(54) Title: METHOD AND SYSTEM FOR LOCALIZING A BLIND NODE

(A)

(B)

FIG. 1

(57) Abstract: The present invention relates to a method and system for localizing a blind node. More in particular, the invention relates to a method and system for localizing a blind node, having an unknown position, relative to a plurality of reference nodes, each reference node having a known and different position. According to the invention, the position of the blind node is found by maximizing the extent of linear correlation between measured and predicted values corresponding to a physical parameter. These values are derived from signals exchanged between the reference nodes and the blind node or are calculated based on a composite function, such as the log-normal shadowing model.
Method and system for localizing a blind node

The present invention relates to a method and system for localizing a blind node. More in particular, the invention relates to a method and system for localizing a blind node, having an unknown position, relative to a plurality of reference nodes, each reference node having a known and different position.

Localization refers to a process of identifying the relative or absolute position of blind nodes. Localization applications range from tracking large objects such as containers, ships and planes down to small battery-powered sensors in Wireless Sensor Networks (WSN). Although the Global Positioning System (GPS) provides a worldwide infrastructure for positioning devices outdoors, no such infrastructure is available indoors. Moreover, the price, energy consumption and accuracy of the GPS, limit the application in outdoor environments.

Localization can be performed in both cooperative and non-cooperative approaches. The difference between cooperative and non-cooperative localizations is illustrated in Figure 1. In the case of non-cooperative localization, illustrated on the left, ranging measurements between reference nodes and a single blind node are used to determine the location of the blind node. In cooperative localization, illustrated on the right, pairwise measurements are used to determine the locations of blind nodes.

Many approaches were proposed to determine the position of an object, for instance Time of Flight (ToF), Angle of Arrival (AoA) and signal-strength based approaches. Although ToF and AoA provide good performance in Line-of-Sight (LoS) environments, they perform poorly in Non-Line-of-Sight (NLoS) environments [ref1]. Moreover, ToF and AoA is generally not available in radio platforms, limiting the application of this technique to specialized hardware.

Signal-strength localization provides a low-cost approach to positioning and Received Signal Strength (RSS) information is available on many low-cost radios. Calculating a position based on signal-strength measurements is however not straightforward. Many localization approaches have been proposed, such as fingerprinting approaches [ref2], calibration-based and calibration-free approaches. Although fingerprinting and calibration-based approaches generally provide good accuracy, they require an initial calibration phase. Fingerprinting requires building a database of signal-strength fingerprints of the environment, whereas calibration-based approaches determine the parameters of the propagation model of the environment. This initial calibration is very laborious and its result generally stays valid for only a short duration because environments change, for example doors open and close and broken beacons need to be replaced.

Calibration-free approaches overcome the problem of requiring an initial calibration phase before positioning can be used. These approaches determine the propagation model parameters at run-time. Examples of such approaches include [ref3], [ref4], [ref5] and [ref6]. All these
approaches use the Log-Normal Shadowing Model (LNSM) and estimate the transmission power, the path loss exponent, and the position of the device by applying a least-squares fitting. Such approaches, however, require an initial estimate of the channel parameters. Moreover, least-squares approaches are generally not resilient against measurement outliers.

Among many proposed approaches for signal-strength localization [ref7], [ref8], and [ref9], the fingerprinting approaches including [ref10] and [ref11] are popular, but require an offline phase for building the fingerprint database. Building this database using a ground-truth measurement is very cumbersome. Approaches such as WiFi-SLAM [ref12] are able to speed up the process of building these maps, but still require an offline phase for building fingerprint maps. Moreover, environments may change as objects may be moved and beacons need to be replaced when broken, thus, the fingerprinting needs to be done periodically. The advantage of fingerprinting localization is that it has a general assumption about the propagation model of the Radio Frequency (RF) signal.

Proximity localization [ref13], connectivity localization [ref14] and sequence-based localization approaches [ref15], [ref16] are types of approaches that have little assumption about the signal propagation. In the case of connectivity and proximity localization, the localization approach only considers whether two nodes are within range, whereas in the case of sequence-based localization, the order of the received beacons is assumed to have a relation with the distance-based order of the nodes. Because a very general assumption about the propagation is made, these approaches are very resilient against ranging errors but generally have low accuracy and precision.

