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Accurate Node Localization with Directional Pulsed Infrared Light for Indoor Ad Hoc Network Applications

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Abstract—**We present a localization scheme for indoor ad hoc networks which use pulsed infrared light as the communication medium.**

Ad hoc networks are formed when devices with wireless communications capabilities spontaneously connect and exchange information packets. Typically, in wireless ad hoc networks, nodes estimate their position relative to their neighbors by processing the location information in conjunction with the certain physical properties of the signals they receive, such as signal strength, bit error rate, or time difference of arrival. Unfortunately, widely used low-cost infrared transmitters and receivers for indoor applications do not allow measurement of these properties easily. To overcome this, we have developed a system which relies only on the reception of a data frame and is capable of estimating the angular direction of the infrared signal source within an error margin of +/- 5 degrees. Then, through the application of triangulation, a node estimates its relative position with respect to its neighbors.

One effective method of translating a relative position to an absolute one is to use anchor nodes. These nodes broadcast their exact location. Each receiving node then progressively fixes its position and broadcasts the position updates, leading to the entire network localizing itself. A major drawback of this approach arises in large networks, where the average hop distance between an anchor and ordinary nodes is large, and position estimation errors inevitably start to accumulate. In order to alleviate this problem, we have developed the Anchor Hop Distance Weighted Localization (AHDWL) algorithm to selectively weigh position estimates at each hop. We found that the AHDWL algorithm is very effective in reducing propagation of positioning errors.

I. INTRODUCTION

Wireless ad hoc networks are cooperating devices with wireless communication capability which can form and maintain a fully connected communication system without any infrastructure support. The devices can be stationary or mobile. A typical application of such networks could be a swarm of indoor vacuum cleaners that communicate to effectively coordinate the cleaning of large areas. Due to the rapid drop of the cost of hardware and development of miniaturization, the potential uses of ad hoc networks, especially in indoor environments, are rapidly expanding. Some examples are *The Internet of Things* [1]–[3], Machine-to-Machine (M2M) communications networks [4]–[7], and smart environments [8], [9].

Localization in wireless ad hoc networks is important since it allows the nodes to learn their precise location, and use this information for various self-organization algorithms, including interacting intelligently with their environment or other nodes in the network.

In this paper, we present a pulsed infrared (IR) light based localization scheme for indoor ad hoc networks. Our main objective was to build a system which is fairly accurate, uses extremely low-cost components only, and is therefore suitable for inexpensive consumer applications. The scheme is unique in two ways: First, explicit received signal strength (RSS) information is not required to determine angles or distances between nodes (this approach allows the use of readily available IR transmitter/receiver modules, which do not provide any RSS information). Second, to mitigate the propagation of localization errors, and to improve the accuracy of the scheme, *Anchor Hop Distance Weighting Localization (AHDWL)* was developed.

In the following sections, after a brief discussion of the localization techniques, the scheme's details and its performance data are provided.

A. Localization in Wireless Ad Hoc Networks

Many applications in ad hoc networks require localization to determine node positions (either relative to each other or absolutely). Many higher layer applications require at least relative localization information to perform tasks such as geographical routing, location based addressing and sensor mapping. In the case of MANETs localization information is particularly critical as nodes must be able to determine their locations and that of their neighbors to effectively interact with each other and coordinate tasks.

An obvious way to achieve localization would be to use existing infrastructure such as GPS, but in a network of multiple nodes such a solution would increase node complexity and costs as well as reducing lifespan. Also such a system would be limited to the infrastructure that supports it, for example GPS is often only accurate for outdoors. A more autonomous approach is for nodes to determine their positions from their immediate neighbors, forming a distributed localization network which has the added advantage of energy efficiency.

There are two families of localization techniques for wireless ad hoc networks. Namely, range based techniques in which nodes measure distances or angles to other reference nodes to determine their position, and range free techniques where nodes are not required to do so, relying on connectivity

