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(54) PARACTICAL NETWORK NODE COORDINATE ESTIMATION

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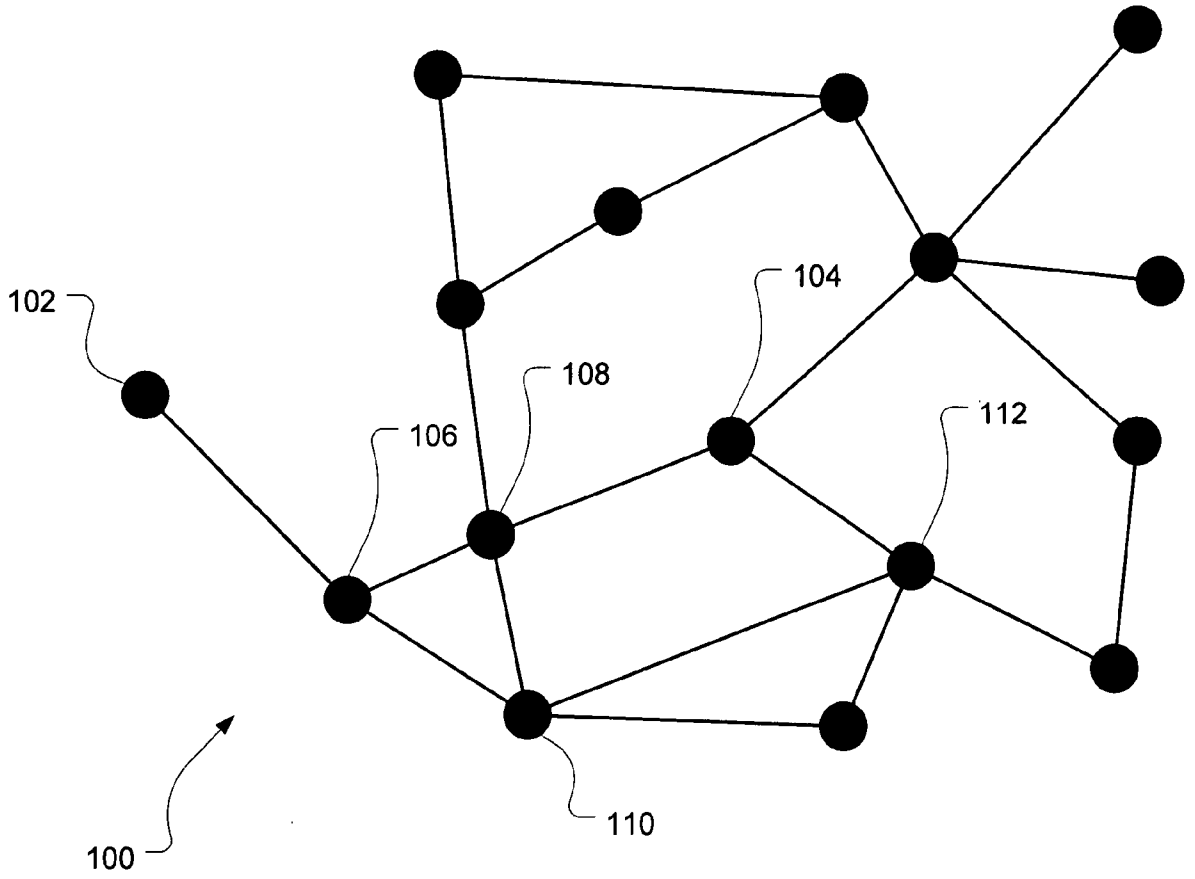
(52) **U.S. Cl.** **370/252**; 370/254; 370/338

(57) **ABSTRACT**

Substantially accurate estimation of coordinates of a subject network node in a coordinate space is accomplished by considering designated coordinates of other positioned nodes within the network. The designation of coordinates in the coordinate space to such nodes allows the computation of predicted coordinate distances between two network nodes based on the coordinates. By optimizing the network distance errors between measured distances and predicted coordinate distances, the predicted coordinates of a subject node joining the network can be iteratively refined. With these estimated coordinates, the coordinate distance between two points in the space may be computed as a prediction of the network distance between the two corresponding nodes. Furthermore, coordinate-based coordinate estimation lends itself to security precautions to protect against malicious reference nodes or external interference.



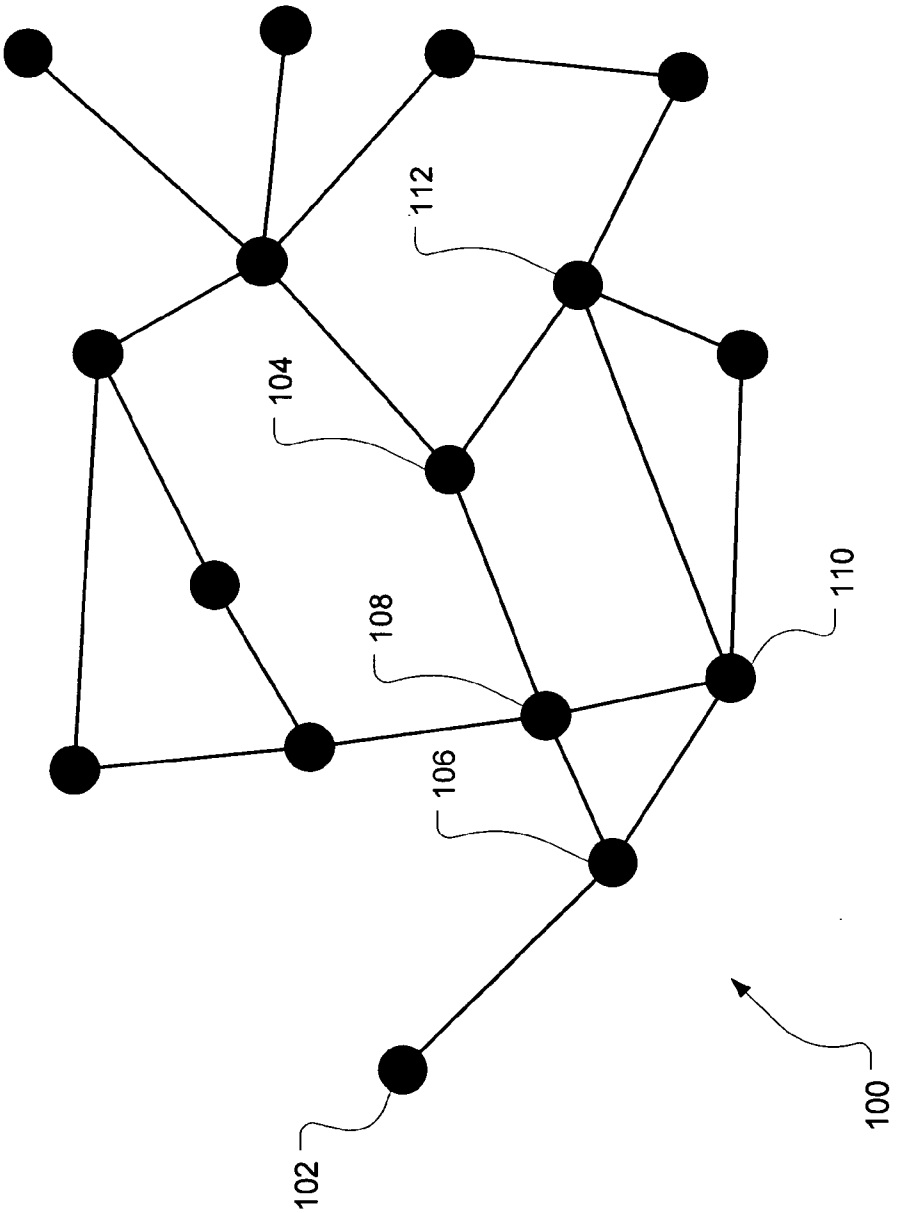
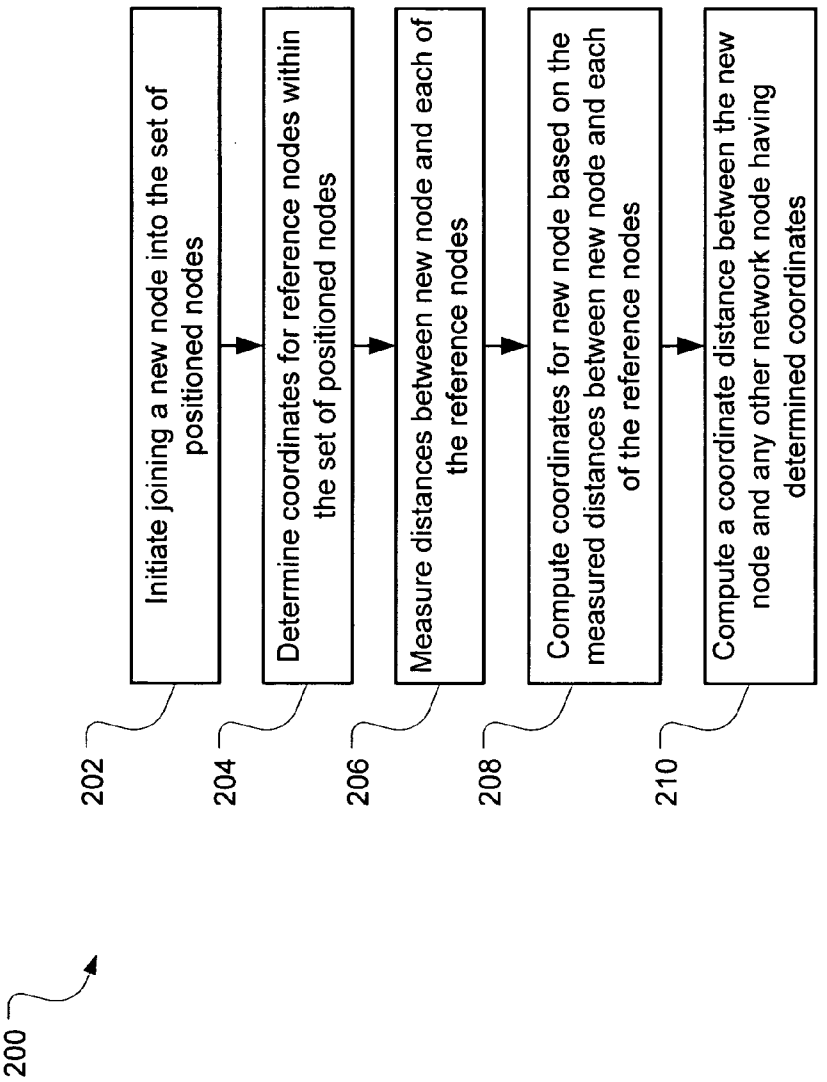