The radiofrequency (RF) signal is generally considered to follow the LNSM in indoor environments [ref17]. Many existing approaches use the LNSM, which defines the decay of the signal over a distance as follows:

\[
P_d = P_{d0} - 10 n_p \log_{10} \left( \frac{d}{d_0} \right) + \mathcal{N}(0, \sigma^2)
\]

The LNSM defines the received signal strength \( P_d \) as a function of the distance \( d \) and two environmental parameters \( P_{d0} \) and \( n_p \). \( P_{d0} \) is the transmission power of the reference transmitter measured at a certain distance, and \( n_p \) is the path-loss exponent and defines the signal decay over distance. The parameter \( d_0 \) is used to obtain a dimension-less number. Finally, the received signal strength has an error \( \mathcal{N}(0, \sigma^2) \) that is normally distributed with zero mean and a standard deviation of \( \sigma \), and is considered independent from the distance. In [ref17], the ratio \( \sigma/n_p \) is used to make the error independent from the \( n_p \) path-loss parameter.

To calculate the distance using the received signal strength, the parameters \( P_{d0} \) and \( \mathcal{N} \) of the LNSM needs to be known or calculated. Approaches such as [ref3], [ref4], [ref5] and [ref6] use
a Maximum-Likelihood Estimator (MLE) and apply a least-squares fitting technique to calculate
the position of the blind node as well as estimate the optimal LNSM model parameters. Some of
these approaches only estimate the path-loss exponent $n_p$, whereas others estimate both the path-
loss exponent $n_p$ as well as the transmission power $P_{do}$.

The applicant has found that the outcome of available prior art approaches is sensitive to
the environmental parameters that describe the environment, such as $P_{do}$ and $n_p$. This may
jeopardize either the numerical stability of the method and/or the accuracy of the final result.

An object of the present invention is to provide a solution to at least one of the
abovementioned problems.

This object is achieved using the method of the invention for localizing a blind node
having an unknown position, relative to a plurality of reference nodes, each reference node having
a known and different position. The method according to the invention comprises:

- exchanging a signal between the reference nodes and the blind node;
- for each signal exchanged between a given reference node and the blind node, deriving a
  value for a given physical parameter from said exchanged signal;
- providing a composite function $f(g)$ for predicting the value of the physical parameter as a
  function of the distance between a given reference node and the blind node, wherein $g$ is a strictly
  increasing or decreasing function of this distance and wherein $f$ is a linear function;
- optimizing an estimated position of the blind node by maximizing the extent of linear
  correlation between the plurality of derived values of said physical parameter and a corresponding
  plurality of values of said physical parameter that are predicted using the estimated position of the
  blind node.

Preferably, a signal is exchanged between each of the reference nodes and the blind node.
However, in some cases such exchange may not be possible. For instance, the signal path between
reference node and blind node may be blocked or the blind node may be out of range. In such
cases, the measurements relating to this signal can be discarded during the optimization.

According to an embodiment, the particular form of the composite function allows a
position of the blind node to be found without having to assume or determine model or calibration
parameters. This particularly holds if the composite function comprises at least one parameter for
describing at least one of transmitter properties, receiver properties, and signal propagation
properties, related to the exchange of said signal, wherein the at least one parameter is only
incorporated in function $f$. Hence, function $g$ is only depending on the distance and does not
comprise any parameter that needs to be determined as part of the optimization of the estimated
position of the blind node. Additionally, the composite function may comprise at least one known
parameter for describing at least one of transmitter properties, receiver properties, and signal
propagation properties, related to the exchange of said signal, wherein the at least one known
parameter is incorporated in function \( f \) and/or function \( g \). In this case, function \( g \) may comprise parameters as long as these parameters are known prior to the optimization of the estimated position of the blind node.

The abovementioned parameters may include parameters related to the transmission of the signal, such as source strength, polarization, directivity, etc. The parameters may also relate to the reception of the signal, such as sensitivity of the receiver or the antenna orientation or directionality. Finally, the parameters may also relate to the physical channel between transmitter and receiver and may include signal propagation constants and multi-path properties.

Determining the extent of linear correlation may comprise using the covariance of the plurality of derived values and the corresponding plurality of predicted values, divided by the standard deviation of the plurality of predicted values. Alternatively, determining the extent of linear correlation may comprise using the product-moment correlation of the plurality of derived values and the corresponding plurality of predicted values. Here, the product-moment correlation of a set of values \( X \) and \( Y \) is defined as the covariance of \( X \) and \( Y \) divided by the standard deviation of \( X \) and the standard deviation of \( Y \).