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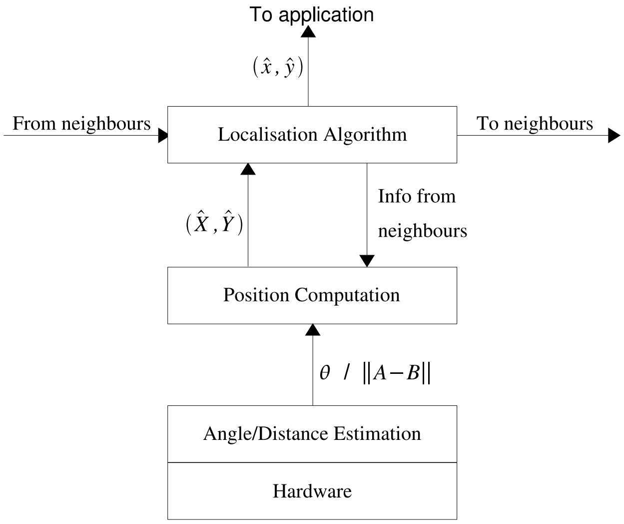

Fig. 1. Components of a typical localization system. A node calculates an instantaneous estimate of its position $(\hat{X}, \hat{Y})$ and the localization algorithm improves the accuracy of this position estimate over time using various methods to give $(\hat{x}, \hat{y})$.

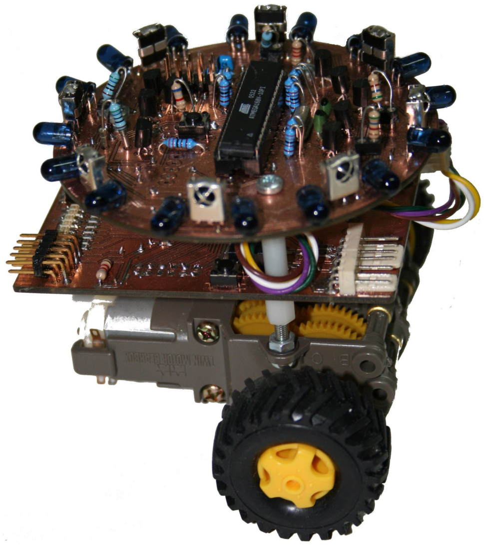

Fig. 2. One of the nodes of our wireless ad hoc network testbed. The localization board containing the 16 infrared LED transmitters and 8 receivers is seen at the top.

information to determine node positions. IR communications are suitable for range based localization as angles can be readily calculated due to the high directionality of IR transceivers.

The procedure for range based localization can be broken into three stages. Firstly, nodes must determine their distances and bearings to other reference nodes. Then using this information, by geometric principles (triangulation for example), a position estimate can be calculated. A localization algorithm is used to determine how position estimates are shared and combined to produce accurate localization across the network. An overview of the process is depicted in Figure 1.

Often, in an ad hoc network, a small number of nodes will know their absolute position exactly, being either pre-programmed and stationary or having access to outside localization means such as GPS. These nodes are commonly referred to as anchor nodes, acting as fixed known points in the network. In many ad hoc localization schemes, nodes adjacent to the anchor nodes can determine their positions, and following this their neighbors can do likewise. In this way, localization information can propagate through the network over time through iterations. The goal of such schemes is to allow nodes with unknown locations to make accurate, stable and quickly converging position estimates. A problem with iterative schemes is the potential accumulation of errors at each hop away from the anchor nodes, which can render position estimates unreliable in large networks.

II. LOCALIZATION WITH DIRECTIONAL PULSED INFRARED LIGHT

Relative bearing estimation by each node forms the basis of this range based localization scheme. The nodes share the current position estimation and bearing data with their immediate neighbors. The scheme requires a small number of nodes in the network to know their positions absolutely (at least two anchor nodes are required to allow initial position estimates to be made). Once initial estimates have been made, other nodes not adjacent to the anchors can make position estimates, followed then by their neighbors. The iterative localization scheme presented here makes use of an anchor hop distance weighted localization (AHDWL) algorithm to weigh position estimates based on node hop count from anchors in order to reduce the effects of error accumulation from the anchors.

First, nodes determine bearings to their immediate neighbors as described in Section II-B. Bearing calculations are done by processing the sequences of messages sent over a range of power levels, via the circular IR transmitter/receiver arrays on the nodes (Figure 2) which form the testbed for the project. Then, once bearing and position data are obtained from other nodes, they calculate a position estimate via intersection of circles (Section II-C). The calculation is refined iteratively as new information is received. Finally, position estimates are combined using the AHDWL algorithm in order to accurately determine a nodes current position (Section II-D).

