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Spain, Jr. et al.

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(45) **Date of Patent: Oct. 3, 2006**

(54) **LOCATION ESTIMATION OF WIRELESS TERMINALS THROUGH PATTERN MATCHING OF DEDUCED AND EMPIRICAL SIGNAL-STRENGTH MEASUREMENTS**

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(21) Appl. No.: **10/798,988**

(22) Filed: **Mar. 12, 2004**

(65) **Prior Publication Data**

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Related U.S. Application Data

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

(52) **U.S. Cl.** **455/456.1**; 455/456.5; 455/513

(58) **Field of Classification Search** 455/456.1, 455/456.2, 456.3, 456.5, 513, 457, 134, 115.3, 455/161.3, 402, 226.1, 226.2
See application file for complete search history.

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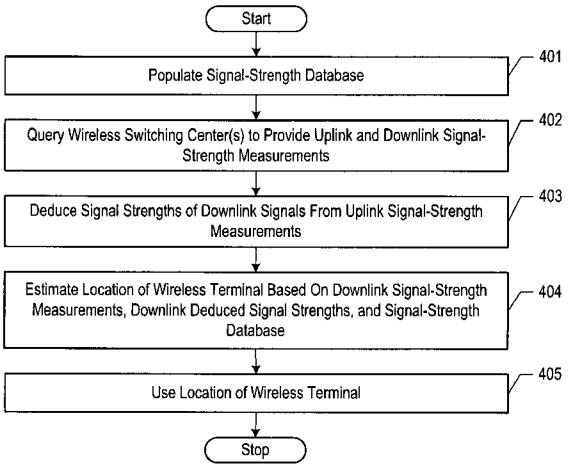
(74) *Attorney, Agent, or Firm*—DeMont & Breyer, LLC

(57) **ABSTRACT**

A method of estimating the location of a wireless terminal is disclosed. The illustrative embodiment of the present invention is based on the observation that the signal strength of a signal from a transmitter is different at some locations, and, therefore, the location of a wireless terminal can be estimated by comparing the signal strength it currently observes against a map or database that correlates locations to signal strengths. Furthermore, the illustrative embodiment deduces the signal strength of one or more base stations' control channels at the wireless terminal based on the principal of reciprocity, whether or not the wireless terminal can actually receive the base stations' control channels but so long as the base station can receive and measure the uplink signal from the wireless terminal. The deduced signal-strength measurements can then used—alone or in combination with the empirical signal-strength measurements—to estimate the location of the wireless terminal.

19 Claims, 14 Drawing Sheets



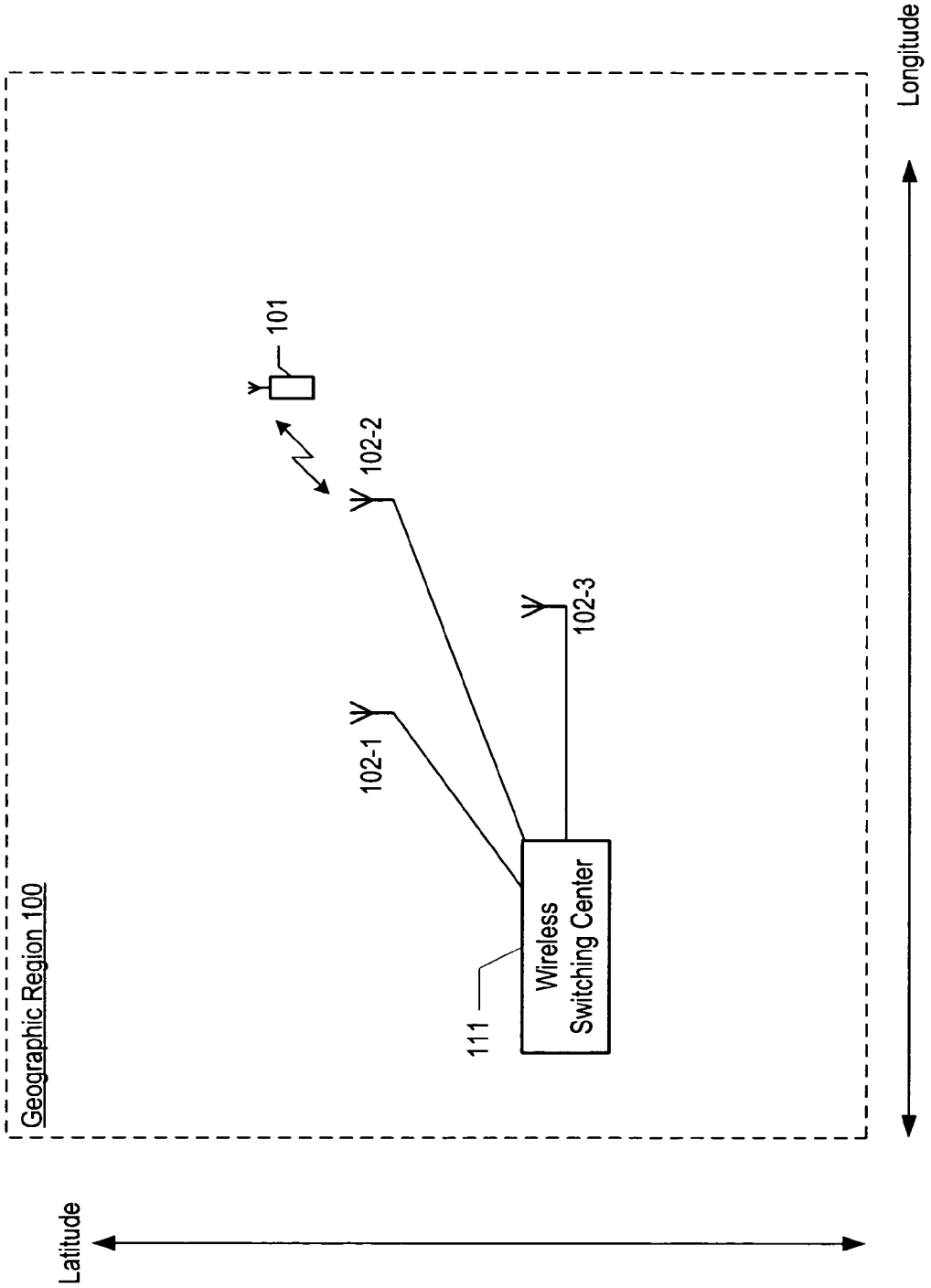


FIG. 1 (Prior Art)

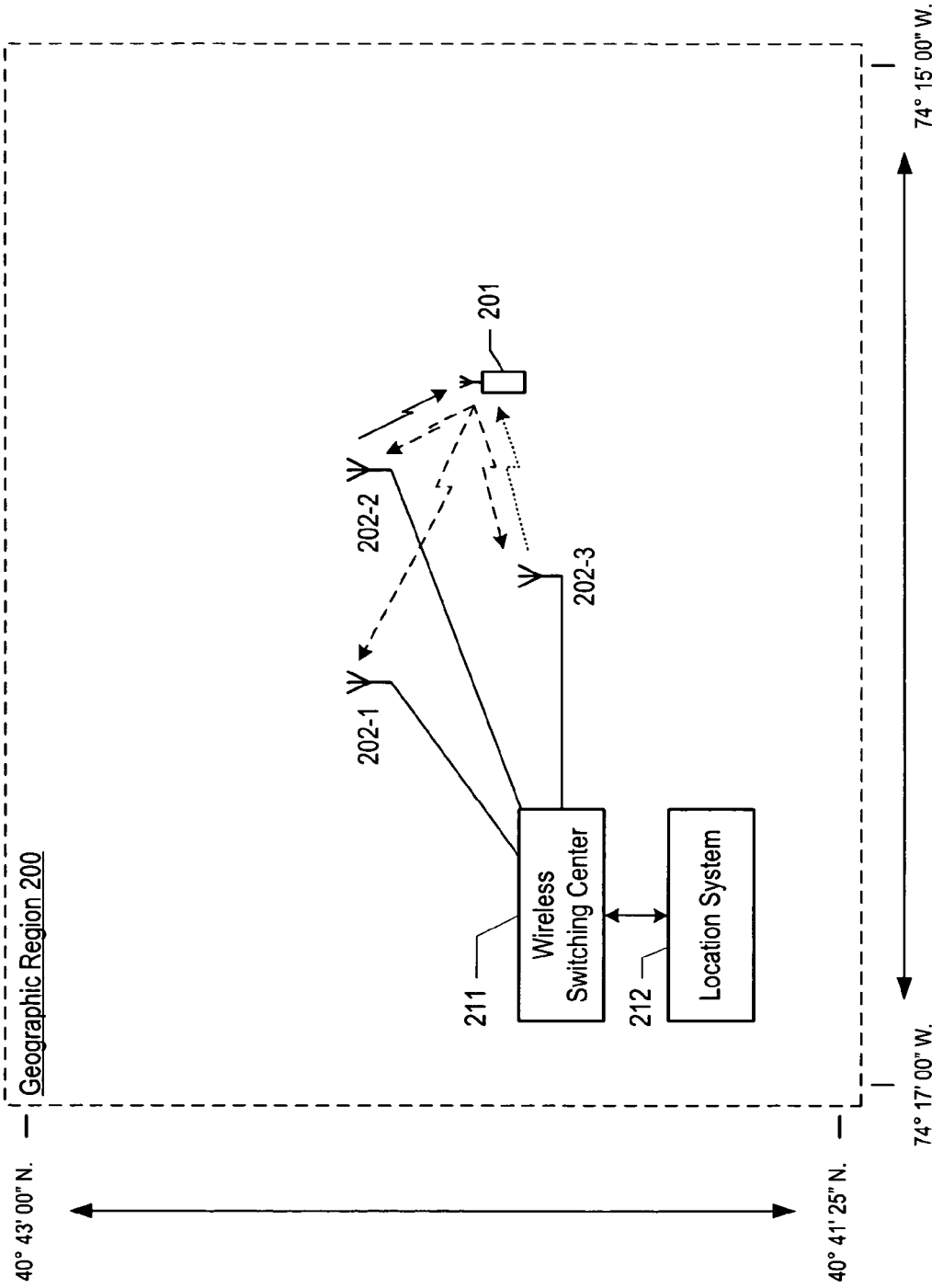

Geographic Region 200
201
202-1
202-2
202-3
211
Wireless Switching Center
212
Location System
40° 43' 00" N.
40° 41' 25" N.
74° 15' 00" W.
74° 17' 00" W.

FIG. 2

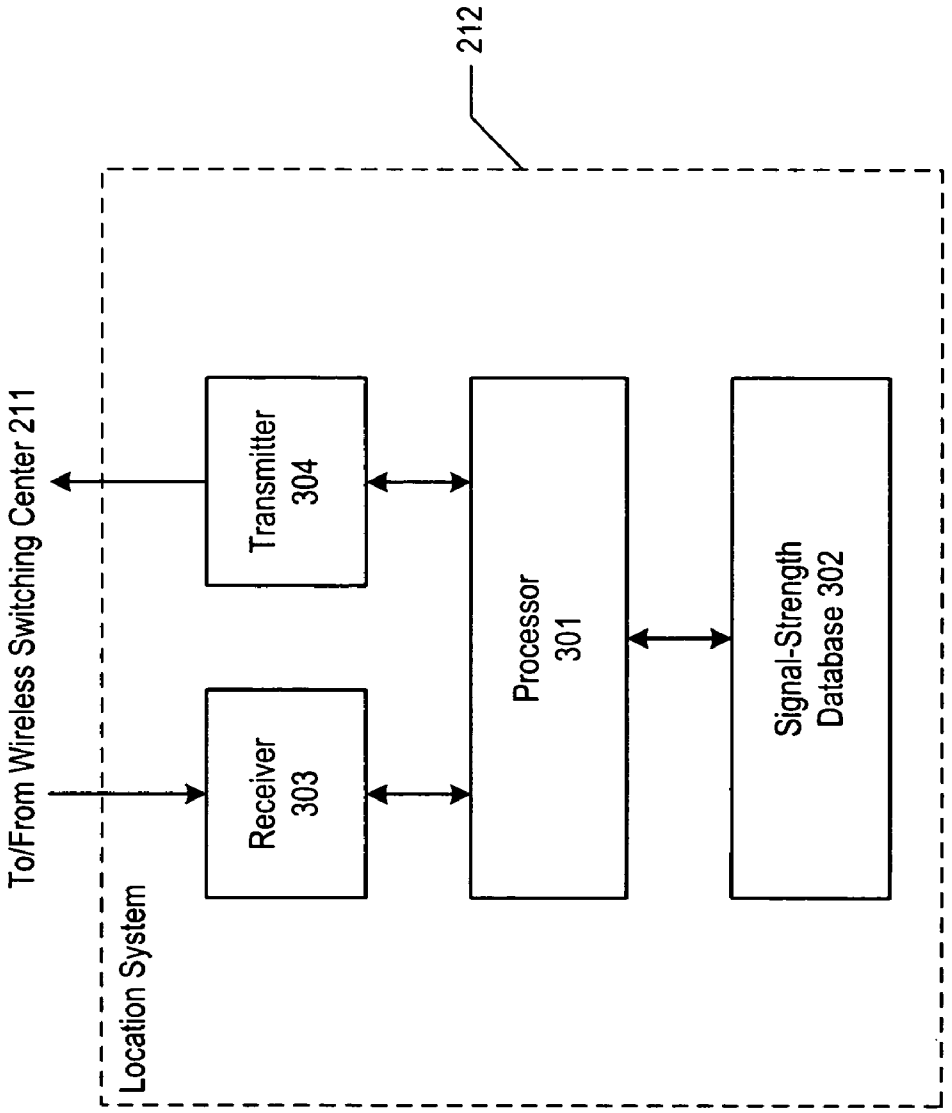

212
To/From Wireless Switching Center 211
Location System
Receiver 303
Transmitter 304
Processor 301
Signal-Strength Database 302