At the start of optimizing the estimated position of the blind node, the mean position of the reference nodes may be taken as an initial estimate for the position of the blind node.

Instead of exchanging a single signal between a reference node and the blind node with the blind node being at substantially the same position, it is preferred to exchange a plurality of signals between the reference nodes and the blind node. Again, it is preferred to exchange such plurality of signals between each of the reference nodes and the blind node. The value for said physical parameter may then be derived from each of the exchanged signals, and for each reference node a mean of the derived values may be determined. The optimizing may then comprise optimizing an estimated position of the blind node by maximizing the extent of linear correlation between the plurality of determined mean values of said physical parameter and a corresponding plurality of values of said physical parameter that are predicted using the estimated position of the blind node.

The present invention is not limited to using the mean of the derived values. Alternatively, a different function of the plurality of derived values can be used as long as the outcome of this function can be modelled.

The exchanged signal may comprise an electromagnetic, acoustic, light, magnetic or electrical signal that is sent from the blind node to the reference node or an electromagnetic, acoustic, light, magnetic or electrical signal that is sent from the reference node to the blind node, wherein the physical parameter comprises a received signal strength of the signal received by the reference node or blind node, respectively. In this case, the composite function comprises a log-normal shadowing model. In a preferred embodiment, the signal comprises a radio-frequency (RF) electromagnetic signal.
Alternatively, the exchanged signal may comprise an electromagnetic, acoustic, magnetic or electrical signal that is sent from the blind node to the reference node or an electromagnetic, acoustic, light, magnetic or electrical signal that is sent from the reference node to the blind node, wherein the physical parameter comprises a time of flight of the signal between the reference node and the blind node. Here, time of flight may correspond to the time required for the signal to go from the reference node to the blind node or vice versa.

Instead of a single blind node, an additional blind node may be provided of which the position needs to be determined. In that case, the method may comprise:

- exchanging a signal between the reference nodes and an additional blind node;
- for each signal exchanged between a given reference node and the additional blind node, deriving a value for said physical parameter from said exchanged signal;
- optimizing an estimated position of the blind node and the additional blind node by maximizing the extent of linear correlation between the plurality of derived values of said physical parameter and a corresponding plurality of values of said physical parameter that are predicted using the estimated position of the blind node and the estimated position of the additional blind node.

Again, it is preferred to exchange a signal between each of the reference nodes and the additional blind node.

In addition to exchanging signals between the additional blind node and the reference nodes, it may equally be possible to exchange signals between the blind node and the additional blind node and deriving a value for said physical parameter from said exchanged signal. This value may be used in the optimization as well.

For some applications, the entire localization process can be described using a single set of model parameters, such as $P_{ai}$ and $n_p$. However, for some applications, these parameters may differ throughout the localization region, for example due to the fact that the signal propagation is different. As an example, the localization region may comprise a building with multiple floors, wherein each floor comprises a different structure and/or comprises different walls, furniture etc. In such case, it may be advantageous to group the plurality of reference nodes, the blind node and/or the additional blind node in a plurality of node groups, wherein the optimizing comprises determining, for each node group, the extent of linear correlation between the plurality of derived values and the corresponding plurality of predicted values, and maximizing the combined extent of linear correlation using the determined extent of linear correlation of each node group. Hence, the optimization uses a term for each node group which term describes the extent of linear correlation for that group. The sum of these terms is then maximized instead of maximizing each term individually. The present invention does not exclude that different node groups comprise the same reference node, blind node, and/or additional blind node.
Within a given node group, the parameter set to be used mostly depends on the transmitting node. In most cases, the reference nodes will be transmitting signals to the blind node and the additional node.

Generally, the blind node(s) remain fixed during the optimization process or at least during the signal exchange required for the optimization. Alternatively, the position of the blind node and/or additional blind node may change during the exchanging of signals between the blind node, the additional blind node and the reference nodes. In this case, each exchanged signal is associated with the position the blind node or the additional blind node was at during the exchange of said signal. The method then further comprises taking one position of the blind node or the additional blind node among the different positions during said exchanging of signals as the main position of the blind node or additional blind node, and calculating the other positions of the blind node or additional blind node during said exchanging of signals based on the main position and a calculated displacement of the blind node or additional blind node when moving from the main position to the other positions. The optimizing then comprises optimizing the main position of the blind node or the additional node by maximizing the extent of linear correlation between the plurality of derived values of said physical parameter and a corresponding plurality of values of said physical parameter that are predicted using the estimated main position and the other positions of the blind node or the additional blind node.