FIG. 1

FIG. 2


200
202
Initiate joining a new node into the set of positioned nodes
204
Determine coordinates for reference nodes within the set of positioned nodes
206
Measure distances between new node and each of the reference nodes
208
Compute coordinates for new node based on the measured distances between new node and each of the reference nodes
210
Compute a coordinate distance between the new node and any other network node having determined coordinates

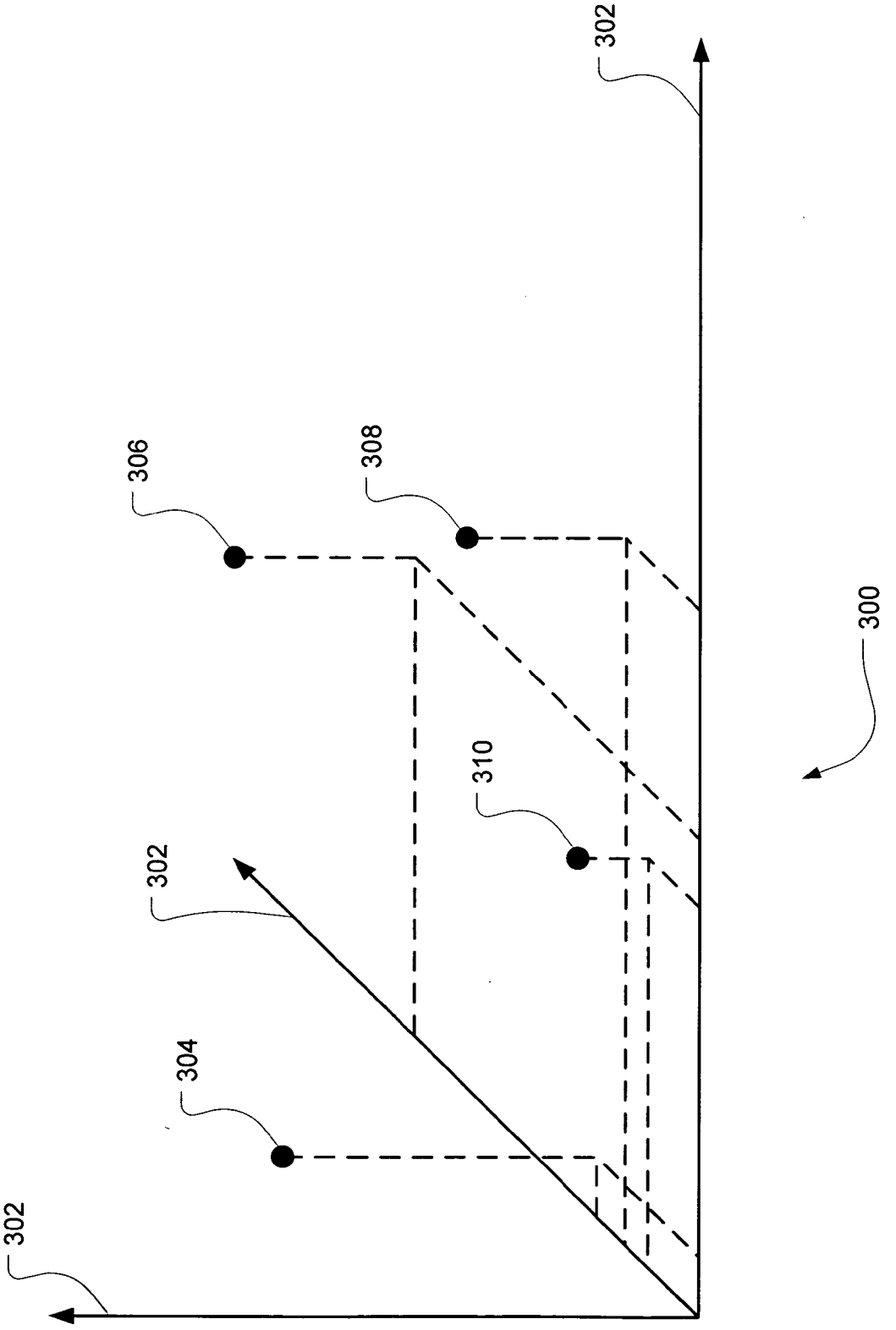


FIG. 3

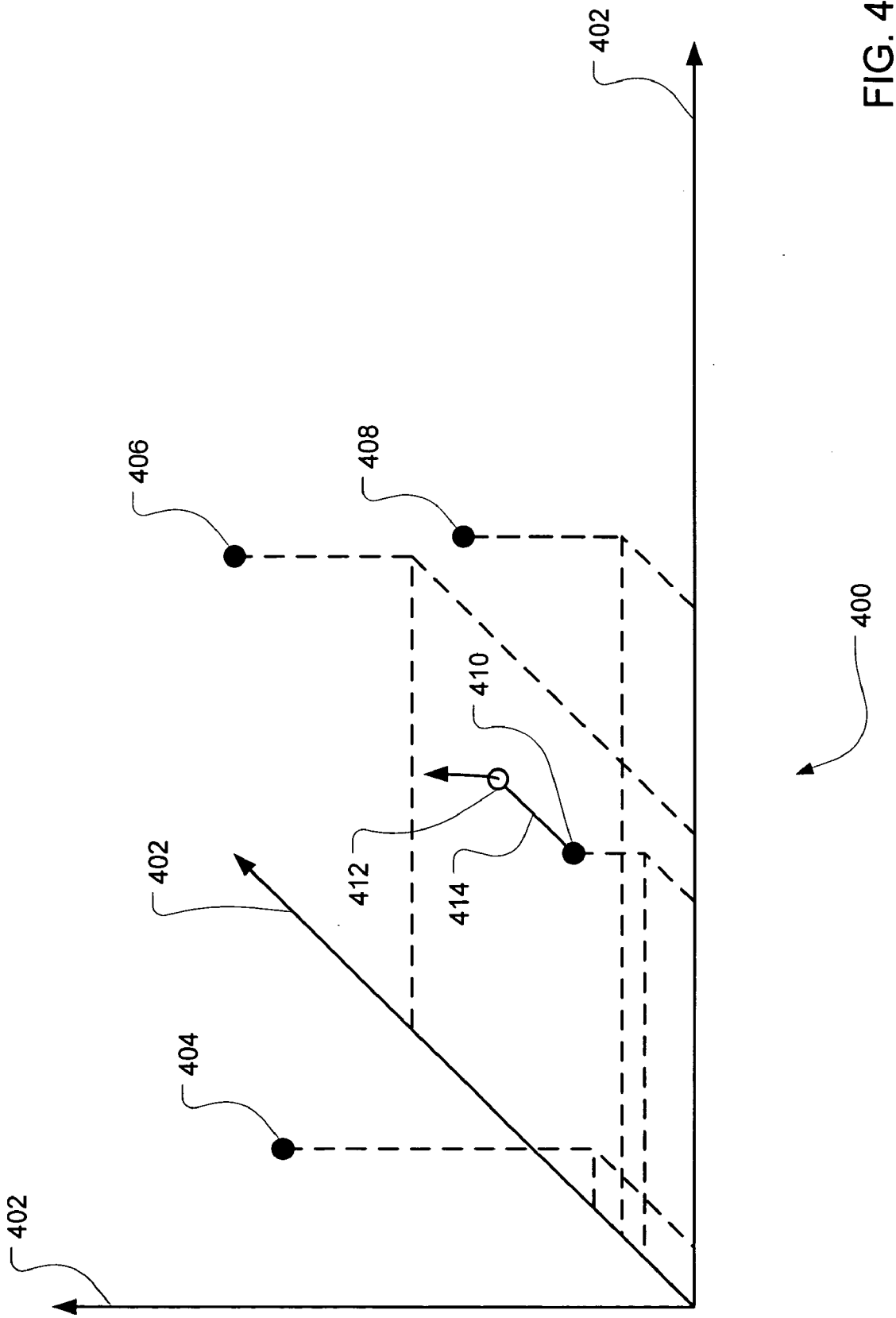


FIG. 4

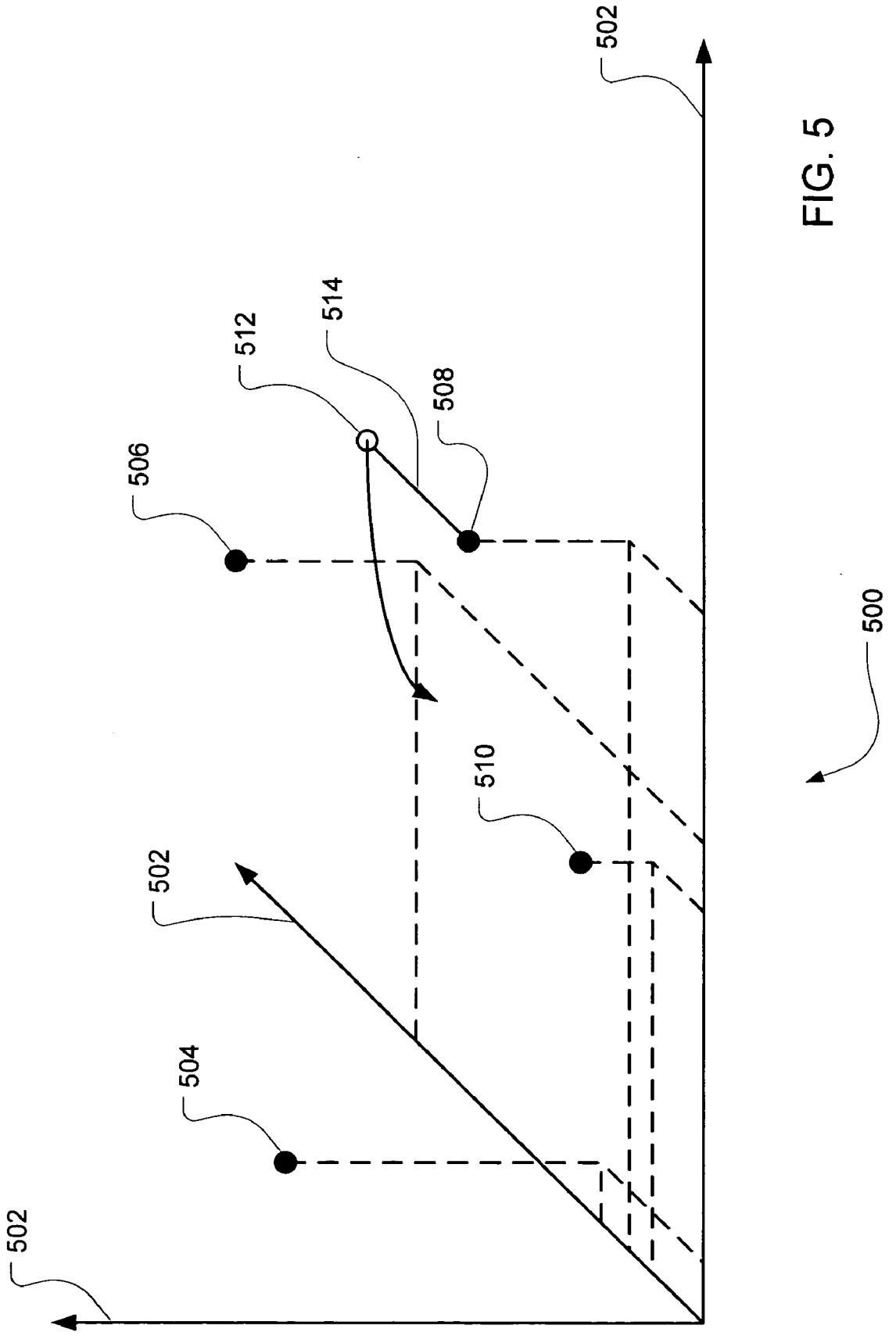


FIG. 5

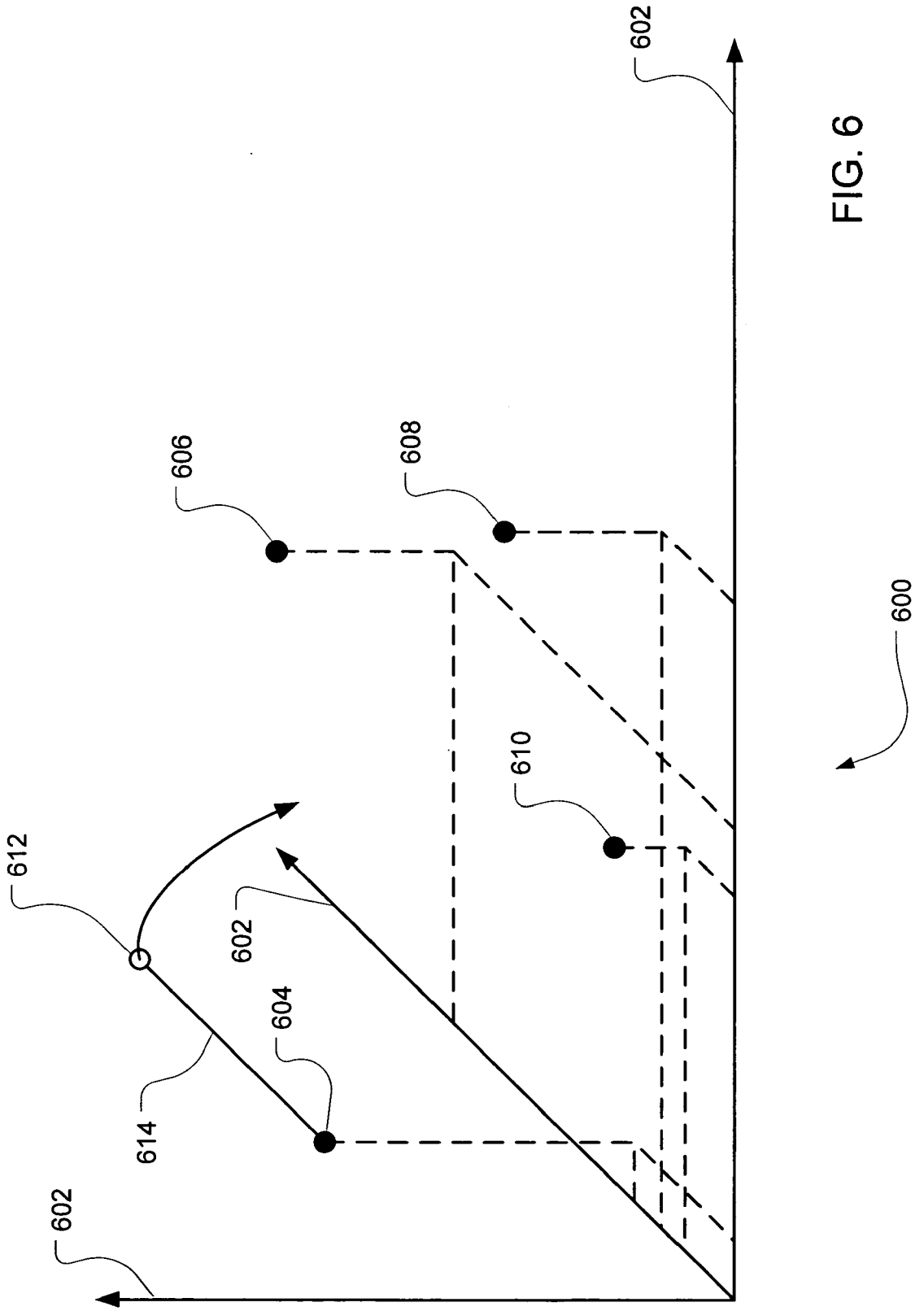


FIG. 6

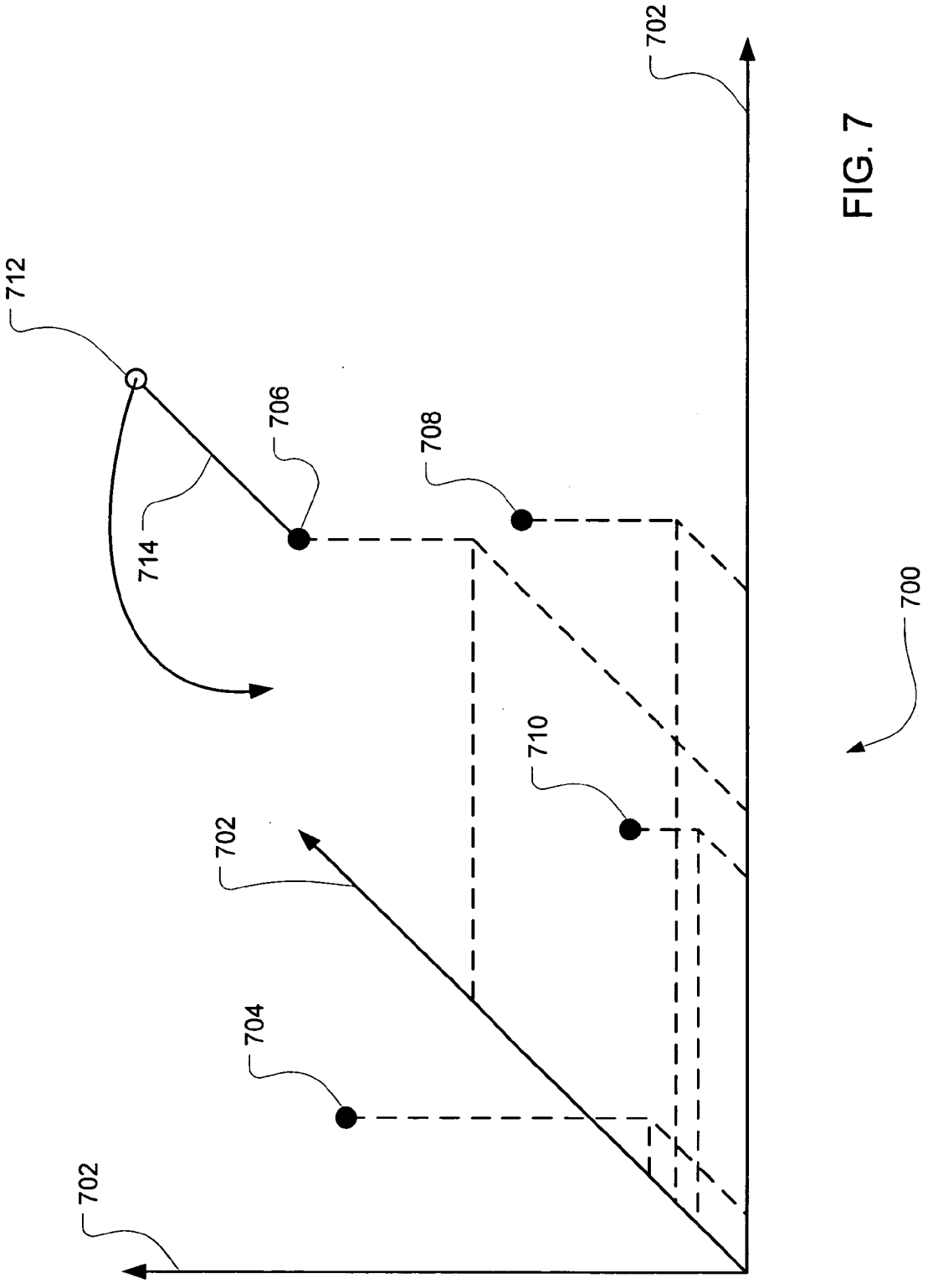


FIG. 7

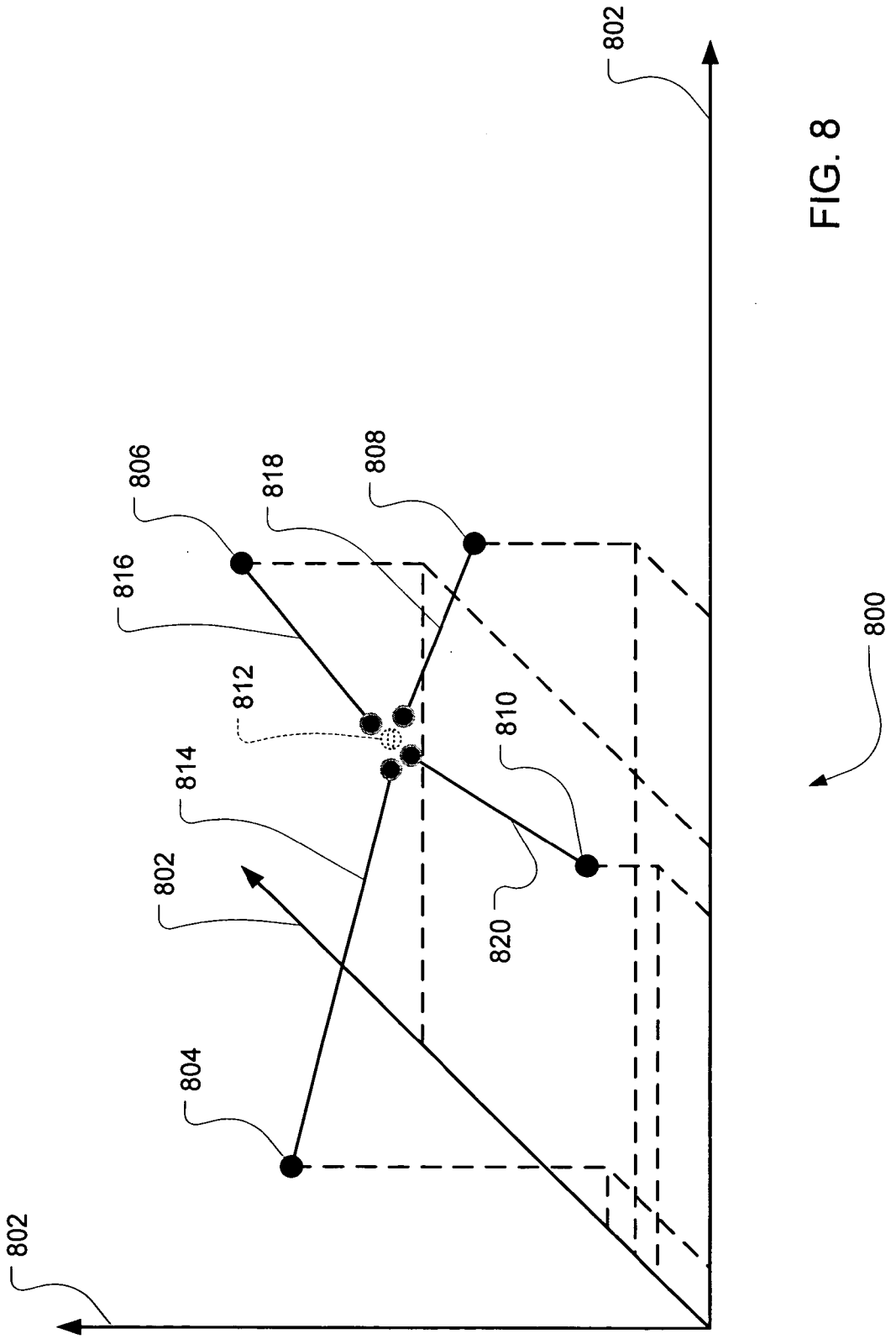


FIG. 8

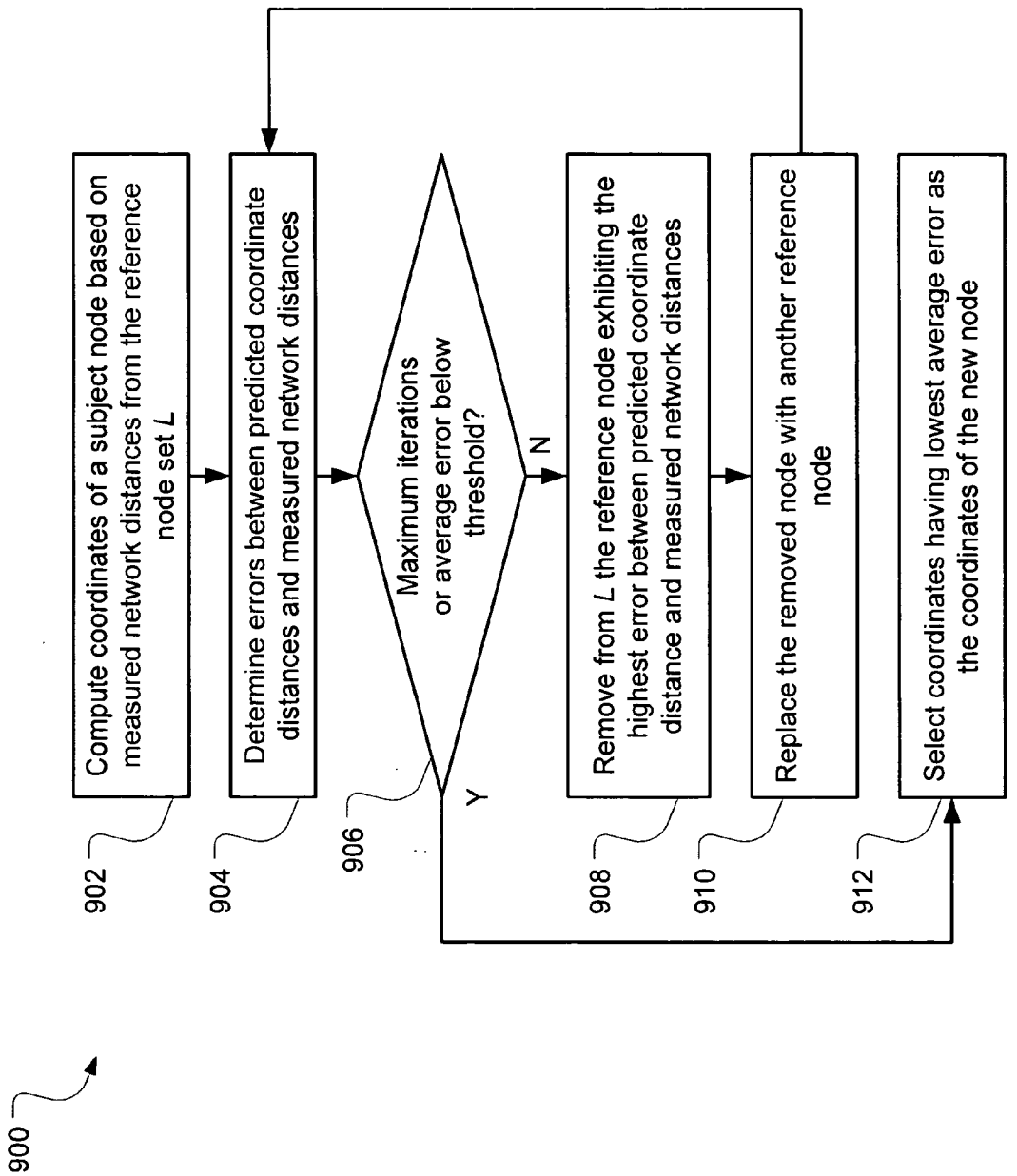

900
902
Compute coordinates of a subject node based on measured network distances from the reference node set L
904
Determine errors between predicted coordinate distances and measured network distances
906
Maximum iterations or average error below threshold?
Y
N
908
Remove from L the reference node exhibiting the highest error between predicted coordinate distance and measured network distances
910
Replace the removed node with another reference node
912
Select coordinates having lowest average error as the coordinates of the new node

