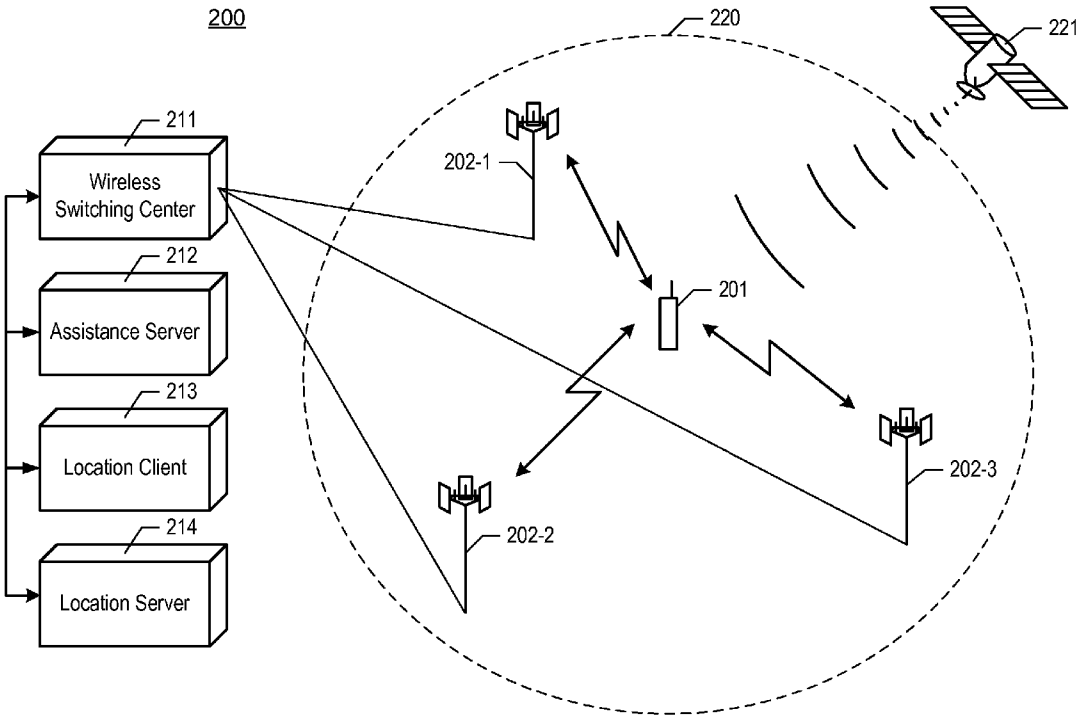

200
220
221
211
Wireless Switching Center
212
Assistance Server
213
Location Client
214
Location Server
202-1
201
202-2
202-3

Figure 3

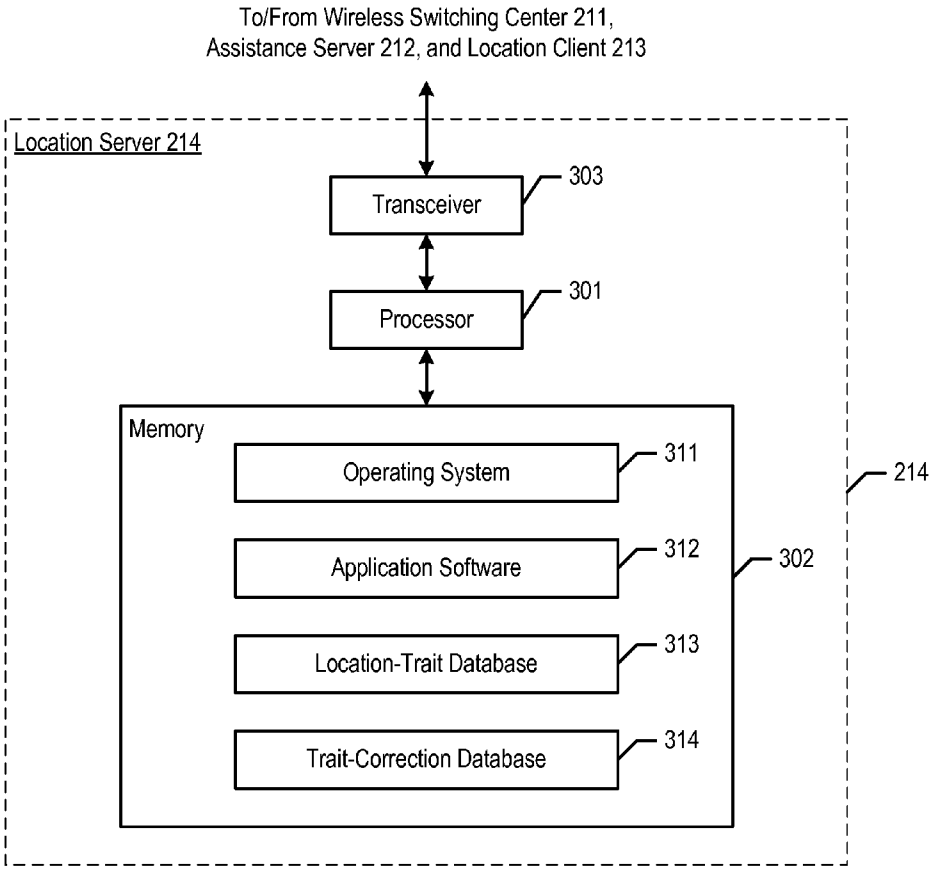

To/From Wireless Switching Center 211,
Assistance Server 212, and Location Client 213
Location Server 214
Transceiver
303
Processor
301
Memory
Operating System
311
Application Software
312
Location-Trait Database
313
Trait-Correction Database
314
302
214

Figure 4

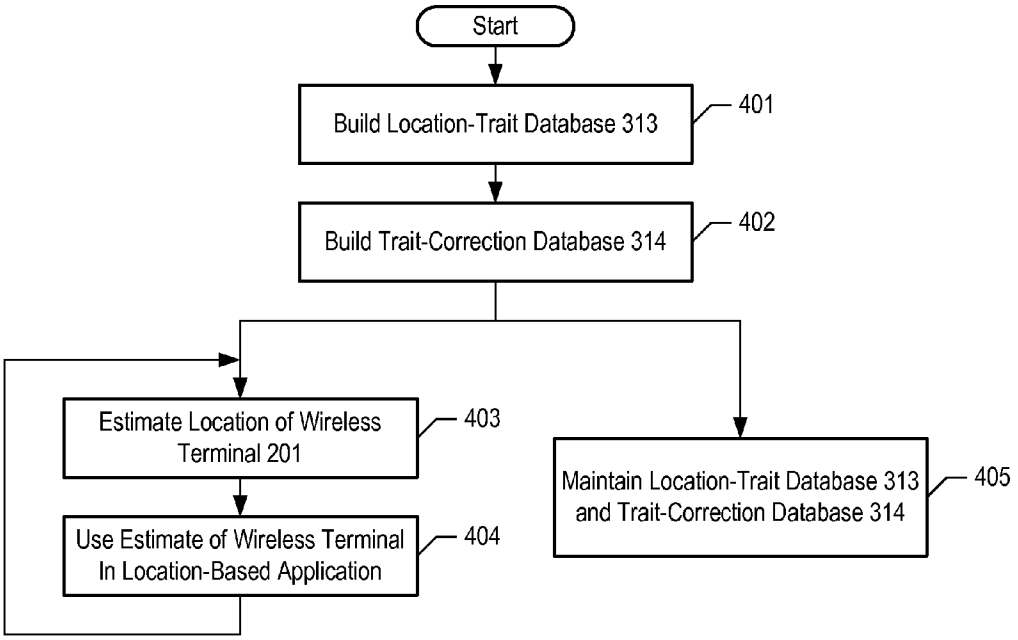

Start
Build Location-Trait Database 313
401
Build Trait-Correction Database 314
402
Estimate Location of Wireless Terminal 201
403
Use Estimate of Wireless Terminal In Location-Based Application
404
Maintain Location-Trait Database 313 and Trait-Correction Database 314
405

Figure 5

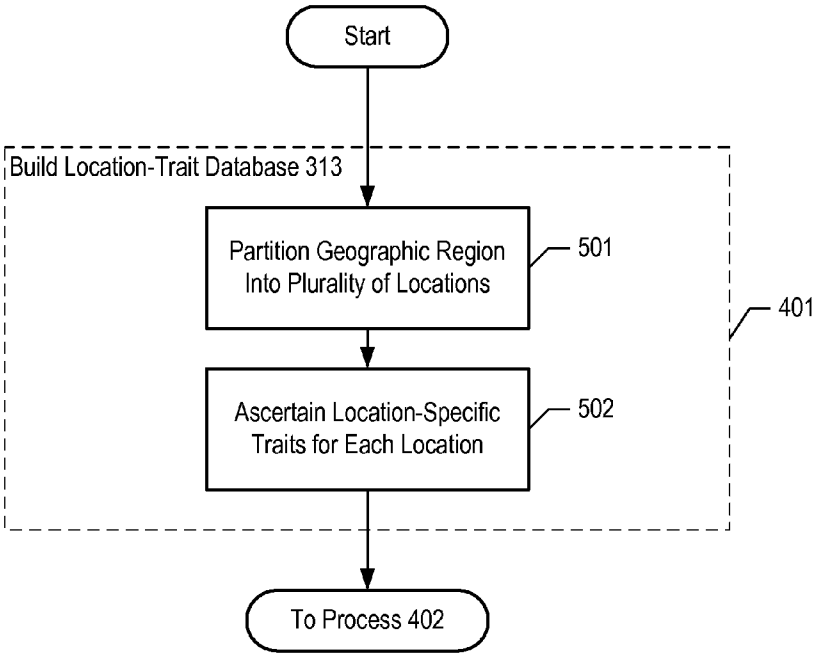

Start
Build Location-Trait Database 313
Partition Geographic Region Into Plurality of Locations
501
Ascertain Location-Specific Traits for Each Location
502
401
To Process 402

Figure 6a

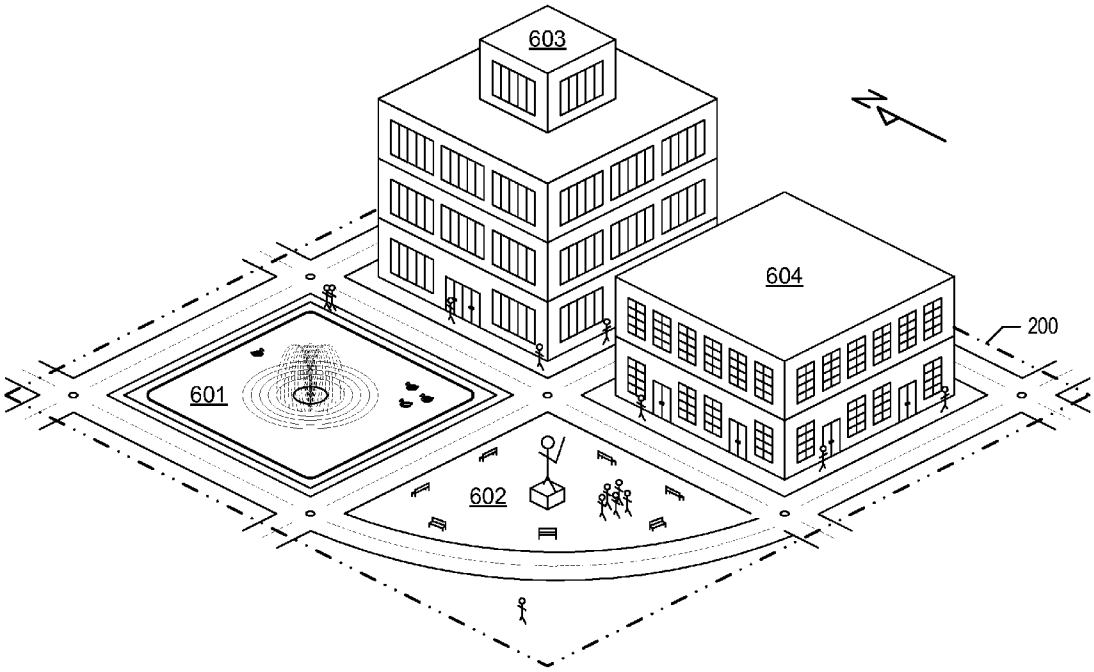


Figure 6b

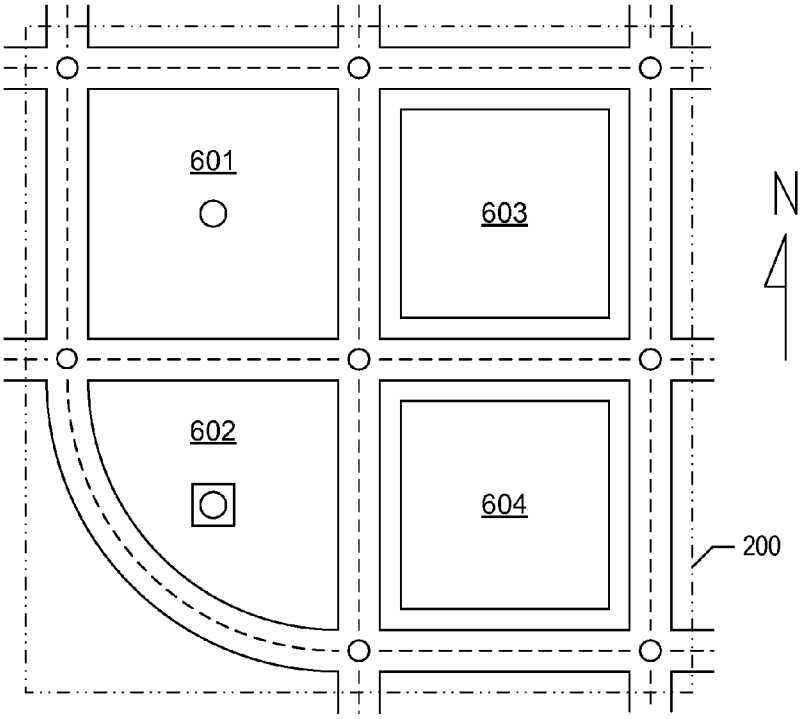


Figure 6c

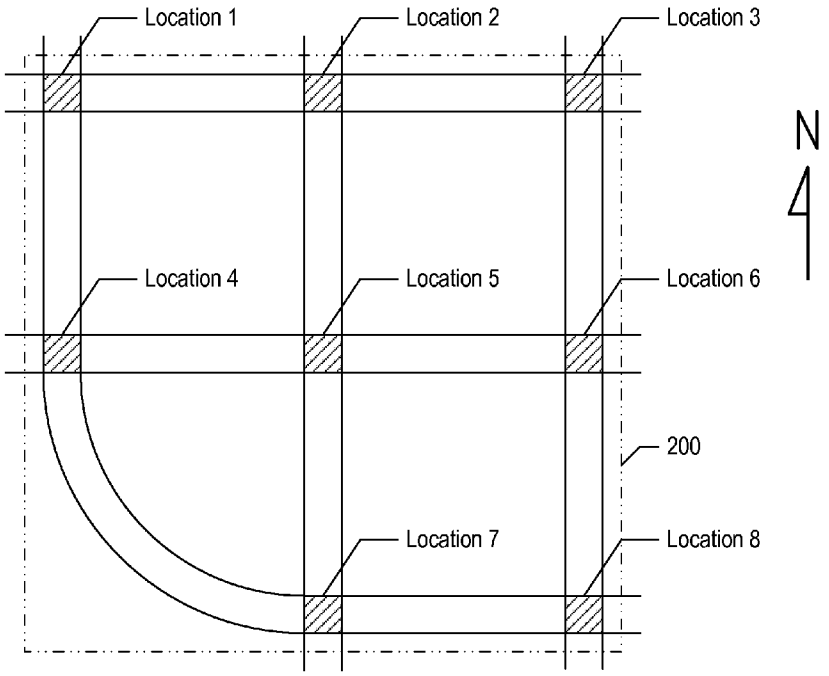

Location 1
Location 2
Location 3
N
Location 4
Location 5
Location 6
200
Location 7
Location 8

Figure 6d

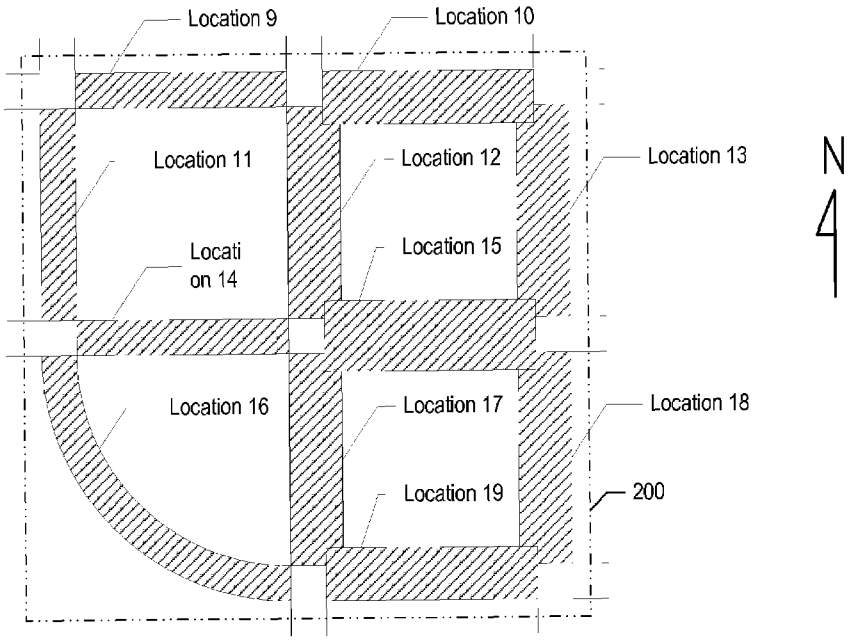

Location 9
Location 10
Location 11
Location 12
Location 13
Locati
on 14
Location 15
Location 16
Location 17
Location 18
Location 19
200
N