FIG. 3

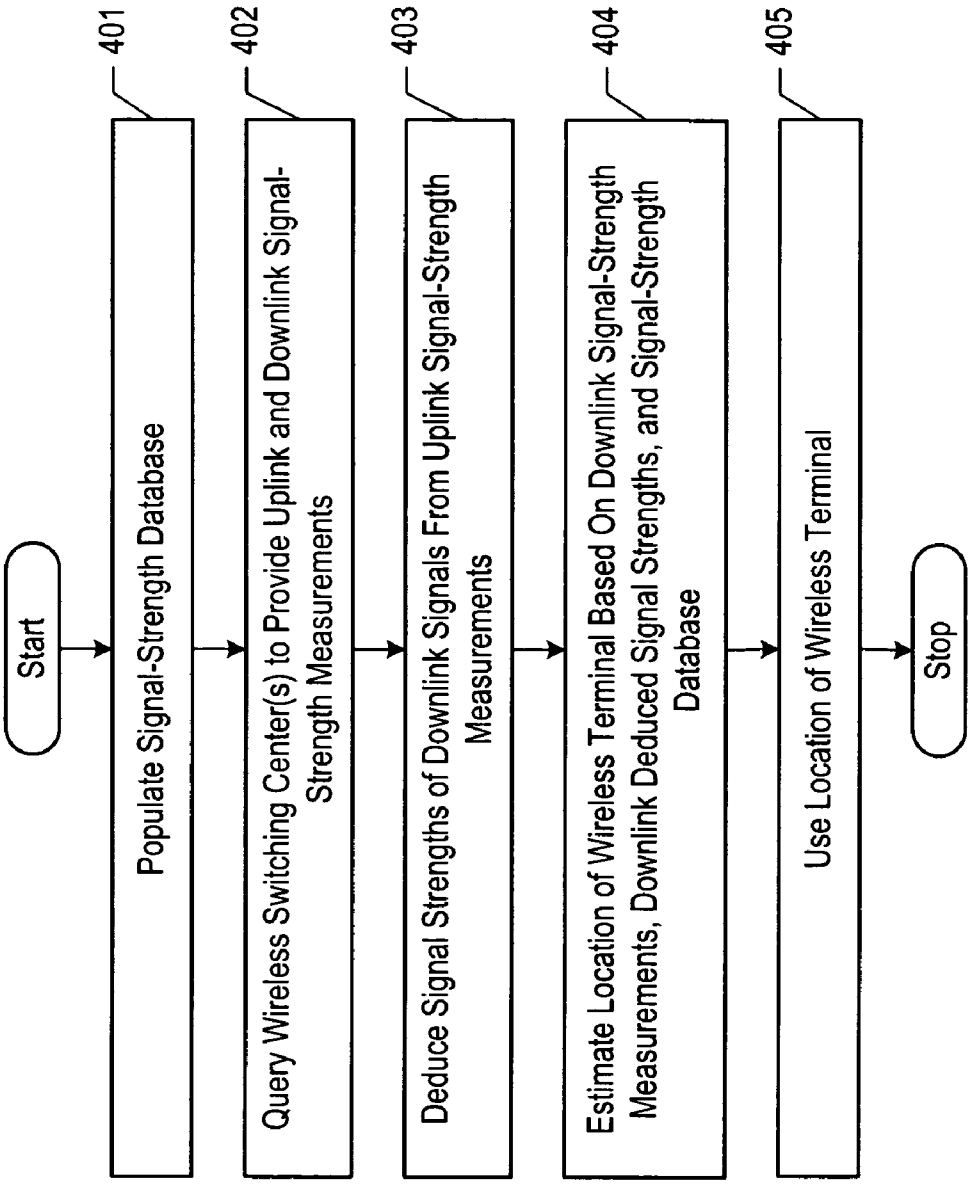

Start
401
Populate Signal-Strength Database
402
Query Wireless Switching Center(s) to Provide Uplink and Downlink Signal-Strength Measurements
403
Deduce Signal Strengths of Downlink Signals From Uplink Signal-Strength Measurements
404
Estimate Location of Wireless Terminal Based On Downlink Signal-Strength Measurements, Downlink Deduced Signal Strengths, and Signal-Strength Database
405
Use Location of Wireless Terminal
Stop

FIG. 4

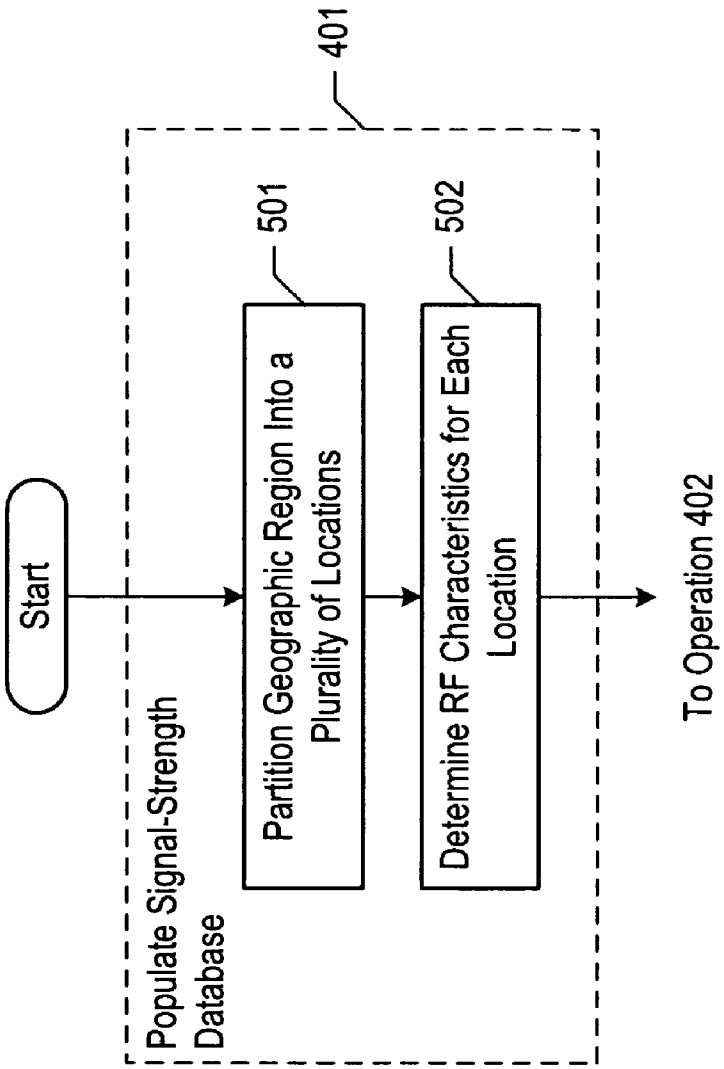

Start
Populate Signal-Strength Database
401
Partition Geographic Region Into a Plurality of Locations
501
Determine RF Characteristics for Each Location
502
To Operation 402

FIG. 5

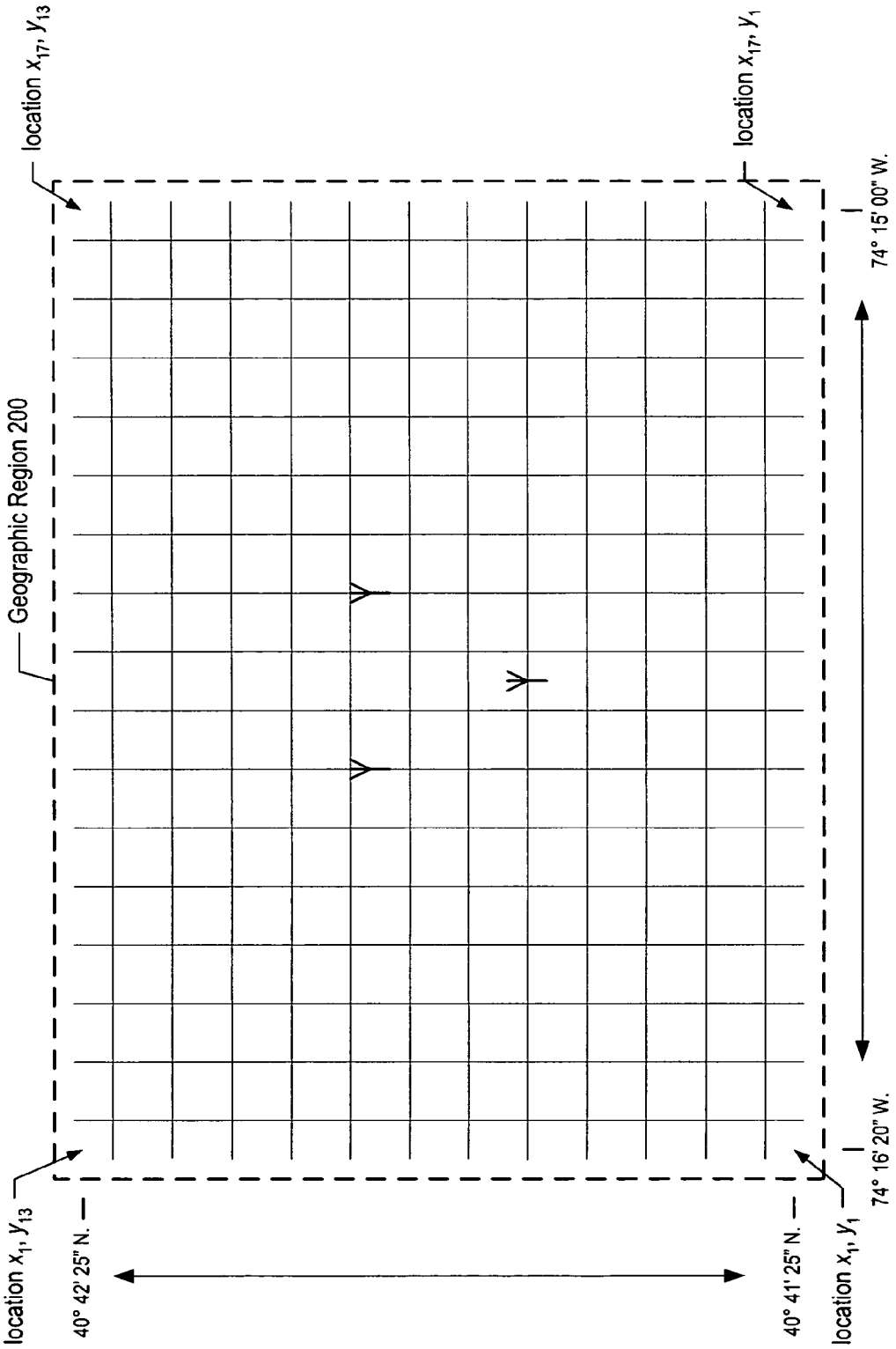

location x_{17}, y_{13}
location x_{17}, y_1
Geographic Region 200
74° 15' 00" W.
74° 16' 20" W.
location x_1, y_{13}
location x_1, y_1
40° 42' 25" N.
40° 41' 25" N.