FIG. 9

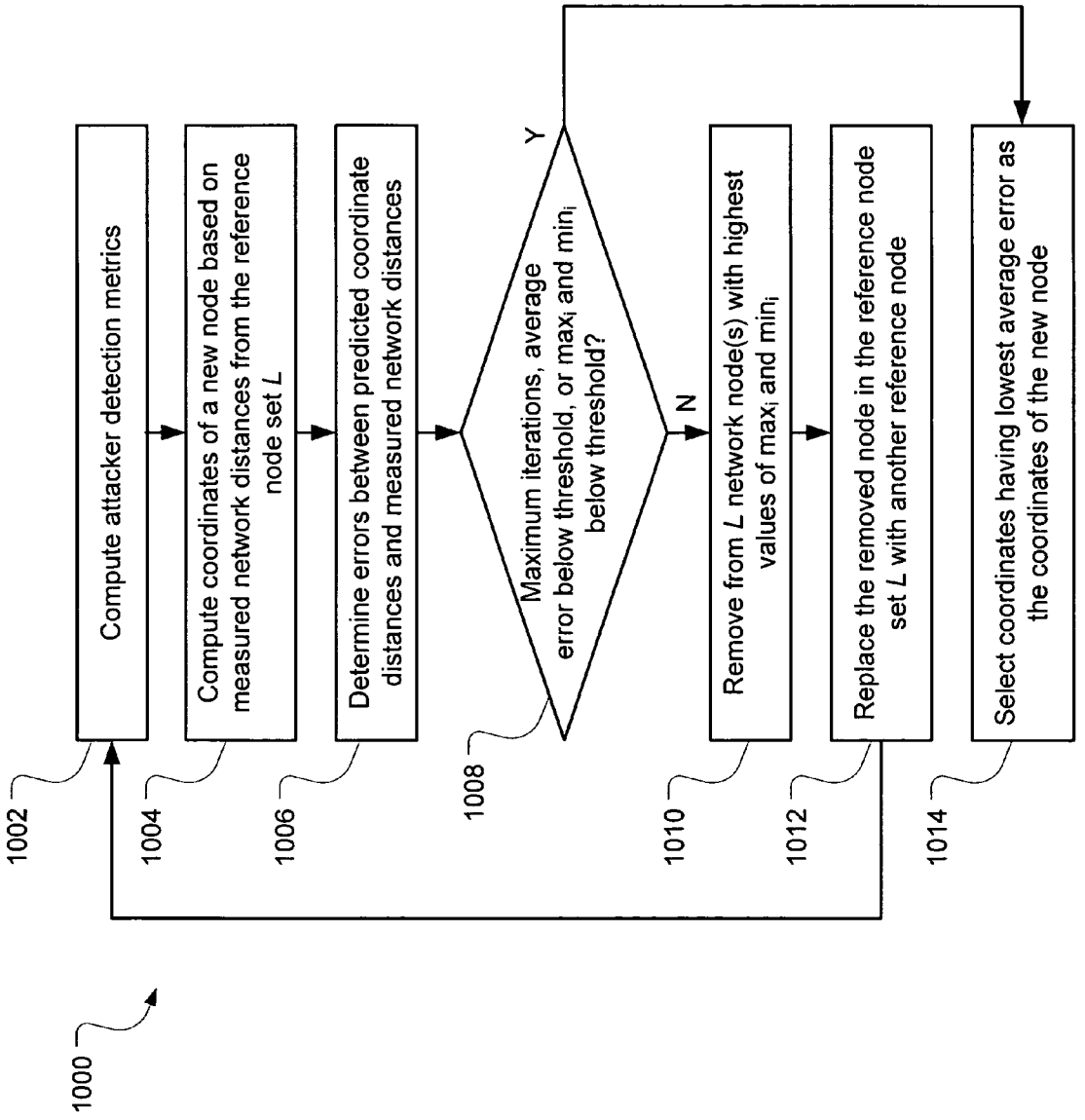
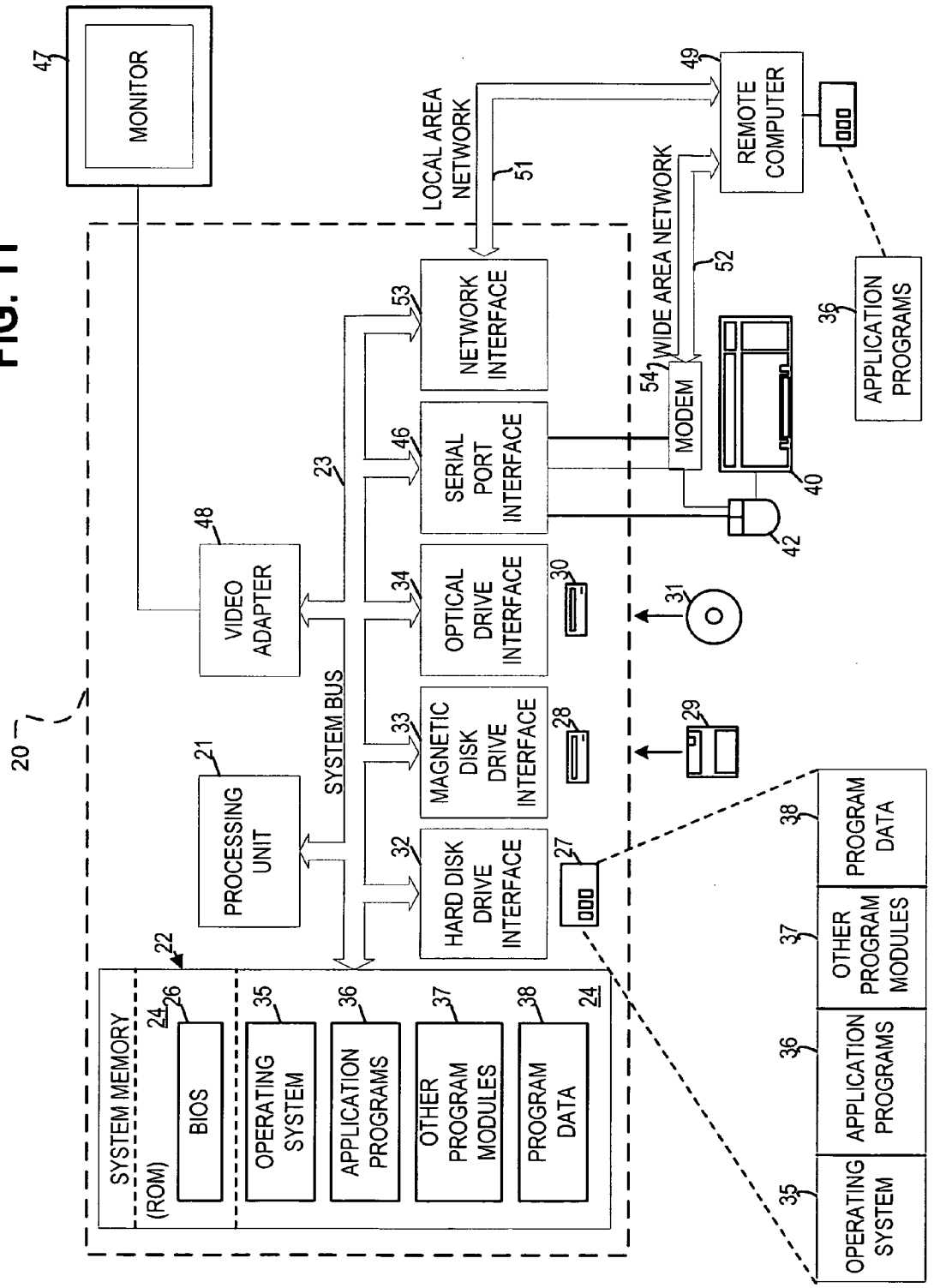

1000
1002
Compute attacker detection metrics
1004
Compute coordinates of a new node based on measured network distances from the reference node set L
1006
Determine errors between predicted coordinate distances and measured network distances
1008
Maximum iterations, average error below threshold, or max_i and min_i below threshold?
Y
N
1010
Remove from L network node(s) with highest values of max_i and min_i
1012
Replace the removed node in the reference node set L with another reference node
1014
Select coordinates having lowest average error as the coordinates of the new node

FIG. 10

FIG. 11


MONITOR
47
LOCAL AREA NETWORK
51
REMOTE COMPUTER
49
WIDE AREA NETWORK
52
APPLICATION PROGRAMS
36
NETWORK INTERFACE
53
SERIAL PORT INTERFACE
46
MODEM
54
40
42
VIDEO ADAPTER
48
OPTICAL DRIVE INTERFACE
34
30
31
MAGNETIC DISK DRIVE INTERFACE
33
28
29
HARD DISK DRIVE INTERFACE
32
27
PROCESSING UNIT
21
SYSTEM BUS
23
20
SYSTEM MEMORY (ROM)
22
BIOS
24
26
OPERATING SYSTEM
35
APPLICATION PROGRAMS
36
OTHER PROGRAM MODULES
37
PROGRAM DATA
38
24
PROGRAM DATA
38
OTHER PROGRAM MODULES
37
APPLICATION PROGRAMS
36
OPERATING SYSTEM
35

PARACTICAL NETWORK NODE COORDINATE ESTIMATION

RELATED APPLICATIONS

[0001] This application is a continuation of U.S. patent application Ser. No. 10/454,411, filed Jun. 4, 2003, titled "Practical Network Node Coordinate Estimation, which claims the benefit of U.S. Provisional Application No. 60/431,470, filed Dec. 6, 2002 and titled "Peer-to-Peer Network Distance Estimation", each of which is hereby incorporated herein by reference.

TECHNICAL FIELD

[0002] The invention relates generally to communication networks, and more particularly to estimating coordinates of a node in a network.

DESCRIPTION

[0003] In many network or distributed applications, it is helpful to determine the network distance between two different network nodes. Generally, there are several ways to define a network distance, including without limitation a round-trip delay, a bandwidth characteristic, and/or a number of hops among intermediate nodes to reach the destination. Knowledge of a network distance between two nodes may be used, for example, when building a peer-to-peer network overlay. In addition, peer-to-peer applications, such as file sharing, can benefit greatly from using overlays that are optimized using estimated network distances between source and destination nodes.

[0004] However, existing approaches for measuring network distances require a dedicated infrastructure of landmark nodes within the network or an excessive amount of communication (e.g. "pings" or "probes") to determine the network distance between two nodes. Moreover, neither of these existing approaches scales well as the network changes and churns.

[0005] Implementations described and claimed herein solve the discussed problems by assigning a point in a coordinate space (e.g., a metric or topological space) to nodes in a network. A measured network distance may be measured (e.g., by measuring round trip time) between a subject network node and another node that already has designated coordinates. By considering the network distance error between the measured network distance and a predicted coordinate distance, the estimated coordinates of a subject network node can be refined to the point of acceptable accuracy. The assignment of coordinates in the coordinate space to such nodes thereby allows the computation of predicted coordinate distances between two network nodes based on the estimated coordinates of each node.

[0006] In a d-dimensional coordinate space, optimizing the estimated coordinates of the subject network node using the provided coordinates of at least d+1 reference nodes can yield a substantially accurate estimate of the subject node's coordinates. For these estimated coordinates, the coordinate distance between two points (e.g., corresponding to network nodes) in the space may be computed as a prediction of the network distance between the two nodes. Furthermore, such coordinate-based estimation lends itself to security precautions to protect against malicious reference nodes or external interference.

[0007] In various implementations, articles of manufacture are provided as computer program products. One implementation of a computer program product provides a computer program storage medium readable by a computer system and encoding a computer program that estimates network node coordinates. Another implementation of a computer program product may be provided in a computer data signal embodied in a carrier wave by a computing system and encoding the computer program that estimates network node coordinates.

[0008] The computer program product encodes a computer program for executing on a computer system a computer process for estimating network node coordinates. Measured network distances are measured between a subject node and each reference node of a plurality of reference nodes selected from a network. At least one reference node is randomly selected from the network. Each reference node is designated by coordinates in a coordinate space. Coordinates in the coordinate space are computed for the subject node based on the measured network distances and the coordinates for each of the reference nodes.

[0009] In another implementation, a method of estimating network node coordinates is provided. Measured network distances are measured between a subject node and each reference node of a plurality of reference nodes selected from a network. At least one reference node is randomly selected from the network. Each reference node is designated by coordinates in a coordinate space. Coordinates in the coordinate space are computed for the subject node based on the measured network distances and the coordinates for each of the reference nodes.

[0010] In yet another implementation, a system for estimating network node coordinates is provided. A network distance module measures measured network distances between a subject node and each reference node of a plurality of reference nodes selected from a network. At least one reference node is randomly selected from the network. Each reference node is designated by coordinates in a coordinate space. A coordinate estimation module computes coordinates in the coordinate space for the subject node based on the measured network distances and the coordinates for each of the reference nodes.

[0011] Other implementations are described and claimed herein.

[0012] Brief descriptions of the drawings included herein are listed below.

[0013] **FIG. 1** illustrates a schematic of an exemplary network.

[0014] **FIG. 2** illustrates operations for an exemplary method of estimating network node coordinates.

[0015] **FIG. 3** illustrates four reference nodes randomly selected within a network and mapped into a 3-dimensional coordinate space.

[0016] **FIG. 4** illustrates a subject node at a tentative location based on a measured network distance from one of the four reference nodes.

[0017] **FIG. 5** illustrates a subject node at a tentative location based on a measured network distance from another one of the four reference nodes.