A. *Infrared Localization Boards*

We designed the localization boards of the ad hoc network nodes as follows. Each node's localization board consists of a circular arrangement of sixteen directional IR LEDs and eight BRM-1030 IR receivers in a circular arrangement as shown in Figure 3. The ATmega168 microcontroller is used for generating pulses and processing the received information. As the figure shows, a beacon message sent by a transmitter can be received simultaneously by a number of receivers. Each beacon message contains the sending node's ID, transmitting LED's ID and power at which the packet transmitted. This information, when received by one or multiple receivers, is used to calculate the relative bearing between a transmitting

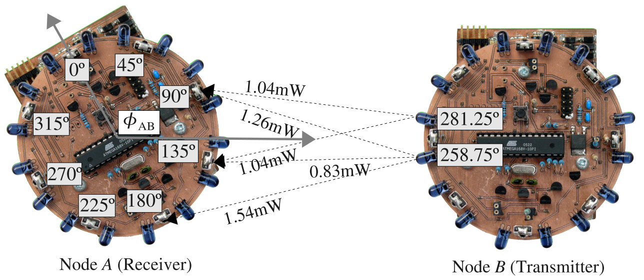

Fig. 3. An example of relative bearing (ϕ_{AB}) estimation based on received beacon messages.

and receiving node. The details of the calculation are described next.

B. Bearing Calculation

The BRM-1030 receiver module [10] is a low cost IR receiver, used in typical low data rate domestic applications such as remote controls. It is an integrated package which buffers the received signal through amplifier, band pass filter (centered at 38 kHz), integrator and comparator stages to obtain a digital signal. It is not possible to measure the properties of the original signal with such a device, particularly received signal strength (RSS), having passed the signal through this multistage system.

However, the characteristics of the BRM-1030 allow for "channel connectivity" to be used as an indirect measure of RSS. In our extensive tests [11], we found that for a series of transmitted pulses, the device either receives almost all pulses or none at all, so it can be said that the channel is either "connected" or not. We also identified a clear relationship between transmission power, transmitter and receiver angles. Detection of a packet, "a series of transmitted pulses", fail as the relative angle between a transmitter and receiver increases. To combat this, either a higher transmission power or shorter transmitter-receiver distance is required for a packet to be detected. This finding, combined with the arrangement of the arrays of transmitters and receivers on the system allowed us to do "indirect measurements" of RSS, utilizing transmission power to calculate bearings.

The method is similar to Hoyt, McKennoch and Bushnells approach [12], where the centroid of the received signals is calculated by taking their power levels into account. However, their approach involves taking explicit RSS measurements at the receivers of a signal transmitted at constant power. In our method, rather than taking RSS measurements of a constant power signal, a series of beacon packets at increasing transmission power levels is sent in all directions and connectivity of the receivers is used to determine a neighbors bearing (relative to an arbitrary 0° bearing) as follows

$$\phi_{ij} = \frac{\sum_{n=1}^{N}(P_{\text{max}} - P_n)\varphi_n}{\sum_{n=1}^{N}(P_{\text{max}} - P_n)} \tag{1}$$

where,

ϕ_{ij} = bearing of node $j$relative to node i
N = total number of receivers which received a message from node$j$
P_{max} = maximum power level at which a message in the beacon packet sequence is transmitted
P_n = minimum transmission power at which a message was received on Rx_n
φ_n = local bearing of receiver relative to 0° bearing

The centroid of the received sequence is found by recording the lowest transmission power of the received packets for each receiver, and giving greater weighting to those receivers that received packets at lowest power. The distance between nodes is not critical as the circular arrangement of the transmitter and receiver arrays means symmetric pairs will form, effectively cancelling each other out in Equation 1.

There are two ways in which bearings can be estimated using this technique. The first is passive reception of the packet sequences, where the lowest transmission power packet correctly decoded on each receiver is recorded and placed into Equation 1 to obtain a bearing estimate. The second method is active reception, where nodes that receive beacon packets send reply packets back to the transmitting nodes (where the estimate is made) indicating what packets have been received and from which transmitter LED. This would provide for more accurate estimates given that a node has double the number of transmitters as receivers, but the transmission of reply messages from several nodes would require the use of a quite sophisticated media access control (MAC) in order to prevent collisions. On the other hand, since the passive reception at the receiver does not require replies to be sent, the likelihood of collisions is reduced. In this project, we used the passive bearing estimation.