FIG. 6

FIG. 7b

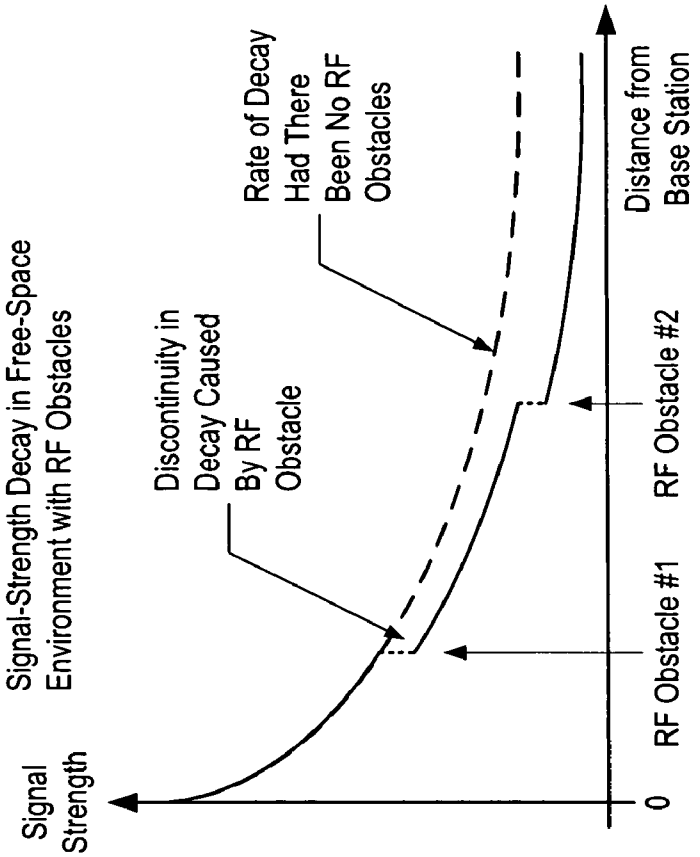

Signal-Strength Decay in Free-Space Environment with RF Obstacles
Signal Strength
Discontinuity in Decay Caused By RF Obstacle
Rate of Decay Had There Been No RF Obstacles
0
RF Obstacle #1
RF Obstacle #2
Distance from Base Station

FIG. 7a

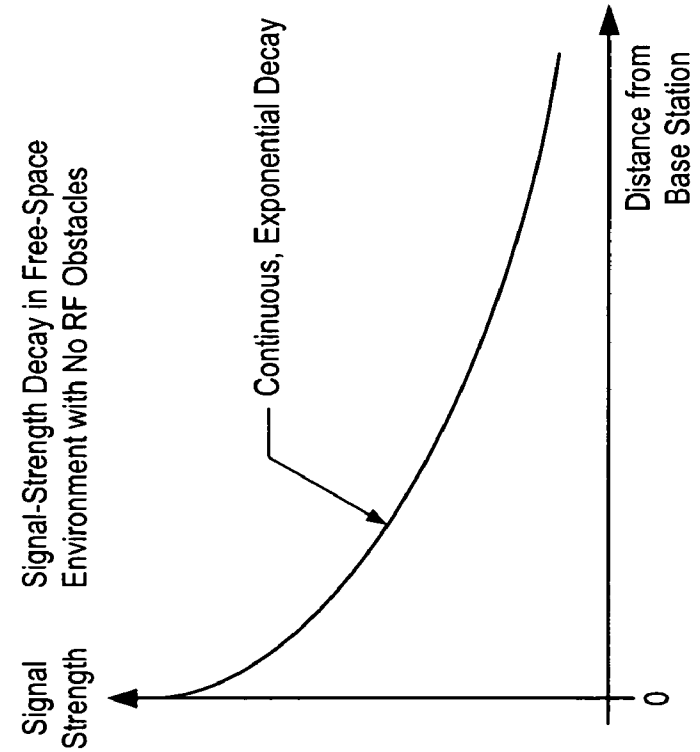
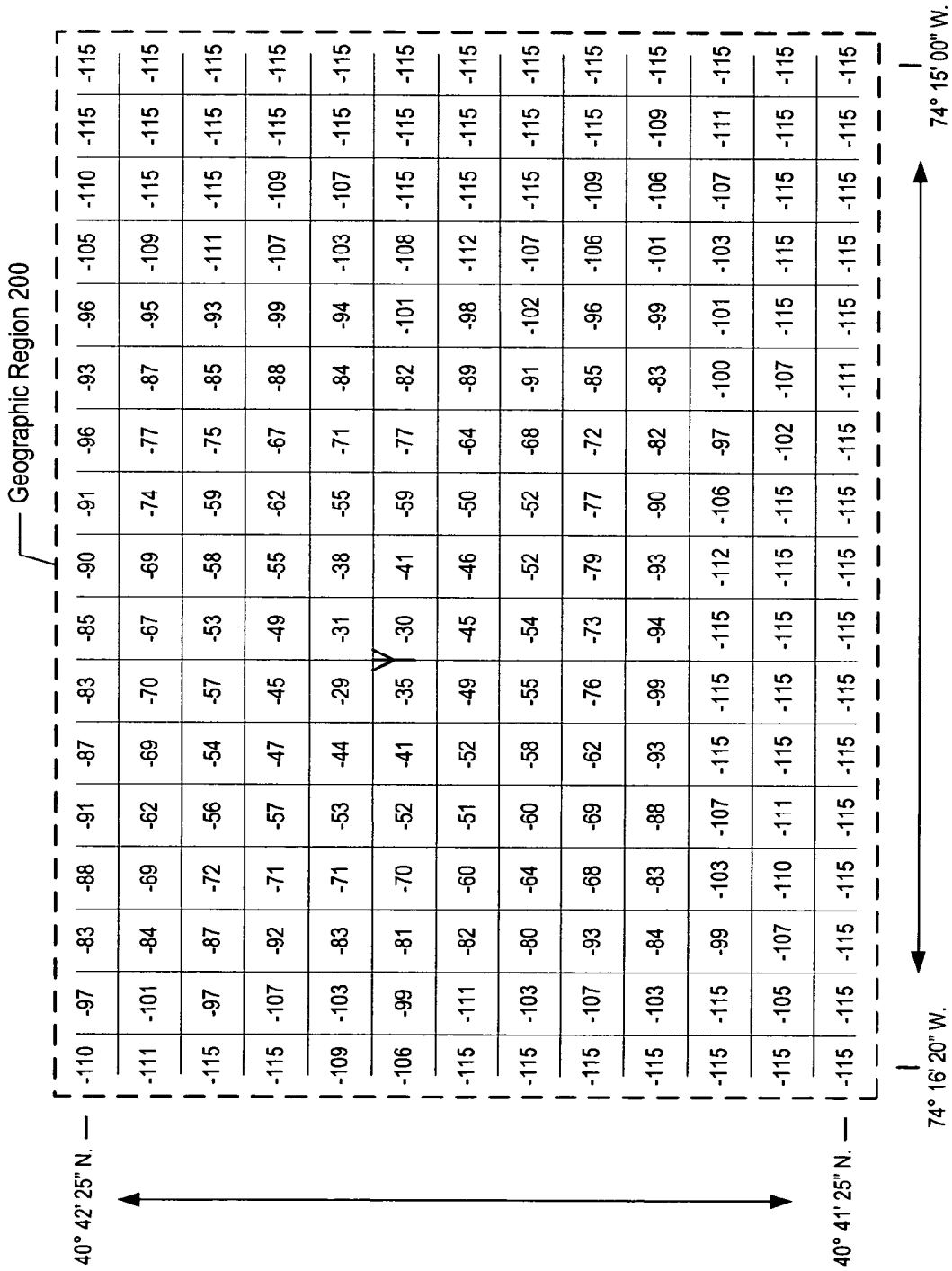

Signal-Strength Decay in Free-Space Environment with No RF Obstacles
Signal Strength
Continuous, Exponential Decay
0
Distance from Base Station

FIG. 8



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

FIG. 9

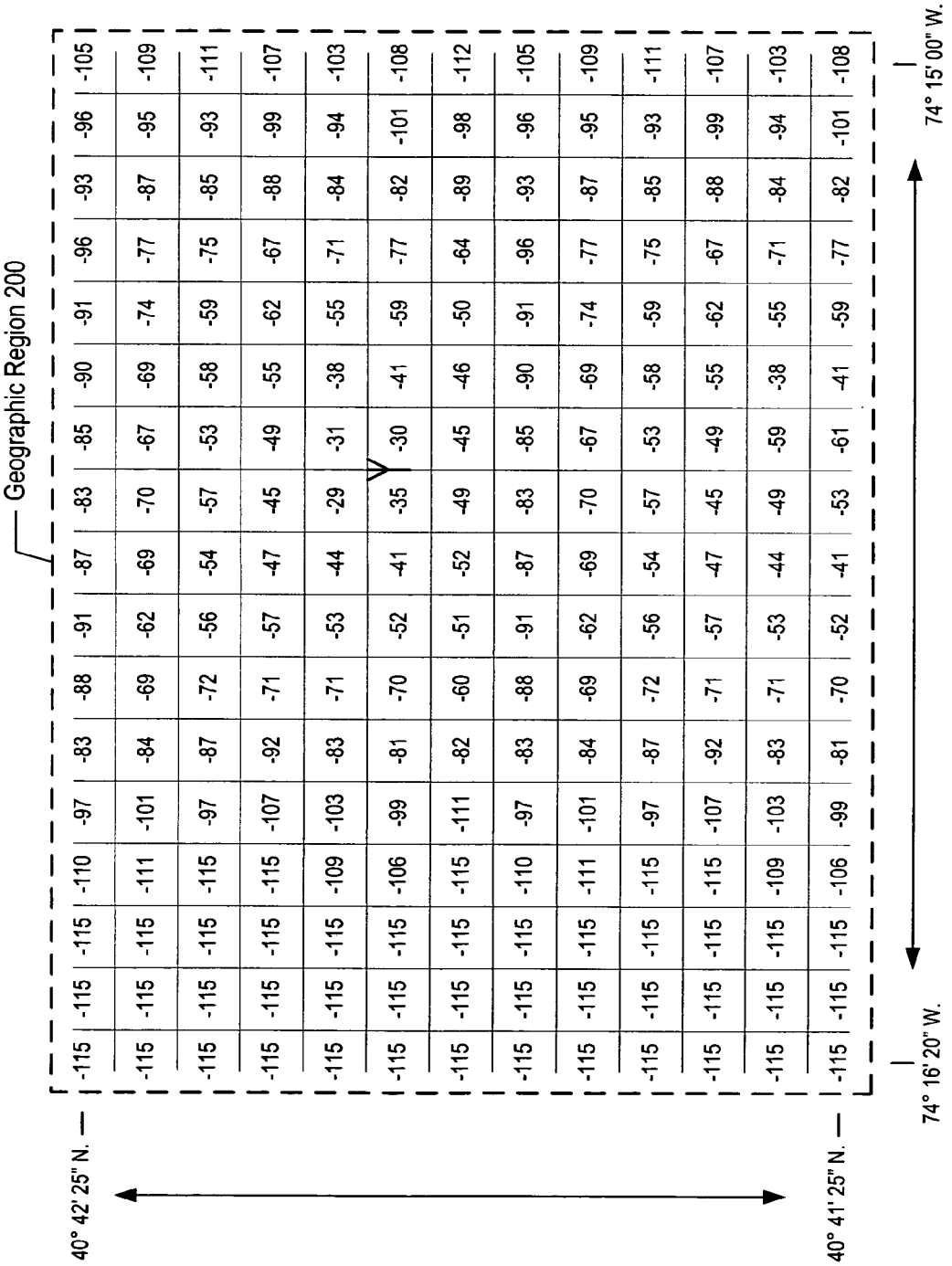

Geographic Region 200
40° 42' 25" N.
40° 41' 25" N.
74° 16' 20" W.
74° 15' 00" W.
-115 -115 -115 -110 -97 -83 -88 -91 -87 -83 -85 -90 -91 -96 -93 -96 -105
-115 -115 -115 -111 -101 -84 -69 -62 -69 -70 -67 -69 -74 -77 -87 -95 -109
-115 -115 -115 -115 -97 -87 -72 -56 -54 -57 -53 -58 -59 -75 -85 -93 -111
-115 -115 -115 -115 -107 -92 -71 -57 -47 -45 -49 -55 -62 -67 -88 -99 -107
-115 -115 -115 -109 -103 -83 -71 -53 -44 -29 -31 -38 -55 -71 -84 -94 -103
-115 -115 -115 -106 -99 -81 -70 -52 -41 -35 -30 -41 -59 -77 -82 -101 -108
-115 -115 -115 -115 -111 -82 -60 -51 -52 -49 -45 -46 -50 -64 -89 -98 -112
-115 -115 -115 -110 -97 -83 -88 -91 -87 -83 -85 -90 -91 -96 -93 -96 -105
-115 -115 -115 -111 -101 -84 -69 -62 -69 -70 -67 -69 -74 -77 -87 -95 -109
-115 -115 -115 -115 -97 -87 -72 -56 -54 -57 -53 -58 -59 -75 -85 -93 -111
-115 -115 -115 -115 -107 -92 -71 -57 -47 -45 -49 -55 -62 -67 -88 -99 -107
-115 -115 -115 -109 -103 -83 -71 -53 -44 -49 -59 -38 -55 -71 -84 -94 -103
-115 -115 -115 -106 -99 -81 -70 -52 -41 -53 -61 -41 -59 -77 -82 -101 -108

FIG. 10

Geographic Region 200

40° 42' 25" N.