[0018] **FIG. 6** illustrates a subject node at a tentative location based on a measured network distance from yet another one of the four reference nodes.

[0019] **FIG. 7** illustrates a subject node at a tentative location based on a measured network distance from yet another one of the four reference nodes.

[0020] **FIG. 8** illustrates a subject node at a predicted location based on the measured network distances from each of the four reference nodes.

[0021] **FIG. 9** illustrates operations of an exemplary secure network node coordinate estimation process.

[0022] **FIG. 10** illustrates operations of another exemplary secure network node coordinate estimation process.

[0023] **FIG. 11** illustrates an exemplary system useful for implementing an embodiment of the present invention.

[0024] A measure of "network distance" is useful in many applications, including distributed content hosting servers, content addressable overlay networks and peer-to-peer file sharing. For example, if a first network node attempts to download streaming video, it is likely that the best performance may be obtained from the nearest network node that is capable of providing that streaming video.

[0025] To estimate a network distance between a source and destination node, one or more nodes in a network may be characterized as points in a coordinate space (e.g., a d-dimensional Euclidean space) using multidimensional scaling techniques, such that estimated coordinates are assigned to each network node. Accordingly, because the network nodes can be mapped into this coordinate space, a coordinate distance between two points (e.g., nodes) in the space may also be used as an estimate of the corresponding network distance.

[0026] The number of dimensions d required to adequately represent the substantially accurate network distances depends on the problem space. In general, the higher the number of dimensions, the greater the accuracy of the mapping, but the more cumbersome the mapping. However, beyond a certain point, there is typically a point of diminishing returns, where adding extra dimensions adds little to the prediction accuracy.

[0027] The number of dimensions may be chosen in advance or may be chosen automatically by the insertion algorithm that inserts a subject network node into the set of network nodes having designated coordinates. Such network nodes are called "positioned nodes". Informally, the number of dimensions is related to the dimensions of the distance matrix. That is, if the distance matrix is a "true" distance matrix, such that all distances satisfy the triangle inequality, then the number of dimensions d is the (matrix) rank of the transform of the distance matrix. In typical scenarios, d may be of the order of about 10, although no formal minimum or maximum has been set. Empirical data has shown good accuracy estimation for $d \geqq 8$ and little benefit for $d \geqq 12$, although dimensions outside this range are contemplated.

[0028] **FIG. 1** illustrates a schematic of an exemplary network **100**. Network nodes, such as a node **102**, represent hardware and/or software logically interconnected with other network nodes. The network nodes support a shared set of protocols to allow communications among each of the network nodes. The exemplary network **100** may represent a large network, such as the Internet, in which each network node is logically part of the network and can participate in the network communications as a source, a destination, or an intermediary. It should be understood, however, that a particular size is not a specific constraint of the illustrated network **100**.

[0029] Selected network nodes, referred to as "positioned nodes" in the network **100**, have been designated with coordinates in the coordinate space. A source network node originates transmission of a message through the network toward a destination node. In addition, for some messages, an intermediary node can receive the message and forward it toward the destination node. For example, if the source node **102** transmits a message to a destination node **104**, the message may physically pass through intermediary nodes **106** and **108**. Alternatively, the message may pass through a different network path, such as through intermediary nodes **106**, **110**, and **112**, to arrive at the destination node **104**. Which of these different paths are used for communication of a given message between source and destination nodes may be influenced by various characteristics of the network, including without limitation the available bandwidth between the various nodes, the routing algorithm at each node, and the load being experienced at each node.

[0030] It should be understood that the network distances between given network nodes can change, such as with the insertion of a new node to the network or the removal of a node from the network. Furthermore, other events can impact network distance between nodes, such as loss or addition of other network segments, significant changes in network bandwidth in certain segments, etc.

[0031] It should also be understood that, in various application, it may be useful for a given network node to determine the network distance between it and another network node, such as to determine the nearest network node capable of providing desired streaming data. Likewise, it may also be useful for a given network node to determine the network distance between any two other network nodes, such as to develop a peer-to-peer network overlay. By estimating network node coordinates as described herein, estimated network distances between any two positioned nodes may be calculated from the coordinates of the nodes.

[0032] **FIG. 2** illustrates operations for an exemplary method **200** of estimating node coordinates. In an initiating operation **202**, a new node n initiates the process of joining a set of P positioned nodes. For example, the new node n may determine that it needs designated coordinates to service an application or to participate in a given network operation, such as building a peer-to-peer overlay. A node attempting to join the set of P positioned nodes is referred to as a "subject node".

[0033] A coordinate operation **204** determines the coordinates of a subset of L reference nodes within the set of P positioned nodes. If the coordinate space is a d-dimensional space, then the subset of reference nodes has size $L \geqq d+1$. The selection of which reference nodes are included in this subset L may be made entirely or partially at random within the set P of positioned nodes. That is, it is unnecessary to determine the coordinates and/or identifications of special predefined landmark nodes. Likewise, it is unnecessary to "ping" or probe a great multitude of network nodes in order

to determine the members of the subset L. Furthermore, various exemplary modes for selecting the members of the subset L—random, close, and hybrid—are described later in this description.

[0034] In one implementation, the coordinates of these reference nodes have been previously estimated and stored in a storage location from which they can be transmitted to the subject node n or to any other node that is capable of performing the network node coordinate estimation process. For example, the subject node can perform the entire computation or another node can perform the computation in cooperation with the subject node. In an alternative implementation, the coordinates of these positioned nodes may be previously or dynamically computed in accordance with the method described herein or using any coordinate designation method. Generally, the selection of which positioned nodes are included in the set of reference nodes for any given subject node maintains some form of randomness.

[0035] A network distance operation **206** measures the network distances between the subject node and each of the reference nodes in L. In one implementation, the round-trip delay time may be determined to represent network distance using an average of ICMP (Internet Control Message Protocol) ping response times, although other methods of measuring network distance may be employed, including measuring round-trip delay using application-level probes, counting hops between the source and destination nodes using network or operating system utilities (such as traceroute, which gives the path from the source to the destination), making a determination of network congestion along the segments connecting the source and destination nodes, measuring the bandwidth between the source and the destination nodes using inference from probes, such as packet pair, etc. The distance itself could also be multidimensional, for example, representing both delay and number of hops, etc.

[0036] A coordinate estimating operation **208** computes the coordinates of the subject node based on the measured network distances between the subject node and each of the reference nodes. In one implementation, a multi-dimensional global optimization algorithm (such as simplex downhill, controlled random search, simulated annealing, etc.) is performed to compute the coordinates for the subject node.

[0037] The optimization algorithm starts with an initial prediction of the coordinates of the subject node. In various implementations, this initial prediction may be random, may be based on previous estimates (e.g., for nodes having their coordinates re-estimated), may be part of the algorithm used to calculate the coordinates, etc. Coordinate distances are computed between the initial prediction of the subject node's coordinates and the coordinates of each of the reference nodes. Thereafter, the errors between the measured network distances (determined in measuring operation **206**) and the computed coordinate distances are then calculated. The errors may be represented by various target error functions, including without limitation the sum of squares relative errors:

$$\varepsilon = \sum_{i=1}^{|L|} \left(\frac{(d_i^m - d_i^p)}{d_i^m} \right)^2 \quad (1)$$

[0038] where d_i^m represents the distance measured between the subject node and the i^{th} node in L and d_i^p represents the coordinate distance (i.e., the predicted coordinate distance) computed between the predicted coordinates of the subject node and the coordinates of the i^{th} node in L.

[0039] After this first pass, the optimization algorithm determines a new prediction of the subject node coordinates, based on the specific characteristics of the chosen optimization algorithm. New coordinate distances are computed based on these new predicted coordinates, and the errors between the measured network distances and the newly computed coordinate distances are re-calculated. The optimization algorithm iterates to find the optimal coordinates of the subject node that minimize the error between the measured network distances and the computed coordinate distances.

[0040] It should be understood that other methods of computing the subject node coordinates, including using geometric properties of the space to affect the calculation, are also contemplated. Eventually, the error between the measured network distances and the computed coordinate distances decreases within an acceptable range, such that the final predicted coordinates are deemed the estimated coordinates of the subject node.

[0041] A network distance estimation operation **210** computes the coordinate distance between the subject node and any other network node that has already had its coordinates determined, based on the coordinates of the subject node and the coordinates of the other node. The computed coordinate distance is deemed the estimated network distance between the two nodes. The nature of the computed coordinate distance depends on the network distance measure or metric associated with the d dimensional space. For example, in the case that the d dimensional space is Euclidean, the natural Euclidean distance may be used, namely, the square root of the sum of the squared differences of the d coordinates of the two nodes.

[0042] **FIG. 3** illustrates four reference nodes randomly (or partially randomly) selected within a network and mapped into a 3-dimensional coordinate space **300**. It should be understood that a coordinate space with greater or fewer than three dimensions is also contemplated. In one implementation, for example, an 8-dimensional coordinate space is employed. However, a 3-dimensional coordinate space **300** is illustrated to clearly illustrate the principle.

[0043] The illustrated coordinate space **300** is defined by three axes **302**. The reference nodes **304**, **306**, **308**, and **310** are selected and are defined as having coordinates locating them at the illustrated locations in the coordinate space **300**.

[0044] **FIG. 4** illustrates a subject node at a tentative location based on a measured network distance from one of the four reference nodes. The 3-dimensional coordinate space **400** is illustrated as described in **FIG. 3**, with three

axes **402** and four reference nodes **404**, **406**, **408**, and **410**. The network distance between the subject node **412** and the reference node **410** is measured, such as using an average of ICMP ping response times or probe results. The determined network distance represents a radius **414** around the reference node **410** in the 3-dimensional coordinate space **400**.

[**0045**] **FIG. 5** illustrates a subject node at a tentative location based on a measured network distance from another one of the four reference nodes. The 3-dimensional coordinate space **500** is illustrated as described in **FIG. 3**, with three axes **502** and four reference nodes **504**, **506**, **508**, and **510**. The network distance between the subject node **512** and the reference node **508** is measured. The determined network distance represents a radius **514** around the reference node **508** in the 3-dimensional coordinate space **500**.

[**0046**] **FIG. 6** illustrates a subject node at a tentative location based on a measured network distance from yet another one of the four reference nodes. The 3-dimensional coordinate space **600** is illustrated as described in **FIG. 3**, with three axes **602** and four reference nodes **604**, **606**, **608**, and **610**. The network distance between the subject node **612** and the reference node **604** is measured. The determined network distance represents a radius **614** around the reference node **604** in the 3-dimensional coordinate space **600**.