Figure 6e

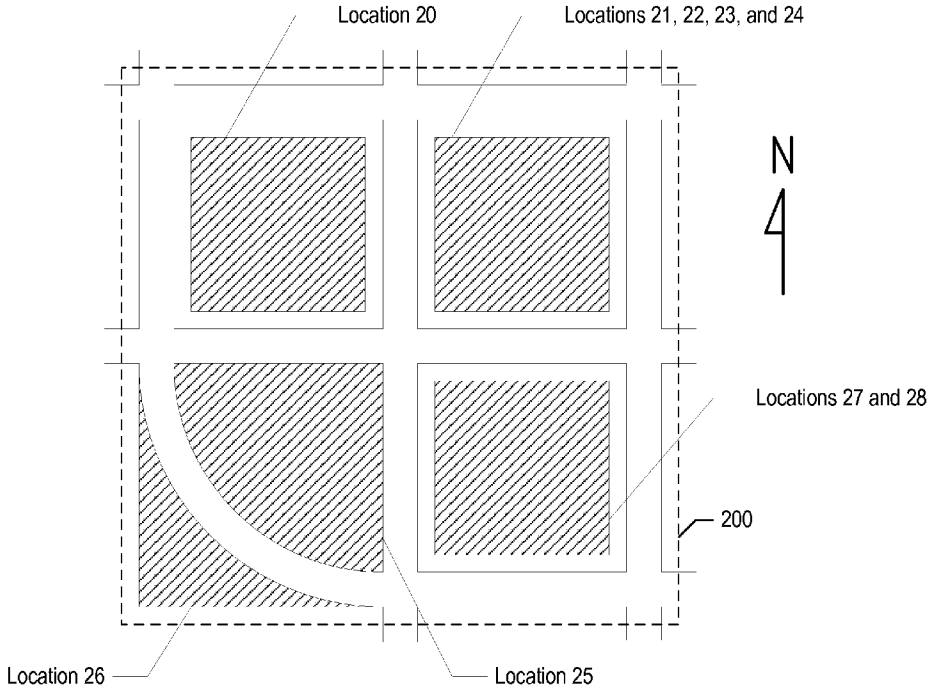

Location 20
Locations 21, 22, 23, and 24
N
Locations 27 and 28
200
Location 26
Location 25

Figure 6f

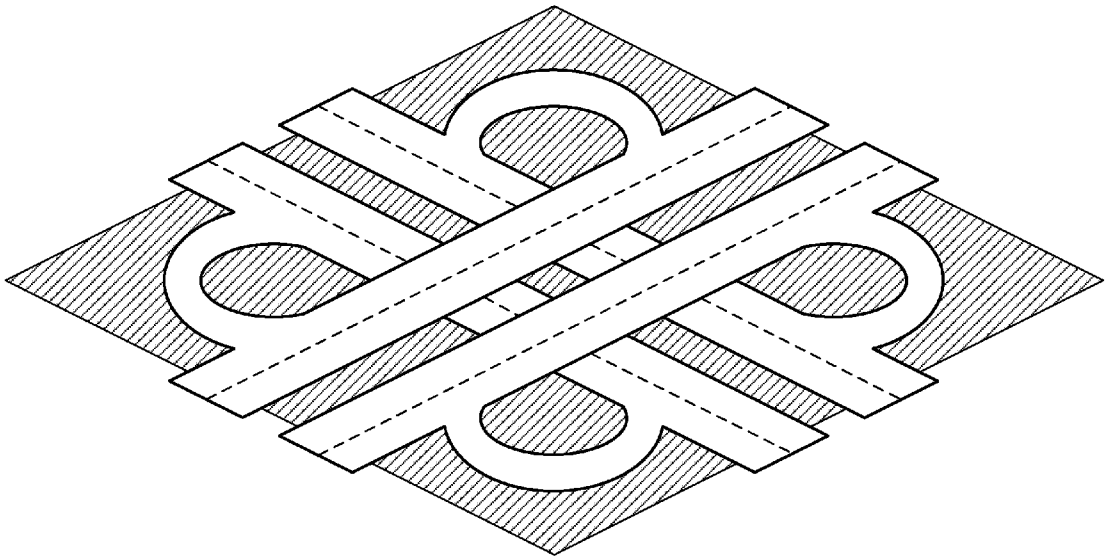


Figure 6g

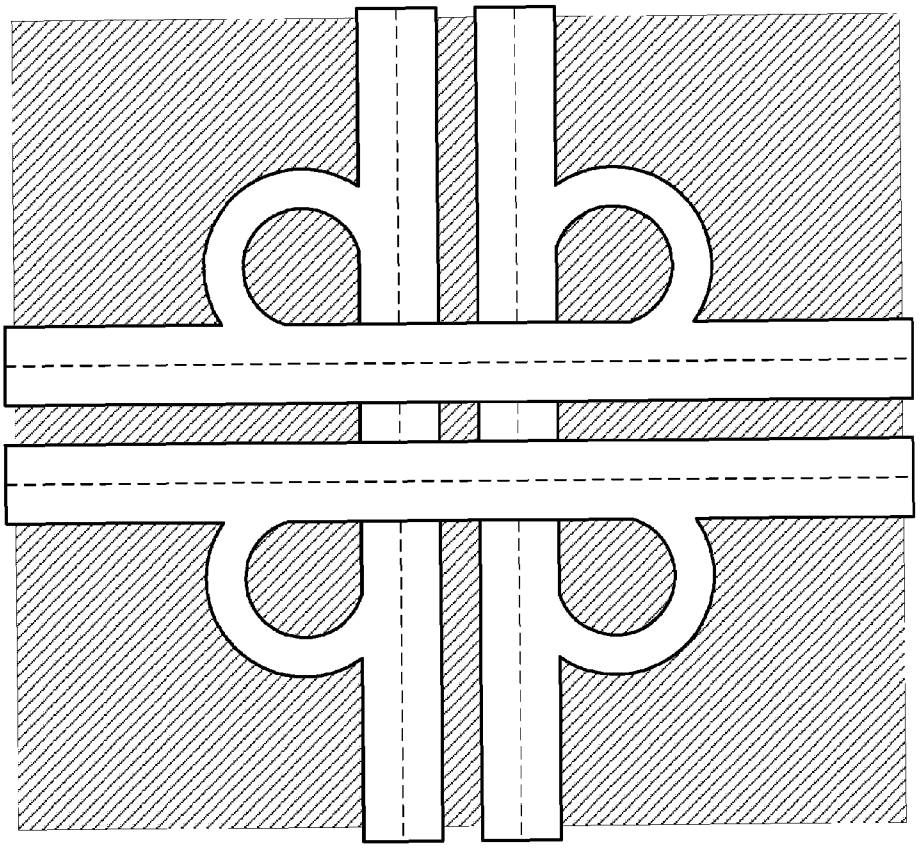


Figure 6h

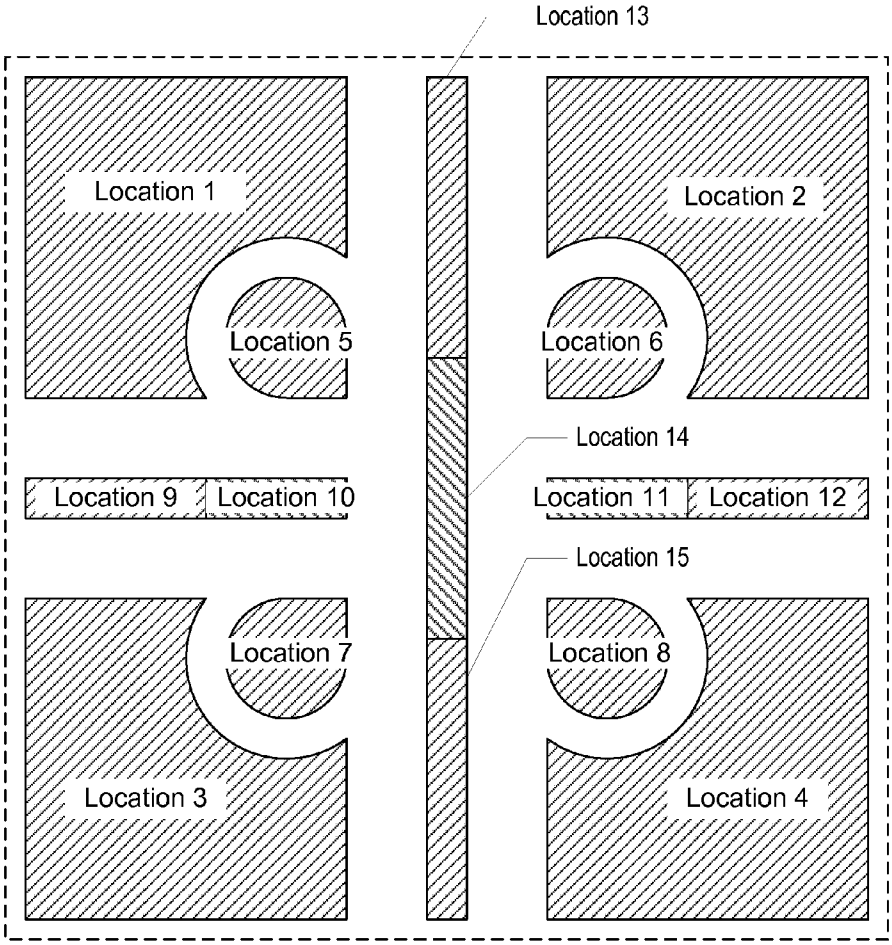

Location 13
Location 1
Location 2
Location 5
Location 6
Location 14
Location 9
Location 10
Location 11
Location 12
Location 15
Location 7
Location 8
Location 3
Location 4

Figure 6i

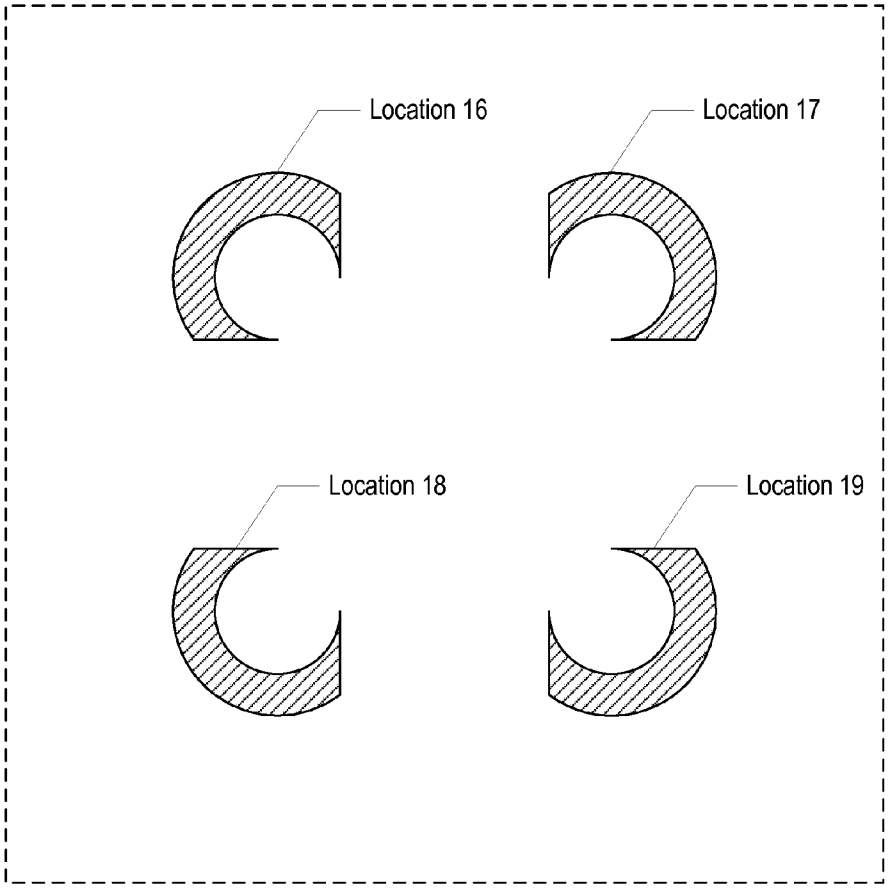


Figure 6j

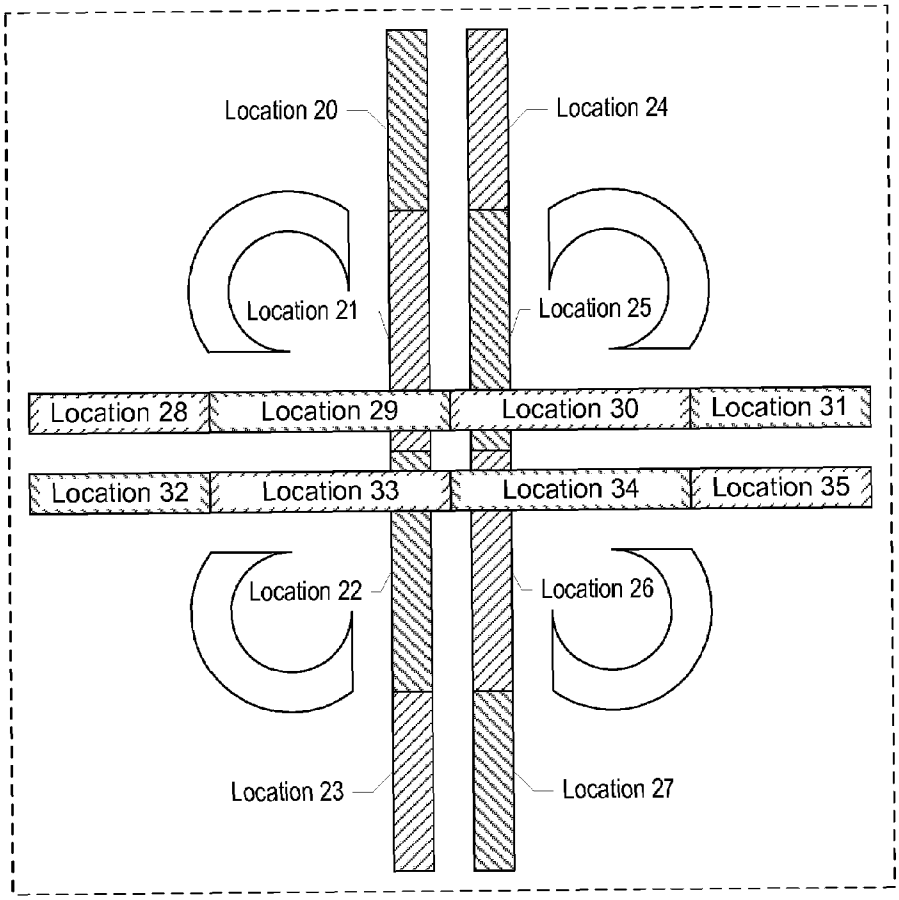

Location 20
Location 24
Location 21
Location 25
Location 28
Location 29
Location 30
Location 31
Location 32
Location 33
Location 34
Location 35
Location 22
Location 26
Location 23
Location 27

Figure 6k

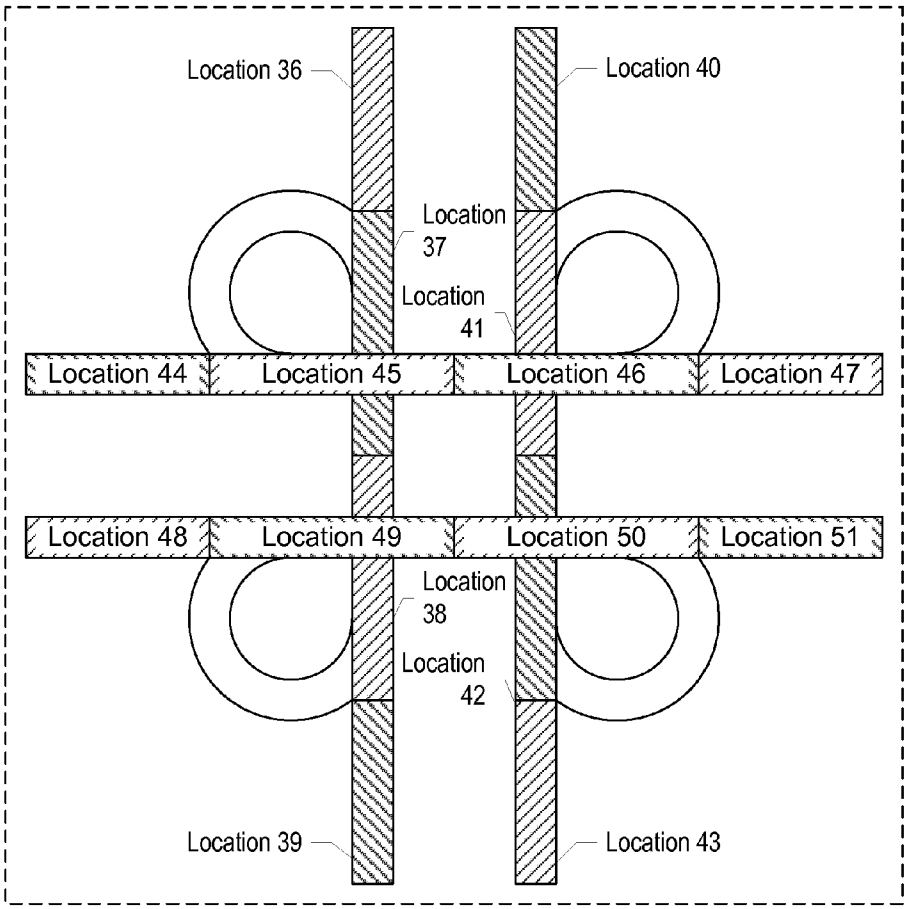

Location 36
Location 40
Location 37
Location 41
Location 44
Location 45
Location 46
Location 47
Location 48
Location 49
Location 50
Location 51
Location 38
Location 42
Location 39
Location 43

