Abstract: A network operating center for a network comprising known-location and unknown-location nodes can be configured to receive from each unknown-location node estimates of the distances from that node to each of its neighbor nodes. The network controller can then choose an initial location estimate for each unknown-location node and compute distances from the initial location estimates to the corresponding neighbor nodes. The network operating center can then choose subsequent location estimates of the unknown-location nodes by minimizing an error criterion based on a comparison of the received neighbor node distance estimates with the computed neighbor node distances.
METHODS AND SYSTEMS FOR LOCATION ESTIMATION

FIELD OF DISCLOSURE

[0001] The field of this disclosure relates to positioning systems and more particularly to methods and systems for estimating the location of a network node based on estimates of the distance between the node and other network nodes of both known and unknown locations.

BACKGROUND

[0002] Networks may include nodes whose locations are known as well as nodes whose locations are unknown. For example, in a wireless communication network, mobile units may comprise nodes in the network. Because these nodes are mobile, they do not remain at a fixed location. Typically, a network operating center maintains information about the locations of the known-location nodes in a database and attempts to maintain up-to-date estimates of the locations of the unknown-location nodes as well. The approach utilized by the network operating center to keep track of the unknown-location nodes can be a function of the nature of the network. For example, certain types of nodes may be able to estimate the distance from itself to a neighbor node. Such information can then be used to help estimate where the node is located at any given time.

[0003] The present subject matter relates to novel approaches to estimating the locations of unknown-location nodes in a network based on estimates of distances from the unknown-location nodes to their neighbor nodes.

SUMMARY

[0004] Embodiments comprise methods and systems of position location estimation in a network comprising known-location and unknown-location nodes.

[0005] In some embodiments, estimates of the distances from an unknown-location node to its neighbor nodes are communicated to a network control center, which uses these distance estimates to estimate the physical location of the unknown-location node.
In some embodiments, methods of estimating the physical location of one or more unknown-location nodes in a network comprising known-location nodes and unknown-location nodes comprise maintaining in a database known locations of the known-location nodes and estimates of locations of the unknown-location nodes; receiving neighbor node distance estimates for each of the one or more unknown-location nodes; choosing an initial location estimate for each of the one or more unknown-location nodes; computing neighbor node distances for each of the one or more unknown-location nodes; and choosing a subsequent location estimate for each of the one or more unknown-location nodes based on a comparison of the neighbor node distance estimates with the computed neighbor node distances.

These illustrative embodiments are mentioned not to limit or define the limits of the present subject matter, but to provide examples to aid understanding hereof. Illustrative embodiments are discussed in the Detailed Description, and further description is provided there. Advantages offered by the various embodiments may be further understood by examining this specification and/or by practicing one or more embodiments of the claimed subject matter.

BRIEF DESCRIPTION OF DRAWINGS

These and other features, aspects, and advantages of the present disclosure are better understood when the following Detailed Description is read with reference to the accompanying drawings, wherein:

Figure 1 illustrates an exemplary system in certain embodiments.
Figure 2 illustrates an exemplary network node in certain embodiments.
Figure 3 is a flowchart illustrating a method according to certain embodiments.
Figure 4 illustrates an exemplary access node in certain embodiments.
Figure 5 illustrates an exemplary network operating center in certain embodiments.
Figure 6 illustrates a concept related to position estimation based on distance estimation.
Detailed embodiments are disclosed herein. However, it is to be understood that the disclosed embodiments are merely exemplary and that different embodiments are possible. The figures are not necessarily to scale, and some features may be exaggerated or minimized to show details of particular components. Therefore, specific structural and functional details disclosed herein are not to be interpreted as limiting, but merely as a basis for the claims and as a representative basis for teaching one skilled in the art to variously employ the present disclosure.

An exemplary embodiment estimates the location of a network node whose location is unknown through use of estimates of the distance from the node to that node's neighbor nodes. Figure 1 illustrates an exemplary network comprising nodes whose positions are known as well as nodes whose positions are unknown. In particular, the node labeled 101 is exemplary of a
node whose position is unknown ("DUP")- In this exemplary network, DUP 101 has neighbor nodes 101, 102, 103, 104, and 105, which comprise both DUPs and nodes whose positions are known ("DKPs"). Thus, in Figure 1, each DUP node 101, 103, 105 may be termed an "unknown-location node" whereas each DKP node 102, 104, 106 may be termed a "known-location node." In addition, this exemplary network includes an access node 110, which comprises a network controller that serves as a gateway between the network nodes and to a network operating center 120.