40° 41' 25" N.

74° 16' 20" W.

74° 15' 00" W.

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

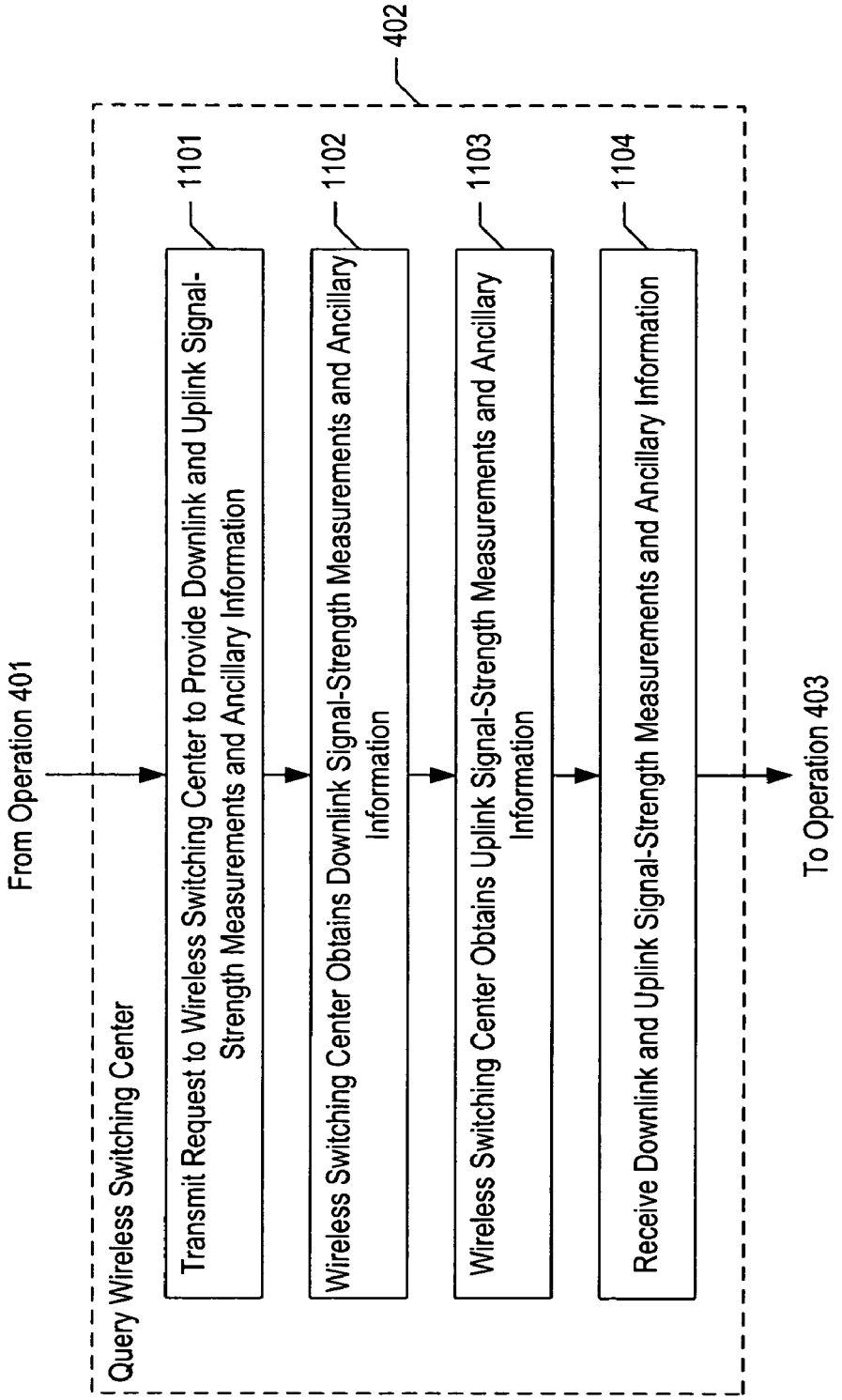

402
Query Wireless Switching Center
From Operation 401
1101
Transmit Request to Wireless Switching Center to Provide Downlink and Uplink Signal-Strength Measurements and Ancillary Information
1102
Wireless Switching Center Obtains Downlink Signal-Strength Measurements and Ancillary Information
1103
Wireless Switching Center Obtains Uplink Signal-Strength Measurements and Ancillary Information
1104
Receive Downlink and Uplink Signal-Strength Measurements and Ancillary Information
To Operation 403

FIG. 11

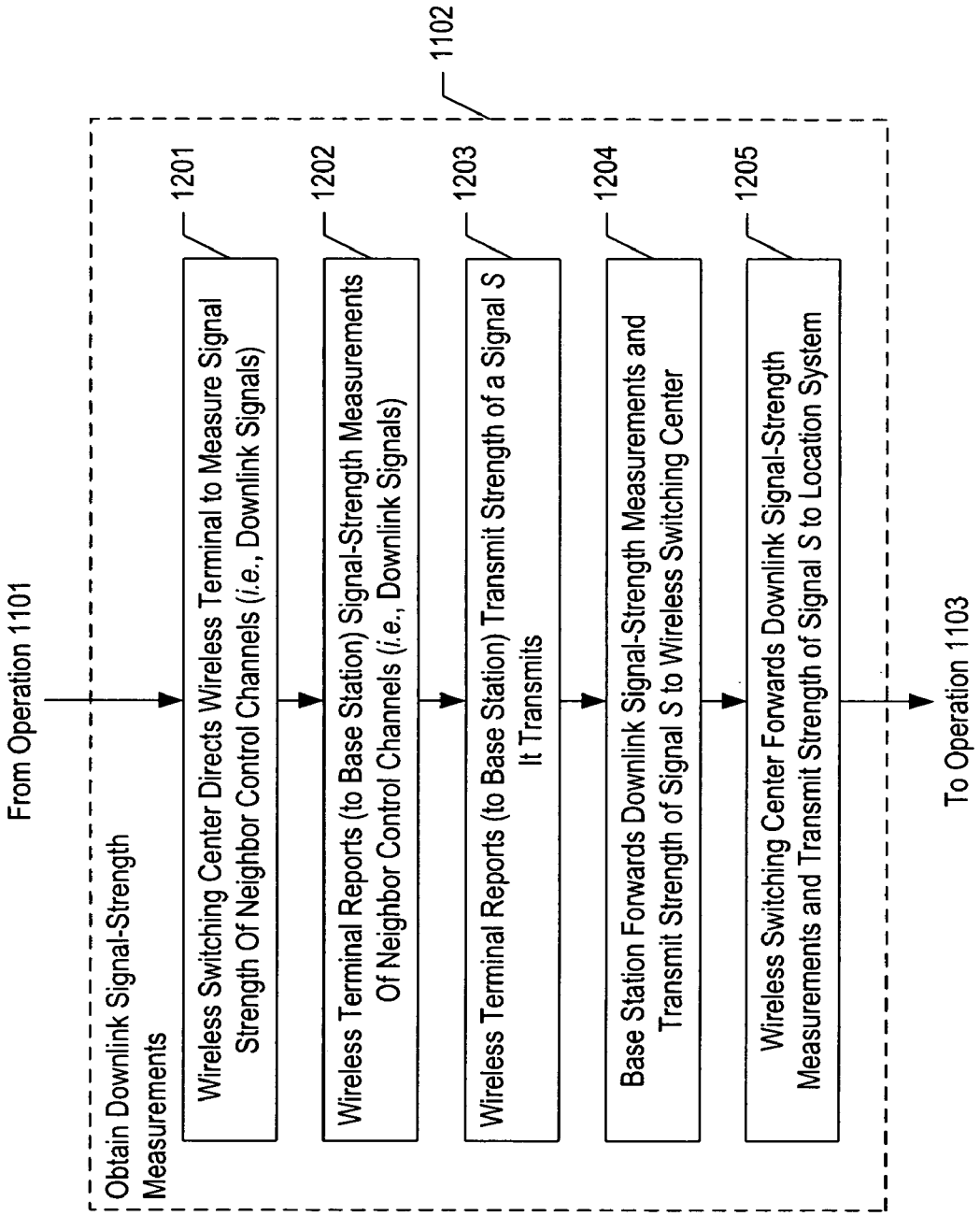

1102
From Operation 1101
Obtain Downlink Signal-Strength Measurements
1201
Wireless Switching Center Directs Wireless Terminal to Measure Signal Strength Of Neighbor Control Channels (i.e., Downlink Signals)
1202
Wireless Terminal Reports (to Base Station) Signal-Strength Measurements Of Neighbor Control Channels (i.e., Downlink Signals)
1203
Wireless Terminal Reports (to Base Station) Transmit Strength of a Signal S It Transmits
1204
Base Station Forwards Downlink Signal-Strength Measurements and Transmit Strength of Signal S to Wireless Switching Center
1205
Wireless Switching Center Forwards Downlink Signal-Strength Measurements and Transmit Strength of Signal S to Location System
To Operation 1103