Figure 6L

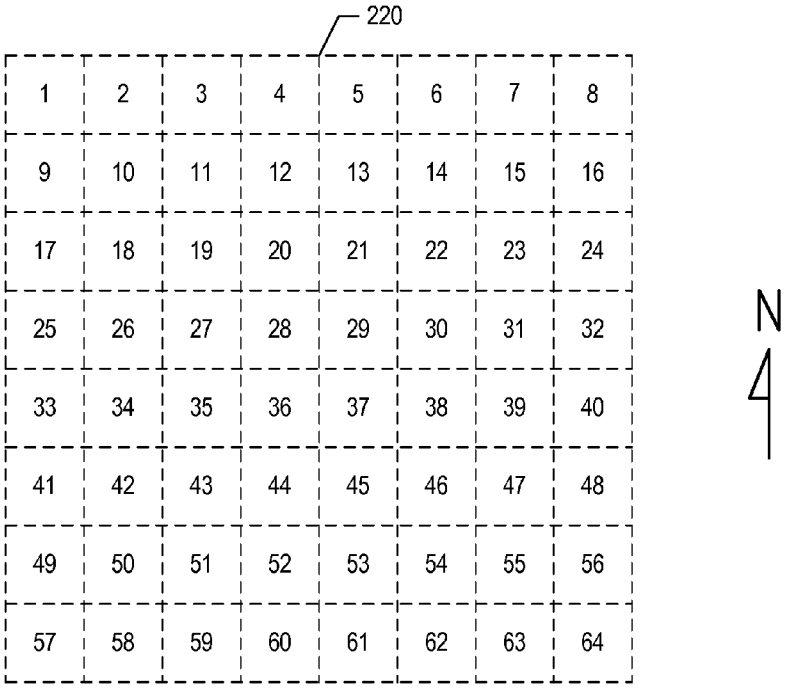

220
1 2 3 4 5 6 7 8
9 10 11 12 13 14 15 16
17 18 19 20 21 22 23 24
25 26 27 28 29 30 31 32
33 34 35 36 37 38 39 40
41 42 43 44 45 46 47 48
49 50 51 52 53 54 55 56
57 58 59 60 61 62 63 64
N

Figure 6m

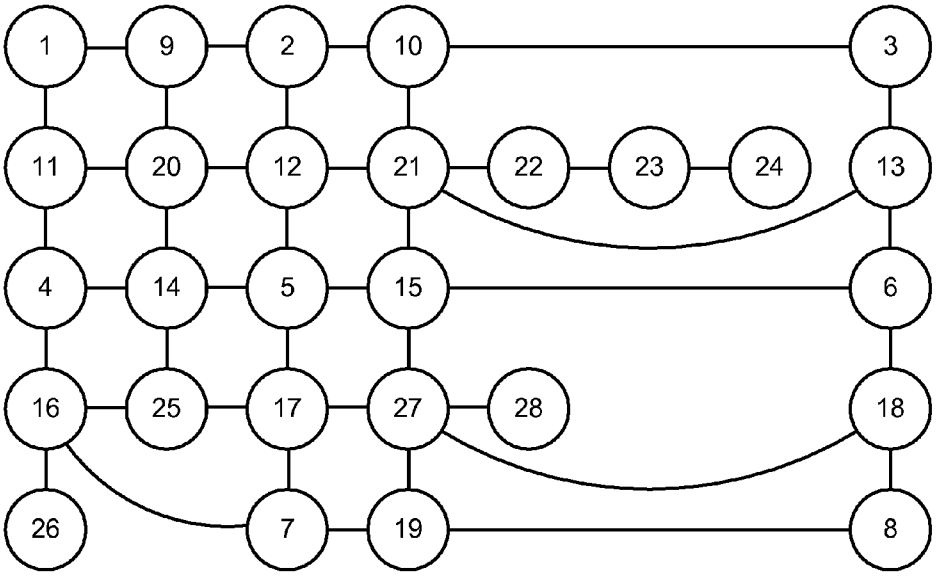
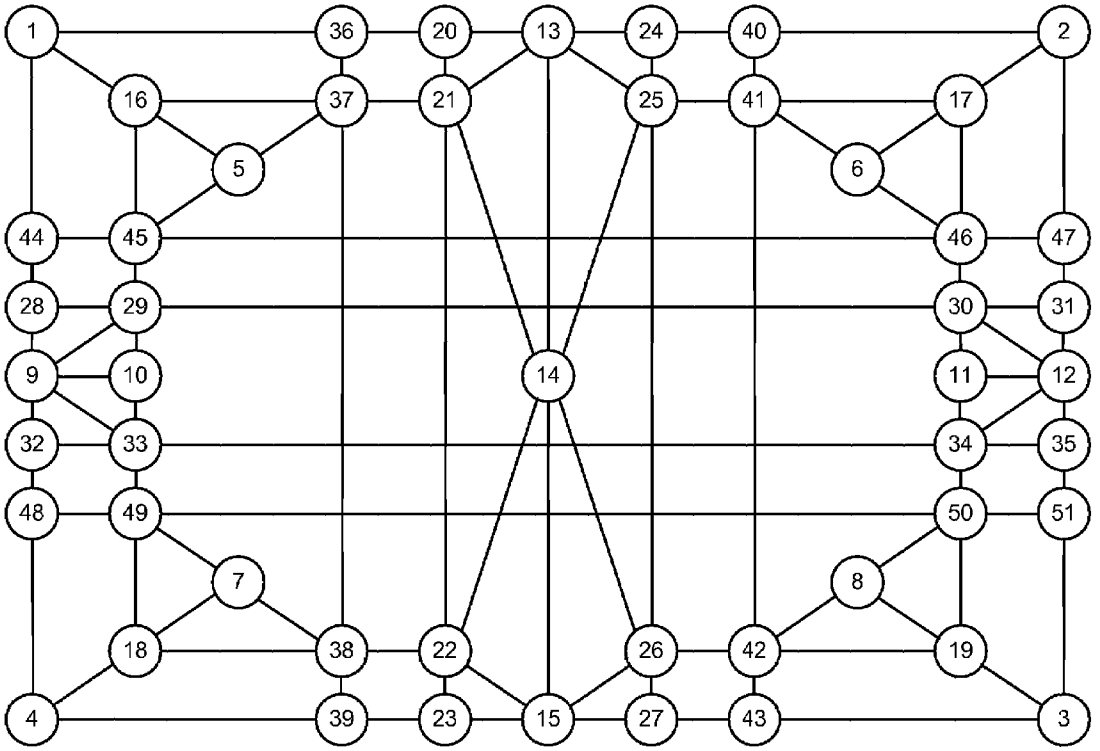


Figure 6n


1
36
20
13
24
40
2
16
37
21
25
41
17
5
6
44
45
46
47
28
29
30
31
9
10
14
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12
32
33
34
35
48
49
50
51
7
8
18
38
22
26
42
19
4
39
23
15
27
43
3

Figure 7

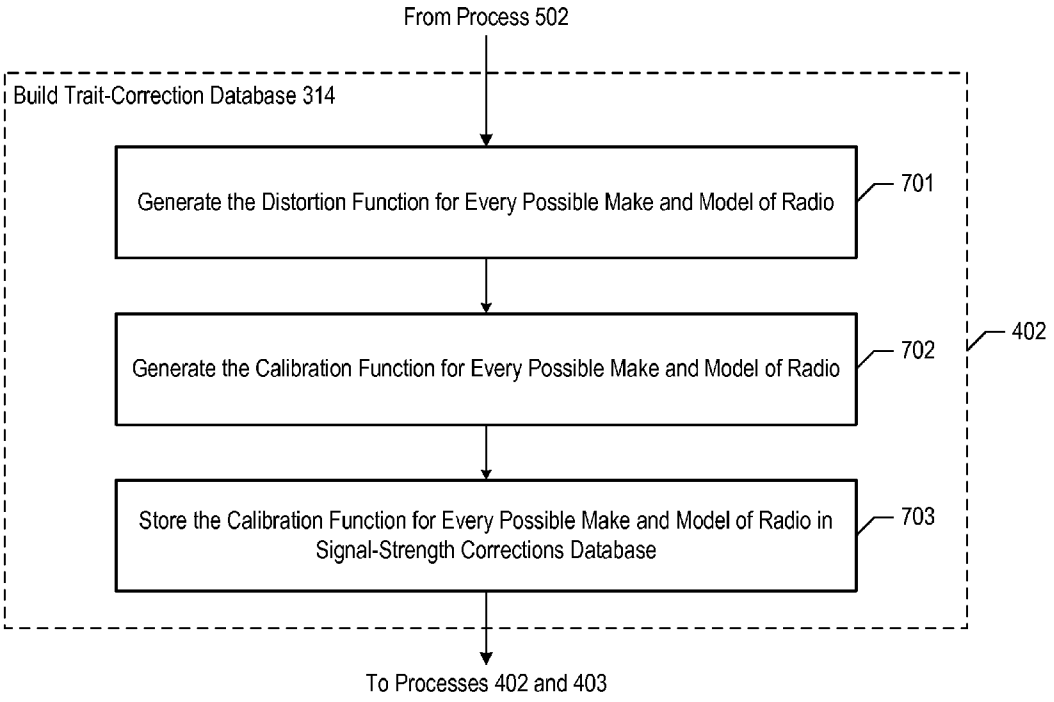

From Process 502
Build Trait-Correction Database 314
Generate the Distortion Function for Every Possible Make and Model of Radio
701
Generate the Calibration Function for Every Possible Make and Model of Radio
702
402
Store the Calibration Function for Every Possible Make and Model of Radio in Signal-Strength Corrections Database
703
To Processes 402 and 403

Figure 8a

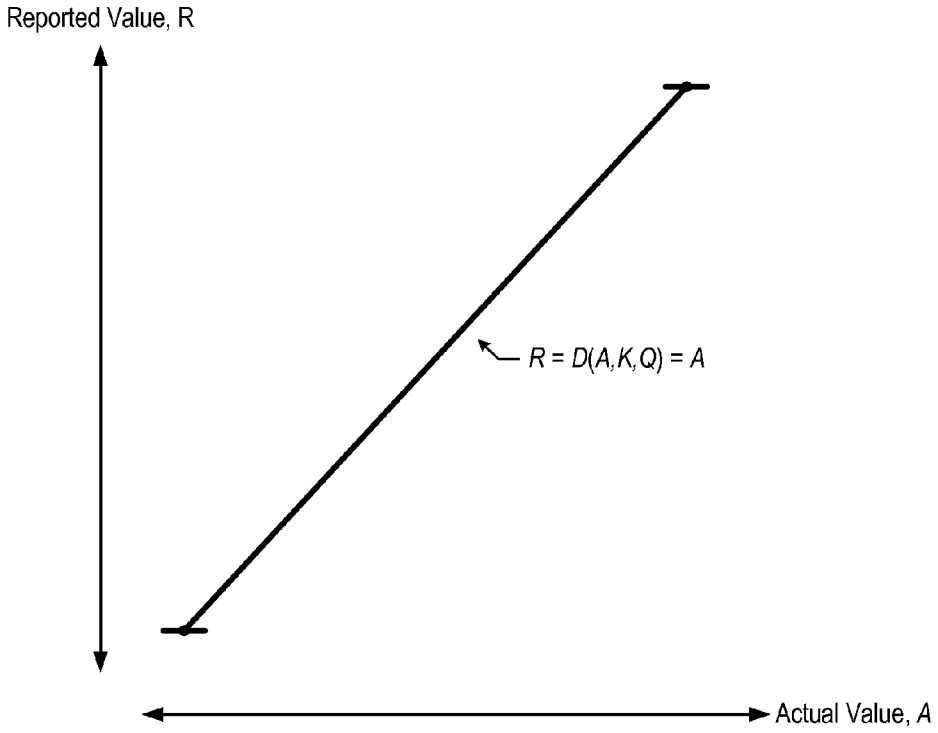


Figure 8b

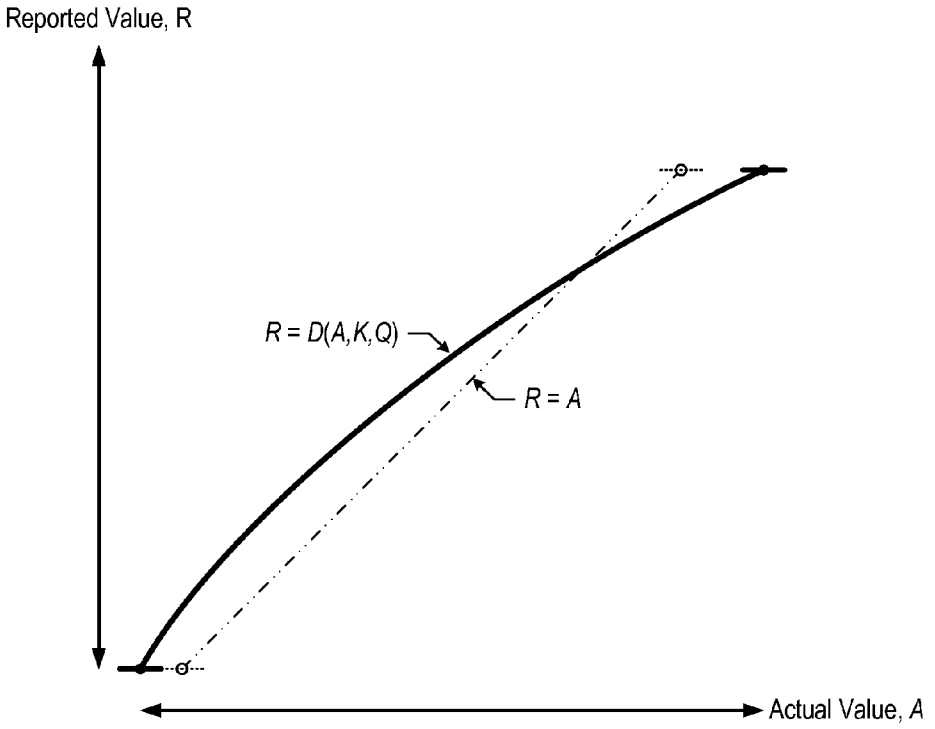


Figure 8c

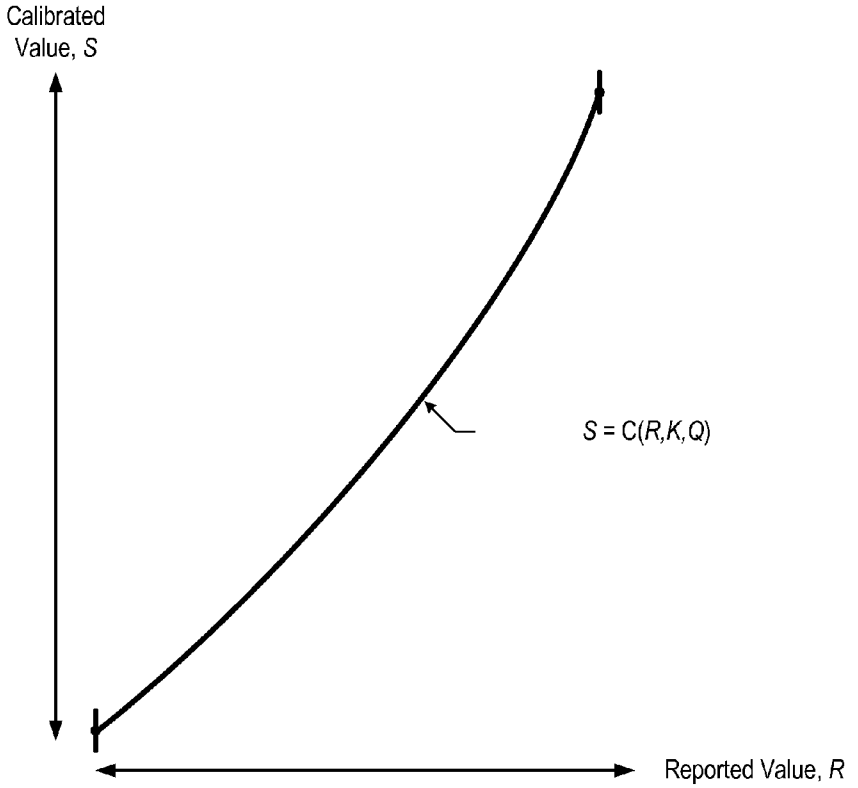


Figure 9

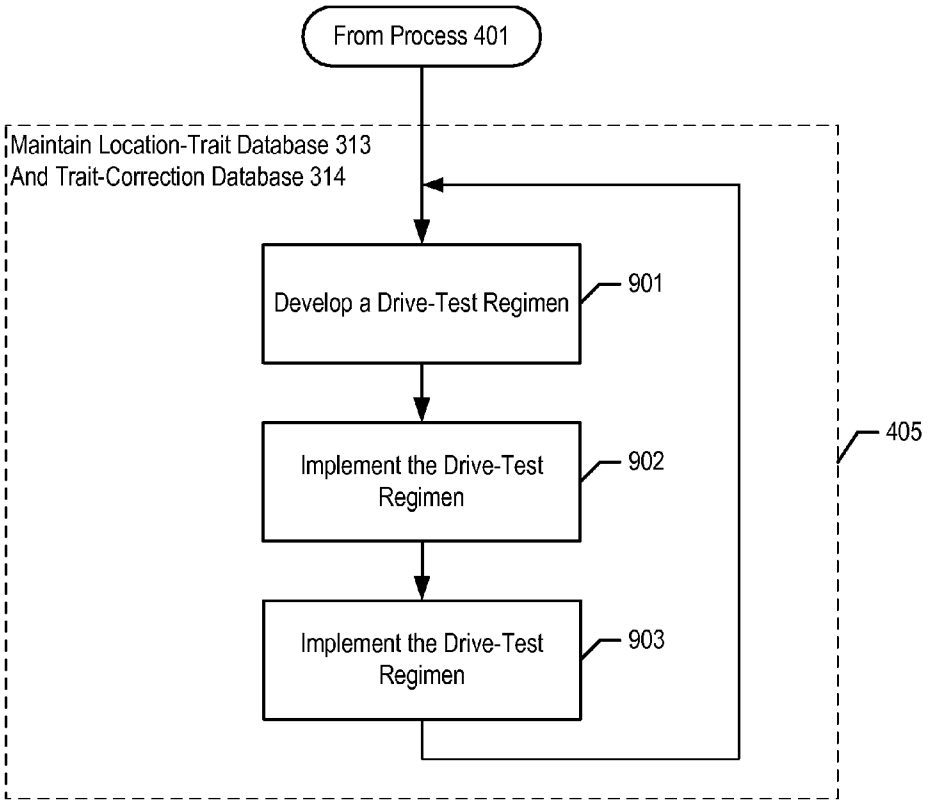

From Process 401
Maintain Location-Trait Database 313
And Trait-Correction Database 314
Develop a Drive-Test Regimen
901
Implement the Drive-Test Regimen
902
Implement the Drive-Test Regimen
903
405