C. Position Estimation

In traditional trilateration based localization systems, a node requires three external reference points to unambiguously calculate its position in two dimensions. The nodes of our experimental ad hoc network however, can calculate the bearings of its neighbour nodes, and based on this information then determine the discrimination angles between nodes. This allows position estimates to be made with only two reference nodes of known position.

The algorithm presented in this research does not require nodes within the network to have a consistent orientation, or known bearing relative to their neighbours.The nodes only measure angles to neighbours relative to an arbitrary, but locally consistent, local 0° bearing as discussed in Section II-B. These angles are denoted by ϕ_{ij} (see Figure 4), which represents the angle the node i sees node j, relative to node i's local bearing. The discrimination angle between the nodes can then be found by calculating the difference between two ϕ angles. For example, the discrimination angles in Figure

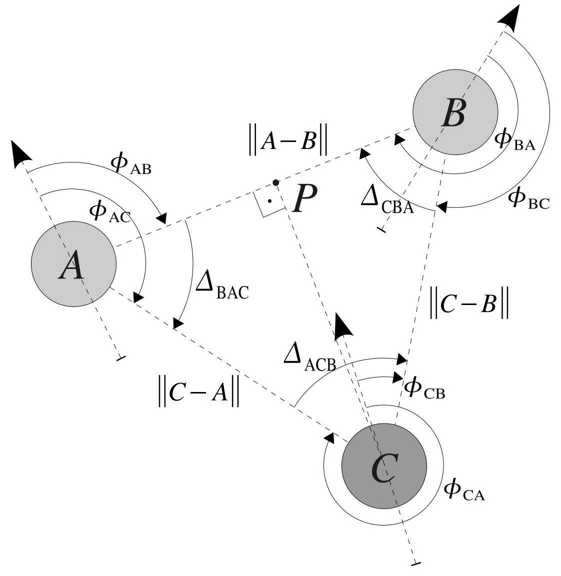

Fig. 4. The angles and a neighbor triangle used for localization.

4 Δ_{BAC}, Δ_{CBA} and Δ_{BAC} can be calculated using the following equations

$$\begin{aligned}\Delta_{ACB} &= (\phi_{CB} - \phi_{CA} + 360)(\mathrm{mod}360) \quad (2)\\ \Delta_{CBA} &= (\phi_{BA} - \phi_{BC} + 360)(\mathrm{mod}360) \quad (3)\\ \Delta_{BAC} &= (\phi_{AC} - \phi_{AB} + 360)(\mathrm{mod}360) \quad (4)\end{aligned}$$

The positions of the reference nodes A and B are also shared, from which the distance $\| A - B \|$ between them can be calculated. Using this and the calculated discrimination angles, node C can calculate its distance to the reference nodes A and B using the sine rule

$$\|C - A\| = \frac{\|A - B\| \sin(\Delta_{CBA})}{\sin(\Delta_{ACB})}, \quad (5)$$

$$\|C - B\| = \frac{\|A - B\| \sin(\Delta_{BAC})}{\sin(\Delta_{ACB})}. \quad (6)$$

The problem is then reduced to an intersection of two circles (Figure 5). Here, we introduce point P along the line AB which is perpendicular to node C. By Pythagoras theorem

$$\|C - A\|^2 = \|P - A\|^2 + \|P - C\|^2 \quad (7)$$

and

$$\|C - B\|^2 = \|P - B\|^2 + \|P - C\|^2 \quad (8)$$

also

$$\|P - A\| = \|A - B\| - \|P - B\| \,. \quad (9)$$

From Equations 7, 8 and 9 it is found that

$$\|P - B\| = \frac{\|C - B\|^2 - \|C - A\|^2 + \|A - B\|^2}{2\,\|A - B\|}. \quad (10)$$

Using this result and Equation 8,

$$\|P - C\| = \sqrt{\|C - B\|^2 - \|P - B\|^2}. \quad (11)$$

As points A, B and P lie on the same line, coordinates of P can be calculated using the ratios of PB and AB as follows

$$x_P = x_B - \frac{\|P - B\|\,(x_B - x_A)}{\|A - B\|} \quad (12)$$

$$y_P = y_B - \frac{\|P - B\|\,(y_B - y_A)}{\|A - B\|}. \quad (13)$$

This then allows the coordinates of node C to be calculated by using the equation of a point perpendicular to AB for a distance $\|P - C\|$ away from point P. Note that, as there are only two reference nodes, it is an undetermined system with two symmetric solutions as shown in Figure 5:

$$\begin{aligned}x_{C1} &= x_P + \frac{\|P - C\|\,(y_A - y_B)}{\|A - B\|} \quad (14)\\ y_{C1} &= y_P - \frac{\|P - C\|\,(x_A - x_B)}{\|A - B\|} \quad (15)\end{aligned}$$

and

$$\begin{aligned}x_{C2} &= x_P - \frac{\|P - C\|\,(y_A - y_B)}{\|A - B\|} \quad (16)\\ y_{C2} &= y_P + \frac{\|P - C\|\,(x_A - x_B)}{\|A - B\|}. \quad (17)\end{aligned}$$