FIG. 12

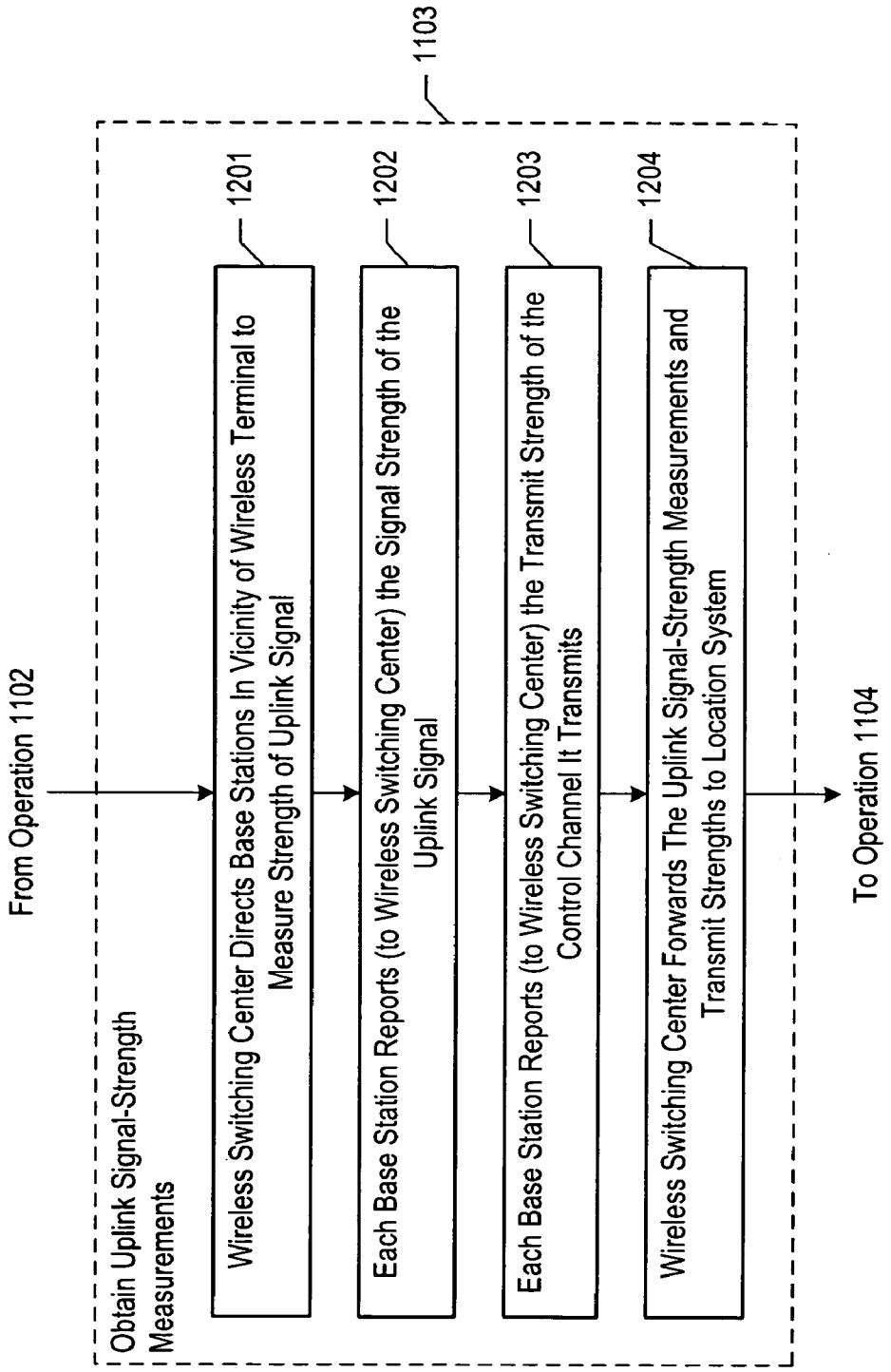

1103
From Operation 1102
Obtain Uplink Signal-Strength Measurements
1201
Wireless Switching Center Directs Base Stations In Vicinity of Wireless Terminal to Measure Strength of Uplink Signal
1202
Each Base Station Reports (to Wireless Switching Center) the Signal Strength of the Uplink Signal
1203
Each Base Station Reports (to Wireless Switching Center) the Transmit Strength of the Control Channel It Transmits
1204
Wireless Switching Center Forwards The Uplink Signal-Strength Measurements and Transmit Strengths to Location System
To Operation 1104

FIG. 13

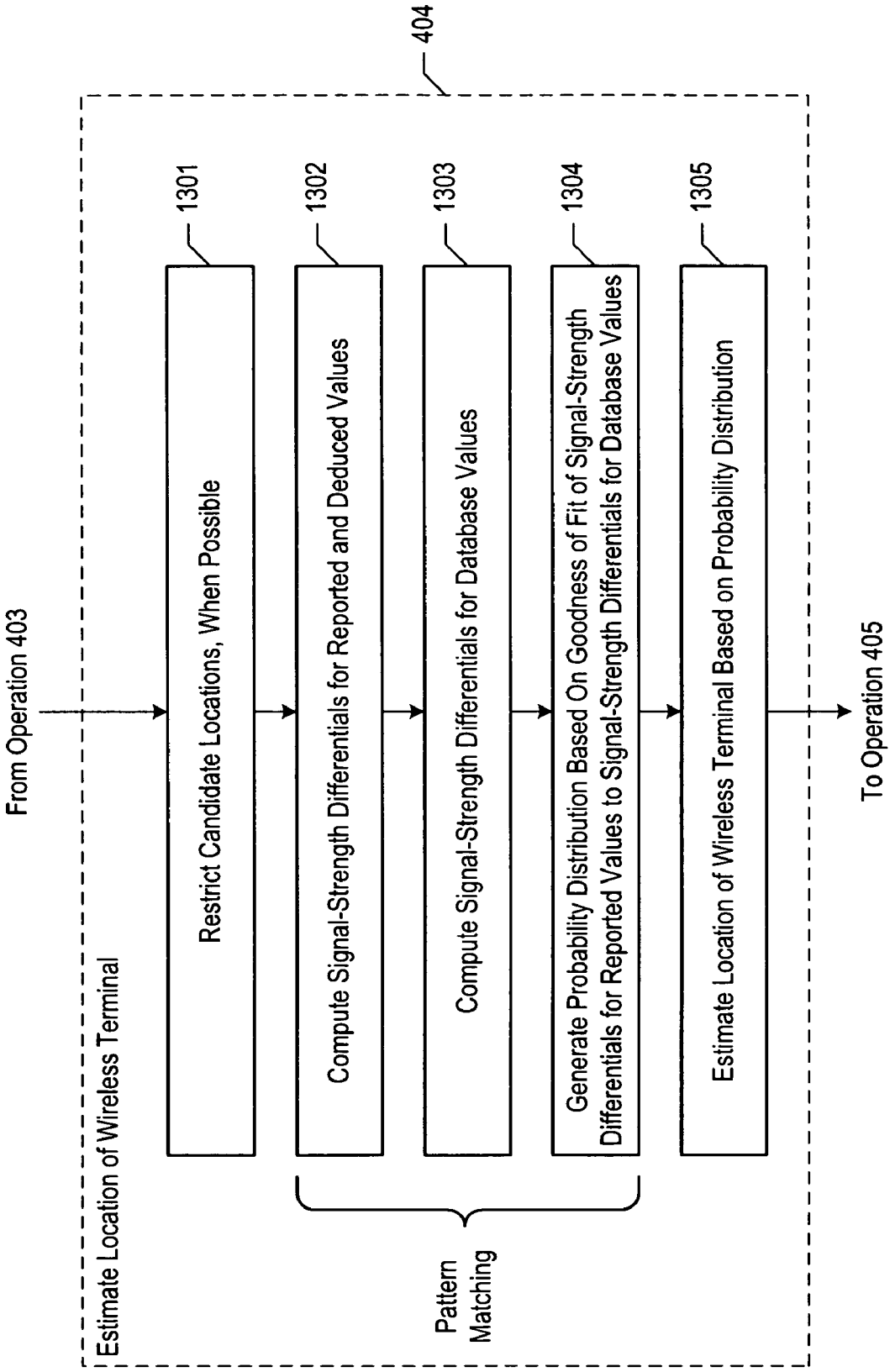

404
Estimate Location of Wireless Terminal
From Operation 403
1301
Restrict Candidate Locations, When Possible
1302
Compute Signal-Strength Differentials for Reported and Deduced Values
1303
Compute Signal-Strength Differentials for Database Values
1304
Generate Probability Distribution Based On Goodness of Fit of Signal-Strength Differentials for Reported Values to Signal-Strength Differentials for Database Values
1305
Estimate Location of Wireless Terminal Based on Probability Distribution
Pattern Matching
To Operation 405

FIG. 14

LOCATION ESTIMATION OF WIRELESS TERMINALS THROUGH PATTERN MATCHING OF DEDUCED AND EMPIRICAL SIGNAL-STRENGTH MEASUREMENTS

CROSS-REFERENCE TO RELATED APPLICATIONS

This application claims the benefit of:

i. U.S. Provisional Patent Application No. 60/488,866, filed 19 Jul. 2003, and entitled "Location Estimation of Wireless Terminals Through Pattern Matching of Deduced Signal Strengths", which application is also incorporated by reference.

The underlying concepts, but not necessarily the nomenclature, of the following are incorporated by reference:

i. U.S. Pat. No. 6,269,246, issued 31 Jul. 2001;
ii. U.S. patent application Ser. No. 09/532,418, filed 22 Mar. 2000;
iii. U.S. patent application Ser. No. 10/128,128, filed 22 Apr. 2002;
iv. U.S. patent application Ser. No. 10/299,398, filed 18 Nov. 2002;
v. U.S. patent application Ser. No. 10/357,645, filed 4 Feb. 2003;
vi. U.S. patent application Ser. No. 60/449,569, filed 24 Feb. 2003; and
vii. U.S. patent application Ser. No. 60/461,219, filed 8 Apr. 2003.

FIELD OF THE INVENTION

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

BACKGROUND

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

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

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

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

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

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

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

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

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

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

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

SUMMARY OF THE INVENTION

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

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

signal, it is more likely that the wireless terminal is at the second location than it is at the first location.

The accuracy of the estimate of the location of a wireless terminal can be enhanced when the principle uses multiple transmitters and multiple signals. A simplified example illustrates this point. A first radio station, Radio Station A, transmits a strong signal to Location **1** and Location **2**, but a weak signal to Location **3** and Location **4**, and a second radio station, Radio Station B, transmits a strong signal to Location **1** and Location **3**, but a weak signal to Location **2** and Location **4**. This information is summarized in the table below and forms the basis for a map or database that correlates locations to signal strength.

TABLE 1

Illustrative Signal Strength Database (Absolute Signal Strength)

	Radio Station A	Radio Station B
Location 1	Strong Signal	Strong Signal
Location 2	Strong Signal	Weak Signal
Location 3	Weak Signal	Strong Signal
Location 4	Weak Signal	Weak Signal

If a given wireless terminal at an unknown location receives Radio Station A with a weak signal and Radio Station B with a strong signal, it is more likely that the wireless terminal is at Location **3** than it is at either Location **1**, **2**, or **4**.

Furthermore, the accuracy of the estimate of the location of a wireless terminal can be enhanced when the signal strength of each signal at each location is quantified. A simplified example illustrates this point. If a particular radio station is known to be received in one location with a strength of −50 dBm, at a second location with a strength of −53 dBm, and at a third location with a strength of −55 dBm, then the reception of the signal with a strength of −56 dBm suggests that the wireless terminal is more likely at the third location than at either the first or second location.

In the prior art, a wireless terminal measures the signal strength of the control channels of the base stations that it can receive and that are not serving it and reports some or all of those signal-strength measurements back to the wireless switching center. In the prior art this is performed so that the wireless switching center can intelligently decide which base station the wireless terminal should be served by. In accordance with the illustrative embodiment of the present invention, these signal-strength measurements are also used, in conjunction with a map or database that correlates locations to signal strength, to estimate the location of the wireless terminal.

In general, more signal-strength measurements provide a better estimate of the location of the wireless terminal than fewer signal-strength measurements, and, therefore, the acquisition of additional signal-strength measurements is typically advantageous. One way of acquiring an additional signal-strength measurement is to actually physically measure a signal at the wireless terminal, but most legacy terminals are not equipped to measure and report on an arbitrary number of signals.

Another way of acquiring a "signal-strength measurement" is by inference or deduction based on other information, and this is what the illustrative embodiment does.

In particular, the illustrative embodiment deduces the signal strength of one or more base stations' control channels at the wireless terminal based on the principal of reciprocity, whether or not the wireless terminal can actually receive the base stations' control channels but so long as the base station can receive and measure an uplink traffic channel signal from the wireless terminal. This is accomplished in accordance with the principal of reciprocity. The principal of reciprocity states that the attenuation of a signal transmitted from Point A to Point B is the same as that for a signal that is transmitted from Point B to Point A.

In other words, the signal strength of the base station's control channel signal at the wireless terminal, R_D, can be deduced from the strength at which the control channel signal is transmitted by the base station, T_D, and the attenuation of that signal between the base station and the wireless terminal, A_D, by the function:

$$R_D=T_D-A_D \quad \text{(Eq. 1)}$$

The principal of reciprocity indicates that the attenuation of the signal between the base station and the wireless terminal, A_D, equals the attenuation of that signal between the wireless terminal and the base station, A_U, as represented by Equation 2:

$$A_D=A_U \quad \text{(Eq. 2)}$$

The attenuation of the signal between the wireless terminal and the base station, A_U, is equal to the strength at which the signal is transmitted by the wireless terminal, T_U, minus the signal strength of the signal as measured by the base station, R_U, as represented by Equation 3:

$$A_U=T_U-R_U \quad \text{(Eq. 3)}$$

By substituting Equation 3 into Equation 2 and Equation 2 into Equation 1, the signal strength of the base station's control channel signal at the wireless terminal, R_D, can be deduced from the strength at which the control channel signal is transmitted by the base station, T_D, the strength at which the signal is transmitted by the wireless terminal, T_U, and the signal strength of the uplink traffic channel signal from the wireless terminal as measured by the base station, R_U, as represented by Equation 4:

$$R_D=T_D-(T_U-R_U) \quad \text{(Eq. 4)}$$

The deduced signal-strength measurements can then used—alone or in combination with the empirical signal-strength measurements—to estimate the location of the wireless terminal.

The illustrative embodiment comprises: receiving a signal-strength measurement for a first downlink signal that is received by a wireless terminal and a signal-strength measurement for an uplink signal that is transmitted by the wireless terminal; and estimating the location of the wireless terminal based on the signal-strength measurement for the first downlink signal and on the signal-strength measurement for the uplink signal.