Figure 10

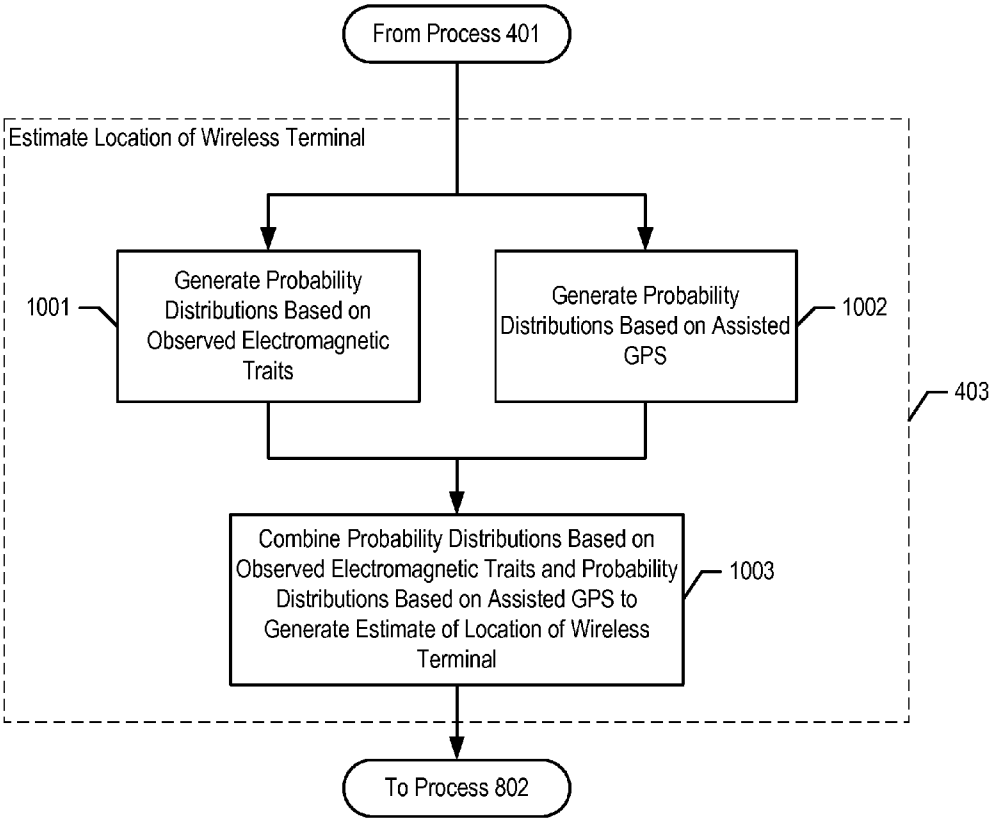

From Process 401
Estimate Location of Wireless Terminal
1001
Generate Probability Distributions Based on Observed Electromagnetic Traits
Generate Probability Distributions Based on Assisted GPS
1002
403
Combine Probability Distributions Based on Observed Electromagnetic Traits and Probability Distributions Based on Assisted GPS to Generate Estimate of Location of Wireless Terminal
1003
To Process 802

Figure 11a

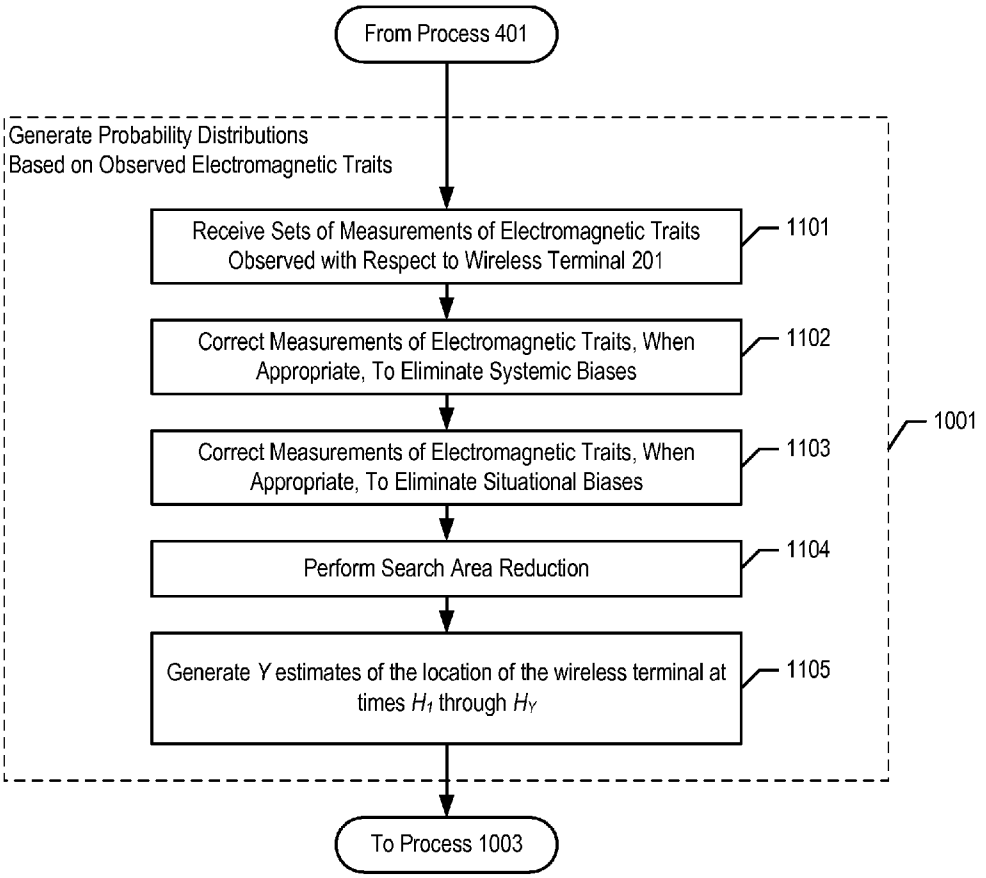

From Process 401
Generate Probability Distributions
Based on Observed Electromagnetic Traits
Receive Sets of Measurements of Electromagnetic Traits Observed with Respect to Wireless Terminal 201
1101
Correct Measurements of Electromagnetic Traits, When Appropriate, To Eliminate Systemic Biases
1102
Correct Measurements of Electromagnetic Traits, When Appropriate, To Eliminate Situational Biases
1103
Perform Search Area Reduction
1104
Generate Y estimates of the location of the wireless terminal at times H_1 through H_Y
1105
1001
To Process 1003

Figure 11b

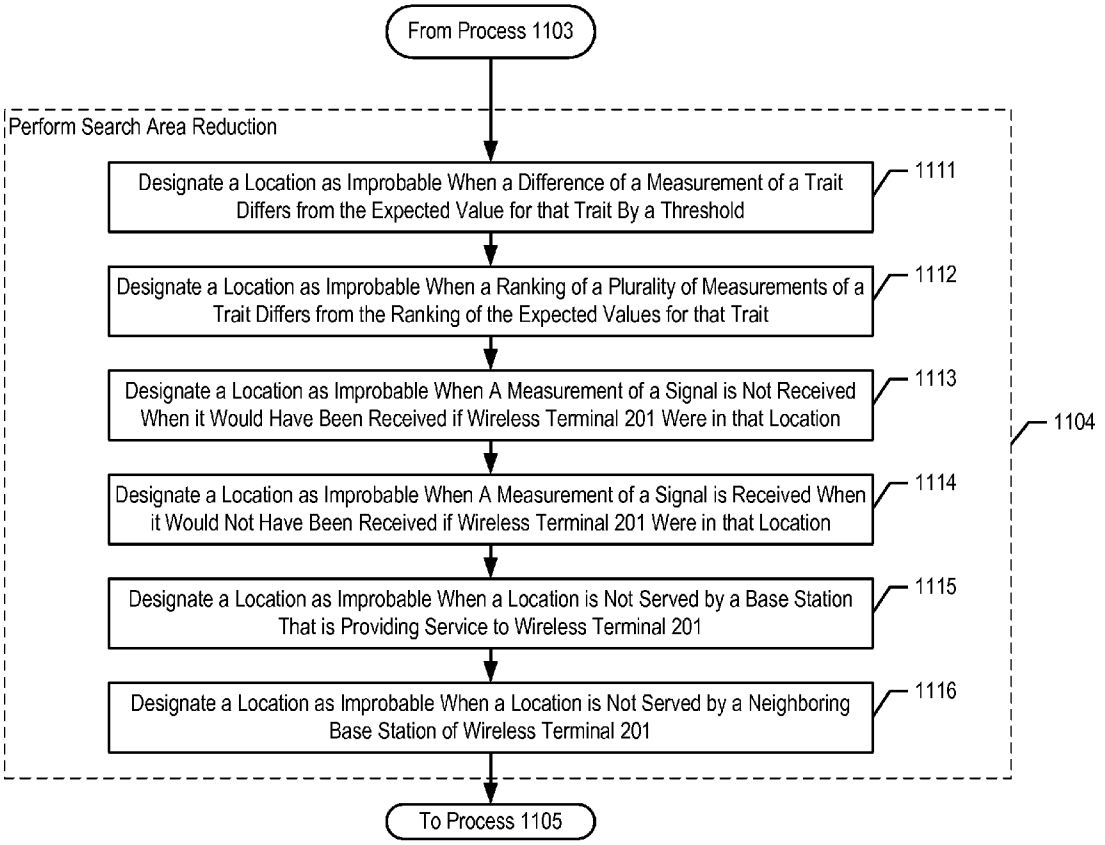

From Process 1103
Perform Search Area Reduction
Designate a Location as Improbable When a Difference of a Measurement of a Trait Differs from the Expected Value for that Trait By a Threshold
1111
Designate a Location as Improbable When a Ranking of a Plurality of Measurements of a Trait Differs from the Ranking of the Expected Values for that Trait
1112
Designate a Location as Improbable When A Measurement of a Signal is Not Received When it Would Have Been Received if Wireless Terminal 201 Were in that Location
1113
1104
Designate a Location as Improbable When A Measurement of a Signal is Received When it Would Not Have Been Received if Wireless Terminal 201 Were in that Location
1114
Designate a Location as Improbable When a Location is Not Served by a Base Station That is Providing Service to Wireless Terminal 201
1115
Designate a Location as Improbable When a Location is Not Served by a Neighboring Base Station of Wireless Terminal 201
1116
To Process 1105

Figure 11c

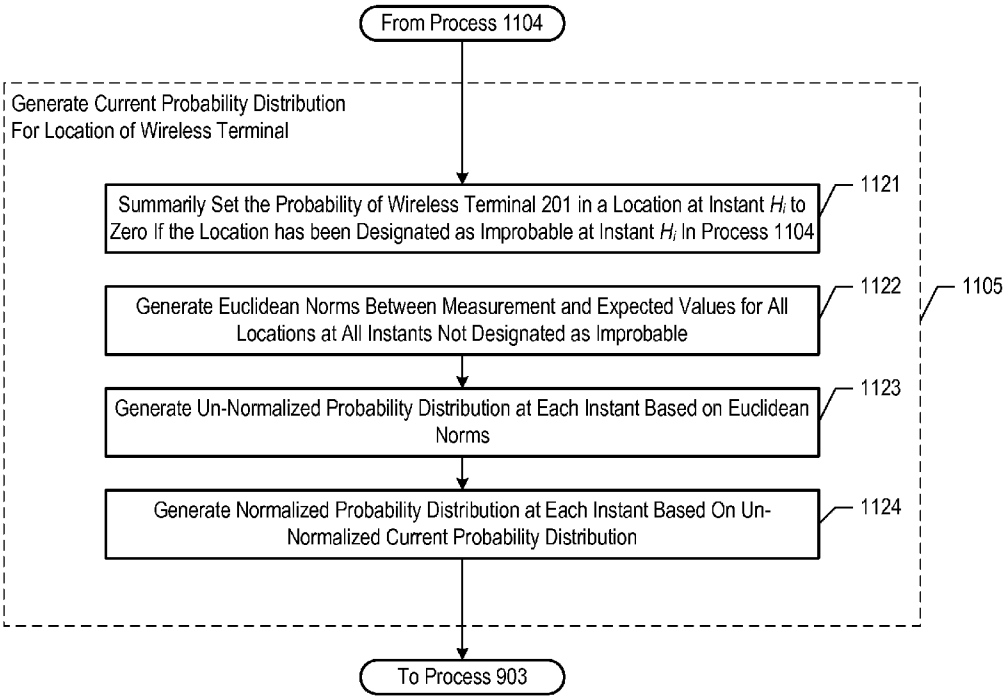

From Process 1104
Generate Current Probability Distribution For Location of Wireless Terminal
Summarily Set the Probability of Wireless Terminal 201 in a Location at Instant H_i to Zero If the Location has been Designated as Improbable at Instant H_i In Process 1104
1121
Generate Euclidean Norms Between Measurement and Expected Values for All Locations at All Instants Not Designated as Improbable
1122
1105
Generate Un-Normalized Probability Distribution at Each Instant Based on Euclidean Norms
1123
Generate Normalized Probability Distribution at Each Instant Based On Un-Normalized Current Probability Distribution
1124
To Process 903

Figure 12

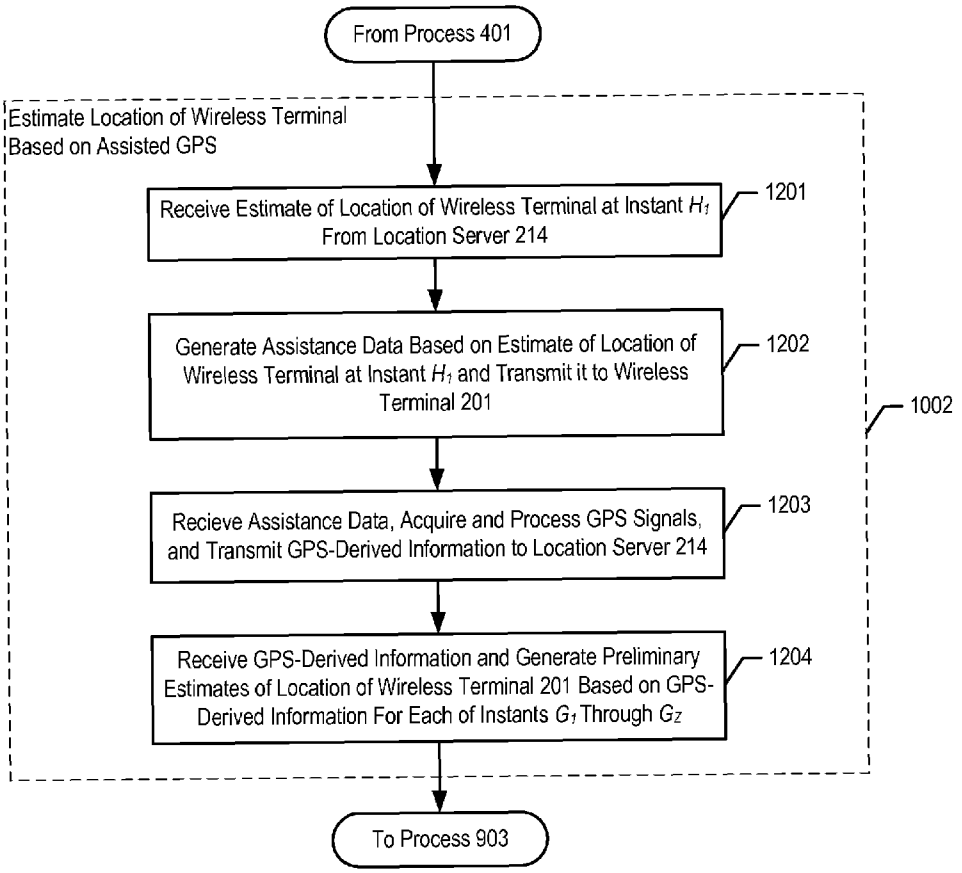

From Process 401
Estimate Location of Wireless Terminal Based on Assisted GPS
Receive Estimate of Location of Wireless Terminal at Instant H_1 From Location Server 214
1201
Generate Assistance Data Based on Estimate of Location of Wireless Terminal at Instant H_1 and Transmit it to Wireless Terminal 201
1202
1002
Recieve Assistance Data, Acquire and Process GPS Signals, and Transmit GPS-Derived Information to Location Server 214
1203
Receive GPS-Derived Information and Generate Preliminary Estimates of Location of Wireless Terminal 201 Based on GPS-Derived Information For Each of Instants G_1 Through G_Z
1204
To Process 903

Figure 13

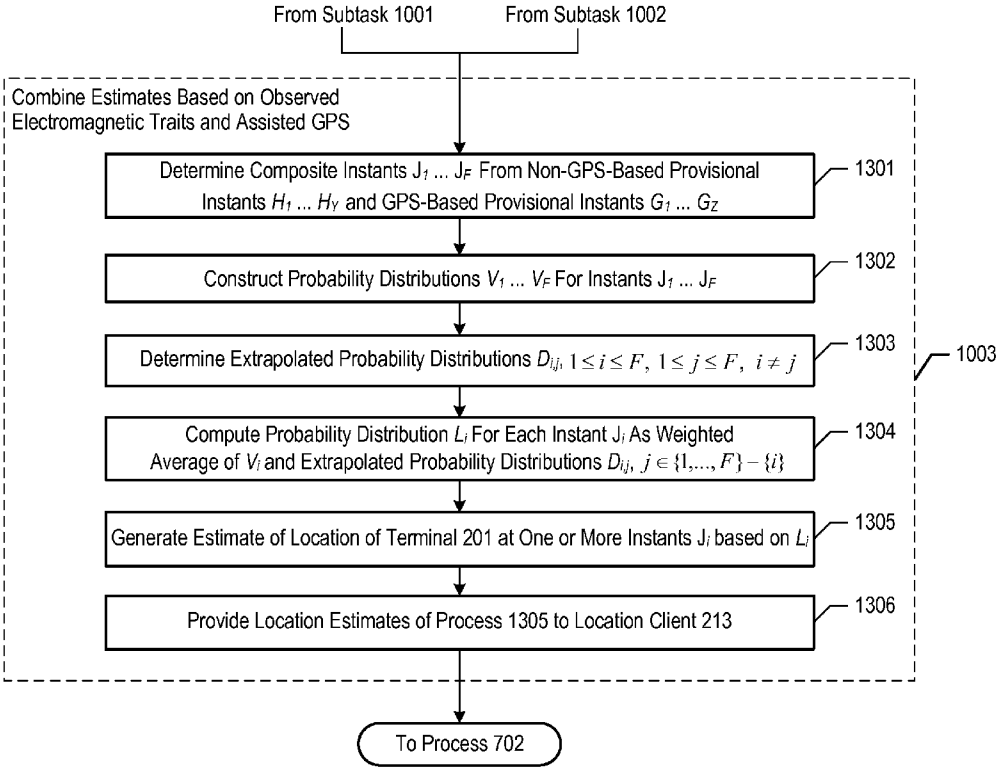

From Subtask 1001
From Subtask 1002
Combine Estimates Based on Observed Electromagnetic Traits and Assisted GPS
Determine Composite Instants $J_1 \ldots J_F$ From Non-GPS-Based Provisional Instants $H_1 \ldots H_Y$ and GPS-Based Provisional Instants $G_1 \ldots G_Z$
1301
Construct Probability Distributions $V_1 \ldots V_F$ For Instants $J_1 \ldots J_F$
1302
Determine Extrapolated Probability Distributions $D_{i,j}$, $1 \le i \le F,\ 1 \le j \le F,\ i \ne j$
1303
1003
Compute Probability Distribution L_i For Each Instant J_i As Weighted Average of V_i and Extrapolated Probability Distributions $D_{i,j}$, $j \in \{1,\ldots,F\} - \{i\}$
1304
Generate Estimate of Location of Terminal 201 at One or More Instants J_i based on L_i
1305
Provide Location Estimates of Process 1305 to Location Client 213
1306
To Process 702