To eliminate the geometrically incorrect "phantom" solution, we used the following disambiguation method:

```
if $\|x_A - x_B\| \geq \|y_A - y_B\|$ then
  if $x_A < x_B$ then
    if $\theta_{ACB} < 180$ then
      Choose solution with smallest $y$
    else
      Choose solution with largest $y$
    end if
  else
    if $\theta_{ACB} < 180$ then
      Choose solution with largest $y$
    else
      Choose solution with smallest $y$
    end if
  end if
else
  if $y_A < y_B$ then
    if $\theta_{ACB} < 180$ then
      Choose solution with largest $x$
    else
      Choose solution with smallest $x$
    end if
  else
    if $\theta_{ACB} < 180$ then
      Choose solution with smallest $x$
    else
      Choose solution with largest $x$
    end if
  end if
end if
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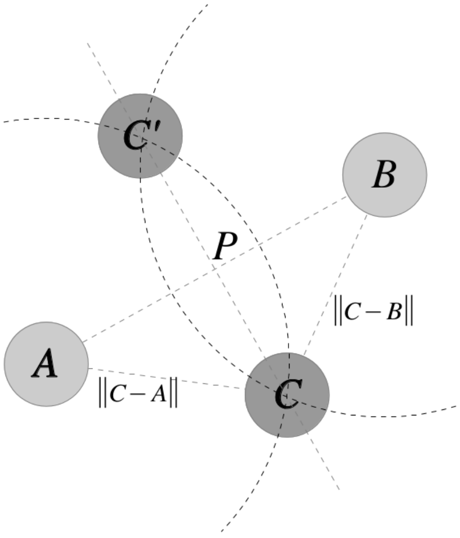


Fig. 5. Localization with intersection of two circles and elimination of the phantom location by using discrimination angles.

A correct position estimate is made based on the size of the angle between the two reference nodes about the node C. The phantom elimination algorithm is run in the x or y exis, whichever provides greatest distance between the two reference nodes. This improves the reliability in the event of measurement errors, reducing the risk of an incorrect solution being selected. This method also works for cases where $\|y_A - y_B\| = \|x_A - x_B\|$.

An additional point to note about position estimation is the requirement that only "well conditioned" triangles as described by Chandra [13] should be used to make estimates.

D. Anchor Hop-Distance Weighted Localization

In a relatively dense ad hoc network, nodes will have multiple neighbours from which they can make position estimates. All of these estimates must be combined into a single estimate which a node takes as its current estimated position and communicates to its neighbours. In iterative localization schemes, as time goes on, more nodes become able to estimate their positions, these nodes then become references from which their neighbours can make position estimates. Over time, localization information propagates from anchor nodes across the network and accuracy improves as more reference nodes become available to do position estimation.

The AHDWL algorithm is based on an iterative exponential weighted moving average (EWMA). An EWMA applies weighting coefficients to data points which decrease exponentially; in localization terms this means that the weighting for each older position estimate decreases exponentially giving greater importance to recent estimates whilst not totally discarding the older estimates. A general EWMA equation is given by

$$\begin{aligned} S_t &= \alpha S_{t-1} + \beta Y_t && (18) \\ \alpha &= 1 - \beta && (19) \end{aligned}$$

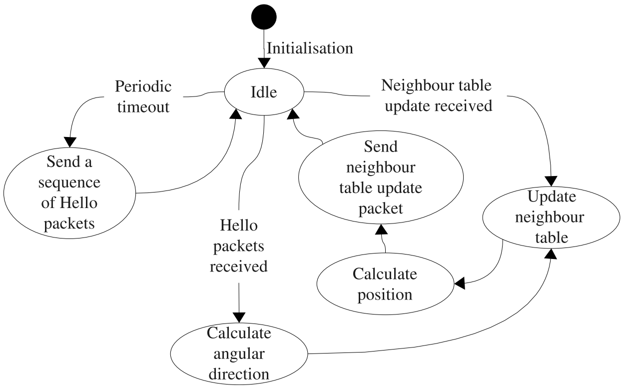


Fig. 6. Overview of the operation of the AHDWL algorithm on a node.

where, S_t and S_{t-1} are current and previous EWMA values, and Y_t is the latest estimate made. For localization, Equation 18 can be used to continually update a nodes position each time a new position estimate is made. In that case S_t is its averaged new position, S_{t-1} is its previous averaged position, and Y_t is the latest instantaneous position estimate made.