BRIEF DESCRIPTION OF THE DRAWINGS

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

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

FIG. **3** depicts a block diagram of the salient components of location system **212**.

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

FIG. **5** depicts a flowchart of the salient operations performed in operation **401**.

FIG. **6** depicts a map of how geographic region **200** is partitioned into **500** locations in accordance with the illustrative embodiment of the present invention.

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

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

FIG. **8** depicts a map of the signal-strength measurements of the signal radiated from base station **202-1** at each location in geographic region **200**.

FIG. **9** depicts a map of the signal-strength measurements of the signal radiated from base station **202-2** at each location in geographic region **200**.

FIG. **10** depicts a map of the signal-strength measurements of the signal radiated from base station **202-3** at each location in geographic region **200**.

FIG. **11** depicts a flowchart of the salient operations performed in operation **402**

FIG. **12** depicts a flowchart of the salient operations performed in operation **1102**.

FIG. **13** depicts a flowchart of the salient operations performed in operation **1103**.

FIG. **14** depicts a flowchart of the salient operations performed in operation **404**.

DETAILED DESCRIPTION

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

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

Wireless switching center **211** is a switching center as is well-known to those skilled in the art in most respects but is different in that it is capable of communicating with location system **212** in the manner described below. After reading this disclosure, it will be clear to those skilled in the art how to make and use wireless switching center **211**. It will also be clear to those skilled in the art that a wireless switching center is also known by other names, such as a mobile switching center, a mobile telephone switching office, etc.

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

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

Each of base stations **202-1**, **202-2**, and **203-3** is capable, in well-known fashion, of:

i. measuring the signal strength of an uplink traffic channel signal as transmitted by wireless terminal **201** and reporting that measurement to wireless switching center **211**; and

ii. informing wireless switching center **211** of the strength at which it transmits the control channel.

The first of these capabilities is performed, for example, by the Digital Locate Radio in IS-136 TDMA systems. It will be clear to those skilled in the art how to make and use alternative embodiments of the present invention in which some of the base stations measure another uplink signal, such as an uplink signaling channel signal, etc.

In accordance with the illustrative embodiment, base station **202-1** receives and measures the signal strength of the uplink signal S (depicted as a dashed zig-zag arrow in FIG. **2**) from wireless terminal **201**. Base station **202-1** is in the vicinity of wireless terminal **201**, but base station **202-1** is neither (1) the serving base station for wireless terminal **201** nor (2) on wireless terminal **201**'s list of neighboring base stations. Although the illustrative embodiment depicts only one base station in the vicinity of wireless terminal **201** for receiving and measuring the strength of the uplink signal S and that is neither (1) the serving base station nor (2) on wireless terminal **201**'s list of neighboring base stations, it will be clear to those skilled in the art how to make and use embodiments of the present invention that have any number of such base stations.

In accordance with the illustrative embodiment, base station **202-2** is the serving base station for wireless terminal **201** and, therefore, base station **202-2** receives and measures the signal strength of the uplink signal S (depicted as a dashed zig-zag arrow in FIG. **2**) from wireless terminal **201**. In accordance with the illustrative embodiment, wireless terminal **201** does not measure the signal strength of the control channel from base station **202-2**. In accordance with the illustrative embodiment, wireless terminal **201** receives a downlink traffic channel (depicted as a solid zig-zag arrow in FIG. **2**) from base station **202-2**. Although the illustrative embodiment depicts only one serving base station for wireless terminal **201**, it will be clear to those skilled in the art how to make and use embodiments of the present invention that have one or more serving base stations (e.g., in IS-95 Code-Division Multiple Access systems, etc.).

In accordance with the illustrative embodiment, base station **202-3** is on wireless terminal **201**'s list of neighboring base stations, and, therefore, wireless terminal **201** receives and measures the signal strength of the control channel (depicted as a dotted zig-zag arrow in FIG. **2**) from base station **202-3**. Although the illustrative embodiment depicts only one base station on wireless terminal **201**'s list of neighboring base stations, it will be clear to those skilled in the art how to make and use embodiments of the present

invention in which a wireless terminal has any number of base stations in it's list of neighboring base stations.

Base station **202-3** is in the vicinity of wireless terminal **201**, and, therefore, base station **202-3** receives and measures the signal strength of the uplink signal S (depicted as a dashed zig-zag arrow in FIG. **2**) from wireless terminal **201**. This is not a necessary consequence of base station **202-3** being on wireless terminal **201**'s list of neighboring base stations, but is merely a result of the proximity of base station **202-3** and wireless terminal **201**. In some embodiments of the present invention a base station on a wireless terminal's list of neighboring base stations will be able to receive and measure the signal strength of the uplink signal S from wireless terminal **201** and in some cases it will not. It will be clear to those skilled in the art how to make and use embodiments of the present invention in which some, none, or all of the base stations on a wireless terminal's list of neighboring base stations are able to receive and measure the signal strength of the uplink signal S from wireless terminal **201**.

Wireless terminal **201** is a standard GSM wireless terminal as it is currently manufactured and used throughout the world. Wireless terminal **201** is equipped, in well-known fashion, with the hardware and software necessary to measure and report to wireless switching center **211** on the signal strength of signals from the base stations that are on its list of neighboring base stations.

A GSM wireless terminal, such as wireless terminal **201**, is capable of reporting the signal strength of a signal as one of 64 levels between −47 dBm and −110 dBm. Any signal stronger than −47 dBm is reported as −47 dBm, and any signal weaker than −110 dBm is reported as −110 dBm.

In accordance with the illustrative embodiment of the present invention all of the specific portions of the radio frequency spectrum fall within the same band that wireless terminal **201** uses to communicate with base stations **202-1**, **202-2**, and **202-3**. In some alternative embodiments of the present invention, however, some or all of the specific portions of the radio frequency spectrum are outside the band that wireless terminal **201** uses to communicate with base stations **202-1**, **202-2**, and **202-3**. In any case, it will be clear to those skilled in the art how to make and use wireless terminal **201**.

Location system **212** is a computer system that is capable of estimating the location of wireless terminal **201**, as described in detail below. Although the illustrative embodiment depicts location system **212** as estimating the location of only one wireless terminal, it will be clear to those skilled in the art that location system **212** is capable of estimating the location of any number of wireless terminals serviced by wireless switching center **211**.

Furthermore, although location system **212** is depicted in FIG. **2** as being distinct from wireless switching center **211**, this is done principally to highlight the distinction between the functions performed by wireless switching center **211** and the functions performed by location system **212**. In other words, it will be clear to those skilled in the art how to make and use embodiments of the present invention in which location system **212** resides within or without wireless switching center **211** or is a fully-integrated part of wireless switching center **211**.

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

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

As shown in FIG. **3**, location system **212** comprises: processor **301**, signal-strength database **302**, receiver **303**, and transmitter **304**, which are interconnected as shown.

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

Processor **301** is a general-purpose processor as is well-known in the art that is capable of performing the operations described below and with respect to FIG. **4**. Processor **302** receives input from receiver **303** and sends output to transmitter **304** in well-known fashion.

Signal-strength database **302** is a non-volatile memory that stores signal-strength measurements as described below and with respect to FIG. **4**.

Transmitter **304** receives output from processor **301** and transmits this output to wireless switching center **211** in well-known fashion.

Overview—FIG. **4** depicts a broad overview of the salient operations performed by the illustrative embodiment in ascertaining the location of wireless terminal **201** in geographic region **200**. In summary, the tasks performed by the illustrative embodiment can be grouped for ease of understanding into five operations:

i. the population of signal-strength database **302**,

ii. the querying of the wireless switching center **211** to provide uplink and downlink signal-strength measurements,

iii. the deduction of the signal strengths at the wireless terminal for downlink signals whose signal strength was not empirically measured at the wireless terminal,

iv. the estimation of the location of wireless terminal **201** based on measured downlink and deduced downlink signal strengths, and

v. the use of the estimated location of wireless terminal **201**.

The details of each of these operations are described briefly below and in detail afterwards with respect to FIGS. **5** though **14**.

At operation **401**, signal-strength database **302** associates each location within geographic region **200** with a tuple of signal-strength measurements for specific signals for that location. Operation **401** is generally complex and potentially expensive, and it is, therefore, preferably performed only occasionally. The details of operation **401** are described in detail below and with respect to FIG. **5**.

At operation **402**, location system **212** queries wireless switching center **211** to learn:

i. the empirical signal-strength measurements for one or more control channel signals as received by wireless terminal **211** and the corresponding transmit power of those control channel signals; and

ii. one or more empirical signal-strength measurements for the uplink signal S as transmitted by wireless terminal **201** and the corresponding transmit power of signal S.

The query is not for specific data but for whatever data wireless switching center **211** can provide. In accordance with the illustrative embodiment, location system **212** receives the following data (which is summarized in Table 2):

i. empirical signal-strength measurements of the (downlink) control channels transmitted by base station **202-3**, as received by wireless terminal **201**, which is designated as $R_D(3)$, respectively;

ii. the transmit power of (uplink) signal S transmitted by wireless terminal **201**, T_U, at substantially the same moment that wireless terminal **201** makes measurement $R_D(3)$;

iii. the empirical signal-strength measurements of (uplink) signal S as received by base stations **201-1**, **202-2**, and **202-3**, which are $T_U(1)$, $T_U(2)$, and $T_U(3)$, respectively, at substantially the same moment that wireless terminal **201** makes measurement $R_D(3)$; and

iv. the transmit power of the (downlink) control channel transmitted by base stations **201-1**, **202-2**, and **202-3**, which are $T_D(1)$, $T_D(2)$, and $T_D(3)$, respectively, at substantially the same moment that wireless terminal **201** makes measurement $R_D(3)$.

$T_D(1)$, $T_D(2)$, and $T_D(3)$ are needed along with T_U to deduce $R_D(1)$, $R_D(2)$, and $R_D(3)$. Although a value for $R_D(3)$ was determined empirically and directly by wireless terminal **201**, for reasons given below, the deduced value of $R_D(3)$ might be preferred.

TABLE 2

Signal-Strength Measurements Received by Location System 212 In Accordance with Illustrative Embodiment

	i	$R_D(i)$	$R_U(i)$	$T_D(i)$
Base station 202-1	1	—	$R_U(1)$	$T_D(1)$
Base station 202-2	2	—	$R_U(2)$	$T_D(2)$
Base station 202-3	3	$R_D(3)$	$R_U(3)$	$T_D(3)$

In accordance with the illustrative embodiment, wireless terminal **201** periodically or sporadically provides $R_D(3)$ and T_U to wireless switching center **211** in well-known fashion, and the measurements are forwarded to location system **212**. The details of operation **402** are described in detail below and with respect to FIGS. **11**, **12**, and **13**.

At operation **403**, location system **212** deduces the values of $R_D(i)$ based on T_U, $R_U(i)$, and $T_D(i)$. In particular, location system **212** computes the uplink attenuation $A_U(i)$ of signal S along path i in accordance with Equation 4:

$$R_D(i)=T_D(i)-(T_U-R_U(i)) \quad \text{(Eq. 4)}$$

When $R_D(i)$ and $R_U(i)$ are at different frequencies, as in, for example, a frequency-division duplexed system, the effects of fast fading (i.e., Rayleigh fading) must be removed from $R_U(i)$ to ensure that the deduced value of $R_D(i)$ is independent of fast fading at the frequency of $R_U(i)$. As is well known in the art, the effects of fast fading can be removed from $R_U(i)$ through well-known filtering techniques. The details of operation **403** are described in detail below and with respect to FIG. **12**.

At operation **404**, location system **212** estimates the location of wireless terminal **201** based on all of the downlink signal-strength measurements (i.e., the measured signal-strength measurements, $R_1, \ldots R_{n-1}$, and the deduced signal-strength measurements, $R_D(1), \ldots R_D(3)$), and a map or database that correlates locations to signal-strength measurements.

In some cases, location system **212** will receive an empirical signal-strength measurement for a downlink signal and will be able to deduce the signal strength of that same downlink signal. In this case, the deduced value should be used instead of the empirical measurement because the accuracy of the uplink signal-strength measurement is typically better than the accuracy of the downlink signal-strength measurement. It will be clear to those skilled in the art, however, after reading this specification, how to make and use embodiments of the present invention in which one or more empirical measurements are used instead of deduced values for the measurements.

The details of operation **404** are described in detail below and with respect to FIG. **14**.

At operation **405**, location system **212** transmits the location estimated in operation **405** to an entity (not shown) for use in an application. It is well known to those skilled in the art how to use the estimated location of a wireless terminal in an application.