Figure 14

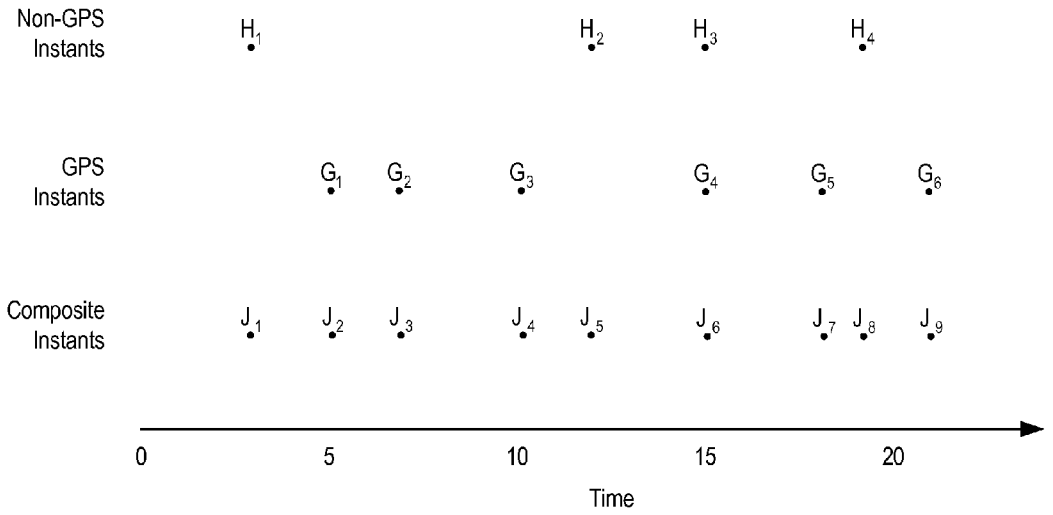
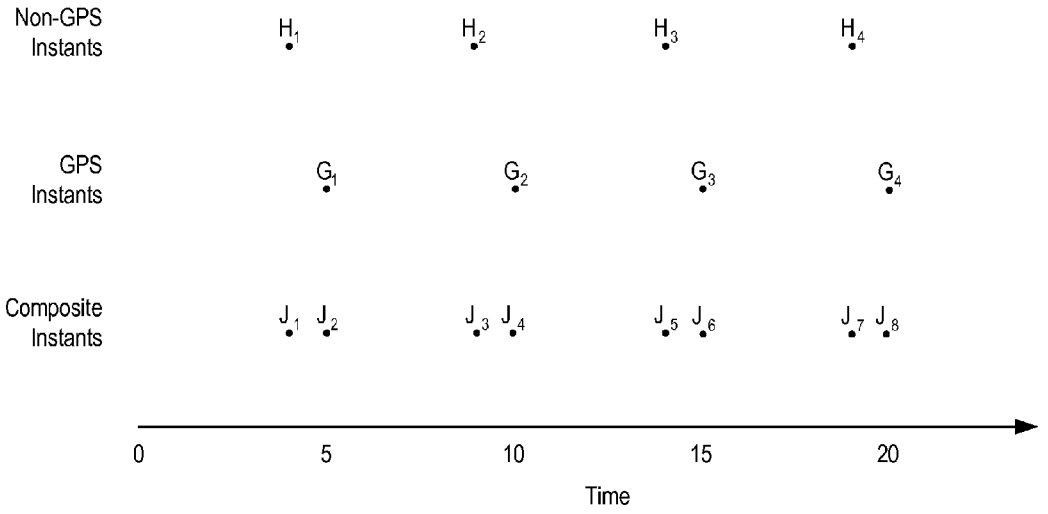

Non-GPS Instants
H1
H2
H3
H4
GPS Instants
G1
G2
G3
G4
G5
G6
Composite Instants
J1
J2
J3
J4
J5
J6
J7
J8
J9
0
5
10
15
20
Time

Figure 15


Non-GPS Instants
H1
H2
H3
H4
GPS Instants
G1
G2
G3
G4
Composite Instants
J1
J2
J3
J4
J5
J6
J7
J8
0
5
10
15
20
Time

ESTIMATING THE LOCATION OF A WIRELESS TERMINAL BASED ON NON-UNIFORM PROBABILITIES OF MOVEMENT

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 and using the estimate of the location in a location-based application.

BACKGROUND

FIG. **1** depicts a diagram of the salient components of wireless telecommunications system **100** in accordance with the prior art. Wireless telecommunications system **100** comprises: wireless terminal **101**, base stations **102-1**, **102-2**, and **102-3**, wireless switching center **111**, assistance server **112**, location client **113**, and Global Positioning System ("GPS") constellation **121**. Wireless telecommunications system **100** provides wireless telecommunications service to all of geographic region **120**, in well-known fashion.

The salient advantage of wireless telecommunications over wireline telecommunications is the mobility that is afforded to the users. 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 or might seek advice in navigation.

In addition, 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 an E 9-1-1 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 or centroid of the sector 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 (in present cellular systems), 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 multilaterating the time of arrival of the signals transmitted by the wireless terminal. This technique can achieve accuracy to within a few hundreds of meters and is advantageous in that it can be used with legacy wireless terminals. The disadvantage of this second technique, however, is that it generally requires that hardware be added to the telecommunication system's base stations, which can be prohibitively 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 typically accurate to within tens of meters but is disadvantageous in that it does not work consistently well indoors, in heavily wooded forests, or in urban canyons. Furthermore, the accuracy of this third technique can be severely degraded by multipath reflections.

Therefore, the need exists for a technique for estimating the location of a wireless terminal with higher resolution than the first technique and without some of the costs and disadvantages of the second and third techniques.

SUMMARY OF THE INVENTION

The present invention enables the construction and use of a system that can estimate the location of a wireless terminal without some of the costs and limitations associated with techniques for doing so in the prior art.

The present invention is based on the recognition that there are traits of electromagnetic signals that are dependent on topography, the receiver, the location of the transmitter, and other factors. For example, if a particular radio station is known to be received strongly at a first location and weakly at a second location, and a given wireless terminal at an unknown location is receiving the radio station weakly, it is more likely that the wireless terminal is at the second location than at the first location.

By quantifying "strongly" and "weakly" and extending this principle to multiple traits and multiple signals, the present invention can estimate the location of a wireless terminal with greater accuracy.

The illustrative embodiment comprises: estimating the location of a wireless terminal at time t from among a plurality of candidate locations based on: (i) a first probability distribution for the location of the wireless terminal at time t among the plurality of candidate locations; (ii) a second probability distribution for the location of the wireless terminal at time $t-\Delta$ among the plurality of candidate locations, wherein Δ is nonzero; and (iii) one or more of a plurality of non-isotropic transition probabilities for the wireless terminal moving among the plurality of candidate locations from the earlier of time t and time $t-\Delta$ to the later of time t and time $t-\Delta$.

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 diagram of the salient components of wireless telecommunications system **200** in accordance with the illustrative embodiment of the present invention.

FIG. **3** depicts a block diagram of the salient components of location server **214**, as shown in FIG. **2**, in accordance with the illustrative embodiment.

FIG. **4** depicts a flowchart of the salient processes performed in accordance with the illustrative embodiment of the present invention.

FIG. **5** depicts a flowchart of the salient processes performed in accordance with process **401** of FIG. **4**: building Location-Trait Database **313**.

FIGS. **6***a* through **6***k* depict geographic regions and their deconstruction into a plurality of locations.

FIG. **6**L depicts an alternative partitioning of geographic region **220** into **64** square locations.

FIG. **6***m* depicts a graphical representation of an adjacency graph of geographic region **220** as partitioned in FIGS. **6***c* through **6***e*.

FIG. **6***n* depicts a graphical representation of an adjacency graph of the highway intersection partitioned in FIGS. **6***h* through **6***k*.

FIG. **7** depicts a flowchart of the salient processes performed as part of process **402** of FIG. **4**: populating Trait-Correction Database **313**.

FIGS. **8***a* through **8***c* depict illustrative distortion and correction curves.

FIG. **9** depicts a flowchart of the salient processes performed in process **403** (of FIG. **4**): maintaining Location-Trait Database **313**.

FIG. **10** depicts a flowchart of the salient processes performed in process **701** of FIG. **7**: estimating the location of wireless terminal **201**.

FIG. **11***a* depicts a flowchart of the salient processes performed in process **901** of FIG. **9**: generating the probability distribution for the location of wireless terminal **201** based on the traits of one or more signals received by, or transmitted to, wireless terminal **201** at instants H_1 through H_Y.

FIG. **11***b* depicts a flowchart of the salient processes performed in accordance with process **1104** of FIG. **11***a*: search area reduction.

FIG. **11***c* depicts a flowchart of the salient processes performed in accordance with process **1105**: generating the probability distribution for that wireless terminal **201** at each of instants H_1 through H_Y.

FIG. **12** depicts a flowchart of the salient processes performed in process **902** of FIG. **9**: generating the probability distribution for the location of wireless terminal **201** based on GPS-derived information (i.e., information from GPS constellation **221**).

FIG. **13** depicts a flowchart of the salient processes performed in process **903** of FIG. **9**: combining non-GPS-based and GPS-based probability distributions for the location of wireless terminal **201**.

FIG. **14** depicts a first example of combining non-GPS-based instants H_1 through H_Y and GPS-based instants G_1 through G_Z into composite instants J_1 through J_F.

FIG. **15** depicts a second example of combining non-GPS-based instants H_1 through H_Y and GPS-based instants G_1 through G_Z into composite instants J_1 through J_F.

DETAILED DESCRIPTION

For the purposes of this specification, the following terms and their inflected forms are defined as follows:

The term "location" is defined as a one-dimensional point, a two-dimensional area, or a three-dimensional volume.

The term "staying probability" is defined as an estimate of the probability $P_S(b, T, N, W)$ that wireless terminal W in location b at calendrical time T will still be in location b at time $T+\Delta t$, given environmental conditions, N.

The term "moving probability" is defined as an estimate of the probability $P_M(b, T, N, W, c)$ that wireless terminal W in location b at calendrical time T will be in adjacent location c at time $T+\Delta t$, given environmental conditions, N.

The term "environmental conditions N," are defined to include one or more physical aspects of the environment, and includes, but is not limited to, the weather, the astronomical conditions, atmospheric conditions, the quantity and density of radio traffic, the quantity and density of vehicular traffic, road and sidewalk construction, etc.

The term "calendrical time T" is defined as the time as denominated in one or more measures (e.g., seconds, minutes, hours, time of day, day, day of week, month, month of year, year, etc.).

Overview—FIG. **2** depicts a diagram of the salient components of wireless telecommunications system **200** in accordance with the illustrative embodiment of the present invention. Wireless telecommunications system **200** comprises: wireless terminal **201**, base stations **202-1**, **202-2**, and **202-3**, wireless switching center **211**, assistance server **212**, location client **213**, location server **214**, and GPS constellation **221**, which are interrelated as shown. The illustrative embodiment provides wireless telecommunications service to all of geographic region **220**, in well-known fashion, estimates the location of wireless terminal **201** within geographic region **220**, and uses that estimate in a location-based application.

In accordance with the illustrative embodiment, wireless telecommunications service is provided to wireless terminal **201** in accordance with the Universal Mobile Telecommunications System, which is commonly known as "UMTS." 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 one or more other air-interface standards (e.g., Global System Mobile "GSM," CDMA-2000, IS-136 TDMA, IS-95 CDMA, 3G Wideband CDMA, IEEE 802.11 WiFi, 802.16 WiMax, Bluetooth, etc.) in one or more frequency bands.

Wireless terminal **201** comprises the hardware and software necessary to be UMTS-compliant and to perform the processes described below and in the accompanying figures. For example and without limitation, wireless terminal **201** is capable of:

i. measuring one or more traits of one of more electromagnetic signals and of reporting the measurements to location server **214**, and

ii. transmitting one or more signals and of reporting the transmission parameters of the signals to location server **214**, and

iii. receiving GPS assistance data from assistance server **212** to assist it in acquiring and processing GPS ranging signals.

Wireless terminal **201** is mobile and can be at any location within geographic region **220**. Although wireless telecommunications system **200** comprises only one wireless terminal, 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 wireless terminals.

Base stations **202-1**, **202-2**, and **202-3** communicate with wireless switching center **211** and with wireless terminal **201** via radio in well-known fashion. As is well known to those skilled in the art, base stations are also commonly referred to by a variety of alternative names such as access points, nodes, network interfaces, etc. 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.

In accordance with the illustrative embodiment of the present invention, base stations **202-1**, **202-2**, and **202-3** are terrestrial, immobile, and within geographic region **220**. 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 the base

stations are airborne, marine-based, or space-based, regardless of whether or not they are moving relative to the Earth's surface, and regardless of whether or not they are within geographic region **220**.

Wireless switching center **211** comprises a switch that orchestrates the provisioning of telecommunications service to wireless terminal **201** and the flow of information to and from location server **214**, as described below and in the accompanying figures. As is well known to those skilled in the art, wireless switching centers are also commonly referred to by other names such as mobile switching centers, mobile telephone switching offices, routers, etc.

Although the illustrative embodiment comprises one wireless switching center, 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 wireless switching centers. For example, when a wireless terminal can interact with two or more wireless switching centers, the wireless switching centers can exchange and share information that is useful in estimating the location of the wireless terminal. For example, the wireless switching centers can use the IS-41 protocol messages HandoffMeasurementRequest and HandoffMeasurementRequest**2** to elicit signal-strength measurements from one another. The use of two or more wireless switching centers is particularly common when the geographic area serviced by the wireless switching center is small (e.g., local area networks, etc.) or when multiple wireless switching centers serve a common area.

In accordance with the illustrative embodiment, all of the base stations servicing wireless terminal **201** are associated with 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 any number of base stations are associated with any number of wireless switching centers.

Assistance server **212** comprises hardware and software that is capable of performing the processes described below and in the accompanying figures. In general, assistance server **212** generates GPS assistance data for wireless terminal **201** to aid wireless terminal **201** in acquiring and processing GPS ranging signals from GPS constellation **221**. In accordance with the illustrative embodiment, assistance server **212** is a separate physical entity from location server **214**; 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 in which assistance server **212** and location server **214** share hardware, software, or both.

Location client **213** comprises hardware and software that use the estimate of the location of wireless terminal **201**—provided by location server **214**—in a location-based application, as described below and in the accompanying figures.

Location server **214** comprises hardware and software that generate one or more estimates of the location of wireless terminal **201** as described below and in the accompanying figures. It will be clear to those skilled in the art, after reading this disclosure, how to make and use location server **214**. Furthermore, although location server **214** is depicted in FIG. **2** as 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 server **214** is wholly or partially integrated with wireless switching center **211**.

In accordance with the illustrative embodiment, location server **214** communicates with wireless switching center **211**, assistance server **212**, and location client **213** via a local area network; 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 in which location server **214** communicates with one or more of these entities via a different network such as, for example, the Internet, the Public Switched Telephone Network (PSTN), etc.

In accordance with the illustrative embodiment, wireless switching center **211**, assistance server **212**, location client **213**, and location server **214** are outside of geographic region **220**. 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 wireless switching center **211**, assistance server **212**, location client **213**, and location server **214** are instead within geographic region **220**.

Location Server **214**—FIG. **3** depicts a block diagram of the salient components of location server **214** in accordance with the illustrative embodiment. Location server **214** comprises: processor **301**, memory **302**, and local-area network transceiver **303**, which are interconnected as shown.

Processor **301** is a general-purpose processor that is capable of executing operating system **311** and application software **312**, and of populating, amending, using, and managing Location-Trait Database **313** and Trait-Correction Database **314**, as described in detail below and in the accompanying figures. It will be clear to those skilled in the art how to make and use processor **301**.

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

i. operating system **311**, and

ii. application software **312**, and

iii. Location-Trait Database **313**, and

iv. Trait-Correction Database **314**.

It will be clear to those skilled in the art how to make and use memory **302**.

Transceiver **303** enables location server **214** to transmit and receive information to and from wireless switching center **211**, assistance server **212**, and location client **213**. In addition, transceiver **303** enables location server **214** to transmit information to and receive information from wireless terminal **201** and base stations **202-1** through **202-3** via wireless switching center **211**. It will be clear to those skilled in the art how to make and use transceiver **303**.

Operation of the Illustrative Embodiment—FIG. **4** depicts a flowchart of the salient processes performed in accordance with the illustrative embodiment of the present invention.

In accordance with process **401**, Location-Trait Database **313** is built. For the purposes of this specification, the "Location-Trait Database" is defined as a database that maps each of a plurality of locations to one or more expected traits associated with a wireless terminal at that location. The details of building Location-Trait Database **313** are described below and in the accompanying figures.

In accordance with process **402**, Trait-Correction Database **314** is built. For the purposes of this specification, the "Trait-Correction Database" is defined as a database that indicates how the measurement of traits can be adjusted to compensate for systemic measurement errors. The details of building Trait-Correction Database **314** are described below and in the accompanying figures.

In accordance with process **403**, the location of wireless terminal **201** is estimated based on location-trait database **401**, trait-correction database **402**, and a variety of traits that

vary based on the location of wireless terminal **201**. The details of process **403** are described below and in the accompanying figures.