[0025] In one exemplary embodiment the DKP and DUP network nodes comprise radio nodes. In certain embodiments a radio node comprises a radio frequency ("RF") modem and one or more application-dependent boards, which perform application specific functions, for example data acquisition, information display, power up, etc. Figure 2 provides an illustration of one embodiment of a radio node 200, comprising an input/output ("I/O") board 210 and a radio modem 220. In this illustrative embodiment the I/O board further comprises a signal conditioning unit 211, which couples to a multiplexer ("MUX") 212, which couples to an analog-to-digital ("A/D") converter 213, which in turn couples to a processor unit ("MCU") 214. Further, the I/O board 210 also comprises a digital I/O unit 215 which couples to the MCU 214 and an internal power supply 216, which couples to a power line 217 and battery 218 as well as the MCU 214. The radio modem 220 of exemplary radio node 200 comprises a radio 221 coupled to its own processor unit ("MCU") 222 and memory ("EEPROM") 223. The radio 221 also comprises an antenna 224.

[0026] The radio modem 220 enables the radio node 200 to communicate data bidirectionally with other radio nodes. In particular, a DUP node 101 may estimate the distance between it and its neighbor nodes 102, 103, 104, 105, 106 and report these distance estimates to other network nodes, such as access node 110, which in turn may communicate these distance estimates to the network operating center 120. Methods for estimating the distance between nodes are well-known in the art and include, without limitation, methods utilizing received signal
strength indication ("RSSI"), time of arrival ("TOA"), phase estimation, as well as other known methods or any combination of these methods. DUP node 101 can employ any of these well-known methods to estimate the distances between itself and its neighbor nodes 102, 103, 104, 105, 106 and can communicate these neighbor node distance estimates to network operating center 120 through the network itself, either in specially designed messages or embedded in regular data messages.

[0027] Flowchart 300 of Figure 3 illustrates an approach to obtaining neighbor node distance estimates at DUP node 101 in an exemplary embodiment. The following discussion applies to each neighbor node of a given node, for example neighbor nodes 102, 103, 104, 105, 106 of DUP node 101. At block 301 DUP 101 measures the distance between it and a neighbor node using any known measurement technique utilizing a signal or signals transmitted between the unknown-location node and the neighbor node. Techniques to measure a distance to a neighbor node are well-known and include, without limitation, measurement of a signal strength sent to or received from the neighbor node, measurement of the phase of signal received at the unknown-location node or the neighbor node, and measurement of the time of arrival of a signal sent to or received from a neighbor node. One of ordinary skill in the art would recognize that other distance estimation techniques are available and could be utilized herein. Exemplary techniques for estimating the locations of nodes in a network or the distance to one or more nodes from a given location may be found in U.S. Patent 5,602,903, U.S. Patent 5,883,598, 6,327,474, and 6,473,038, each of which is incorporated herein in its entirety for all purposes.

[0028] Such measurements are repeated over a configurable period of time, e.g., an hour, and at block 302 the measurements collected over that period of time are averaged to obtain a neighbor node distance estimate. Such averaging helps to eliminate false readings and smooth out measurement errors. At decision block 303, DUP node 101 checks whether the elapsed time since the last report of a neighbor node distance estimate exceeds some configurable threshold, e.g. 24 hours, and if so the process branches to block 305 where the neighbor node distance
estimate is reported to network operating center 120. If the elapsed time does not exceed the
threshold, then the process branches to decision block 304, where the neighbor node distance
estimate is then compared to the neighbor node estimate previously reported to network operating
center 120. If the neighbor node distance estimate deviates from the previously reported neighbor
node distance estimate by a configurable percentage or more, the process branches to block 305
where the neighbor node distance estimate is reported to network operating center 120. If the
neighbor node distance estimate does not differ from the previously reported estimate by a
sufficiently large amount, then the node does not report the neighbor node distance estimate to
network operating center 120 and the process branches back to block 301 to resume. Such an
approach saves system resources by eliminating unnecessary communications to network
operating center 120. After a neighbor node distance estimate is reported to network operating
center 120 at block 305, the process branches back to block 301 to resume.

