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An Anchorless Cooperative Localization System for Wireless Ad-Hoc Networks

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Abstract **– In this paper, we propose a wireless ad-hoc localization system where each node is assumed to be equipped with ranging (RSSI/TDoA) and AoA capability. Using these capabilities each node can measure distance and bearing of neighboring nodes. These measurements are supplied to each connected nodes in the network. Using the measurements of each neighboring node pairs, a node can construct a whole network coordinate map, where the location of every node is shown relative to a reference point (i.e. the node's own location). Using this network coordinate map, the nodes can maintain connectivity with their neighbors. Unlike triangulation, the system does not need at least two or more neighbors of each node for approximating the node position, rather it can attain this even with a single neighbor. We will also show that the system has reliable accuracy when more accurate ranging and angulation systems are used.**

Keywords **– Ad-Hoc Networks, Localization, Triangulation, Lateration, Angulation, Network Coordinate Map.**

I. Introduction

Mobile ad hoc networks (MANET) are dynamic networks formed on-the-fly as mobile nodes move in and out of each other's transmission ranges. In general, the mobile ad hoc networking model makes assumption that the nodes know neither their own locations nor their neighbors. However, earlier researches show that location-awareness of the ad-hoc nodes can enhance fundamental tasks such as routing and energy-conservation. Positioning of nodes is important for ad-hoc protocols like Location Aided Routing (LAR) [1] and Geodesic Packet Forwarding [2] protocols. Many applications, e.g., asset tracking, determining direction, emergency notification, and location sensitive content delivery can be built on top of positioning systems. Again most related works on ad-hoc networks focusing on maintaining networking connectivity of the networks emphasize on the location awareness of the nodes.

In this paper, we presume that we got a finite and limited number of nodes browsing over a large geographic area. The terrain characteristics may be counted as an important factor, for example in disaster recovery tasks. In such uneven fading condition a node has a great chance to get stuck at local minima of RSS (Received Signal Strength). As the number of nodes in the team is shallow thus each node has an important role as a relay. If any node is out of the network then the whole or partial network connectivity is interrupted and it may be quite difficult to recover it. But if the node has the knowledge that it can retain the RSS by moving a few steps towards a certain direction then we can guarantee that the network connectivity between the nodes can be maintained with higher quality. Thus we can see that location awareness of the nodes of themselves and the neighbors can provide rich connectivity in an ad-hoc system.

Therefore, we see that in wireless ad-hoc networks, irrespective to their environment and scale, we need nodes to be able to locate themselves, which we refer to as 'localization', is a challenging one and key for many ad-hoc applications.

Now we review the facts in positioning of nodes in such scenario we depicted above. We got an option to implant a GPS chip in each or some nodes, which is not quite cost effective, and may be impractical due to power and form factor constraints. Again GPS need LOS, for which it is erroneous in indoor locations. In this paper, we assume that we cannot have some node acting as anchors or landmarks due to some inconvenience.

In terrestrial positioning systems, most of them are based on triangulation which demands at least two or more neighbors to exist always. But the fact is, we cannot have at least two or three neighbors of a node all the time where the total number of nodes in the network is limited but the space is large enough. Fig. 1 shows a simulation result of a MANET with 10 (ten) nodes roaming over 200 meter × 200 meter space. The nodes have transmission power of 0.1 watt with unit antenna gain and no internal losses. The nodes are moving towards random directions at maximum speed of 1 meter/second. The simulation is run for 100 seconds. The graph shows the number of one hop neighbors of an arbitrary node with respect to time. From the graph we see that the node has more than two neighbors only 23% of the time, while it has more than one neighbor 45% of the time. 30% of the time the node has only one neighbor. During this time, the node has connectivity with the network, but cannot be located exactly by other nodes using traditional triangulation methods.

Based on the fact that, most triangulation based localization method make use of a single measurement metric such as RSSI (Received Signal Strength Indicator), AoA (Angle of Arrival), ToA (Time of Arrival), TDoA (Time Difference of Arrival), BER (Bit Error Rate) etc., and are proven much efficient in presence of sufficient number of neighbors, may become despicable without sufficient number of neighbors.