[**0047**] **FIG. 7** illustrates a subject node at a tentative location based on a measured network distance from yet another one of the four reference nodes. The 3-dimensional coordinate space **700** is illustrated as described in **FIG. 3**, with three axes **702** and four reference nodes **704**, **706**, **708**, and **710**. The network distance between the subject node **712** and the reference node **706** is measured. The determined network distance represents a radius **714** around the reference node **706** in the 3-dimensional coordinate space **700**.

[**0048**] **FIG. 8** illustrates a subject node at a predicted location based on the measured network distances from each of the four reference nodes. The 3-dimensional coordinate space **800** is illustrated as described in **FIG. 3**, with three axes **802** and four reference nodes **804**, **806**, **808**, and **810**. In addition, a coordinate estimation module has estimated the coordinates of the subject node **812** based on the measured distances **814**, **816**, **818**, and **820** between the subject node and each of the reference nodes **804**, **806**, **808**, and **810**. It can be seen in **FIG. 8** that four (or more) reference nodes **804**, **806**, **808** and **810** may not define a unique intersection point (e.g., note that the endpoints of the measured distances **814**, **816**, **818**, and **820** do not all intersect at a unique point but merely approximate such a point). That is, in a coordinate space of arbitrary dimensionality d, for example, at least d+1 reference nodes and their associated distances from the subject node may not necessarily define a unique point for the subject node in the d-dimension coordinate space. As such, the described method provides an estimate of a best fit point for the coordinates of the subject node in the d-dimension coordinate space, such as by minimizing the differences between (1) the measured network distances between the subject node **812** and each reference node, and (2) the computed network distances between the subject node **812** and each reference node, based on estimated coordinates of these nodes. In addition, given these coordinates and the coordinates of any other positioned node, the coordinate distance between the subject node and any other positioned node may be computed by the estimated coordinate network distance between the two nodes.

[**0049**] It should be understood that the forgoing descriptions associated with **FIGS. 4, 5, 6, 7** and **8** are exemplary in nature, particularly with regard to the selection of a 3-dimensional coordinate space. It should also be understood the geometric description of **FIGS. 4, 5, 6, 7**, and **8** illustrates how the subject node relates to the reference nodes in the d-dimension coordinate space, not necessarily how the algorithm estimates the coordinates of the subject node.

[**0050**] The selection of the reference nodes within the set of positioned nodes may involve a variety of selection modes. Three exemplary selection modes that use coordinates of randomly selected reference nodes are described below:

[**0051**] (1) Random —Any positioned node that is capable of providing its coordinates in the coordinate space (or having those coordinates provided for it) may be randomly selected as a reference node for inclusion in the subset L.

[**0052**] (2) Close —Any positioned node that is close to the subject node, according to some distance function (examples include, but are not limited to, geographic distance, network delay and network bandwidth) may be selected as a reference node for inclusion in the subset L. Several algorithms can be used to discover close nodes, some algorithms are described below (3) Hybrid—A subset L of positioned nodes are selected such that L includes one or more randomly selected positioned nodes and some reference nodes that are close to the subject node. In this case, $L=L_{random}+L_{close}$ (the union of one or more reference nodes selected according to the Random selection mode (L_{random}) and one or more reference nodes selected according to the Close selection mode (L_{close}).

[**0053**] In the Close and Hybrid selection modes discussed above, several algorithms may be used to discover nodes close to the subject node. One algorithm for finding nodes close to the subject node uses expanding ring IP multicast messages to ask close nodes to announce their presence. Another algorithm employs a physical link attachment (for example, but not limited to, wired communication links and wireless communication links) to contact close nodes.

[**0054**] Yet another algorithm uses successive coordinate refinements to find close nodes. In this algorithm, after an initial estimation of the subject node's coordinates using the random selection, for example, the coordinates of the subject node and the coordinates of the other positioned nodes are used to find nodes close to the subject node by computing its predicted distances to the other positioned nodes. This operation can be repeated several times by restarting it with a new set of reference nodes L_{close}, such that the size of $L_{close} \geqq d+1$ and L_{close} includes the positioned nodes that are predicted to be close (e.g., within a threshold distance or within a given distance range) to the subject node.

[**0055**] One particular algorithm, based on successive refinement of coordinates, proceeds as follows:

[**0056**] 1. Each network node in the network maintains a record of a set of positioned nodes, called set N.

[0057] 2. The subject node performs an initial estimation of its coordinates using a random selection mode or some other selection mode.

[0058] 3. The subject node keeps a set K of known nodes, initialized with L and a set P of probed nodes, also initialized with L.

[0059] 4. Thereafter the subject node sends its estimated coordinates to the closest node in set P, and the node that receives the coordinates replies with a set of M nodes selected from N, wherein the set of M nodes are the closest to the subject node according to the estimated distances.

[0060] 5. Upon receiving the reply, the subject node adds the M returned nodes to set K and probes the network distance to a subset of the M returned nodes (the subset can be selected based on a number of criteria, for instance the predicted closest), adds the probed nodes to P and re-computes its coordinates based on the distances and coordinates of nodes in P.

[0061] 6. Steps **4** and **5** are repeated while the closest node in set P was not yet contacted.

[0062] 7. Thereafter, the subject node can optionally further probe distances to a subset of the predicted closest nodes in set K, add the probed nodes to set P, and re-compute its coordinates.

[0063] 8. The subject node can optionally repeat this process, starting from a node picked randomly from set K.

[0064] 9. The output from this algorithm is a subset $L_{closest}$ of set P that contains the X nodes of P that are closest to the subject node.

[0065] It should be noted that malicious nodes may introduce security problems by lying about their coordinates or interfere with distance measurements. However, the described system can ensure that distances are predicted accurately, despite the possible involvement of such malicious nodes. Because the estimation process can utilize more than d+1 reference nodes and because one or more of the nodes may be randomly chosen, it is possible to isolate and omit presumably maliciously introduced data. A security module utilizing the measured and coordinate distances may enhance the security and accuracy of the coordinate and distance estimations.

[0066] **FIG. 9** illustrates operations of an exemplary secure coordinate estimation process **900**. A coordinate estimation operation **902** computes the coordinates of a subject node based on measured network distances between the subject node and the reference nodes in the subset L, such as by using the process described with regard to **FIG. 2**. A determining operation **904** calculates the errors between the predicted coordinate distances (i.e., the distances calculated based on the coordinates of the new node and the coordinates of the reference nodes) and the measured network distances.

[0067] A decision operation **906** determines whether the number of iterations in this security process has exceed a given iteration threshold or whether the average network distance error (as computed in determining operation **904** for this iteration) is below a given network distance error threshold. If so, processing proceeds to a selection operation **912**. Otherwise, a removal operation **908** removes from the network subset L the reference node exhibiting the highest error between the predicted coordinate distance and the measured network distance. This reference node is presumed to be malicious.

[0068] A replacement operation **910** replaces the removed node with another reference node, selected from the network. The new reference node may be selected randomly or based on a constraint. For example, referring to the description of the random, close, and hybrid modes, if the removed node was from the subset L_{random}, then the new reference node is selected randomly. Likewise, if the removed node was from the subset L_{close}, then another close unused reference node is selected as the new reference node in the subset L. Processing then loops back to the coordinate estimation operation **902** using the newly modified subset L

[0069] In an alternative embodiment, the replacement operation **910** may be omitted. For example, if enough (i.e., $\geqq$d+1) reference nodes remain after removing the malicious node, the coordinates of the subject node may be estimated using the remaining nodes.

[0070] The selection operation **912** selects the coordinates (computed in coordinate estimation operation **902** over all iterations) having the lowest average error as the coordinates of the new node. If the decision operation **906** terminates the loop based on the average error being below the network distance error threshold, then the final estimated coordinates will have been generated in the last iteration. If the decision operation **906** terminates the loop based on the number of iterations, then any previous iteration may have generated the lowest network distance error; therefore, the coordinates yielding the lowest error from any iteration are selected.

[0071] **FIG. 10** illustrates operations of another exemplary secure coordinate estimation process **1000**. A metric computation operation **1002** computes attacker detection metrics for each reference node in the subset L. Although various metrics may be employed for this process, algorithms for computing exemplary attached detection metrics are listed below:

$$\max_i = \sum_{j=1}^{|L|} \begin{cases} d^m_{g,i} - (d^m_{g,j} + d^P_{i,j}) & \text{if } (d^m_{g,j} + d^P_{i,j}) < d^m_{g,i} \\ 0 & \text{otherwise} \end{cases} \quad (2)$$

$$\min_i = \sum_{j=1}^{|L|} \begin{cases} |d^m_{g,j} - d^P_{i,j}| - d^m_{g,i} & \text{if } |d^m_{g,j} - d^P_{i,j}| > d^m_{g,i} \\ 0 & \text{otherwise} \end{cases} \quad (3)$$

[0072] where $d_{g,i}^m$ represents the measured distance between the subject node g and the i^{th} reference node in L, and $d_{i,j}^P$; represents the predicted coordinate distance computed between the i^{th} and j^{th} reference nodes in L. These metrics compute deviations from upper and lower bounds derived from triangular inequality relations.

[0073] A coordinate estimation operation **1004** computes the coordinates of a subject node based on measured network distances between the subject node and the reference nodes in the subset L, such as by using the process described with regard to **FIG. 2**. A determining operation **1006** calculates the errors between the predicted coordinate distances

(i.e., the distances calculated based on the coordinates of the new node and the coordinates of the reference nodes) and the measured network distances.

[0074] A decision operation **1008** determines whether the number of iterations in this secure process has exceed a given iteration threshold, whether the average network distance error (as computed in determining operation **1006** for this iteration) is below a given network distance error threshold, or whether maxi and mini are below one or more attacker detection metric thresholds. If not, processing continues to a removal operation **1002** to create a modified subset L. Otherwise, a selection operation **1014** selects the coordinates (computed in computing operation **1004** over all iterations) having the lowest average error as the coordinates of the new node. If the decision operation **1008** terminates the loop based on the average error being below the network distance error threshold or the maxi and $\min_i$ values being below the one or more attacker detection metric thresholds, then the final coordinates will have been generated in the last iteration. If the decision operations **1008** terminates the loop based on the number of iterations, then any previous iteration may have generated the lowest error; therefore, the coordinates yielding the lowest error from any iteration are selected.