In accordance with process **404**, the estimate of the location of wireless terminal **201** is used in a location-based application, such as and without limitation, E 9-1-1 service. The details of process **404** are described below and in the accompanying figures.

In accordance with process **405**, Location-Trait Database **313** and Trait-Correction Database **314** are maintained so that their contents are accurate, up-to-date and complete. Process **405** is advantageous because the effectiveness of the illustrative embodiment is based on—and limited by—the accuracy, freshness, and completeness of the contents of Location-Trait Database **313** and Trait-Correction Database **314**. The details of process **405** are described below and in the accompanying figures.

Building Location-Trait Database **313**—FIG. **5** depicts a flowchart of the salient processes performed in accordance with process **401**—building Location-Trait Database **313**.

In accordance with process **501**, geographic region **220** is partitioned into B(T,N) locations, wherein B(T,N) is a positive integer greater than one, and wherein B(T,N) varies as a function of calendrical time T and the environmental conditions N. 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 number of locations that geographic region **220** is partitioned into is static. Furthermore, 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 number of locations that geographic region **220** is partitioned into is not dependent on the calendrical time T or the environmental conditions N.

Some traits of the radio frequency spectrum and of individual signals are different at different locations in geographic region **220**. Similarly, some traits of the radio frequency spectrum and of individual signals transmitted by wireless terminal **201** change at base stations **202-1**, **202-2**, and **202-3** when wireless terminal **201** is at different locations. Furthermore, some traits (e.g., hand-off state, etc.) of wireless telecommunications system **200** change when wireless terminal **201** is at different locations.

When wireless terminal **201** is at a particular location, the values of the traits that vary with the location of wireless terminal **201** represent a "fingerprint" or "signature" for that location that enables location server **214** to estimate the location of wireless terminal **201**. For example, suppose that under normal conditions the traits have a first set of values when wireless terminal **201** is at a first location, and a second set of values when wireless terminal **201** is at a second location. Then when wireless terminal **201** is at an unknown location and the traits at that unknown location match the second set of values, it is more likely that wireless terminal **201** is at the second location.

Although human fingerprints and handwritten signatures are generally considered to be absolutely unique, the combination of traits associated with each location might not be absolutely unique in geographic region **220**. The effectiveness of the illustrative embodiment is enhanced, however, as differences in the values of the traits among the locations increases. It will be clear to those skilled in the art, after reading this disclosure, how to select locations and traits in order to increase the likelihood that the values of the traits associated with each location are distinguishable from the values of the traits associated with the other locations.

Each location is described by:

i. a unique identifier b,

ii. its dimensionality (e.g., one-dimension, two dimensions, three dimensions, four-dimensions, etc.),

iii. the coordinates (e.g., latitude, longitude, altitude, etc.) that define its scope (e.g., position, area, volume, etc.), which can be static or, alternatively, can vary as a function of calendrical time T or the environmental conditions N, or both the calendrical time T and the environmental conditions N.

iv. the expected value E(b, T, N, W, Q) for each trait, Q, when wireless terminal W is at location b at calendrical time T given environmental conditions, N,

v. the identities of its adjacent locations, and

vi. the staying and moving probabilities P_S(b, T, N, W) and P_M(b, T, N, W, c).

In accordance with the illustrative embodiment, the identifier of each location is an arbitrarily-chosen positive integer. 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 identifier of some or all locations is not arbitrarily chosen. Furthermore, 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 identifier of some or all locations is not a positive integer.

In accordance with the illustrative embodiment, the scope of each location is three-dimensional and is described by (i) one or more three-dimensional coordinates and geometric identifiers that define its boundaries, (ii) a three-dimensional coordinate that resides at the centroid of the location, and (iii) a description of how the scope changes as a function of calendrical time T and environmental conditions N. 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 scope of some or all of the locations are one-dimensional or two-dimensional. Furthermore, 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 scope of some or all of the locations are not a function of calendrical time T or environmental conditions N.

In accordance with the illustrative embodiment, the scope of two or more locations can overlap at zero, one, two, more than two, or all points of latitude and longitude (e.g., an overpass and underpass, different stories in a multi-story building as described below, etc.).

In accordance with the illustrative embodiment, the boundaries of each location are based, at least in part, on:

i. natural and man-made physical attributes of geographic region **220** (e.g., buildings, sidewalks, roads, tunnels, bridges, hills, walls, water, cliffs, rivers, etc.),

ii. legal laws governing geographic region **220** (e.g., laws that pertain to the location and movement of people and vehicles, etc.),

iii. theoretical predictions and empirical data regarding the location and movement of individuals and groups of people and vehicles in geographic region **220**,

iv. the desired accuracy of the estimates made by location server **214**, and

v. patterns of the location and movement of people and vehicles within geographic region **220**,

vi. the calendrical time T, and

vii. the environmental conditions N,

subject to the following considerations:

First, the accuracy with which wireless terminal **201** can be located potentially increases with smaller location sizes. Not all locations need to be the same size, however, and areas requiring greater accuracy can be partitioned into smaller sizes, whereas areas requiring less accuracy can be partitioned into larger sizes.

Second, as the number of locations in geographic region **220** increases, so does the computational burden on location server **214** as described below with respect to FIG. **10**.

Third, as the size of adjacent locations decreases, the likelihood increases that the expected values for the traits in those locations will be identical or very similar, which can hinder the ability of location server **214** to correctly determine when wireless terminal **201** is in one location versus the other.

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 partition geographic region **220** into any number of locations of any size, shape, and arrangement. 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 in which the locations are identical in size and shape.

FIG. **6***a* depicts an isometric drawing of geographic region **220** and FIG. **6***b* depicts a map of geographic region **220**. Geographic region **220** comprises water fountain **601**, park **602**, four-story building **603**, two-story building **604**, various streets, sidewalks, and other features that are partitioned into 28 locations as described below and depicted in FIGS. **6***c* through **6***e*. Although geographic region **220** comprises approximately four square blocks in the illustrative embodiment, it will be clear to those skilled in the art how to make and use alternative embodiments of the present invention with geographic regions of any size, topology, and complexity.

In accordance with the illustrative embodiment, the eight road intersections are partitioned into Locations 1 through 8, as depicted in FIG. **6***c*. In accordance with the illustrative embodiment, the street sections and their adjacent sidewalks up to the edge of buildings **603** and **604** are partitioned into Locations 9 through 19, as depicted in FIG. **6***d*. In accordance with the illustrative embodiment, water fountain **601** is partitioned into Location 20, park **602** is partitioned into Location 25, each floor of building **604** is classified as one of Locations 21, 22, 23, and 24, and each floor of building **603** is classified as of one of Locations 27 and 28. It will be clear to those skilled in the art, however, after reading this disclosure, how to partition geographic region **220** into any number of locations of any size and shape.

In accordance with an alternative embodiment of the present invention, a geographic region that comprises a clover-leaf intersection of two, four-lane divided highways is partitioned into 51 locations. FIG. **6***f* depicts an isometric drawing of the intersection, and FIG. **6***g* depicts a map of the intersection. In accordance with the illustrative embodiment, the grass and medians have been partitioned into 15 locations as depicted in FIG. **6***g*, the four ramps have been partitioned into four locations as depicted in FIG. **6***h*, the inner or "passing" lanes have been partitioned into eight locations as depicted in FIG. **6***i*, and the outer or "travel" lanes have been partitioned into eight locations as depicted in FIG. **6***j*.

FIG. **6**L depicts an alternative partitioning of geographic region **220** into 64 square locations.

In accordance with process **502**, the expected values E(b, T, N, W, Q) for the following traits is associated with each location:

i. the expected pathloss of all of the signals receivable by wireless terminal **201** when wireless terminal **201** is at the location, from all transmitters (e.g., base stations **202-1**, **202-2**, and **202-3**, commercial television, commercial radio, navigation, ground-based aviation, etc.), as a function of the calendrical time, T, and the environmental conditions, N; and

ii. the expected pathloss of all of the signals transmitted by wireless terminal **201** when wireless terminal **201** is in the location as receivable at base stations **202-1**, **202-2**, and **202-3**, as a function of the calendrical time, T, and the environmental conditions, N; and

iii. the expected received signal strength of all of the signals receivable by wireless terminal **201** when wireless terminal **201** is in the location, from all transmitters, as a function of the calendrical time, T, and the environmental conditions, N; and

iv. the expected received signal strength of all of the signals transmitted by wireless terminal **201** when wireless terminal **201** is in the location as receivable at base stations **202-1**, **202-2**, and **202-3**, as a function of the calendrical time, T, and the environmental conditions, N; and

v. the expected received signal-to-impairment ratio (e.g., Eb/No, etc.) of all of the signals receivable by wireless terminal **201** when wireless terminal **201** is in the location, from all transmitters, as a function of the calendrical time, T, and the environmental conditions, N; and

vi. the expected received signal-to-impairment ratio of all of the signals transmitted by wireless terminal **201** when wireless terminal **201** is in the location as receivable at base stations **202-1**, **202-2**, and **202-3**, as a function of the calendrical time, T, and the environmental conditions, N; and

vii. the expected received temporal difference of each pair of multipath components (e.g., one temporal difference for one pair of multipath components, a pair of temporal differences for a triplet of multipath components, etc.) of all of the signals receivable by wireless terminal **201** when wireless terminal **201** is in the location, from all transmitters, as a function of the calendrical time, T, and the environmental conditions, N; and

viii. the expected received temporal difference of each pair of multipath components (e.g., one temporal difference for one pair of multipath components, a pair of temporal differences for a triplet of multipath components, etc.) of all of the signals transmitted by wireless terminal **201** when wireless terminal **201** is in the location as receivable at base stations **202-1**, **202-2**, and **202-3**, as a function of the calendrical time, T, and the environmental conditions, N; and

ix. the expected received delay spread (e.g., RMS delay spread, excess delay spread, mean excess delay spread, etc.) of all of the signals receivable by wireless terminal **201** when wireless terminal **201** is in the location, from all transmitters, as a function of the calendrical time, T, and the environmental conditions, N; and

x. the expected received delay spread (e.g., RMS delay spread, excess delay spread, mean excess delay spread, etc.) of all of the signals transmitted by wireless terminal **201** when wireless terminal **201** is in the location as receivable at base stations **202-1**, **202-2**, and **202-3**,

as a function of the calendrical time, T, and the environmental conditions, N; and

xi. the expected received relative arrival times of two or more multipath components of all of the signals receivable by wireless terminal **201** when wireless terminal **201** is in the location, from all transmitters (which can be determined by a rake receiver in well-known fashion), as a function of the calendrical time, T, and the environmental conditions, N; and

xii. the expected received relative arrival times of two or more multipath components of all of the signals transmitted by wireless terminal **201** when wireless terminal **201** is in the location as receivable at base stations **202-1**, **202-2**, and **202-3**, as a function of the calendrical time, T, and the environmental conditions, N; and

xiii. the expected round-trip time of all of the signals transmitted and receivable by wireless terminal **201** through base stations **202-1**, **202-2**, and **202-3**, as a function of the calendrical time, T, and the environmental conditions, N; and

xiv. the expected round-trip time of all of the signals transmitted and receivable by base stations **202-1**, **202-2**, and **202-3** through wireless terminal **201**, as a function of the calendrical time, T, and the environmental conditions, N; and

xv. the identity of the base stations that provide telecommunications service to the location, as a function of the calendrical time, T, and the environmental conditions, N; and

xvi. the identities of the neighboring base stations that provide telecommunications service to the location, as a function of the calendrical time, T, and the environmental conditions, N; and

xvii. the handover state (e.g., soft, softer, 1×, 2×, etc.) of wireless terminal **201** and wireless telecommunication system **200** when wireless terminal **201** is in the location as a function of the calendrical time, T, and the environmental conditions, N.

In accordance with the illustrative embodiment of the present invention, all signals transmitted by wireless terminal **201** are for communicating with base stations **202-1** through **202-3**, and all of the signals received by wireless terminal **201** are:

signals transmitted by base stations **202-1** through **202-3** for communicating with wireless terminal **201**,

television signals,

radio signals,

aviation signals, and

navigation signals.

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 use different signals.

In accordance with the illustrative embodiment, the expected values of these traits are determined through a combination of:

i. a plurality of theoretical and empirical radio-frequency propagation models, and

ii. a plurality of empirical measurements of the traits within geographic region **220**, in well-known fashion. The empirical measurements of the traits are stored within location-trait database **313** and updated as described below.

In accordance with the illustrative embodiment of the present invention, each location b is described by the identities of its adjacent locations, (i.e., the locations that wireless terminal **201** can reasonably move into from location b within one time step Δt.) In accordance with the illustrative embodiment, two locations are considered to be "adjacent" when and only when they have at least two points in common. 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 two locations are considered adjacent when they have zero points or one point in common.

Adjacency Graph—In accordance with the illustrative embodiment, a data structure is created that indicates which locations are adjacent. This data structure is called an "adjacency graph" and it is stored within Location-Trait Database **313** in sparse-matrix format. FIG. **6*m*** depicts a graphical representation of the adjacency graph for the 28 locations that compose geographic area **220**, and FIG. **6*n*** depicts a graphical representation of the adjacency graph for the 51 locations that compose the highway intersection in FIGS. **6*f*** through **6*k***.

As described in detail below and in the accompanying figures, the adjacency graph is used in the temporal analysis of wireless terminal **201**'s movements. It will be clear to those skilled in the art, after reading this disclosure, how to make the adjacency graph for any partitioning of geographic region **220**.

In accordance with the illustrative embodiment, the staying and moving probabilities $P_S(b, T, N, W)$ and $P_M(b, T, N, W, c)$ for all b are generated based on a model of the movement of wireless terminal W that considers:

i. the topology of the adjacency graph; and

ii. the calendrical time T; and

iii. the environmental conditions N; and

iv. the natural and man-made physical attributes that affect the location and movement of wireless terminals and the entities that carry them (e.g., buildings, sidewalks, roads, tunnels, bridges, hills, walls, water, cliffs, rivers, etc.); and

v. the legal laws governing the location and movement of wireless terminals and the entities that carry them (e.g., one-way streets, etc.); and

vi. the past data for the movement of all wireless terminals; and

vii. the past data for the movement of wireless terminal W.

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 use any subcombination of i, ii, iii, iv, v, vi, and vii to generate the staying and moving probabilities for each location b.

The moving probabilities $P_M(b, T, N, W, c)$ associated with a location b can be considered to be either isotropic or non-isotropic. For the purposes of this specification, "isotropic moving probabilities" are defined as those which reflect a uniform likelihood of direction of movement and "non-isotropic moving probabilities" are defined as those which reflect a non-uniform likelihood of direction of movement. For example, for locations arranged in a two-dimensional regular hexagonal grid the values of $P_M(b, T, N, W, c)$ of location b are isotropic if and only if they are all equal (e.g., $P_M(b, T, N, W, c)=1/6$ for each adjacent location c). Conversely, the values of $P_M(b, T, N, W, c)$ are non-isotropic if there are at least two probabilities with different values. As another example, for locations arranged in a two-dimensional "checkerboard" grid, the values of $P_M(b, T, N, W, c)$ are isotropic if and only if:

(i) the north, south, east, and west moving probabilities out of location b all equal p,

(ii) the northeast, northwest, southeast, and southwest moving probabilities out of location b all equal $p/\sqrt{2}$, and

(iii) $4p(1+1/\sqrt{2})+P_S(b, T, N, W)=1$.

Isotropic moving probabilities are simple to generate, but are considerably less accurate than non-isotropic moving probabilities that are generated in consideration of the above criteria. Therefore, in accordance with the illustrative embodiment, the moving probabilities are non-isotropic, 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 that use isotropic moving probabilities.

Populating Trait-Correction Database **313**—FIG. **7** depicts a flowchart of the salient processes performed as part of process **402**: populating Trait-Correction Database **313**.

In general, the ability of location server **214** to estimate the location of wireless terminal **201** is limited by the accuracy with which the traits are measured by wireless terminal **201** and by base stations **202-1**, **202-2**, and **202-3**. When the nature or magnitude of the measurement errors is unpredictably inaccurate, there is little that can be done to overcome them.

In contrast, when the nature and magnitude of the measurement errors are predictable, they can be corrected, and the nature and magnitude of some measurement errors are, in fact, predictable. For example, one make and model of wireless terminal is known to erroneously measure and report the signal strength of signals by −2 dB. If the measurements from this model of wireless terminal are left uncorrected, this −2 dB error could cause location server **214** to erroneously estimate the location of the wireless terminal. In contrast, if location server **214** adds 2 dB to the measurements from that make and model of wireless terminal, the likelihood that location server **214** would erroneously estimate the location of the wireless terminal would be reduced.

Trait-Correction Database **313** comprises the information needed by location server **214** to be aware of systemic measurement errors and to correct them. A technique for eliminating some situational errors in the measurements is described below and in the accompanying figures.

In accordance with process **701**, a distortion function is generated for every radio that might provide measurements to location server **214** and for every trait whose measurements can be erroneous.

In general, the distortion function D(A,K,Q) relates the reported measurement R for a trait Q to the actual value A for that trait and the defining characteristic K of the radio making the measurement:

$$R=D(A, K, Q). \quad \text{(Eq. 1)}$$

In accordance with the illustrative embodiment, the distortion function D(A,K,Q) is provided to the owner/operator of location server **214** by the radio manufacturer. It will be clear to those skilled in the art, however, after reading this disclosure, how to generate the distortion function D(A,K,Q) for any radio without the assistance of the radio manufacturer.

An ideal radio perfectly measures and reports the value of the traits it receives and the distortion function D(A,K,Q) for one trait and for an ideal radio is depicted in FIG. **8***a*. As can be seen from the graph in FIG. **8***a*, the salient characteristic of an ideal radio is that the reported value of the measurement, R, is exactly equal to the actual value of the trait A at the radio (i.e., there is no measurement or reporting error).

In contrast, most real-world radios do not perfectly measure the traits of the signals they receive. This is particularly true for measurements of signal-strength where the errors can be large. For example, FIG. **8***b* depicts a graph of the distortion function of an illustrative real-world radio. In this case, the reported measurement is too high for some values, too low for others, and correct for only one value.