At this point, operations **401** through **404** are described in detail.

Population of Signal-Strength Database **302**—FIG. **5** depicts a flowchart of the salient operations performed in operation **401**.

At task **501**, geographic region **200** is partitioned into a plurality of tessellated locations. Geographic region **200** is rectangular and comprises 5,525 square arc-seconds, which near the equator equals almost 5 square kilometers (see FIG. **6**). After reading this specification, it will be clear to those skilled in the art how to make and use embodiments of the present invention that operate with geographic regions of any size and shape.

In accordance with the illustrative embodiment of the present invention, geographic region **200** is partitioned into a grid of **221** square locations that are designated location x_1, y_1 through location x_{17}, y_{13}. The number of locations into which geographic location **200** is partitioned is arbitrary, subject to the considerations described below. In accordance with the illustrative embodiment, each location is an area of approximately 5 arc-seconds in length by 5 arc-seconds in height. Five arc-seconds near the equator equals approximately 150 meters.

The size of the locations defines the highest resolution with which the illustrative embodiment can locate a wireless terminal. In other words, the illustrative embodiment can only estimate the location of a wireless terminal to within one location (i.e., 5 by 5 arc-seconds in the illustrative embodiment). If greater resolution is desired, for example 1 arc-second resolution, then geographic region **200** would need to be partitioned into 1 arc-second by 1 arc-second locations. If geographic region **200** were partitioned into 1 arc-second by 1 arc-second locations, there would be 5,525 squares, which is considerably more than the **221** used in the illustrative embodiment. Although the ostensibly higher resolution of 1 arc-second versus 5 arc-seconds is advantageous, there are considerable disadvantages to a large number of locations.

The number of locations to partition geographic region **200** into is based on three factors. First, as the size of each location goes down, the resolution of the embodiment increases. Second, as the size of each location decreases, the number of locations in a region increases, and, consequently, the computational complexity of operation **404** increases quickly. Third, each location must be large enough so that it has (at least slightly) different signal-strength characteristics than its adjacent areas. This is because the illustrative embodiment might—but won't necessarily—have difficulty distinguishing between adjacent locations that have the same signal-strength characteristics. It will be clear to those skilled in the art how to consider these three factors when deciding how to partition a geographic region.

At task **502**, the signal-strength measurements for a signal from each base station are determined at each location in geographic region. In accordance with the illustrative embodiment, the signal used from each base station is the control channel because it is broadcast at a constant power and because wireless terminal **201** can distinguish it from every other control channel, if it can decode its BSIC (for GSM networks).

Because there are three base stations in the illustrative embodiment, each with one control channel, a tuple of three signal-strength measurements at each location must be determined.

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

In accordance with the illustrative embodiment, the tuple of three signal-strength measurements for each location are determined through a combination of:

(i) a theoretical radio-frequency propagation model, and

(ii) empirical signal-strength measurements.

It will be clear to those skilled in the art how to accomplish this.

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

$$P \propto \frac{1}{r^2}, \qquad \text{(Eq. 5)}$$

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

$$P \propto \frac{1}{r^4} \qquad \text{(Eq. 6)}$$

The location of the break-point is determined through empirical signal-strength measurements as the location at which the ground bounce signal interferes with the line-of-sight signal.

In accordance with another well-known model, the signal-strength measurements at each location are determined by taking empirical measurements at various locations and by interpolating for the locations in between the sampled locations. This method is advantageous in that it does not require many empirical measurements to be made, but it is less accurate than taking measurements at every location.

It will be clear to those skilled in the art how to determine the signal-strength measurements for each location in the geographic region whether through:

(i) theoretical radio-frequency propagation models, or

(ii) empirical signal-strength measurements, or

(iii) any combination of i and ii.

In accordance with the illustrative embodiment, FIG. **8** depicts the signal strength of the signal from base station **202-1** (hereinafter referred to as "Signal **1**") at each location in geographic region **200**. In general, Signal **1** is stronger near base station **202-1** and weaker far away from base station **202-1**.

In accordance with the illustrative embodiment, FIG. **9** depicts the signal strength of the signal from base station **202-2** (hereinafter referred to as "Signal **2**") at each location in geographic region **200**. Like Signal **1**, Signal **2** is stronger near base station **202-2** and weaker far away from base station **202-2**.

In accordance with the illustrative embodiment, FIG. **10** depicts the signal strength of the signal from base station **202-3** (hereinafter referred to as "Signal **3**") at each location in geographic region **200**. Like Signals **1** and **2**, Signal **3** is stronger near base station **202-3** and weaker far away from base station **202-3**.

When the signal-strength tuples for each location in geographic region **200** have been determined, they are stored in signal-strength database in a data structure that associates each location with the tuple for that location. The data structure is then stored in signal-strength database **302**.

TABLE 3

Signal-Strength Database			
	Signal-Strength Tuple		
Location	Strength of Signal 1	Strength of Signal 2	Strength of Signal 3
x_1, y_1	−115	−115	−115
x_2, y_1	−115	−115	−111
.	.	.	.
.	.	.	.
.	.	.	.
X_7, y_7	−45	−51	−49
X_8, y_7	−46	−52	−55
X_9, y_7	−50	−49	−62
.	.	.	.
.	.	.	.
.	.	.	.
X_{16}, y_{13}	−115	−96	−115
X_{17}, y_{13}	−115	−105	−115

Table 3 depicts a portion of an illustrative data structure for associating each location with the signal-strength tuple for that location.

The three signal-strength measurements in a row of table 1 constitute a "tuple" or non-empty set of ordered elements. For example, the signal-strength tuple at Location x_7, y_7 are the 3-tuple {−45, −51, −49}. In general, the illustrative embodiment of the present invention estimates the location of a wireless terminal by pattern matching the signal-strength measurements by the wireless terminal at a location against the signal-strength tuples in signal-strength database **302**. This process is described in detail below and with respect to operation **402**.

From task **502**, control passes to operation **402** in FIG. **4**.

Query of Transmit Strength and Signal-Strength Measurements from Wireless Switching Center—FIG. **11** depicts a flowchart of the salient operations performed in operation **402**.

At task **1101**, location system **212** transmits a request to wireless switching center **211** to provide:

i. the uplink transmit signal strength for wireless terminal **201**, Tu,

ii. the downlink signal-strength measurements from wireless terminal **201**, $R_D(3)$ for some or all of the control channels that wireless terminal **201** is able to receive, and

iii. the uplink signal-strength measurements at various base stations that can receive and measure wireless terminal **201**'s uplink signal, $R_U(1)$ through $R_U(3)$.

The third of these can be requested from wireless switching center **211** in the form of an IS-41 HandoffMeasurementRequest or HandoffMeasurementRequest2 message, in well-known fashion.

At task **1102**, wireless switching center **211** obtains the uplink transmit signal strength for wireless terminal **201**, T_U, and the downlink signal-strength measurements from wireless terminal **201**, $R_D(3)$ for some or all of the control channels that wireless terminal **201** is able to receive (e.g., base station **202-2** in FIG. **2**, etc.) in well-known fashion. Task **1102** is described in detail below and with respect to FIG. **12**.

At task **1103**, wireless switching center **211** obtains the uplink signal-strength measurements, $R_U(1)$ through $R_U(3)$, in well-known fashion. Task **1103** is described in detail below and with respect to FIG. **13**.

At task **1104**, location system **212** receives from wireless switching center **211**:

i. the uplink transmit signal strength for wireless terminal **201**, T_U,

ii. the downlink signal-strength measurements from wireless terminal **201**, $R_D(3)$ for some or all of the control channels that wireless terminal **201** is able to receive, and

iii. the uplink signal-strength measurements at various base stations that can receive and measure wireless terminal **201**'s uplink signal, $R_U(1)$ through $R_U(3)$.

FIG. **12** depicts a flowchart of the salient operations performed in task **1102**.

At subtask **1201**, wireless switching center **211** directs wireless terminal **201**, in well-known fashion, to (1) attempt to receive the control channels for the base stations on its list of neighboring base stations, (2) report back a signal-strength value for each received control channel, and (3) report back the transmit strength of a signal that it transmits.

At subtask **1202**, wireless terminal **201** reports, in well-known fashion, signal-strength measurements $R_1 \ldots R_{n-1}$ for some or all of the control channels that it is able to receive to its serving cell's base station (e.g., base station **202-2** in FIG. **2**, etc.).

At subtask **1203**, wireless terminal **201** reports to its serving cell's base station, in well-known fashion, the transmit strength of a signal S transmitted by wireless terminal **201**, R_U. As is well-known in the art, wireless terminal **201** regularly transmits signals, and any of these signals can be used as "signal S" with respect to tasks **1103** and **1202**, disclosed below.

At subtask **1204**, the base station forwards (i) the signal-strength measurements received at task **1102**, and (ii) the transmit strength received at task **1103**, to wireless switching center **211** in well-known fashion.

At subtask **1205**, wireless switching center **211** forwards (i) the signal-strength measurements received at task **1102**, and (ii) the transmit strength received at task **1103**, to location system **212** in well-known fashion.

It will be clear to those skilled in the art how to make and use embodiments of the present invention that perform operation **402**. From task **1205**, control passes to operation **1104** in FIG. **11**.

Receipt of (iii) Transmit Strength of control channels and (iv) Signal-Strength Measurement of Signal S—FIG. **13** depicts a flowchart of the salient operations performed in operation **1103**.

At subtask **1301**, wireless switching center **211** directs the base stations in the vicinity of wireless terminal **201** to measure and report the signal-strength of the uplink signal from wireless terminal **201**, in well-known fashion.

At subtask **1302**, each of the base stations that are able to measure the signal strength of the uplink signal from wireless terminal **201** reports to wireless switching center **211** the measured signal strength, in well-known fashion.

At subtask **1303**, each of the base stations that reported a value in subtask **1302** reports to wireless switching center **211** the transmit strength of the control channel that it transmits, in well-known fashion.

At subtask **1304**, wireless switching center **211** forwards the signal-strength measurements received in subtask **1302** and the control channel transmit strengths received in subtask **1303** to location system **212** in well-known fashion.

It will be clear to those skilled in the art how to make and use embodiments of the present invention that perform operation **1103**. From task **1204**, control passes to operation **1104** in FIG. **11**.

Estimation of the Location of Wireless Terminal **201**—FIG. **14** depicts a flowchart of the salient operations performed in operation **404**. For pedagogical purposes, operation **404** as depicted in FIG. **14** is described three times. First, operation **404** is described in the abstract with a focus on describing its underlying theory. Next, operation **404** is described as it is applied to the first report, and finally, operation **404** is described as it is applied to the second report.

In accordance with the first report, the signal strength of Signal **1**, $R_D(1)$, is deduced and equals −98, the signal strength of Signal **2**, $R_D(2)$, is deduced, and equals −64, and the signal strength of Signal **3**, $R_D(3)$, is empirically measured, and equals −51.

In accordance with the second report, the signal strength of Signal **1**, $R_D(1)$, is deduced and equals −98, the signal strength of Signal **2**, $R_D(2)$, is deduced, and equals −64, and the signal strength of Signal **3**, $R_D(3)$, is empirically measured, and equals −50.

Estimation in General—Subtask **1401** begins with 211 (17×13=211) candidate locations that must be considered as the location for wireless terminal **201**, and, therefore, 211 signal-strength tuples (i.e., the 211 tuples in signal-strength database **302**) that must be processed. Subtasks **1402** through **1405** can be computationally intense, and the computational burden increases with the number of candidate locations that must be considered. Therefore, location system **212** attempts, at subtask **1401**, to reduce the number of candidate locations that must be processed in subtasks **1402** through **1405**.

To reduce the number of candidate locations that must be processed in subtasks **1402** through **1405**, location system **212** uses the following observation. When a downlink signal is reported with a maximum signal strength (i.e., "−47" in the illustrative embodiment), location system **212** can reasonably eliminate from consideration as a candidate location every location where the signal-strength measurement for that signal is below the maximum (minus a factor for measurement errors and systematic bias). In other words, when a signal is reported with a maximum signal strength, location system **212** can restrict consideration in subtasks **1402** through **1405** to those candidate locations where signal-strength database **302** predicts the signal strength to

be greater than or equal to the maximum reportable value (minus a factor for measurement errors and systematic bias). In accordance with the illustrative embodiment, the factor for measurement errors and systematic bias is 3 dBm, and, therefore when a downlink signal is reported with −47, location system **212** can restrict consideration in subtasks **1402** through **1405** to those candidate locations where signal-strength database **302** predicts the signal strength to be greater than or equal to −50 dBm. It will be clear to those skilled in the art how to determine and use other factors for measurement errors and systemic bias.