According to a further aspect, the present invention provides a localization system, comprising a processing unit, a plurality of reference nodes that each have a known and different position, and a blind node having an unknown position. The reference nodes each comprise a transmitter, a receiver or a transceiver and the blind node comprises a transmitter, a receiver or a transceiver. The reference nodes and the blind node are configured to exchange a signal between the reference nodes and the blind node, and the reference nodes and/or the blind node comprise(s) a deriving unit for deriving a value for a given physical parameter from the exchanged signal and for sending the derived value to the processing unit. The processing unit is configured for carrying out the method of any of the previous claims to find an estimated position of the blind node using the derived values.

The skilled person readily understands that different communication technologies can be used for communicating the required parameters for the localization to the processing unit. For example, the reference nodes may be configured to send their position to the processing unit.

The processing unit can be implemented remote from the reference nodes and the blind node. Alternatively, the processing unit is implemented in a reference node or in the blind node.

The system defined above can be enlarged by adding one or more additional blind nodes as discussed above.
Next, the invention will be described in more detail referring to the appended drawings, wherein:

Figure 1 illustrates an example of non-cooperative (left) and cooperative (right) localization;

Figure 2 illustrates a comparison between the method according to the invention and a prior art approach for non-cooperative localization; and

Figure 3 illustrates a comparison between the method according to the invention and a prior art approach for cooperative localization.

Without loss of generality, it is assumed that a blind node needs to be localized using the received signal strength measurements from a set of \( n \) transmitters with known locations, called reference nodes. Assume that the received signal strength measured at the position of the blind node is a function of the distance \( d_i \) between the blind node and transmitter \( i \) and can be expressed by a given model (such as the log-normal shadowing model). Moreover, assume that this model is described by a set of parameters \( \alpha_k \).

If the model is perfect and the measurement of received signal strength is errorless, then, for a given set of estimated model parameters \( \hat{\alpha}_k \), denoted by \( \hat{\alpha}_k \), the following holds:

\[
\hat{P}_i^M = P_i
\]

where \( \hat{P}_i^M \) is the measured received signal strength of the signal from transmitter \( i \) and \( P_i \) is the corresponding modelled signal strength, if the blind node is at a position having a distance of \( d_i \) to transmitter \( i \). Under these circumstances, the set of measurements \( \hat{P}_i^M = \{ \hat{P}_i^M, i = 1, \ldots, n \} \) measured at corresponding distances \( d_i \) and the set of predicted signal strengths \( P = \{ P_i, i = 1, \ldots, n \} \) are linearly correlated.

According to the invention, the model can be expressed as a composite function \( f \circ g(d_i) \), where \( g(.) \) is a strictly increasing/decreasing function of \( d_i \), and \( f(.) \) is a linear function. This means that for an arbitrary set \( \alpha_k \), the modelled signal strength \( \hat{P}_i \) can be computed using:

\[
P_i = \alpha_0 + \alpha_1 g(d_i) + \mathcal{N}(0, \sigma^2)
\]

where it is assumed that the signal strength from transmitter \( i \) is normally distributed around a modelled mean \( \hat{P}_i \) with a variance \( \sigma^2 \). Mean \( \hat{P}_i \) can be computed using:

\[
\hat{P}_i = \alpha_0 + \alpha_1 g(d_i)
\]
When the model corresponds to the Log-Normal Schadowing model of equation (1), one finds:

\begin{align}
\alpha_0 &= p_{d_0} \\
\alpha_1 &= -10n_p \\
g(d_i) &= \log_{10}\left(\frac{d_i}{d_0}\right)
\end{align}

Typically, multiple measurements are performed with the blind node being at a given position. In order to have a good performance on localization accuracy, it is preferred if these measurements are normally distributed around a mean \(\mu_l^M\) with a variance \(\sigma^2\), wherein the mean can be modelled using:

\[ \frac{p^M_l}{\mu_l} = \mu_l \]

Hence, when the estimated position of the blind node is correct, equation (8) holds and \(\frac{p^M_l}{\mu_l}\) will correlate linearly with \(\mu_l\). However, when inspecting equation (4), it can be concluded that in that case \(\mu_l\) and \(\frac{p^M_l}{\mu_l}\) will both correlate linearly with \(g(d_i)\). This latter equation does not depend on unknown model parameters \(\alpha_i\). Accordingly, when the estimated position of the blind node is correct, and the model and measurements are accurate, \(\frac{p^M_l}{\mu_l}\), \(\mu_l\), and \(g(d_i)\) will all be linearly correlated to each other.