The nature and magnitude of each of the errors in the reported measurements is inherent in the distortion function D(A,K,Q), and, therefore, knowledge of the distortion function enables the measurement errors to be compensated for. In other words, when location server **214** knows exactly how a radio distorts a measurement, it can correct—or calibrate—the reported measurement with a calibration function to derive the actual value of the trait. The calibration function, denoted C(R,K,Q), is generated in process **1102**.

In accordance with the illustrative embodiment, the distortion function D(A,K,Q) for all measurements is represented in tabular form. For example, the distortion function for one type of signal-strength measurement for various radios is shown in Table 1. It will be clear to those skilled in the art, after reading this disclosure, however, how to make and use alternative embodiments of the present invention in which the distortion function for some or all measurements is not represented in tabular form. Furthermore, 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 distortion functions for any type of measurement of any type of trait and for any radio.

TABLE 1

The Distortion function D(A, K, Q) in Tabular Form

	R = D(A, K, Q)		
A	K = Motorola Model A008; Q = Signal Strength	. . .	K = Samsung Model A800; Q = Signal Strength
−110	−115	. . .	−107
−109	−114	. . .	−106
. . .	. . .	. . .	. . .
−48	−38	. . .	−50
−47	−37	. . .	−49

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

For example, the characteristic, K, 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 ("IMSI"), 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 measuring component, etc.); or

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

The most accurate characteristic is the unique identity of wireless terminal **201** because that would enable location server **214** 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, K, 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, K, because it is believed that the amount of variation between wireless terminals of the same make and model will be small enough that a single calibration function for that model should provide acceptably accurate calibrated measurements for every wireless terminal of that make and model.

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, K, is based on something else.

In accordance with process **502**, the calibration function C(R,K,Q) is generated for every radio that might provide measurements to location server **214** and for every trait whose measurements can be distorted.

In general, the calibration function C(R,K,Q) relates the calibrated measurement S of a trait Q, to the reported measurement R of trait Q and the defining characteristic K of the radio making the measurement:

$$S=D(R, K, Q) \quad \text{(Eq. 2)}$$

The calibration function C(R,K,Q) is the inverse of the distortion function D(A,K,Q). In other words, the salient characteristic of the calibration function C(R,K,Q) is that it satisfies the equation 3:

$$S=A=C(D(A, K, Q),K, Q) \quad \text{(Eq. 3)}$$

so that the calibrated measurement, S, is what the reported measurement, R, would have been had the radio making and reporting the measurement been ideal. It will be clear to those skilled in the art, after reading this disclosure, how to derive C(R,K,Q) from D(A,K,Q). FIG. **8***c* depicts a graph of the calibration function C(R,K,Q) for the distortion function D(A,K,Q) depicted in FIG. **8***b*.

In accordance with the illustrative embodiment, the function C(R,K,Q) is represented in tabular form, such as that shown in Table 2.

TABLE 2

The Calibration Function C(R, C, N) in Tabular Form

	S = C(R, C, N)		
R	C = Motorola Model A008; Q = Signal Strength	. . .	C = Samsung Model A800; Q = Signal Strength
−110	−115	. . .	−107
−109	−114	. . .	−106
. . .	. . .	. . .	. . .
−48	−38	. . .	−50
−47	−37	. . .	−49

In accordance with process **402**, the calibration functions C(R,K,Q) are stored in Trait-Corrections Database **313**.

Maintaining Location-Trait Database **313**—FIG. **9** depicts a flowchart of the salient processes performed in process **403**: maintaining Location-Trait Database **313** and Trait-Corrections Database **314**. The ability of the illustrative embodiment to function is based on—and limited by—the accuracy, freshness, and completeness of the information contained in Location-Trait Database **313** and Trait-Corrections Database **314**.

In accordance with process **901**, a drive-test regimen is developed that periodically makes empirical measurements throughout geographic region **220** with highly-accurate equipment to ensure the accuracy, freshness, and completeness of the information contained in Location-Trait Database **313** and Trait-Corrections Database **314**.

In accordance with process **902**, the drive-test regimen is implemented.

In accordance with process **903**, Location-Trait Database **313** and Trait-Corrections Database **314** are updated, as necessary.

Estimating the Location of Wireless Terminal **201**—FIG. **10** depicts a flowchart of the salient processes performed in process **403**: estimating the location of wireless terminal **201**. In accordance with the illustrative embodiment, process **403** is initiated by a request from location client **213** for the location of wireless terminal **201**. 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 process **403** is initiated periodically, sporadically, or in response to some other event.

In accordance with process **1001**, Y probability distributions for the location of wireless terminal **201** are generated for each of instants H_1 through H_Y in the temporal interval ΔT, wherein Y is a positive integer, based on comparing the measurements of traits associated with wireless terminal **201** at each of instants H_1 through H_Y to expected values for those traits at those times. Each of the Y probability distributions provides a first estimate of the probability that wireless terminal **201** is in each location at each of instants H_1 through H_Y. The details of process **1001** are described below and in the accompanying figures.

In accordance with process **1002**, Z probability distributions for the location of wireless terminal **201** are generated for each of instants A_1 though A_Z in the temporal interval ΔT, wherein Z is a positive integer, based on Assisted GPS measurements at wireless terminal **201** at each of instants A_1 though A_Z. Each of the Z probability distributions provides a first estimate of the probability that wireless terminal **201** is in each location at each of instants A_1 though A_Z. The details of process **1002** are described below and in the accompanying figures.

In accordance with process **1003**, the Y probability distributions generated in process **1001** and the Z probability distributions generated in process **1002** are combined, taking into account their temporal order, to generate a second estimate of the location of wireless terminal **201**. The details of process **1003** are described below and in the accompanying figures.

Generating the Probability Distributions for the Location of Wireless Terminal **201** Based on Pattern Matching of Traits—FIG. **11***a* depicts a flowchart of the salient processes performed in process **1001**—generating the Y probability distributions for the location of wireless terminal **201** based on comparing the measurements of traits associated with wireless terminal **201** at each of instants H_1 through H_Y to expected values for those traits at those times. In accordance

with the illustrative embodiment, location server **214** performs each of processes **1101** through **1105** as soon as the data necessary for performing the process becomes available to it.

In accordance with process **1101**, location server **214** receives Y non-empty sets of measurements of the traits, M_1 though M_Y, associated with wireless terminal **201**. Each set of measurements is made at one of instants H_1 through H_Y.

In accordance with the illustrative embodiment, each set of measurements comprises:

i. the pathloss of all of the signals received by wireless terminal **201** from all transmitters (e.g., base stations **202-1**, **202-2**, and **202-3**, commercial television, commercial radio, navigation, ground-based aviation, etc.); and

ii. the pathloss of all of the signals transmitted by wireless terminal **201** as received at base stations **202-1**, **202-2**, and **202-3**; and

iii. the received signal strength of all of the signals received by wireless terminal **201** from all transmitters; and

iv. the received signal strength of all of the signals transmitted by wireless terminal **201** as received at base stations **202-1**, **202-2**, and **202-3**; and

v. the received signal-to-impairment ratio of all of the signals received by wireless terminal **201** from all transmitters; and

vi. the received signal-to-impairment ratio of all of the signals transmitted by wireless terminal **201** as received at base stations **202-1**, **202-2**, and **202-3**; and

vii. the received temporal difference of each pair of multipath components of all of the signals received by wireless terminal **201** from all transmitters; and

viii. the received temporal difference of each pair of multipath components of all of the signals transmitted by wireless terminal **201** as received at base stations **202-1**, **202-2**, and **202-3**; and

ix. the received delay spread of all of the signals received by wireless terminal **201** from all transmitters; and

x. the received delay spread of all of the signals transmitted by wireless terminal **201** as received at base stations **202-1**, **202-2**, and **202-3**; and

xi. the received relative arrival times of two or more multipath components of all of the signals received by wireless terminal **201** from all transmitters; and

xii. the received relative arrival times of two or more multipath components of all of the signals transmitted by wireless terminal **201** as received at base stations **202-1**, **202-2**, and **202-3**; and

xiii. the round-trip time of all of the signals transmitted and received by wireless terminal **201** through base stations **202-1**, **202-2**, and **202-3**; and

xiv. the round-trip time of all of the signals transmitted as received at base stations **202-1**, **202-2**, and **202-3** through wireless terminal **201**; and

xv. the identity of the base stations that provide telecommunications service to wireless terminal **201**; and

xvi. the identities of the neighboring base stations that can provide telecommunications service to wireless terminal **201**; and

xvii. the handover state (e.g., soft, softer, 1×, 2×, etc.) of wireless terminal **201** and wireless telecommunication system **200**; and

xviii. an indication of the calendrical time, T; and

xix. an indication of the environmental conditions, N.

In accordance with the illustrative embodiment, wireless terminal **201** provides its measurements directly to location server **214** via the user plane and in response to a request from location server **214** to do so. This is advantageous because the quality of the estimate of the location of wireless terminal **201** is enhanced when there are no limitations on the nature, number, or dynamic range of the measurements—as might occur when measurements are required to be made in accordance with the air-interface standard. 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 wireless terminal **201** provides its measurements periodically, sporadically, or in response to some other event. Furthermore, 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 wireless terminal **201** provides its measurements to location server **214** via the UMTS protocol.

In accordance with the illustrative embodiment, base stations **202-1**, **202-2**, and **202-3** provide their measurements to location server **214** via wireless switching center **211** and in response to a request from location server **214** to do so. 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 base stations **202-1**, **202-2**, and **202-3** provide their measurements to location server **214** periodically, sporadically, or in response to some other event.

As part of process **1101**, location server **214** also receives from wireless terminal **201**:

i. the identities of the base stations that provided service to wireless terminal **201** at each of instants H_1 through H_Y, and

ii. the identities of the neighboring base stations that provided service to the location of wireless terminal **201** at each of instants H_1 through H_Y.

This information is used by location server **214** in performing search area reduction, which is described in detail below.

In accordance with process **1102**, location server **214** uses the calibration functions C(R,K,Q) in the Trait-Corrections Database **314** to correct the systemic errors in the measurements received in process **1001**.

In accordance with process **1103**, location server **214** computes the differentials, in those cases that are appropriate, of the measurements to correct the situational errors in the measurements received in process **1001**. Many factors, including the condition of wireless terminal **201**'s antenna, the state of its battery, and whether or not the terminal is inside a vehicle can introduce situational measurement errors. This is particularly true for measurements of pathloss and signal strength.

The illustrative embodiment ameliorates the effects of these factors by pattern matching not the measurements themselves—whether corrected in process **1102** or not—to the expected values for those traits, but by pattern matching the pair-wise differentials of those measurements to the pair-wise differentials of the expected values for those traits. 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 different measurements are corrected for situational errors by the use of pair-wise differentials.

A simple example involving signal strengths illustrates this approach. 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 signal strength.

TABLE 3

Illustrative Location-Trait Database (Differential Reception)

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

If a given wireless terminal with a broken antenna and at an unknown location receives Radio Station A at −47 dBm and Radio Station B at −61 dBm, then it registers Radio Station A as 14 dBm stronger than Radio Station B. This suggests that the wireless terminal is more likely to be at Location 2 than it is at Location 1, 3, or 4. If the measured signal strengths themselves were pattern matched into Location-Trait Database **313**, the resulting probability distribution for the location of wireless terminal **201** might not be as accurate.

A disadvantage of this approach is that the situational bias is eliminated at the expense of (1) doubling the variance of the random measurement noise, and (b) reducing the number of data points to pattern 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.

In accordance with process **1104**, location server **214** performs a technique called "search area reduction" in preparation for process **1105**. To understand what search area reduction is and why it is advantageous, a brief discussion of process **1105** is helpful. In process **1105** location server **214** estimates the probability that wireless terminal **201** is in each location at each of instants H_1 through H_Y. This requires generating Y multi-dimensional probability distributions, one for each of instants H_1 through H_Y.

The process for generating each multi-dimensional probability distribution can be computationally intensive and the intensity depends on the number of locations that must be considered as possible locations for wireless terminal **201**. When the number of locations that must be considered is small, the process can be performed quickly enough for many "real-time" applications. In contrast, when the number of locations that must be considered is large, the process can often take too long.

Nominally, all of the locations in geographic region **220** must be considered because, prior to process **1104**, wireless terminal **201** could be in any location. In accordance with the illustrative embodiment, geographic region **220** comprises only **28** locations. In many alternative embodiments of the present invention, however, geographic region **220** comprises thousands, millions, or billions of locations. The consideration of thousands, millions, or billions of locations for each instant by location server **214** might take too long for many real-time applications.

Therefore, to expedite the performance of process **1105**, location server **214** performs some computationally-efficient tests that quickly and summarily eliminate many possible locations for wireless terminal **201** from consideration, and, therefore, summarily set to zero the probability that wireless terminal **201** is at those locations. This reduces the number of locations that must be fully considered in process **1105** and generally improves the speed with which process **1001** is performed.

In accordance with search area reduction, for each of instants H_1 through H_Y location server **214** uses six computationally efficient tests in an attempt to designate one or more locations as improbable locations for wireless terminal **201**. A location that is designated as improbable by one or more of the six tests at instant H_i is designated as improbable by process **1104** at instant H_i. To the extent that a location is designated as improbable at instant H_i, the computational burden on location server **214** of generating the probability distribution for that instant is reduced.

There are two types of errors that can be made by process **1104**. The first type of error—a Type I error—occurs when process **1104** designates a location as improbable when, in fact, it is not improbable for wireless terminal **201** to be in that location. The second type of error—a Type II error—occurs when process **1104** fails to designate a location as improbable when, in fact, it is improbable that wireless terminal **201** is in that location.

In general, a Type I error affects the accuracy with which the illustrative embodiment can estimate the location of wireless terminal **201**, and a Type II error affects the speed with which processor **1104** can generate the probability distributions. In accordance with the illustrative embodiment, the tests and their parameters are chosen to balance the number of Type I and Type II errors with the computational complexity and value of process **1104**. For example, when there are too many Type II errors, the value of process **1104** is undermined by the computational burden of process **1104**. It will be clear those skilled in the art, after reading this disclosure, how to make and use alternative embodiments of the present invention that have any number of Type I and Type II errors.

FIG. **11***b* depicts a flowchart of the salient processes performed in accordance with process **1104**: search area reduction.

In accordance with process **1111**, location server **214** designates a location as improbable when the difference between a measured value of a trait and the expected value of that trait at that location exceeds a threshold. The theory underlying this test is that a major discrepancy between a measurement of a trait and the expected value of a trait at a location suggests that the measurement was not made when wireless terminal **201** was in that location. In accordance with the illustrative embodiment, location engine **214** performs process **1111** on each measured value of each trait for each signal for each of instants H_1 through H_Y. It will be clear to those skilled in the art, after reading this disclosure, how to choose the traits and signals and thresholds to achieve the desired number of Type I and Type II errors. 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 omit process **1111** or that omit testing one or more traits and/or one or more signals in process **1111**.

In accordance with process **1112**, when the magnitude of two measurements of a trait at one instant exceed a first threshold and the magnitude of the expected values for that trait at a location exceed a second threshold, location server **214** designates that location as improbable when a ranking of the two measurements differs from a ranking of the expected values. The theory underlying this test is that a major discrepancy between the ranking of the measurements

of a trait and the ranking of the expected values of that trait in the location suggests that the measurements were not made when wireless terminal **201** was in that location. In accordance with the illustrative embodiment, location engine **214** performs process **1112** on each pair of measurements of each trait for each of instants H_1 through H_Y. It will be clear to those skilled in the art, after reading this disclosure, how to choose the traits and signals and thresholds to achieve the desired number of Type I and Type II errors. 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 omit process **1112** or that omit testing one or more traits and/or one or more signals in process **1112**.

In accordance with process **1113**, location server **214** designates a location as improbable when a measurement of traits of a signal is not received when it is expected if wireless terminal **201** were, in fact, in that location. In accordance with the illustrative embodiment, location engine **214** performs process **1113** on each trait of each expected signal for each of instants H_1 through H_Y. This test is highly prone to Type I errors and should be used judiciously. 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 omit process **1113** or that omit testing one or more traits and/or one or more signals in process **1113**.

In accordance with process **1114**, location sever **214** designates a location as improbable when a measurement of a trait of a signal is received when it is not expected if wireless terminal **201** were, in fact, in that location. In accordance with the illustrative embodiment, location engine **214** performs process **1114** on each trait of each signal for each of instants H_1 through H_Y. In general, this test is less prone to Type I errors than the test in process **1113**. 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 omit process **1114** or that omit testing one or more traits and/or one or more signals in process **1114**.

In accordance with process **1115**, location server **214** designates a location as improbable when the location is not provided wireless telecommunications service by a base station that is known to be providing service to wireless terminal **201** at that instant. The theory underlying this test is that if a base station that provided telecommunications service to wireless terminal **201** at that instant does not provide service to the location, then it suggests that wireless terminal **201** is not in that location at that instant. In general, this test is highly accurate and has a low number of both Type I and Type II errors. 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 omit process **1115**.

In accordance with process **1116**, location server **214** designates a location as improbable designating a possible location as improbable when the location is not within the neighboring coverage area of a base station that is known to be a neighboring base station of wireless terminal **201**. The theory underlying this test is that if a location is not within the neighboring coverage area of a base station that is a neighbor of wireless terminal **201** at that instant, then it suggests that wireless terminal **201** is not in the location at that instant. In general, this test is highly accurate and has a low number of both Type I and Type II errors. 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 omit process **1116**.

A location that that is designated as improbable at instant H_i by one or more of processes **1111** through **1116** is designated as improbable by process **1104** at instant H_i.

In accordance with process **1105**, location server **214** generates each of the Y probability distribution for that wireless terminal **201** at each of instants H_1 through H_Y. To accomplish this, location server **214** performs the processes described below and in FIG. **11***c*.

FIG. **11***c* depicts a flowchart of the salient processes performed in accordance with process **1105**: generating the Y probability distribution for that wireless terminal **201** at each of instants H_1 through H_Y.

In accordance with process **1121**, location server **214** sets the probability of wireless terminal **201** being at a location at instant H_i to zero (0) if the location was designated as improbable at instant H_i by process **1104**.