[0029] In certain embodiments, network 100 comprises an access node 110 that comprises a
network controller and serves as a gateway between nodes (e.g. DUPs 101, 103, 105 and DKPs
102, 104, 106) and to network operating center 120. In an exemplary embodiment access node
110 has a known location and comprises an RF modem for communicating with radio nodes and
one or more communication methods for communicating with network operating center 120.
Figure 4 illustrates a access node 400 in an exemplary embodiment comprising a mother board
410 and a communications board 420. Motherboard 410 further comprises power components
401 and 402 directed at AC power and DC power respectively. It further comprises processing
and memory components in the form of a processor 403, flash memory 404, and random access
memory ("RAM") 405. Additionally there is a USB interface 406 and an Ethernet interface 407.
Communication board 420 comprises USB interface 421, GPRS modem 422, a long-haul
communication module 423, an 802.11 interface 424, and an RF modem 425.

[0030] In an exemplary embodiment, network 100 may take the form of an RF mesh network
in which the radio nodes communicate to the access node either directly or through other radio
nodes. The communication paths are built automatically and if they are broken new paths are established automatically. Such a network is self-configuring and self-healing. The radio nodes utilize an RF mesh protocol to form and operate the RF mesh network.

[0031] Access node 110 communicates neighbor node distance estimates for a node to network operating center 120. In certain embodiments, network operating center 120 ("NOC") comprises a collection of applications that allow network management, data acquisition, storing, presenting, and exporting the data, handling events and/or alarms, determining the location of nodes in the network using a location engine, etc. Figure 5 illustrates a network operating center 500 in an exemplary embodiment. Network operating center 500 comprises various managers, such as a communication manager 510, an alert manager 520, a query manager 530, and a database manager 540. Alert manager 520 mediates between alert server 550 and communication manager 510. Query manager 530 mediates between various applications 560 that allow, for example, network management, data acquisition, storage, presentation, and exporting of data, handling of events, alarms. Another application is determining the position of network nodes using location engine 570, which interacts with database 580, which in turn interacts with database manager 540. Communication manager 510 mediates between the various elements of network operating center 500 and access nodes H0a, H0b, . . . , H0n. Location engine 570 comprises a processor 575.

[0032] As discussed above, in a real deployment some devices will be placed in a known position (DKP) and some devices will be mobile or will be placed in an unknown position (DUP). A DUP will communicate with other DKPs or DUPs and will report to the NOC its estimated distance to each neighbor. The NOC maintains a network management database that stores the current status (i.e. DUP or DKP) of each device. Using those distances the NOC will estimate the position of each DUP.

[0033] If the exact distances from a DUP to several DKPs were known precisely, various techniques, for example triangulation, could be used to obtain precise determination of the
location of the DUP. However, in many cases the exact position between a DUP and a DKP cannot be estimated due to measurement or estimation errors. In such a case, the exact location of the DUP may not be determinable. For instance, as illustrated in Figure 6, if a DUP 600 communicates with a single DKP 610 and the estimated distance between DUP 600 and DKP 610 is $d$, the position of DUP 600 could be anywhere on a circle with radius $d$ and its center at DKP 610. The availability of exact distances to three different DKPs, for example, would give rise to three different such circles, whose intersection would precisely determine the location of the DUP. However, if the distance estimation is affected by an error $\varepsilon$, the position of DUP 600 relative to a single DKP 610 could be anywhere on the area delimited by two circles with the radii $D - \varepsilon$ and $D + \varepsilon$ and their centers at DKP 610. The intersections of three such annular regions will not necessarily lead to a precise location for DUP 600.

[0034] To further illustrate the problem associated with distance estimates that may have errors, consider Figure 7. If the distance estimate $D_1$ from DUP 700 to DKP 710 is 1 unit and the distance estimate $D_2$ from DUP 700 and DKP 720 is 2 units, then there is no physical location at which DUP 700 can be placed that satisfies both distance estimates. In this case, the NOC can guess as to the node's location and then compute the distances from that estimated location to the node's neighbors. It can then compare the computed neighbor node distances with the neighbor node distance estimates it received from the node to refine its guess as to the node's location.