Iterative localization schemes suffer from accumulation of errors at each hop away from the anchor nodes, as they rely only on immediate neighbours to do position estimation. Any position estimation errors will be passed onto neighbours and propagate across the network. This can render position estimates unreliable, particularly in large networks.

The AHDWL algorithm uses the anchor hop counts of reference nodes (how many hops each reference node is from an anchor node) to selectively weigh individual position estimates in the EWMA equation. It assumes that the further away nodes are from an anchor node, the more likely they are to have larger errors in their position estimates due to error accumulation. Likewise, the closer a node is to an anchor node the smaller the error is likely to be. Thus estimates made with anchor nodes, or nodes close to the anchor nodes are considered better quality estimates and given higher weightings.

Additional weighting coefficients are added to the EWMA equation so that new position estimates are weighted based on anchor hop count. There are various ways to go about this, in the following scheme weighting is inversely proportional to hop count:

$$W = \frac{1}{d_A + d_B + 2} \qquad (20)$$

where W is weighting coefficient, d_A and d_B are anchor hop counts of nodes A and B, β is weighting coefficient in EWMA, $\beta = W\beta_{\text{base}}$ and $\beta_{\text{base}} = 2 \times$ maximum value of β. For simplicity β is fiven here as the average hop count of the two reference nodes. β_{base} represents the maximum weighting of a position estimate. In our implementation β_{base} is set to 0.7, so the maximum weighting is 0.35. An overview of the operation of the algorithm is provided in Figure 6.

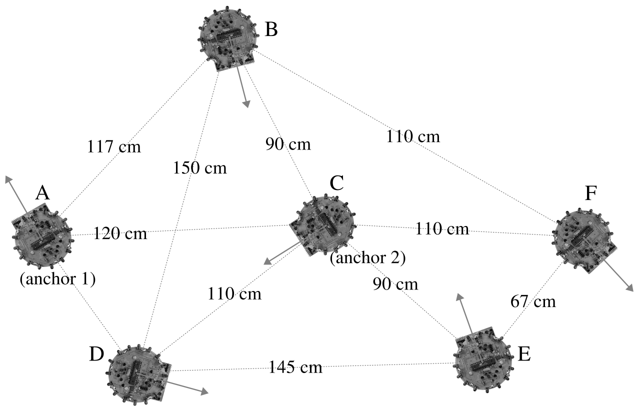


Fig. 7. Configuration of the testbed.

III. PERFORMANCE EVALUATION

We evaluated the performance of the localization scheme in two stages. First, we constructed a small scale testbed to validate the algorithms and also collected data on the properties of the infrared channel. Then, by using the testbed data, we created a simulation environment and calibrated its physical layer model. We used the simulations to investigate the large-scale performance and scalability of the system.

A. Testbed Experiments

The testbed configuration is shown in Figure 7. Our experiments showed an average localization error of 32 cm. Extensive information on code implementation, and a detailed discussion of the collected data can be found in Priestnall's report [14].

B. Simulations

We examined the performance of the AHDWL algorithm on larger topologies by using a simulator created for this purpose as described in [11]. The simulator is based on the experimental infrared channel characteristics obtained from the infrared ad hoc network testbed.