The product-moment correlation of two sets of values \(X\) and \(Y\) is defined by:

\[ \text{cov}(X,Y) \]

\[ \sigma_X\sigma_Y \]

where \(\text{cov}(X,Y)\) is the covariance of sets \(X\) and \(Y\), and wherein \(\sigma_X\) and \(\sigma_Y\) the standard deviation of these sets. The product-moment correlation can attain values between -1 and +1. For two sets that are perfectly linearly correlated, the product-moment correlation equals +1.

Hence, the product-moment correlation can be used to find the position of the blind node because the correlation between measurement and model will only be +1 when the estimated position of the blind node corresponds to the true position. In other words, maximizing the product-moment correlation with respect to an estimated position \((x,y)\) of the blind node:
\[
\max_{x,y} \frac{\text{cov}(P, P^M)}{\sigma_P \sigma_{P^M}}
\]

with \( P^M = \{ P^M_i, i = 1, \ldots, n \} \) and \( P = \{ P_i, i = 1, \ldots, n \} \) will provide the best possible estimate for the position \((x, y)\) of the blind node, regardless of the values of model parameter set \( \omega \). It should be noted that it is equally possible to minimize the difference between 1 and the product-moment correlation to find the best estimated position of the blind node.

According to the invention, the position of the blind node is found by maximizing the linear correlation between measured and predicted values. As stated above, \( P^M_i, P_i \), and \( g(d_i) \) will all be linearly correlated to each other when the estimated position of the blind node is correct.

Accordingly, instead of calculating \( P_i \) in equation (10) above, which comprises unknown model parameters, one can use function \( g(d_i) \), which does not comprise these model parameters. For the log-normal shadowing model, equation (10) reduces to:

\[
\max_{x,y} \frac{\text{cov}(G, P^M)}{\sigma_G \sigma_{P^M}}
\]

where \( G = \{ g(d_i), i = 1, \ldots, n \} \) wherein:

\[
d_i = \sqrt{(x - x_i)^2 + (y - y_i)^2}
\]

with \((x_i, y_i)\) the position of reference node \(i\). This method can be easily extended to cooperative localization. Let \(j\) denote the index of \(m\) blind nodes and \(i\) denote the index of \(n\) reference nodes. For each blind node, a term can be formulated that is similar to equation (10). Then, these terms can be summed and the sum can be maximized with respect to the collection of positions \(\{x_j, y_j\}\) of the blind nodes:

\[
\max_{\{x_j, y_j\}} \sum_{j=1}^{m} \frac{\text{cov}(P_i, P^M_j)}{\sigma_{P_i} \sigma_{P^M_j}}
\]
where $p^M_i = \{p^M_{i,j}, i = 1, \ldots, n + m - 1\}$ and $p_i = \{p_{i,j}, i = 1, \ldots, n + m - 1\}$, with $p^M_{i,j}$ and $p_{i,j}$ respectively corresponding to the mean of the measured and modelled signal strength corresponding to the signals exchanged between reference node $i$ and blind node $j$ for $i < n + l$ and corresponding to the exchange of signals exchanged between the different blind nodes $j$ for $i > n$. In this case, distance $d_{i,j}$ between the nodes can be computed using:

$$ d_{i,j} = \sqrt{(x_j - x_i)^2 + (y_j - y_i)^2} $$

(14)

For calculating distances between blind node $j$ and reference node $i$ when $i < n + l$, and

$$ d_{j,k} = \sqrt{(x_j - x_k)^2 + (y_j - y_k)^2} $$

(15)

between blind nodes $x_j$ and $x_k$ with $k = 1 \ldots m$ and unequal to $j$.