[0035] For example, following such a procedure in one embodiment the NOC could estimate the location of DUP 700 as shown in Figure 8 by choosing a location that minimizes the total error $E$ where total error is determined by the following formula:

$$E = \sum_{E=1}^{2} e_i$$  \hspace{1cm} (1),

where
and $d_1$ and $d_2$ are the computed distances between the location that the NOC chooses for DUP 800 and the neighbor nodes whose distances were estimated, in this example DKPs 801, 802 respectively. Where the estimated distance are between a DUP and n neighbor nodes, which may comprise both DKPs and DUPs, as illustrated for example in Figure 9, then equation (1) can be extended to

$$E = \sum_{i=1}^{n} e_i$$

with equation (2) being applicable for $i = 1, \ldots, n$.

[0036] In one exemplary embodiment, the scope of an algorithm for determining a physical location for a DUP is to determine another position for the DUP so that the total error $E$ for the new position is smaller than the $E$ for the old position. For example, in Figure 10 starting from the current estimated position of DUP 1000 and using an error minimization algorithm, total error $E$ can be computed for 4 more possible positions 1010, 1020, 1030, 1040 situated at $0^\circ$, $90^\circ$, $180^\circ$ and $270^\circ$ respectively from the current position of DUP 1000. The distance between the current position and a future position can be chosen, for example, to be a step size $\delta$. In this case it is obvious that the estimated position 1020 situated at $90^\circ$ from the current position of DUP 1000 has a lower value for $E$.

[0037] Referring again to Figure 5, database 580 at network operating center 500 comprises locations of the known-location nodes and location estimates of the unknown-location nodes. Once a DUP reports the estimated neighbor node distances between it and each of its neighbor nodes to network operating center 500, location engine 510 can utilize these neighbor node distance estimates to update the estimated physical location of the DUP in database 580.
Figure 11 presents a flowchart 1100 in an exemplary embodiment for updating the estimated locations of the unknown-location radio nodes based upon the received neighbor node distance estimates for each unknown-location radio node. Starting at block 1110, the location engine 570 chooses initial location estimates for the unknown location nodes. For each unknown location node, location engine 570 then computes neighbor node distances from the estimated location to each of the neighbor nodes, whose locations are stored in database 580. Using these computed neighbor node distances along with the received neighbor node distance estimates, in block 1130 location engine 570 computes the total error according to equations (2) and (3) for each unknown location node. At block 1140 after the total error has been computed for each unknown location node, the unknown neighbor nodes are sorted into an ordered list such that the unknown location node with the largest total error is first, the unknown location node with the second largest total error is second, and so on.

The process of blocks 1120 through 1130 is implemented for each unknown location node in the network. Each iteration of blocks 1120 through 1130 for all unknown location nodes in the network is called an "epoch." After each epoch when the process has branched to block 1150, a stopping criterion is assessed. The stopping criterion may take the form of

1. The largest total error for all unknown location nodes is smaller than a threshold;
2. The total number of epochs exceeds a threshold; or
3. The sum of the total errors for all unknown location errors, termed the "total system error," is less than a threshold.

If the stopping criterion is not satisfied at block 1150, the process branches back to block 1160 where subsequent location estimates for the unknown location nodes are chosen, after which the process resumes at block 1120. If on the other hand the stopping criterion is satisfied at decision block 1150, then at block 1170 the database is updated with the location estimates for the unknown location nodes and the process stops.
The subsequent location estimate is chosen in one embodiment by taking a step of length $\delta$ in a configurable direction away from the previous location estimate.

In another exemplary embodiment, the direction in which the step is taken to obtain a subsequent location estimate may be based on the concept of tension reduction. In this concept, the link between a DUP and one of its neighbors could be interpreted as a string. The bigger the difference is between the reported distance $D$ and the estimated distance $d$, the more tensioned the links will be. The equation that defines the tension is:

$$t = d - D$$

Figure 12 illustrates links under various amounts of tension. In Figure 12(a), the reported distance $D$ and the estimated distance $d$ are equal, so the link has no tension. In figures 12(b) and (c), the reported distance differs from the estimated distance, so the links have tension. In this approach, the location estimate is chosen so as to reduce tension in the links. If the tension $t$ is negative (as in Figure 12(b)), the subsequent location estimate of an unknown location node will be farther away from the neighbor node. Conversely, if $t$ is positive (as in Figure 12(c)) the subsequent location estimate will be closer to the neighbor node. Hence, in Figure 13(a) an example illustrates DUP 1300 with tensioned links to its neighbors 1301, 1302, 1303, 1304, whereas Figure 13(b) illustrates the same example after the location of DUP 1300 has been moved to reduce the tension in the links.