In accordance with process **1122**, location server **214** generates the Euclidean norm between the measurements of a trait and the expected values for that trait at all instants and for all locations not designated as improbable by process **1104**. To accomplish this, the Euclidean norm is generated between the measurements (as corrected in process **1102**, if necessary and/or the differentials of measurements as the case may be) of the expected values for those traits in Location-Trait Database **313**. To accomplish this, the Euclidean norm is generated as described in Equation 4:

$$V(b, H_i)=\sqrt{\Sigma((E(b,H_i,N,W,Q)-M(b,H_i,N,W,Q))\cdot\omega(Q))^2} \quad \text{(Eq. 4)}$$

wherein $V(b,H_i)$ is the Euclidean norm for Location b at instant H_i based on the square root of the sum of the square of the differences between each (corrected and differential, where appropriate) trait measurement $M(b, H_i, N, W, Q)$ minus the expected value $E(b, H_i, N, W, Q)$ for that trait, where $\omega(Q)$ is a weighting factor that indicates the relative weight to be given discrepancies in one trait versus discrepancies in the other traits.

At accordance with process **1123**, the un-normalized probabilities of the location of wireless terminal **201** at each location are generated based on the Euclidean norms generated in process **1122** as shown in Equation 5.

$$UP(b, H_i) = e^{\left(\frac{-V^2(b,H_i)}{\delta^2}\right)} \quad \text{(Eq. 5)}$$

wherein $UP(b,H_i)$ represents the un-normalized probability that wireless terminal **201** is in Location b at instant H_i, and wherein δ^2 equals:

$$\delta^2=\delta_E^2+\delta_M^2 \quad \text{(Eq. 6)}$$

wherein δ_E^2 is the square of the uncertainty in the error in Location-Trait Database and δ_M^2 is the square of the uncertainty in the calibrated measurements. It will be clear to those skilled in the art, after reading this disclosure, how to generate δ^2.

At process **1124**, the probabilities generated in process **1123** are normalized as described in Equation 7.

$$NP(b, H_i) = \frac{UP(b, H_i)}{\sum UP(b, H_i)} \quad \text{(Eq. 7)}$$

wherein NP(b,H_i) represents the normalized probability that wireless terminal **201** is in Location b.

As part of process **1124**, location server **214** generates a preliminary estimate of the location of wireless terminal **201** at instant H_1 based on the maximum likelihood function of the normalized probability distribution at instant H_1.

Generating the Probability Distributions for the Location of Wireless Terminal **201** Based on Assisted GPS—FIG. **12** depicts a flowchart of the salient processes performed in process **1002**: generating the Z probability distributions for the location of wireless terminal **201** based on GPS-derived information (i.e., information from GPS constellation **221**).

In accordance with processes **1124** and **1201**, location server **214** transmits, and assistance server **212** receives, the preliminary estimate of the location of wireless terminal **201** at instant H_1 as generated in process **1105**.

In accordance with process **1202**, assistance server **212** generates assistance data for wireless terminal **201** based on the preliminary estimate of the location of wireless terminal **201** at instant H_1. In accordance with the illustrative embodiment, assistance server **212** generates "fully-custom" assistance data based on the estimate of the location of wireless terminal **201** at instant H_1. The assistance data is "fully-custom" because it is specifically tailored to the estimated location of wireless terminal **201** at instant H_1. It will be clear to those skilled in the art how to generate fully-custom assistance data for wireless terminal **201** based on the estimated location of wireless terminal **201** at instant H_1. As part of process **1202**, assistance server **212** transmits the assistance data to wireless terminal **201** via wireless switching center **212** in well-known fashion.

In accordance with some alternative embodiments of process **1202**, assistance server **212** pre-computes assistance data for a plurality of diverse locations within geographic region **220** and selects that pre-computed assistance data for wireless terminal **201** based on the estimated location of wireless terminal **201** at instant H_1. Because the assistance data selected for wireless terminal **201** is not specifically tailored to the estimated location of wireless terminal **201** at instant H_1, nor generic to all of geographic region **220** or to the cell or sector of the base station serving wireless terminal **201**, it is deemed "semi-custom" assistance data. In general, semi-custom assistance data is less accurate than fully-custom assistance data, but more accurate, on average, than generic assistance data, which is chosen based on cell ID alone and that is based on one location within geographic region **220**. It will be clear to those skilled in the art, after reading this disclosure, how to generate the fully-custom and semi-custom assistance data for wireless terminal **201**.

In accordance with process **1203**, wireless terminal **201** (a) receives the assistance data from assistance server **212**, in well-known fashion, (b) uses it to facilitate the acquisition and processing of one or more GPS satellite signals in well-known fashion, and (c) transmits Z non-empty sets of GPS-derived information to location server **214** for readings at instants G_1 through G_Z, where Z is a positive integer. In accordance with the illustrative embodiment of the present invention, each set of GPS-derived information comprises:

i. a GPS-derived estimate of the location of wireless terminal **201** (e.g., a latitude, longitude, and altitude coordinate, etc.), or

ii. ranging data (e.g., PRN code phase, etc.) from one or more GPS satellites, or

iii. partially-processed ranging signals (e.g., signals from which the ranging data has not yet been extracted, etc.) from one or more GPS satellites, or

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

In accordance with process **1204**, location server **214** receives Z non-empty sets of GPS-derived information to location server **214** for readings at instants G_1 through G_Z and generates a probability distribution that indicates the likelihood that wireless terminal **201** is in each location at each of instants G_1 through G_Z. It will be clear to those skilled in the art how to perform process **1204**.

FIG. **13** depicts a flowchart of the salient processes performed in process **1003**—combining the Y non-GPS-based probability distributions with the Z GPS-based probability distributions to derive F refined multi-dimensional probability distributions for the location of wireless terminal **201** at each of instants J_1 through J_F, where each J_i corresponds to one of:

i. a particular instant H_y, where $1 \leqq y \leqq Y$, or

ii. a particular instant G_z, where $1 \leqq z \leqq Z$, or

iii. a concurrence of both a particular instant H_y, and a particular instant G_z, where $1 \leqq y \leqq Y$ and $1 \leqq z \leqq Z$.

In other words, each "composite" instant J_i corresponds to either an instant associated with a non-GPS-based probability distribution, or an instant associated with a GPS-based probability distribution, or an instant associated with both a non-GPS probability distribution and a GPS-based probability distribution.

In accordance with process **1003**, the Y non-GPS-based probability distributions with the Z GPS-based probability distributions are intelligently combined, taking into consideration their relative temporal occurrence to derive a refined multi-dimensional probability distribution for the location of wireless terminal **201** at instants J_1 through J_F.

To generate the refined probability distribution for the location of wireless terminal **201** at instant J_i, the probability distributions that occur before instant J_i are temporally-extrapolated progressively to instant J_i, the probability distributions that occur after instant J_i are temporally-extrapolated regressively to instant J_i, and they all are combined with the un-temporally-extrapolated probability distribution for the location of wireless terminal **201** at instant J_i. In this way, the accuracy of all of the refined probability distributions for each instant J_i are enhanced by the empirical data at other instants.

FIG. **14** depicts a first example of determining each of instants J_1 through J_F based on non-GPS-based instants H_1 through H_Y, where Y=4, and GPS-based instants G_1 through G_Z, where Z=6. As can be seen in FIG. **14**, the number of composite instants F is at most Y plus Z, and is at least the maximum of Y and Z—the former occurring when there are no coincident GPS/non-GPS probability distributions, and the latter when there are as many as possible coincident GPS/non-GPS probability distributions.

FIG. **15** depicts a second example of determining each of instants J_1 through J_F based on non-GPS-based instants and GPS-based instants. This second example illustrates that even when the non-GPS-based instants are uniformly spaced in time and the GPS-based instants are uniformly spaced in time, the composite instants are not necessarily uniformly spaced in time.

In accordance with the present invention, the time step Δt is defined as the minimum time interval between any two instants. The time step is atomic in that the time difference between any two instants is an integral multiple of time steps. (Note that two consecutive instants—whether they are non-GPS-based instants, GPS-based instants, or composite instants—might be more than a single time step apart.) The

time step of the present invention is therefore similar to the time step employed in clock-driven discrete event simulations.

As will be appreciated by those skilled in the art, selecting an appropriate value for the time step Δt typically will depend on the particular application, and involves a tradeoff between (1) temporal precision and (2) available memory and processing power. As will be further appreciated by those skilled in the art, after reading this disclosure, the selected time step can affect the definition of locations, the moving and staying probabilities, and consequently the graphs that are derived from them (e.g., the adjacency graph, etc.).

In accordance with process **1301**, location server **214** determines instants J_1 through J_F, as described above.

In accordance with process **1302**, location server **214** constructs unrefined probability distributions V_1 through V_F for instants J_1 through J_F as follows:

i. if J_i corresponds to a particular H_j only, then V_i equals the non-GPS probability distribution at instant H_j,

ii. if J_i corresponds to a particular G_k only, then V_i equals the GPS probability distribution at instant G_k, and

iii. otherwise (C_i corresponds to both a particular H_j and a particular G_k), V_i equals a probability distribution that equals the normalized product of the non-GPS and GPS probability distributions at instant J_i.

In accordance with process **1303**, location server **214** determines for each instant J_i, temporally-extrapolated probability distributions $D_{i,j}$ for all $j \neq i$, $1 \leqq j \leqq F$, which are based on (i) the unrefined probability distribution V_j at instant J_j, (ii) $P_S(b, T, N, W)$, and (iii) $P_M(b, T, N, W, c)$. The extrapolated probability distribution $D_{i,j}$ is therefore a predictive probability distribution at instant J_i that is based on empirical data at instant J_j—but not on any empirical data at other instants, including J_i.

i. the past data for the movement of all wireless terminals; and

ii. the past data for the movement of wireless terminal W; and

iii. the location, speed, and acceleration of wireless terminal W at calendrical time T; and

iv. the state of traffic signals that can affect the movement of wireless terminals in location b.

A temporally-extrapolated probability distribution can be progressed (i.e., projected into the future based on a past probability distribution). For example, if instant J_3 is one time step after instant J_2, then extrapolated probability distribution $D_{3,2}$ is derived by a single application of $P_S(b, T, N, W)$ and $P_M(b, T, N, W, c)$ to unrefined probability distribution V_2. In other words, for any location b:

$$D_{3,2}[b] = V_2[b] \cdot P_S(b, J_2, N, W) + \sum_{(c,b) \in in(b)} V_2[c] \cdot P_M(c, J_2, N, W, b) \quad \text{(Eq. 8)}$$

where in(b) is the set of arcs into location b from other locations in the adjacency graph. Similarly, a temporally-extrapolated probability distribution can be regressed (i.e., projected into the past based on a future unrefined probability distribution) based on the equation:

$$V_3[b] = D_{2,3}[b] \cdot P_S(b, J_2, N, W) + \sum_{(c,b) \in in(b)} D_{2,3}[c] \cdot P_M(c, J_2, N, W, b) \quad \text{(Eq. 9)}$$

by setting up a system of equations (9) for a plurality of locations $\{b_1, b_2, \ldots, b_\eta\}$ and solving for $\{D_{2,3[b1]}, D_{2,3}[b_2], \ldots, D_{2,3[b\eta]}\}$ via matrix algebra.

As will be well-understood by those skilled in the art, after reading this disclosure, when consecutive instants are two or more time steps apart, then Equation 8 can be applied iteratively in well-known fashion. (Because the time step is atomic the number of iterations is always integral.) As will be further appreciated by those skilled in the art, after reading this disclosure, the extrapolated probability distributions for non-consecutive time instants (e.g., $D_{2,4}$, $D_{5,1}$, etc.) can be efficiently computed in a bottom-up fashion from the extrapolated probability distributions for consecutive time instants via dynamic programming.

In accordance with process **1304**, location server **214** computes each refined probability distribution L_i, corresponding to each instant J_i, $1 \leqq i \leqq F$, as a weighted average of:

i. the corresponding unrefined probability distribution V_i, and

ii. all available temporally-extrapolated probability distributions $D_{i,j}$, $j \neq i$:

$$L_i = \frac{V_i + \sum_{j \neq i} [\alpha^{|j-i|} \cdot D_{i,j}]}{1 + \sum_{j \neq i} \alpha^{|j-i|}} \quad \text{(Eq. 10)}$$

wherein α is a constant, $0<\alpha<1$, that acts as an "aging factor" that weights less temporally-extrapolated probability distributions more heavily that more temporally-extrapolated probability distributions because of the more temporally-extrapolated probabilities distributions are less likely to be correct than the less temporally-extrapolated probability distributions. For example, when i=4 and F=5, Equation 10 in expanded form yields:

$$L_4 = \frac{V_4 + \alpha \cdot D_{4,3} + \alpha \cdot D_{4,5} + \alpha^2 \cdot D_{4,2} + \alpha^3 \cdot D_{4,1}}{1 + 2\alpha + \alpha^2 + \alpha^3} \quad \text{(Eq. 11)}$$

Defining $D_{i,i}=V_i$, Equation 10 can be expressed in a simpler form that is particularly convenient for computer processing:

$$L_i = \frac{\sum_{j=1}^{F} [\alpha^{|j-i|} \cdot D_{i,j}]}{\sum_{j=1}^{F} \alpha^{|j-i|}} \quad \text{(Eq. 12)}$$

In accordance with process **1305**, location server **214** generates an estimate of the location of wireless terminal **201** at one or more instants J_i based on the maximum likelihood function of L_i. (As will be appreciated by those

skilled in the art, after reading this disclosure, in some other embodiments of the present invention an estimate might be generated from probability distribution L_i using another function or method.)

In accordance with process **1306**, location server **214** provides the estimate(s) of the location of wireless terminal **201** generated in process **1305** to location client **213**, in well-known fashion.

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 method comprising estimating the location of a wireless terminal at time t from among a plurality of candidate locations based on:

(i) a first probability distribution for the location of said wireless terminal at time t among said plurality of candidate locations;

(ii) a second probability distribution for the location of said wireless terminal at time t−Δ among said plurality of candidate locations, wherein Δ is nonzero; and

(iii) one or more of a plurality of non-isotropic transition probabilities for said wireless terminal moving among said plurality of candidate locations from the earlier of time t and time t−Δ to the later of time t and time t−Δ.

2. The method of claim **1** wherein Δ>0.

3. The method of claim **1** wherein Δ<0.

4. The method of claim **1** wherein said first probability distribution is generated by a process that is independent of the location history of said wireless terminal and of any subsequent movement of said wireless terminal.

5. The method of claim **1** wherein at least one of said non-isotropic transition probabilities is based on past data for the movement of a wireless terminal.

6. The method of claim **1** wherein at least one of said non-isotropic transition probabilities is based on calendrical time.

7. A method comprising estimating the location of a wireless terminal at time t based on:

(i) a first probability distribution for the location of said wireless terminal at time t, wherein said first probability distribution is generated by a process that is independent of the location history of said wireless terminal; and

(ii) a second probability distribution for the location of said wireless terminal at time t, wherein said second probability distribution is based on

(a) an estimated location of said wireless terminal at time t−Δ, wherein Δ>0, and

(b) one or more of a plurality of non-isotropic transition probabilities for the movement of said wireless terminal from time t−Δ to time t.

8. The method of claim **7** wherein said estimated location of said wireless terminal at time t−Δ is based at least in part on an application of said process at time t−Δ.

9. The method of claim **7** wherein at least one of said non-isotropic transition probabilities is based on past data for the movement of a wireless terminal.

10. The method of claim **7** wherein at least one of said non-isotropic transition probabilities is based on calendrical time.

11. The method of claim **7** wherein one or more of said plurality of locations are polygons.

12. A method comprising estimating the location of a wireless terminal at time t based on:

(i) a first probability distribution for the location of said wireless terminal at time t, wherein said first probability distribution is generated by a process that is independent of any subsequent movement of said wireless terminal; and

(ii) a second probability distribution for the location of said wireless terminal at time t, wherein said second probability distribution is based on

(a) an estimated location of said wireless terminal at time t+Δ, wherein Δ>0, and

(b) one or more of a plurality of non-isotropic transition probabilities for the movement of said wireless terminal from time t to time t+Δ.

13. The method of claim **12** wherein said estimated location of said wireless terminal at time t+Δ is based at least in part on an application of said process at time t+Δ.

14. The method of claim **12** wherein at least one of said non-isotropic transition probabilities is based on calendrical time.

15. The method of claim **12** wherein a coordinate for one or more of said plurality of locations varies as a function of an environmental condition.

16. A method comprising estimating the location of a wireless terminal at time t from among a plurality of candidate locations based on:

(i) a first probability distribution for the location of said wireless terminal at time t among said plurality of candidate locations;

(ii) a second probability distribution for the location of said wireless terminal at time t−Δ among said plurality of candidate locations, wherein Δ is nonzero;

(iii) a first transition probability p_1 for said wireless terminal moving from a first location, L_1, of said plurality of candidate locations to a second location, L_2, of said plurality of candidate locations L_2 from the earlier of time t and time t−Δ to the later of time t and time t−Δ; and

(iv) a second transition probability p_2 for said wireless terminal moving from said first candidate location L_1 to a third location, L_3, of said plurality of candidate locations from the earlier of time t and time t−Δ to the later of time t and time t−Δ;

wherein the distance between L_1 and L_2 equals the distance between L_2 and L_3; and wherein $p_1 \neq p_2$.

17. The method of claim **16** wherein Δ>0.

18. The method of claim **16** wherein Δ>0.

19. The method of claim **16** wherein said first probability distribution is generated by a process that is independent of the location history of said wireless terminal and of any subsequent movement of said wireless terminal.

20. A method comprising estimating the location of a wireless terminal at time t from among a plurality of candidate locations based on:

(i) a first probability distribution for the location of said wireless terminal at time t among said plurality of candidate locations;

(ii) a second probability distribution for the location of said wireless terminal at time t−Δ among said plurality of candidate locations, wherein Δ is nonzero;

(iii) a first transition probability p_1 for said wireless terminal moving from a first location, L_1, of said plurality of candidate locations to a second location, L_2, of said plurality of candidate locations from the earlier of time t and time t−Δ to the later of time t and time t−Δ; and

(iv) a second transition probability p_2 for said wireless terminal moving from said first candidate location, L_1, to a third location, L_3, of said plurality of candidate locations from the earlier of time t and time $t-\Delta$ to the later of time t and time $t-\Delta$;

wherein $p_1=p_2$; and

wherein the distance between L_1 and L_2 does not equal the distance between L_2 and L_3.

21. The method of claim **20** wherein $\Delta>0$.

22. The method of claim **20** wherein $\Delta<0$.

23. The method of claim **20** wherein said first probability distribution is generated by a process that is independent of the location history of said wireless terminal and of any subsequent movement of said wireless terminal.

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