In some circumstances, the model parameters differ strongly between groups of reference nodes whereas in the same group, the model parameters are substantially the same. This may for instance happen if the localization region comprises two groups of reference nodes that are remote from each other, for instance because they are located on different floors of a building. In such case, it is possible to extend equation (10) with the possibility to calculate an individual correlation for each reference node group and to then maximize the sum of the product-moment correlation terms for each group:

$$ \max_{x_y} \sum_{\text{groups}} \begin{bmatrix} \text{cov}(P_{G1}, p^M_{G1}) \sigma_{P_{G1}} \sigma_{p^M_{G1}} \\ \text{cov}(P_{G2}, p^M_{G2}) \sigma_{P_{G2}} \sigma_{p^M_{G2}} \end{bmatrix}_{\text{group 1}} + \begin{bmatrix} \text{cov}(P_{G2}, p^M_{G2}) \sigma_{P_{G2}} \sigma_{p^M_{G2}} \end{bmatrix}_{\text{group 2}} $$

(16)

wherein $P_{G1}$ and $p^M_{G1}$, and $P_{G2}$ and $p^M_{G2}$, represent the relevant modelled and measured signal strength values for the reference nodes in group 1 and group 2, respectively. The skilled person will understand that it is equally possible to combine equations (13) and (16). The skilled person also will understand that it is possible to apply equations (10), (11), (13) and (16), when a blind node does not have measurement information to all the reference nodes or to all other blind nodes, by simply discarding the corresponding terms in computing the correlation and the sum of the correlation.
To evaluate the different non-cooperative approaches, the localization approaches were simulated with various ranges of error and the number of reference nodes. In a simulated environment of 100m × 100m, 6…20 reference nodes were deployed. For 5000 random positions the accuracy of the estimated position using the approach of the invention, a prior art least-squares approach from [ref5], and the Cramer-Rao bound (CRB) were calculated. The calculated positions were constrained to the deployment area of 100m × 100m. The Cramer-Rao bound was calculated from the Fisher Information Matrix in previous work [ref17]. This bound is practical approach to estimate the expected performance of a localization system.

All nodes within the deployment area are connected, the communication range is assumed to be larger than \( \sqrt{2 \cdot 100^2} \) m.

For the least-squares approach, the center of the positioning area (50,50) was taken as the initial estimate of the position of the blind node. At this position, the initial environmental parameters \( (P_{dB} \text{ and } n_p) \) were calculated using a linear least squares approach. Next, both the position of the blind node and the optimal calibration parameters \( (P_{dB} \text{ and } n_p) \) were estimated simultaneously during optimization.

For the product-moment correlation approach of the present invention, the center of the positioning area (50, 50) was also taken as the initial estimate of the position of the blind node. As stated above, the product- moment correlation approach of the present invention does not require an initial estimate of the calibration parameters. Hence, only the position of the blind node was estimated during optimization.

This simulation was performed with different numbers of reference nodes, ranging from 5 to 20 reference nodes. The \( \alpha/n_p \) relation was kept at 1.7 for this simulation.

The results illustrated in Figure 2 (left) show that the product-moment approach of the invention follows the CRB quite well, whereas the localization accuracy of the least-squares approach of the prior art improves very little when the number of reference nodes increases. The improvement of the product-moment correlation approach of the invention over the least-squares approach ranges from 9% to 104%. In the case of 20 reference nodes, the product- moment approach is twice as accurate as the least-squares approach.

Another simulation was performed with a fixed number of reference nodes and the ratio \( \alpha/n_p \) varying from 1.5 to 2.9. Again, the simulation was repeated for 5000 random positions in an area of 100m × 100m. The results of this simulation are shown in Figure 2 (right). The results show that the product-moment approach of the invention performs significantly better than the least-squares approach, on average 20% more accurate. The product- moment approach of the invention comes very close to the CRB. It performs on average 3% better than the CRB. Once the error in the measurements increases up to some value, such as when \( \alpha/n_p = 2.1 \), the product-moment approach of the invention starts outperforming the CRB. The CRB assumes the estimator is unbiased,
however because the calculated positions are constrained to the localization area, the estimator is biased and can outperform the CRB.

For the cooperative approach, the localization in a network of 100m x 100m with fixed 6 reference nodes was simulated. The results were evaluated with an increasing number of nodes in the network and with increasing error ratio. In the scenario of an increasing number of nodes, the ratio \( n/n_b \) was fixed at 1.7. The number of blind nodes in the network varied from 14 to 54 nodes. In the scenario of an increasing error ratio, the number of nodes was kept constant, 34 blind nodes and 6 reference nodes, and the error ratio was varied from 1.5 to 2.9.