Flowchart 1400 describes the tension reduction approach in general and is essentially the same as flowchart 1100 described above in connection with Figure 11 except that block 1435 has been added between blocks 1430 and 1440. Accordingly, the description of the blocks common to both flowcharts is not repeated. Rather, only the additional step at block 1435 is described. At block 1435, the tension is computed for each neighbor node of the unknown location node under consideration.
In an exemplary embodiment, the subsequent location estimate for each unknown location node is chosen as follows:

1. Identify the neighbor node link with the highest magnitude tension;
2. Choose the subsequent location estimate by stepping from the previous location estimate along the identified link;
3. If the tension is positive, the direction of the step is toward the neighbor node, whereas if the tension is negative, the step is away from the neighbor node.

The initial location estimates for each unknown location node may be chosen in several different ways. One approach is simply to choose them randomly. In yet another approach, the initial location estimate for an unknown location node is chosen as a point between the two known location neighbor nodes having the two shortest neighbor node distance estimates. If the unknown location node does not have two known location neighbors, then the initial location estimate is chosen as a point between the two unknown location neighbor nodes having the two shortest neighbor node distance estimates.

In an exemplary embodiment, the step length $\delta$ for a subsequent location estimate can be variable. The idea is to increase the value of $\delta$ if for two consecutive epochs the location estimate is changed in the same direction. If the location estimate is then changed in a different direction, the value of $\delta$ is restored to its initial value.

In yet another exemplary embodiment, if for a specified number of epochs the system error does not increase, then the location estimates of the unknown location nodes having the $N$ highest total errors, where $N$ is a configurable number, are replaced with random locations. In yet another exemplary embodiment, the total error is computed as a weighted sum as given by

$$E = w \sum_{i}^{D_{KP}} e_i + \sum_{j}^{D_{UP}} e_j$$  (4)
instead of equation (3), where \( w \) is greater than 1, \( DKP \) is the total number of known location
neighbor nodes and \( DUP \) is the total number of unknown location neighbor nodes.

**GENERAL**

[0048] Embodiments of the present disclosure may comprise systems having different
architecture and methods having different information flows than those shown in the Figures. The
systems shown are merely illustrative and are not intended to indicate that any system
component, feature, or information flow is essential or necessary to any embodiment or limiting
the scope of the present disclosure. The foregoing description of the embodiments has been
presented only for the purpose of illustration and description and is not intended to be exhaustive
or to limit the disclosure to the precise forms disclosed. Numerous modifications and adaptations
are apparent to those skilled in the art without departing from the spirit and scope of the
disclosure.

[0049] Some portions of the detailed description have been presented in terms of algorithms
or processes which may take the form of a series of operations on data or signals stored in a
computer memory. As a result, these operations take the form of manipulation or transformation
of physical quantities. Such quantities may in some instances take the form of electrical or
magnetic signals capable of being transformed, stored, retrieved, compared, combined or
otherwise manipulated. It is to be understood that all such references to algorithms and processes
also refer to the underlying physical quantities and their transformations and manipulations.
Similarly, references herein to terms such as "computing," "processing," "determining," and
similar terms refer to the actions of a computer or similar platform that transforms or otherwise
manipulates data stored as physical quantities within the computer or platform.

[0050] Additional embodiments include a computer readable medium or media tangibly
embodying program code for implementing one or more aspects of the present subject matter.
As an example, embodiments can include media embodying program code executable by one
or more processors of a computing system to cause the system to implement methods of
estimating the physical location of one or more nodes in accordance with one or more aspects of the present subject matter as noted herein.

[0051] For instance, a processor in a computer system at the NOC such as processor 575 may access code that causes the NOC system to perform location estimates and output the resulting estimates to a display and/or store the resulting estimates in one or more computer-readable media.

[0052] Any suitable computer-readable medium or media may be used to implement or practice the presently-disclosed subject matter, including, but not limited to, diskettes, drives, magnetic-based storage media, optical storage media, including disks (including CD-ROMS, DVD-ROMS, and variants thereof), flash, RAM, ROM, and other memory devices, and the like.
CLAIMS

1. A method of estimating the physical location of a first unknown-location node in a network comprising known-location nodes and unknown-location nodes, the method comprising:
   maintaining in a database known locations of the known-location nodes and estimates of locations of the unknown-location nodes;
   receiving neighbor node distance estimates for the first unknown-location node;
   choosing an initial location estimate for the first unknown-location node;
   computing neighbor node distances for the first unknown-location node; and
   choosing a subsequent location estimate for the first unknown-location node based on a comparison of the neighbor node distance estimates with the computed neighbor node distances.