We report the effectiveness of the AHDWL algorithm by comparing its absolute position estimation errors of the nodes against the position estimates obtained using the iterative EWMA algorithm. Each algorithm was tested using 100-node random topologies. A typical network topology is shown in Figure 8. A random topology is typical of a network which may be found in real life, where nodes are placed randomly without regard of resulting topology (however, the nodes are usually arranged with minimum connectivity requirements to ensure a fully connected network). A random network results in many poorly conditioned triangles as discussed in Section II-C, which provide a good basis for the evaluation of the robustness of position estimations.

Each network topology evaluated contained 12 anchor nodes, with 3 nodes positioned at each corner of the simulation area. The anchor nodes must be placed in clusters of at least two, as bearing estimation algorithm described in Section II-B requires at least two reference nodes to calculate a position estimate. The clusters of three anchor nodes at each corner were positioned in an L shape to provide a good geometric basis for localisation. If only two anchor nodes were placed at each corner, it would be possible that the anchor nodes would be colinear with the node attempting to calculate its position, in which case the node would fail to localise itself correctly. Positioning the three anchor nodes in a 90° arrangement allows the nodes to localise themselves with low risk of falling into colinear geometry.

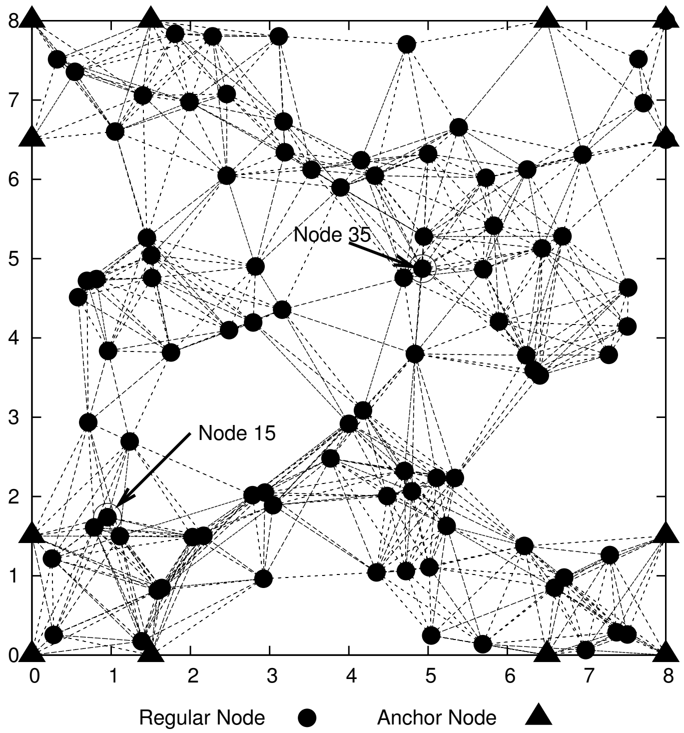


Fig. 8. Randomly placed 100-node topology. Two nodes, 15 and 35, were selected for special attention to illustrate the expected behaviour at different locations within the network.

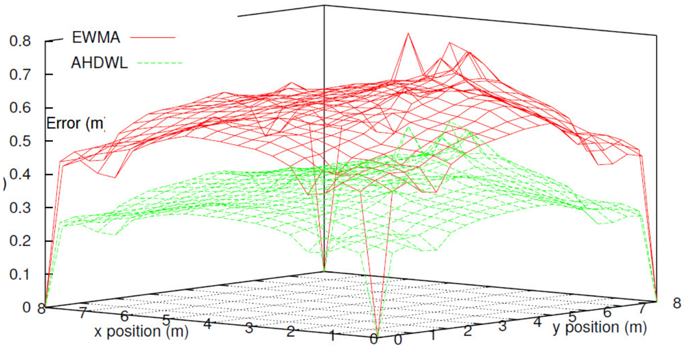
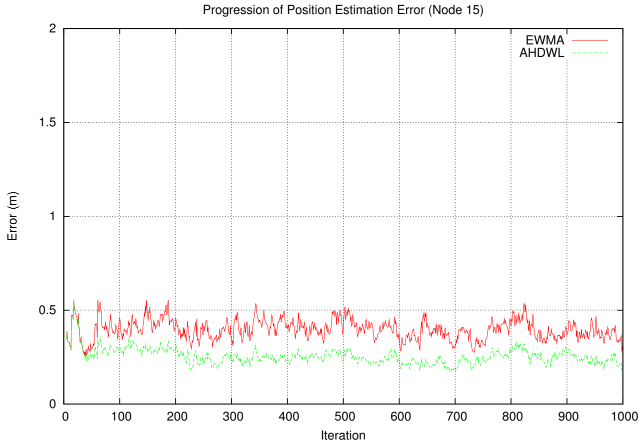
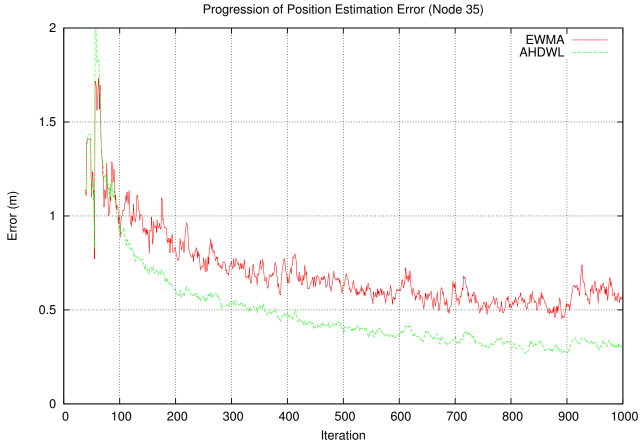


Fig. 9. Distribution of the position estimation errors across the network.

Each scenario was simulated 20 times using different random number seeds. This ensured that the results obtained were



(a) Node 15 (0.9545, 1.7389)



(b) Node 35 (4.926, 4.877)

Fig. 10. Convergence of the position estimation errors.

a reliable indication of what would be expected to occur in a physical, real life, network. Each algorithm (EWMA and AHDWL) was simulated using the same set of 20 seeds, this ensured that node orientation, IR component placement and message ordering was kept constant for each algorithm. This meant that the only variable changed between experiments was the algorithm used to filter the instantaneous position estimates.

For each experiment, the EWMA smoothing factor β_{base} was empirically set to 0.7. The larger β_{base}, the faster the algorithm will respond to changes. However, increasing β_{base} also increases the sensitivity of the algorithm to transient fluctuations. A β_{base} of 0.7 was found to provide quick convergence of position estimates with reasonable noise immunity.

The position estimation error distribution is shown in Figure 9. The red surface represents the position errors when using the iterative EWMA algorithm. The green surface represents the position estimation errors across the network with the AHDWL algorithm. It can be easily seen that the introduction of weighting factors based on the anchor hop distance greatly improves the position estimates for all nodes within the network.