The simulation was repeated for 100 different random deployments of the blind nodes and reference nodes. The results from both scenarios are shown in Figure 3. As shown on the left, when increasing the number of nodes, the product-moment approach of the invention performs on average 40% better than the least-squares approach and performs 122% worse than the CRB. With increasing error-rate, shown on the right, the product-moment approach of the invention performs about 32% better than the least-squares approach and 104% worse than the CRB.

Although the present invention is described using detailed embodiments thereof, the skilled person will appreciate that the invention is not limited to these embodiments but that various modifications can be implemented without deviating from the scope of the invention which is defined by the appended claims.

For example, instead of using received signal strength measurements, the time of flight can be determined for the exchanged signal. Here, the time of flight preferably corresponds to the time it takes for a signal to move from the transmitter to the receiver.

As an example, consider a system wherein the reference nodes are synchronized and transmit an electromagnetic signal (or any other signal modality) to the blind node. The time-of-arrival \( T_i \) of a signal transmitted by reference node \( i \) and received by the blind node can be modelled using:

\[
T_i = \beta_0 + \frac{d_i}{\beta_1} + \mathcal{N}(0, \sigma^2)
\]

wherein \( \beta_0 \) represents the clock offset of the blind node relative to the synchronized reference nodes, and \( \beta_1 \) the propagation speed of the signal. It is noted that equation (17) is also a composite function in the form of \( f(g(d_i)) \) with \( g(d_i) = d_i \). Consequently, the position of the blind node can be computed in a similar manner as described above. For example, the product-moment correlation between the measured and modelled times-of-arrival can be optimized with respect to the estimated position of the blind node. Other parameters than time-of-arrival or received signal strength may also be used to find the position of the blind node.
LIST OF REFERENCES


CLAIMS

1. A method for localizing a blind node having an unknown position, relative to a plurality of reference nodes, each reference node having a known and different position, the method comprising:
   exchanging a signal between the reference nodes and the blind node;
   for each signal exchanged between a given reference node and the blind node, deriving a value for a given physical parameter from said exchanged signal;
   providing a composite function \( f(g) \) for predicting the value of the physical parameter as a function of the distance between a given reference node and the blind node, wherein \( g \) is a strictly increasing or decreasing function of this distance and wherein \( f \) is a linear function;
   optimizing an estimated position of the blind node by maximizing the extent of linear correlation between the plurality of derived values of said physical parameter and a corresponding plurality of values of said physical parameter that are predicted using the estimated position of the blind node.

2. The method of claim 1, wherein the composite function comprises at least one parameter for describing at least one of transmitter properties, receiver properties, and signal propagation properties, related to the exchange of said signal, wherein the at least one parameter is only incorporated in function \( f \).

3. The method of claim 2, wherein the composite function comprises at least one known parameter for describing at least one of transmitter properties, receiver properties, and signal propagation properties, related to the exchange of said signal, wherein the at least one known parameter is incorporated in function \( f \) and/or function \( g \).

4. The method of any of the previous claims, comprising determining the extent of linear correlation using the covariance of the plurality of derived values and the corresponding plurality of predicted values, divided by the standard deviation of the plurality of predicted values.

5. The method of any of the claims 1-4, comprising determining the extent of linear correlation using the product-moment correlation of the plurality of derived values and the corresponding plurality of predicted values.
6. The method of any of the previous claims, wherein said optimization comprises taking the mean position of the reference nodes as an initial estimate for the position of the blind node.

7. The method according to any of the previous claims, comprising exchanging a plurality of signals between the reference nodes and the blind node with the blind node being at substantially the same position, deriving values for said physical parameter from each of the exchanged signals, and determining, for each reference node, a mean of the derived values, wherein said optimizing comprises optimizing an estimated position of the blind node by maximizing the extent of linear correlation between the plurality of determined mean values of said physical parameter and a corresponding plurality of values of said physical parameter that are predicted using the estimated position of the blind node.

8. The method according to any of the previous claims, wherein the exchanged signal comprises an electromagnetic, acoustic, light, magnetic or electrical signal that is sent from the blind node to the reference node or an electromagnetic, acoustic, light, magnetic or electrical signal that is sent from the reference node to the blind node, said physical parameter comprising a received signal strength of the signal received by the reference node or blind node, respectively.