2. The method of claim 1 wherein choosing a subsequent location estimate based on a comparison of the neighbor node distance estimates with the computed neighbor node distances comprises:
   computing a total error from the neighbor node distance estimates and the computed neighbor node distances; and
   choosing a subsequent location estimate to reduce the total error.

3. The method of claim 2 wherein computing a total error from the neighbor node distance estimates and the computed neighbor node distances comprises:
   computing a magnitude of the difference between each neighbor node estimate and each corresponding computed neighbor node distance;
   multiplying the magnitude of the difference by a number larger than or equal to one if the neighbor node associated with the computed neighbor node distance is a known-location node; and
   summing the modified magnitudes and unmodified magnitudes to obtain a total error.
4. The method of claim 3 further comprising:
   computing a stopping criterion; and
   while the stopping criterion does not satisfy a stopping threshold:
       choosing a second subsequent location estimate.

5. The method of claim 4 wherein computing a stopping criterion comprises setting the
   stopping criterion to the total error.

6. The method of claim 4 wherein computing a stopping criterion comprises counting a
   number of epochs.

7. The method of claim 1 wherein choosing an initial location estimate comprises choosing
   the initial location estimate randomly.

8. The method of claim 1 wherein choosing an initial location estimate comprises:
   identifying two known-location neighbor nodes that have the two shortest neighbor node
   distance estimates, and
       choosing the initial location based on the identified neighbor nodes.

9. The method of claim 1 wherein choosing an initial location estimate comprises:
   identifying two unknown-location neighbor nodes that have the two shortest neighbor
   node distance estimates, and
       choosing the initial location based on the identified neighbor nodes.

10. The method of claim 1 wherein choosing a subsequent location estimate that differs from
    a previous location estimate comprises determining the subsequent location estimate to be at a
    configurable distance in a configurable direction relative to the previous location estimate.

11. The method of claim 10 further comprising determining the configurable direction so as to
    minimize the maximum magnitude of tension between the unknown location node and the
    neighbor nodes.

12. The method of claim 1 further comprising updating in the database the estimate of the
    location of the unknown-location node with the subsequent location estimate.
13. The method of claim 1 wherein the unknown-location node is a radio node.

14. A method of estimating the physical locations of a plurality of unknown-location nodes in a network comprising known-location nodes and unknown-location nodes, the method comprising:

   maintaining in a database known locations of the known-location nodes and estimates of locations of the unknown-location nodes; and

   for each unknown-location node:

   receiving neighbor node distance estimates;

   choosing an initial location estimate;

   computing neighbor node distances; and

   choosing a subsequent location estimate based on a comparison of the neighbor node distance estimates with the computed neighbor nodes.

15. The method of claim 14 wherein choosing a subsequent location estimate based on a comparison of the neighbor node distance estimates with the computed neighbor nodes comprises:

   computing a total error from the neighbor node distance estimates and the computed neighbor node distances; and

   choosing a subsequent location estimate to reduce the total error.

16. The method of claim 15 wherein computing a total error from the received neighbor node distance estimates and the computed updated neighbor node distances comprises:

   computing a magnitude of the difference between each received neighbor node estimate and each corresponding computed updated neighbor node distance;

   multiplying the magnitude of the difference by a number larger than or equal to one if the neighbor node associated with the computed updated neighbor node distance is a known-location node; and

   summing the modified magnitudes and unmodified magnitudes to obtain the total error.
17. The method of claim 16 further comprising computing a stopping criterion; and while the stopping criterion does not satisfy a stopping threshold:

for each unknown-location node choosing a second subsequent location estimate.

18. The method of claim 17 wherein computing a stopping criterion comprises determining the largest of the total errors associated with the plurality of unknown-location nodes.

19. The method of claim 17 wherein computing a stopping criterion comprises counting a number of epochs.

20. The method of claim 17 wherein computing a stopping criterion comprises computing the sum of the total errors associated with the plurality of unknown-location nodes.

21. The method of claim 14 wherein choosing an initial location estimate comprises choosing the initial location estimate randomly.