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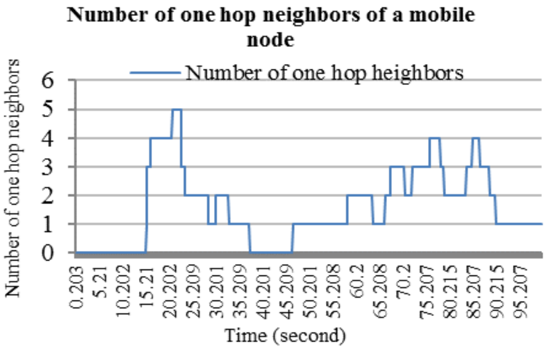

Fig.1. Number of one hop neighbors of a mobile node

In this paper, we propose a system where each node is assumed to be equipped with TDoA and AoA capability. Using these capabilities each node can measure distance and bearing of neighboring nodes. These measurements are supplied to each connected nodes in the network. Using the measurements of each neighboring node pairs, a node can construct a whole network coordinate map, where the location of every node is shown relative to a reference point (in this case, the node's own location). Using this network coordinate map, the nodes can maintain connectivity with their neighbors. The system does not need at least two or more neighbors of each node for approximating the node position, rather it can attain this even with a single neighbor. We will also show that the system has reliable accuracy when more accurate metric measurement systems are used.

II. Related Works

There has been rising interest in ad-hoc networks in recent decades, although in diverse forms such as Mobile Ad-hoc Networks (MANET), Vehicular Ad-hoc Networks (VANET), Sensor networks etc. A number of research projects have been conducted so far regarding localization of ad-hoc nodes. Existing literatures concerning localization service proposes a number of solutions. Some proposes local positioning. Local positioning refers to a technology used to determine the position of any device with respect to the other devices whose positions are already known. There are already several positioning technologies such as Global Positioning System (GPS) [3]. GPS is a precise positioning service. Some papers proposed that all the nodes should be equipped with a GPS chip while some other papers recognize this as impractical due to power and from factor constraints, line-of-sight conditions and cost ineffective for large network sizes. Some proposes a hybrid solution with both a GPS and terrestrial services [4], [5]. In our case we assume that GPS based solution is unachievable or impractical for whatever reasons. Some other papers propose the aid of aerial surveillance to generate strategy for exploration [6]. Some papers also consider the use of aerial surveillance for mapping shadowing contours. However we assume that aerial surveillance cannot be deployed too for some reasons. So, now we have only choice left for terrestrial positioning. Reference [7] proposes an indoor position technique using Bluetooth technology, which is based on trilateration and uses RSSI and Link Quality as the metrics. Another indoor positioning system is discussed in [8] which proposes coarse positioning based on clustering. A self-positioning algorithm based on TDoA is proposed in [9]. A terrestrial positioning system based on connectivity metric, utilizing an idealized radio model is presented in [10]. Reference [11] proposes a RSSI based cooperative localization algorithm using virtual reference nodes for wireless sensor networks, which can estimate the blind node position with an RSS table set. Reference [12] focuses on localization techniques based on angle of arrival information between neighbor nodes. It proposes a new localization and orientation scheme that considers beacon information multiple hops away. Reference [13] proposes a method for all nodes to determine their orientation and position in an ad hoc network where only a fraction of nodes have the positioning capabilities, under the assumption that each node has the AoA capability. A range estimation method utilizing ToA is discussed in [14] while [15] presents a TDoA based Approach.

Most of the above works are based on triangulation/trilateration methods while some proposed to utilize sensing, scene analysis or proximity for mitigating localization error.

As far we went over various localization system proposed in above mentioned and other papers, no localization technique using multiple metrics is proposed previously. But through the simulation of our proposed localization method, it is seen that multi-metric localization can be far better than single-metric localization techniques in critical situations and this location information based mobility decision can help maintain the connectivity of a node with the network.

III. Localization Techniques

A. Localization

Localization is a complex engineering problem that has many aspects beyond ad-hoc networking protocols. In context of ad-hoc networks, the specific challenges are the environment, network size and the power of individual nodes, which may not permit the application of many available solutions.

A well-known positioning system Global Positioning System (GPS), which necessarily utilizes trilateration method, is widely used for positioning of objects in large scale environment. GPS solves the problem of localization in outdoor condition for PC class nodes, i.e. the nodes have high computational power. However, for large networks of very small, cheap and low power devices, practical considerations such as size, form factor, cost and power constraints of the nodes preclude the use of GPS on all nodes. Besides GPS is not a robust positioning technique in indoor conditions. As we wish to have a localization method which requires less computational and operational cost and power of nodes, and can operate in diverse environments, we avoid the decision of using GPS. In the following section we will discuss various terrestrial localization techniques.

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B. Terrestrial Localization Systems

Because positioning is a problem that has been approached under many circumstances, classifications of positioning schemes can be made based on various criteria. There are centralized methods, which will ship all the ad hoc graph description to a central location that will perform all the processing, usually optimization. Distributed methods, by contrast, perform positioning based on localized views of the network, directly in the field.

Traditionally triangulation based algorithms are used for localization while scene analysis or proximity are developed to mitigate the measurement errors. Targeting different applications or services, these three algorithms have unique advantages and disadvantages. Hence, using more than one type of positioning algorithms at the same time could get better performance.