Figure 10 shows the two nodes chosen for special attention in the 100-node random topology. Node 15 was chosen to represent nodes which are close to the anchor nodes, and Node 35 was chosen to represent nodes near the middle of the network. Figure shows that the AHDWL algorithm converges to a more accurate position estimate than the fixed-weight iterative EWMA algorithm. Node 15 is able to localize itself more accurately than node 35, as it is closer to anchor nodes and thus the position estimates have encountered smaller number of hops, and therefore have had less chance to become corrupted by measurement errors.

IV. CONCLUSION

In this paper, we presented a localization scheme for indoor ad hoc networks. It is unique in two ways, firstly in the way position estimates are calculated without the need for signal strength indicators and secondly in the way position estimates are combined to reduce error caused by error propagation over multiple hops.

Typically, in wireless ad hoc networks, nodes estimate their position relative to their neighbors by processing the location information, and certain physical properties of the signal they receive, such as signal strength, bit error rate, or time difference of arrival. But, widely used low-cost IR transmitters and receivers for indoor applications do not allow measurement of these properties easily. To overcome this, we have developed a system which relies only on the reception of a data frame and is capable of estimating the angular direction of the IR signal source within an error margin of +/- 5 degrees. Then, through the application of triangulation, a node estimates its relative position with respect to its neighbors. One effective method of translating a relative location to an absolute one is to use anchor nodes. These nodes know their exact location and broadcast this information to their neighbors. Each node then progressively fixes its position and broadcasts the position updates, leading to the entire network localizing itself. A major drawback of this approach arises in large networks, where the average hop distance between an anchor and ordinary nodes is large, and position estimation errors inevitably start to accumulate. In order to alleviate this problem, we have developed the Anchor Hop Distance Weighted Localization (AHDWL) algorithm to selectively weigh position estimates at each hop. We have found that the AHDWL algorithm is very effective in reducing propagation of positioning errors.

A test network was created to evaluate the performance of the localization system using directional pulsed IR light. In addition, a simulator based on the experimentally obtained channel characteristics was developed for rapid evaluation of the localization algorithm on large networks. Results show that using our approach, an IR network built with low-cost consumer grade components which lack explicit signal strength or bit error rate measurement capabilities, can accurately estimate the position of its member nodes.

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