At subtask **1402**, location system **212** computes the signal-strength differentials for all of the downlink signal-strength measurements (i.e., both the empirical signal-strength measurements and the deduced signal-strength measurements) that are not at the maximum signal strength. In particular, for n unique downlink signal-strength measurements that are not at the maximum signal strength, n−1 signal-strength differentials are computed where:

$$\Delta S_k = S_k - S_1 \quad \text{(Eq. 7)}$$

for k=2, 3, . . . n, wherein ΔS_k is the kth signal-strength differential, S_k is the downlink signal strength of Signal k, and S_1 is the downlink signal strength of Signal **1**. When m of the downlink signals is at the maximum signal strength (i.e., −47 dBm), then

$$n-m-1 \quad \text{(Eq. 8)}$$

pair-wise differentials for the remaining n−m signals are computed, in well-known fashion. At the end of subtask **1402**, location system **212** will have computed n−m−1 pair-wise differentials, ΔS_2 through ΔS_{n-m}.

At subtask **1403**, location system **212** computes the signal-strength differentials for only those locations that were not eliminated from consideration in task **1201**.

Furthermore, location system **212** only computes the signal-strength differentials corresponding to the differentials computed in subtask **1402**; the idea, of course, being to ensure that "apples are compared with apples." In particular, for n reported signals that are not at the maximum signal strength, n−1 signal-strength differentials are computed where:

$$\Delta R_{k,x,y} = R_{k,x,y} - R_{1,x,y} \quad \text{(Eq. 9)}$$

for k=2, 3, . . . n, wherein $\Delta R_{k,x,y}$ is the kth signal-strength differential for location x,y, $R_{k,x,y}$ is the signal-strength of Signal k at location x,y in signal-strength database **302**, and $R_{1,x,y}$ is the reported signal strength of Signal **1** at location x,y in signal-strength database **302**.

At the end of subtask **1403**, location system **212** will have computed n−m−1 pair-wise differentials, $\Delta R_{2,x,y}$ through $\Delta R_{n-m,x,y}$, corresponding to the pair-wise differentials computed in subtask **1403**, for all the candidate locations.

At subtask **1404**, location system **212** compares the signal-strength differentials computed in subtask **1402**, ΔS_2 through ΔS_{n-m}, to the signal-strength differentials in subtask **1403**, $\Delta R_{2,x,y}$ through $\Delta R_{n-m,x,y}$, to generate a probability distribution that indicates the goodness of fit between the signal-strength differentials computed from the values received in operations **402** and **403** to the signal-strength differentials computed from the tuples in signal-strength database **302**. To accomplish this, the Euclidean norm at each of the i candidate locations is computed for the signal-strength differentials computed from the values received in operations **402** and **403** and each of the signal-strength differentials computed from the tuples in signal-strength database **302**. This is described in Equation 10.

$$v_{x,y} = \sqrt{\Sigma_2^n (\Delta R_{k,x,y} - \Delta S_k)^2} \quad \text{(Eq. 10)}$$

wherein $v_{x,y}$ is the Euclidean norm between the signal-strength tuple for location x,y in signal-strength database **302** in comparison to the signal-strength differentials computed from the values received in operations **402** and **403**.

Next, the Euclidean norms computed in Equation **4** are turned into un-normalized probabilities by Equation 11:

$$p_{x,y} = e^{\frac{-v_{x,y}^2}{\tau^2}} \quad \text{(Eq. 11)}$$

where τ^2 represents the amount of uncertainty in both ΔS_k and $\Delta R_{k,x,y}$.

And finally, the values of $P_{x,y}$ are normalized to generate the probability distribution for the location of wireless terminal **201** in geographic region **200**.

At subtask **1405**, location system **212** estimates the location of wireless terminal **201** based on the probability distribution generated in subtask **1404**. In accordance with the illustrative embodiment, location system **212** estimates the location of wireless terminal based on the geometric mean of the probability distribution generated in subtask **1404**. After reading this specification, however, it will be clear to those skilled in the art how to make and use embodiments of the present invention that estimate the location of wireless terminal **201** based on another function of the probability distribution generated in subtask **1404**, such as the maximum likelihood function.

From subtask **1405**, control passes to operation **404** in FIG. **4**.

Estimation as Applied to First Report (Signal **1**=−98. Signal **2**=−64, and Signal **3**=−51)—At subtask **1401**, location system **212** cannot eliminate any candidate locations from consideration based on the fact that none of the reported signals is at the maximum reportable value minus the factor for measurement errors and systematic bias (i.e., 3 dBm). In other words, location system **212** cannot eliminate any candidate signal from consideration because all of the signals are at −51 dBm or less. Therefore, location system **212** must consider all **221** candidate locations in subtasks **1402** through **1305**.

At subtask **1402**, location system **212** computes two (2) signal-strength differentials for the first report in which R_1=Signal **1**=−98, R_2=Signal **2**=−64, and R_3=Signal **3**=−43. In particular, ΔR_2 and ΔR_3 are computed as depicted in Table 4.

TABLE 4

Signal-strength Differentials for Signal 1 = −98, Signal 2 = −64, and Signal 3 = −43

k	ΔR_k	$R_k - R_1$
2	34	−64 − (−98)
3	47	−51 − (−98)

At subtask **1403**, location system **212** computes two (2) signal-strength differentials for each of the **221** locations in signal-strength database **302**, as depicted in Table 5.

TABLE 5

Signal-strength Differentials for Each Tuple in Signal-Strength Database 302

Location	$\Delta S_{2,x,y}$	$\Delta S_{3,x,y}$
x1, y1	−110 − (−110) = 0	−110 − (−110) = 0
x2, y1	−110 − (−110) = 0	−111 − (−110) = −1
x3, y1	−110 − (−110) = 0	−97 − (−110) = 3
.	.	.
.	.	.
.	.	.
x16, y13	−96 − (−110) = 14	−110 − (−110) = 0
x17, y13	−105 − (−110) = 5	−110 − (−110) = 0

At subtask **1404**, location system **212** first computes the Euclidean norm between the signal-strength differentials in Table 2 against the signal-strength differentials for each location in Table 3 to produce the norms shown in Table 6.

TABLE 6

Euclidean Norms for Each Location (First Report)

Location	Vx,y
x1, y1	64.66
x2, y1	63.81
x3, y1	62.13
.	.
.	.
.	.
x16, y13	58.52
x17, y13	62.18

Next, the Euclidean norms in Table 6 are converted to unnormalized probabilities, as described above, and then the unnormalized probabilities are normalized, in well-known fashion, to produce the probability distribution of the location of wireless terminal **201** at each of the **211** locations in geographic region **200**.

Estimation As Applied to Second Report (Signal **1**=−98. Signal **2**=−64, and Signal **3**=−50)—At subtask **1401**, location system **212** can perfunctorily eliminate most of the candidate locations from consideration because the reported signal strength of one of the reported signals—Signal **3**=−50 dBm—is greater than the maximum reported value (−47 dBm) minus the factor for measurement errors and systematic bias (3 dBm). In other words, location system **212** can eliminate from consideration any candidate location in which S_3 is not at least −50 dBm. Therefore, location system **212** can restrict consideration in subtasks **1402** through **1305** to those locations in signal-strength database **302** in which Signal **3** is predicted to be −50 dBm or greater. As can be seen in FIG. **10**, there are only 13 locations (x**8**,y**4**; x**9**,y**4**; x**10**,y**4**; x**7**,y**5**; x**8**,y**5**; x**9**,y**5**; x**10**,y**5**; x**7**,y**6**; x**8**,y**6**; x**9**,y**6**; x**10**,y**6**; x**7**,y**7**; x**8**,y**7**; x**9**,y**7**) at which Signal **3** is predict stronger, and, therefore, location system **212** need only perform subtasks **1402** through **1305**, in the above-described fashion, on those 13 locations. By reducing the number of candidate locations that need to be processed from **221** to **13**, task **1401** has greatly reduced the computational complexity of operation **403**.

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:

receiving a signal-strength measurement for a first downlink signal that is received by a wireless terminal and a signal-strength measurement for an uplink signal that is transmitted by said wireless terminal; and

estimating the location of said wireless terminal based on said signal-strength measurement for said first downlink signal and on said signal-strength measurement for said uplink signal

wherein estimating the location of said wireless terminal comprises pattern matching (i) said signal-strength measurement for said downlink signal against a map that correlates signal-strength measurements and locations.

2. The method of claim **1** further comprising deducing the signal strength of a second downlink signal at said wireless terminal based on said signal-strength measurement for said uplink signal.

3. The method of claim **2** wherein estimating the location of said wireless terminal comprises pattern matching (ii) the deduced signal strength of said downlink signal at said wireless terminal against a map that correlates signal-strength measurements and locations.

4. The method of claim **2** wherein estimating the location of said wireless terminal comprises pattern matching the difference between (i) said signal-strength measurement for said downlink signal and (ii) the deduced signal strength of said downlink signal at said wireless terminal against a map that correlates signal-strength measurements and locations.

5. The method of claim **2** wherein deducing the signal strength of said second downlink signal at said wireless terminal is also based on the transmit strength of said second downlink signal.

6. The method of claim **2** wherein deducing the signal strength of said second downlink signal at said wireless terminal is also based on the transmit strength of said uplink signal.

7. The method of claim **1** further comprising transmitting a request to a mobile switching center to make said signal-strength measurement for said uplink signal.

8. A method comprising:

receiving (i) a first signal-strength measurement for an uplink signal that is transmitted by a wireless terminal and received at a first location and (ii) a second signal-strength measurement for said uplink signal that is transmitted by said wireless terminal and received at a second location;

deducing the signal strength of a first downlink signal at said wireless terminal based on said first signal-strength measurement for said uplink signal;

deducing the signal strength of a second downlink signal at said wireless terminal based on said second signal-strength measurement for said uplink signal; and

estimating the location of said wireless terminal based on the deduced signal strength of said first downlink signal and on the deduced signal strength of said second downlink signal.

9. The method of claim **8** wherein estimating the location of said wireless terminal comprises pattern matching (i) the deduced signal strength of said first downlink signal and (ii) the deduced signal strength of said second downlink signal against a map that correlates signal-strength measurements and locations.

10. The method of claim **8** wherein estimating the location of said wireless terminal comprises pattern matching the difference between (i) the deduced signal strength of said first downlink signal and (ii) the deduced signal strength of said second downlink signal against a map that correlates signal-strength measurements and locations.

11. The method of claim **8** wherein deducing the signal strength of a first downlink signal at said wireless terminal is based on the transmit strength of said first downlink signal.

12. The method of claim **8** wherein deducing the signal strength of a first downlink signal at said wireless terminal is based on the transmit strength of said uplink signal.

13. The method of claim **8** further comprising transmitting a request to a mobile switching center to make said first signal-strength measurement for an uplink signal and said second signal-strength measurement for said uplink signal.

14. The method of claim **8** further comprising receiving a message from a mobile switching center that comprises said first signal-strength measurement for an uplink signal and said second signal-strength measurement for said uplink signal.

15. A method comprising:

transmitting a request to a mobile switching center to make a first signal-strength measurement at a first location and a second signal-strength measurement at a second location for an uplink signal that is transmitted by a wireless terminal;

receiving a message from said mobile switching center that comprises said first signal-strength measurement and said second signal-strength measurement;

deducing the signal strength of a first downlink signal at said wireless terminal based on said first signal-strength measurement;

deducing the signal strength of a second downlink signal at said wireless terminal based on said second signal-strength measurement; and

estimating the location of said wireless terminal based on the deduced signal strength of said first downlink signal and on the deduced signal strength of said second downlink signal.

16. The method of claim **15** wherein estimating the location of said wireless terminal comprises pattern matching (i) the deduced signal strength of said first downlink signal and (ii) the deduced signal strength of said second downlink signal against a map that correlates signal-strength measurements and locations.

17. The method of claim **15** wherein estimating the location of said wireless terminal comprises pattern matching the difference between (i) the deduced signal strength of said first downlink signal and (ii) the deduced signal strength of said second downlink signal against a map that correlates signal-strength measurements and locations.

18. The method of claim **15** wherein deducing the signal strength of a first downlink signal at said wireless terminal is based on the transmit strength of said first downlink signal.

19. The method of claim **15** wherein deducing the signal strength of a first downlink signal at said wireless terminal is based on the transmit strength of said uplink signal.

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