C. Triangulation

Triangulation uses the geometric properties of triangles to estimate the target location. It has two derivations: lateration and angulation. Lateration estimates the position of an object by measuring its distances from multiple reference points. So, it is also called range measurement techniques.

D. Lateration

Lateration techniques are used for distance measurement. Lateration computes the position of an object by measuring its distance from multiple reference positions. Calculating an object's position in two dimensions requires distance measurements from 3 non-collinear points as shown in Fig. 2. In 3 dimensions, distance measurements from 4 non-coplanar points are required.

There are three general approaches of measuring the distances required by the lateration technique: Direct measurement, Time of Flight based and Attenuation based. Time of Flight based techniques are ToA (Time of arrival) TDoA (Time Difference of Arrival), RToF (Round-trip Time of Flight), PoA (Phase of Arrival) etc. RSSI (Received Signal Strength Indicator) is an Attenuation based lateration system. Other lateration methods include BER (Bit Error Rate) based localization and different spread spectrum techniques.

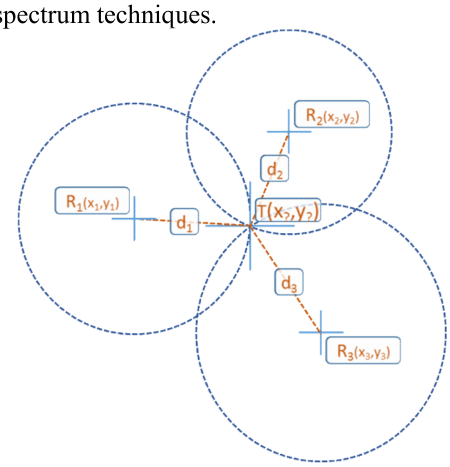

Fig.2. Lateration technique: Node R_1, R_2 and R_3 measures distance from node T, The intersection point is the approximation of position of T.

E. Angulation Techniques (AoA estimation)

In AoA based localization, the location of the desired target can be found by the intersection of several pairs of angle direction lines, each formed by the circular radius from a base station or a beacon station to the mobile target. As shown in Fig. 3, AOA methods may use at least two known reference points (T1, T2), and two measured angles $\alpha 1$, $\alpha 2$ to derive the 2-D location of the target R.

Estimation of AoA, commonly referred to as direction finding (DF), can be accomplished either with directional antennae or with an array of antennae. The advantages of AoA are that a position estimate may be determined with as few as three measuring units for 3-D positioning or two measuring units for 2-D positioning, and that no time synchronization between measuring units is required. The disadvantages include relatively large and complex hardware requirements and location estimate degradation as the mobile target moves farther from the measuring units. For accurate positioning, the angle measurements need to be accurate, but the high accuracy measurements in wireless networks may be limited by shadowing, by multipath reflections arriving from misleading directions, or by the directivity of the measuring aperture. Some literatures also call AoA as Direction of Arrival (DoA).

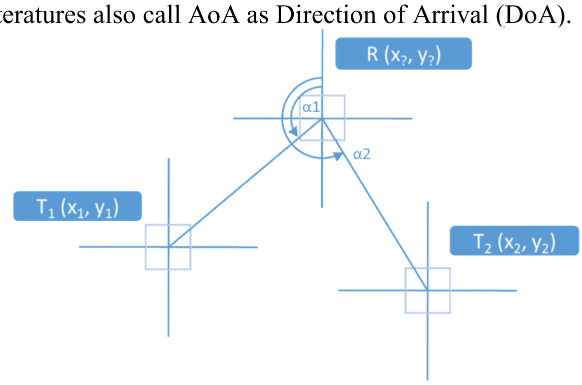

Fig.3. Positioning of Node R, where R calculates bearing of itself with respect to beacons T1 and T2 whose locations are known.

F. Other Techniques

Other localization techniques include Scene analysis and Proximity Algorithms.

G. Performance metrics

It is not enough to measure the performance of a positioning technique only by observing its accuracy. Considering the difference between the indoor and outdoor wireless geo-location, several performance benchmarking is provided for wireless location systems, such as accuracy, precision, complexity, scalability, robustness, and cost.

IV. Proposed Localization Techniques

A. Case study

From the discussion of previous section, we see that commonly used techniques for localization are based on triangulation method. Scene analysis method requires an earlier offline stage while site survey is done, which may not be possible for some applications like disaster

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recovery. Proximity based system relies upon some preinstalled infrastructures. So, for being a versatile localization system we cannot use scene analysis or proximity. Yet, the triangulation method requires each node in the network should have at least two (AoA) or three (ToA, TDoA, RSS) neighbors.

However, we are not certain this condition will always satisfy in our case where the number of nodes is limited but the survey area is large enough. Fig. 4 shows a typical connectivity graph of a simulated network topology with a small number of nodes where the nodes are uniformly distributed over the space.