22. The method of claim 14 wherein choosing an initial location estimate comprises:

identifying two known-location neighbor nodes that have the two shortest neighbor node distance estimates, and

choosing the initial location based on the identified neighbor nodes.

23. The method of claim 14 wherein choosing an initial location estimate comprises:

identifying two unknown-location neighbor nodes that have the two shortest neighbor node distance estimates, and

choosing the initial location based on the identified neighbor nodes.

24. The method of claim 14 wherein choosing a subsequent location estimate that differs from a previous location estimate comprises determining the subsequent location estimate to be at a configurable distance in a configurable direction relative to the previous location estimate.
25. The method of claim 24 further comprising determining the configurable directions so as to minimize the maximum magnitude of tension between the unknown location node and the neighbor nodes.

26. The method of claim 14 further comprising updating in the database the estimates of the locations of the plurality of unknown-location node with the subsequent location estimates.

27. The method of claim 14 wherein each of the plurality of unknown-location nodes is a radio node.

28. A method of estimating the physical locations of one or more unknown-location nodes in a network comprising known-location nodes and unknown-location nodes, the method comprising:

   maintaining in a database known locations of the known-location nodes and estimates of locations of the unknown-location nodes;

   for each unknown-location node:

      receiving neighbor node distance estimates;

      choosing an initial location estimate;

      computing neighbor node distances between the initial location estimate and neighbor node locations of neighbor nodes;

      computing a total error from the received neighbor node distance estimates and the computed neighbor node distances;

      computing a stopping criterion;

      determining if the stopping criterion satisfies a stopping threshold;

   while the stopping criterion does not satisfy the stopping threshold:

      for each unknown-location node:

         choosing a subsequent location estimate that differs from a previous location estimate;
computing updated neighbor node distances between the subsequent location estimate and neighbor node locations of neighbor nodes;
computing an updated total error from the received neighbor node distance estimates and the computed neighbor node distances;
determining if the stopping criterion satisfies a stopping threshold; and
updating in the database the estimate of the locations of the unknown-location nodes if the stopping criterion satisfies the stopping threshold.

29. The method of claim 28 wherein choosing a subsequent location estimate that differs from a previous location estimate comprises determining the subsequent location estimate to be at a configurable distance in a configurable direction relative to the previous location estimate.

30. The method of claim 29 further comprising determining the configurable direction so as to minimize the maximum magnitude of tension between the unknown location node and the neighbor nodes.

31. A position location estimation system for estimating the location of nodes in a network comprising known-location nodes and unknown-location nodes, the position location estimation system comprising a network operating center comprising a processor and a database, wherein:
the database comprises the locations of the known-location nodes and estimates of the locations of the unknown-location nodes;
the network operating center is configured to receive neighbor node distance estimates for each unknown-location radio node;
the processor of the network operating center is configured to:
determine a location estimate for each unknown-location node;
compute neighbor node distances between the location estimate and neighbor node locations for each unknown-location radio node;
determine an updated location estimate for each unknown-location radio node
based on the computed neighbor node estimates and the received neighbor node
distance estimates;

and

the network operating center is further configured to update in the database the estimate of
the locations of the unknown-location nodes.
300

301
Repetitively measure distance to a neighbor node during a configurable time period

302
Compute average of measurements to obtain neighbor node distance estimate

303
Elapsed time since last report greater than threshold?

304
Deviation in distance estimate greater than threshold?

305
Report distance estimated to network operating center

Figure 3
Figure 7
Figure 9
Figure 10
1100

Choose initial location estimates for unknown location nodes

1110

1120

Compute neighbor node distances from an unknown location node to neighbor nodes

1130

Choose subsequent location estimates

1160

Compute total error for unknown location node

Steps inside dashed box are implemented for each unknown location node

1140

Sort into list of total errors from largest total error to smallest total error

1150

Stopping criterion satisfied?

No

Yes

1170

Update database with location estimates for unknown location nodes

Figure 11
Figure 12
Choose initial location estimates for unknown location nodes

Compute neighbor node distances from an unknown location node to neighbor nodes

Choose subsequent location estimates

Compute total error for unknown location node

Compute tension for each neighbor node

Sort into list of total errors from largest total error to smallest total error

Stopping criterion satisfied?

Yes

Update database with location estimates for unknown location nodes

No

Steps inside dashed box are implemented for each unknown location node

Figure 14