9. The method according to claim 8, wherein the composite function comprises a log-normal shadowing model.

10. The method according to any of the claims 1-7, wherein the exchanged signal comprises an electromagnetic, acoustic, light, magnetic or electrical signal that is sent from the blind node to the reference node or an electromagnetic, acoustic, light, magnetic or electrical signal that is sent from the reference node to the blind node, said physical parameter comprising a time of flight of the signal between the reference node and the blind node.

11. The method according to any of the previous claims, further comprising exchanging a signal between each of the reference nodes and an additional blind node; for each signal exchanged between a given reference node and the additional blind node, deriving a value for said physical parameter from said exchanged signal; optimizing an estimated position of the blind node and the additional blind node by maximizing the extent of linear correlation between the plurality of derived values of said physical parameter and a corresponding plurality of values of said physical parameter that are predicted
using the estimated position of the blind node and the estimated position of the additional blind node.

12. The method according to claim 11, further comprising exchanging a signal between the blind node and the additional blind node, and deriving a value for said physical parameter from said exchanged signal.

13. The method according to any of the previous claims, grouping the plurality of reference nodes, the blind node and/or the additional blind node in a plurality of node groups, said optimizing comprising determining, for each node group, the extent of linear correlation between the plurality of derived values and the corresponding plurality of predicted values, and maximizing the combined extent of linear correlation using the determined extent of linear correlation of each node group.

14. The method according to any of the previous claims, wherein the position of the blind node and/or additional blind node changes during the exchanging of signals between the blind node, the additional blind node and the reference nodes, each exchanged signal being associated with the position the blind node or the additional blind node was at during the exchange of said signal, the method further comprising taking one position of the blind node or the additional blind node among the different positions during said exchanging of signals as the estimated main position of the blind node or additional blind node, and calculating the other positions of the blind node or additional blind node during said exchanging of signals based on the main position and a calculated displacement of the blind node or additional blind node when moving from the main position to the other positions, said optimizing comprising optimizing an estimate of the main position of the blind node or the additional node by maximizing the extent of linear correlation between the plurality of derived values of said physical parameter and a corresponding plurality of values of said physical parameter that are predicted using the estimated main position and the other positions of the blind node or the additional blind node.

15. A localization system, comprising:
   a processing unit;
   a plurality of reference nodes, each reference node having a known and different position;
   a blind node having an unknown position;
   wherein the reference nodes each comprise a transmitter, a receiver or a transceiver and
wherein the blind node comprises a transmitter, a receiver or a transceiver, said reference nodes and said blind node being configured to exchange a signal between the reference nodes and the
blind node, wherein the reference nodes and/or the blind node comprise(s) a deriving unit for
deriving a value for a given physical parameter from the exchanged signal and for sending the
derived value to the processing unit;

wherein the processing unit is configured for carrying out the method of any of the
previous claims to find an estimated position of the blind node using the derived values.

16. The localization system according to claim 15, wherein the reference nodes are
configured to send their position to the processing unit.

17. The localization system according to claim 15 or 16, wherein the processing unit is
implemented in the blind node.
FIG. 3
**INTERNATIONAL SEARCH REPORT**

**A. CLASSIFICATION OF SUBJECT MATTER**

INV. G01S5/14  G01S5/30  G01S5/16

According to International Patent Classification (IPC) or to both national classification and IPC

**B. FIELDS SEARCHED**

Minimum documentation searched (classification system followed by classification symbols)

G01S

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

EPO-Internal, WPI Data

**C. DOCUMENTS CONSIDERED TO BE RELEVANT**

<table>
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<tr>
<th>Category*</th>
<th>Citation of document, with indication, where appropriate, of the relevant passages</th>
<th>Relevant to claim No.</th>
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<tr>
<td>X</td>
<td>EP 2 141 957 A1 (IBBT VZW [BE]; UNIV BRUXELLES [BE]) 6 January 2010 (2010-01-06) abstract paragraphs [0010], [0023] -----</td>
<td>1-17</td>
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Further documents are listed in the continuation of Box C.

See patent family annex.

* Special categories of cited documents:

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**Date of the actual completion of the international search**

30 May 2017

**Date of mailing of the international search report**

08/06/2017

Name and mailing address of the ISA/

European Patent Office, P.B. 5818 Patentlaan 2
NL - 2280 HV Rijswijk
Tel. (+31-70) 340-2040,
Fax. (+31-70) 340-3016

Authorized officer

Albergia, Vito
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