[0075] The removal operation **1010** removes from L the reference node(s) having the highest values of $\max_i$ and $\min_i$. Note that more than one node having the highest value of maxi and more than one node having the highest value of mini may be removed. A replacement operation **1012** replaces the removed node with another reference node. Under at least the same circumstances as previously discussed with regard to replacement operation **910** in **FIG. 9**, the replacement operation **1012** may be omitted. The new reference node may be selected randomly or based on a constraint. For example, referring to the description of the random, close, and hybrid modes, if the removed node was from the subset L_{random}, then the new reference node is selected randomly. Likewise, if the removed node was from the subset L_{close}, then another close unused reference node is selected as the new reference node.

[0076] As noted herein, estimated coordinates of nodes within the network may be dynamically refined (e.g., re-estimated) as conditions in the network change. In some implementations, refinement of node coordinates may be accomplished by rerunning the estimation process using the original members of the subset L, with new reference nodes being added to the original members of the subset L, with new reference nodes replacing some or all of the original members of the subset L, or any combination thereof. Triggers for such refinements may include without limitation a time-based trigger (e.g., based on the time since the coordinates were last calculated), a trigger based on inclusion of the given node in another subject node's subset L, detection of a new node in the network (e.g., a new node may broadcast its arrival to the other nodes in the network or to some dedicated "sentry" node) or a commanded trigger (e.g., when told to do so by another network node).

[0077] Refinement of coordinates may or may not be synchronized between network nodes. Synchronized refinement may correspond to any trigger event, including without limitation a trigger command relating to the subset L or some subset thereof.

[0078] A measure of network distance may violate triangular inequality, particularly when defined in reference to the round-trip delay between source and destination nodes. Likewise, network distance may be multi-dimensional, for example, representing both bandwidth and delay. Nevertheless the method described herein may still be applied with suitable adaptation, such as:

[0079] (1) by combining the measures into a single dissimilarity measure that represents the network distance; or

[0080] (2) by using weight vectors which weight the coordinates, as in Individual Difference Scaling—i.e., in a d-dimensional space, where x_i represents the d-vector of coordinates for a positioned node i, the k^{th} dissimilarity measure of the network distance d_{ij} between overlay nodes i and j is approximated by

$$d_{ij}^{k} \approx \sqrt{\sum_{m=1}^{d} w_{km}(x_{im} - x_{jm})^2}\,. \tag{4}$$

[0081] The exemplary hardware and operating environment of **FIG. 11** for implementing the invention includes a general purpose computing device in the form of a computer **20**, including a processing unit **21**, a system memory **22**, and a system bus **23** that operatively couples various system components include the system memory to the processing unit **21**. There may be only one or there may be more than one processing unit **21**, such that the processor of computer **20** comprises a single central-processing unit (CPU), or a plurality of processing units, commonly referred to as a parallel processing environment. The computer **20** may be a conventional computer, a distributed computer, or any other type of computer; the invention is not so limited.

[0082] The system bus **23** may be any of several types of bus structures including a memory bus or memory controller, a peripheral bus, and a local bus using any of a variety of bus architectures. The system memory may also be referred to as simply the memory, and includes read only memory (ROM) **24** and random access memory (RAM) **25**. A basic input/output system (BIOS) **26**, containing the basic routines that help to transfer information between elements within the computer **20**, such as during start-up, is stored in ROM **24**. The computer **20** further includes a hard disk drive **27** for reading from and writing to a hard disk, not shown, a magnetic disk drive **28** for reading from or writing to a removable magnetic disk **29**, and an optical disk drive **30** for reading from or writing to a removable optical disk **31** such as a CD ROM or other optical media.

[0083] The hard disk drive **27**, magnetic disk drive **28**, and optical disk drive **30** are connected to the system bus **23** by a hard disk drive interface **32**, a magnetic disk drive interface **33**, and an optical disk drive interface **34**, respectively. The drives and their associated computer-readable media provide nonvolatile storage of computer-readable instructions, data structures, program modules and other data for the computer **20**. It should be appreciated by those skilled in the art that any type of computer-readable media which can store data that is accessible by a computer, such as magnetic cassettes, flash memory cards, digital video disks, Bernoulli

cartridges, random access memories (RAMs), read only memories (ROMs), and the like, may be used in the exemplary operating environment.

[0084] A number of program modules may be stored on the hard disk, magnetic disk **29**, optical disk **31**, ROM **24**, or RAM **25**, including an operating system **35**, one or more application programs **36**, other program modules **37**, and program data **38**. A user may enter commands and information into the personal computer **20** through input devices such as a keyboard **40** and pointing device **42**. Other input devices (not shown) may include a microphone, joystick, game pad, satellite dish, scanner, or the like. These and other input devices are often connected to the processing unit **21** through a serial port interface **46** that is coupled to the system bus, but may be connected by other interfaces, such as a parallel port, game port, or a universal serial bus (USB). A monitor **47** or other type of display device is also connected to the system bus **23** via an interface, such as a video adapter **48**. In addition to the monitor, computers typically include other peripheral output devices (not shown), such as speakers and printers.

[0085] The computer **20** may operate in a networked environment using logical connections to one or more remote computers, such as remote computer **49**. These logical connections are achieved by a communication device coupled to or a part of the computer **20**; the invention is not limited to a particular type of communications device. The remote computer **49** may be another computer, a server, a router, a network PC, a client, a peer device or other common network nodes, and typically includes many or all of the elements described above relative to the computer **20**, although only a memory storage device **50** has been illustrated in **FIG. 11**. The logical connections depicted in **FIG. 11** include a local-area network (LAN) **51** and a wide-area network (WAN) **52**. Such networking environments are commonplace in office networks, enterprise-wide computer networks, intranets and the Internal, which are all types of networks.

[0086] When used in a LAN-networking environment, the computer **20** is connected to the local network **51** through a network interface or adapter **53**, which is one type of communications device. When used in a WAN-networking environment, the computer **20** typically includes a modem **54**, a type of communications device, or any other type of communications device for establishing communications over the wide area network **52**. The modem **54**, which may be internal or external, is connected to the system bus **23** via the serial port interface **46**. In a networked environment, program modules depicted relative to the personal computer **20**, or portions thereof, may be stored in the remote memory storage device. It is appreciated that the network connections shown are exemplary and other means of and communications devices for establishing a communications link between the computers may be used.

[0087] In an exemplary implementation, computation modules, decision modules, selection modules, or other modules may be incorporated as part of the operating system **35**, application programs **36**, or other program modules **37**. The coordinates, thresholds, error values, and distances (both predicted and measured) may be stored as program data **38**.

[0088] The embodiments of the invention described herein are implemented as logical steps in one or more computer systems. The logical operations of the present invention are implemented (1) as a sequence of processor-implemented steps executing in one or more computer systems and (2) as interconnected machine modules within one or more computer systems. The implementation is a matter of choice, dependent on the performance requirements of the computer system implementing the invention. Accordingly, the logical operations making up the embodiments of the invention described herein are referred to variously as operations, steps, objects, or modules.

[0089] The above specification, examples and data provide a complete description of the structure and use of exemplary embodiments of the invention. Since many embodiments of the invention can be made without departing from the spirit and scope of the invention, the invention resides in the claims hereinafter appended.

1. A computer-readable media embodying computer-executable instructions for performing a method comprising:

computing distances between coordinates of a subject node in a network and coordinates of each of a plurality of reference nodes in the network; and

adjusting the coordinates of the subject node based on the computed distances.

2. A computer-readable media as recited in claim 1, wherein one of the reference nodes is selected randomly from a group of nodes in the network.

3. A computer-readable media as recited in claim 1, wherein all of the reference nodes are selected randomly from a group of nodes in the network.

4. A computer-readable media as recited in claim 1, wherein the method further comprises:

measuring distances between the subject node and each of a plurality of reference nodes.

5. A computer-readable media as recited in claim 1, wherein adjusting the coordinates of the subject node based on the determined distances comprises:

measuring distances between the subject node and each of the plurality of reference nodes;

comparing the computed distances and the measured distances; and

adjusting the coordinates of the subject node based on the comparison.

6. A computer-readable media as recited in claim 1, wherein adjusting the coordinates of the subject node based on the determined distances comprises:

measuring distances between the subject node and each of the plurality of reference nodes;

determining errors between the computed distances and the measured distances; and

adjusting the coordinates of the subject node based on the determined errors.

7. A computer-readable media as recited in claim 1, wherein the coordinates of the subject node and the plurality of reference nodes are relative to a coordinate space having greater than three dimensions.

8. A computer-readable media as recited in claim 1, wherein the coordinates of the subject node and the plurality

of reference nodes are relative to a d-dimensional coordinate space and wherein the number of selected nodes is greater than or equal to (d+1).

9. A computer-readable media as recited in claim 1, wherein the coordinates of at least one of the reference nodes is received from the at least one reference node.

10. A computer-readable media as recited in claim 1, wherein the coordinates for at least one of the reference nodes is received from a reference node other than the at least one reference node.

11. A computer-readable media as recited in claim 6, wherein measuring distances between the subject node and each of a plurality of reference nodes includes determining round-trip delay times between the subject node and each of the reference nodes.

12. A computer-readable media as recited in claim 1, wherein the method further comprises:

measuring distances between the subject node and each of the plurality of reference nodes; and

computing an attacker detection metric based on the measured distances.

13. The method of claim 1, wherein the method further comprises:

measuring distances between the subject node and each of the plurality of reference nodes;

computing an attacker detection metric based on the measured distances;

replacing a reference node with a new reference node selected from the network to define a new plurality of reference nodes, the replaced reference node exhibiting a greater attacker detection metric than any other reference node in the plurality of reference nodes;

measuring a distance between the subject node and the new reference node; and computing new coordinates for the subject node based on the measured distances distance between the subject node and the new plurality of reference nodes and coordinates for each reference node of the new plurality of reference nodes.

14. A system comprising:

a network distance module computing distances between coordinates of a subject node in a network and coordinates of each of a plurality of reference nodes in the network; and

a coordinate estimation module adjusting coordinates for the subject node based on the computed distances and the coordinates for each of the reference nodes.

15. The system of claim 14, further comprising:

a network distance estimation module estimating a network distance between the subject node and a positioned node by computing a coordinate distance between the coordinates of the subject node and coordinates of the positioned node.

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