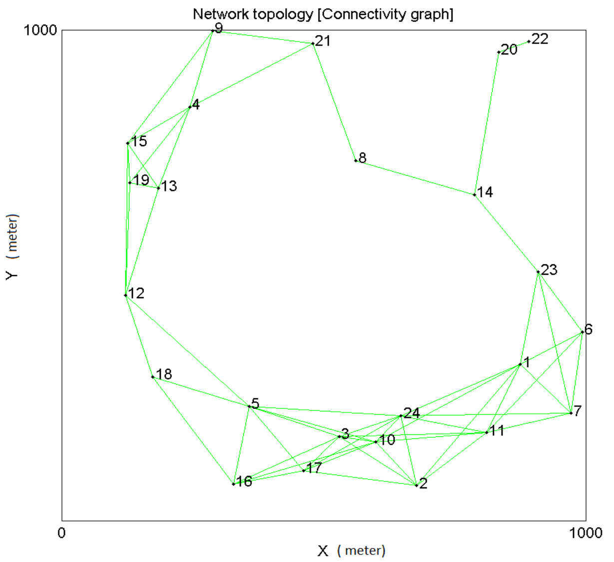

Fig.4. A typical network connectivity graph

Though the situation is not critical in terms of connectivity, but mobility of the nodes can make it crucial. In the figure node 8 and 20 has two neighbors, while node 22 has only one. Thus localization of these nodes through triangulation cannot be accomplished.

B. Proposed Localization Technique

For such cases discussed above we suggest a solution that is based on a really basic idea. Let us assume that we have a point P (x′, y′) where x′ is X-axis coordinate and y′ is the Y-axis coordinate of the point. Now we have another point Q whose coordinates are unknown, but if we only know the Euclidian distance between the points and the angle between the y = y′ line and the line joining the two points we can easily calculate the coordinates of the point Q. Literally, this system is known as polar coordinate system.

Grounding on this basic idea we propose to use the combination of the metrics, Angle of Arrival (AoA) and Received Signal Strength (RSS) / Time of arrival (ToA) / Time Difference of Arrival (TDoA) to approximate the location of a node using a single neighbor, where the availability of more neighbors makes it even more accurate. In this paper we will use AoA and RSS as the metrics.

Fig. 5 depicts the idea; In Fig. 5, the two Nodes N_1 and N_2 can calculate each other's relative locations. Both the nodes N_1 and N_2 transmit omni-directional signals. N_1 measures the bearing and the strength of the signal from N_2 while N_2 measures the bearing and the strength of the signal from N_1. The signal strength is measured in db. These measurements are used to approximate the relative locations of the nodes from each other. Thus using these data each node can construct a Network Coordinate Map (NCM), by which the nodes can make routing or mobility decisions.

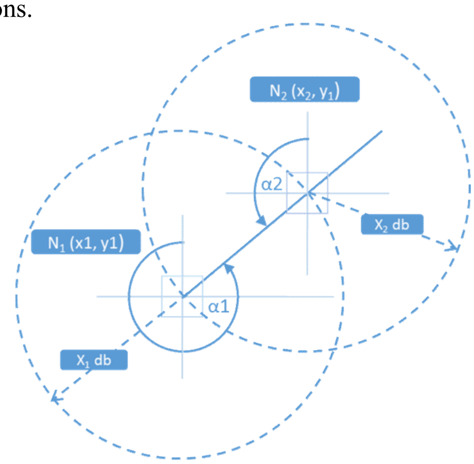

Fig.5. Using AoA and RSS to calculate relative node locations.

C. System Architecture

Let us assume that we have *n* nodes browsing over an Area A. The Nodes are denoted by N_i where $i = 1$ to n. Each node estimates the bearing in degrees (measured by AoA system with smart antenna, we assume that the node knows its own orientation using a compass sensor) and distance in meters (derived from RSS / ToA / TDoA / TDoA + RSS) of its neighboring nodes. Each of the nodes store a $n_{max} \times n_{max}$ sized matrix structured table where n_{max} is the maximum number of possible nodes in the network. Each of the elements in the table is a composite type data with properties: distance, angle and time. We denote this table as LT (short for Localization Table) or $LT_{nmax,\ nmax}$. The rows of the table correspond to the receivers and the columns correspond to transmitters. So a table entry $LT_{i,\ j}$ (b, d, t) corresponds to the bearing b and distance d calculated at time t of the node *j* by the node *i*. The clocks of the nodes must be synchronized approximately. Whenever a node receives a signal from another node it calculates the distance and bearing of the transmitting node.

b_{11} d_{11} t_{11}	b_{12} d_{12} t_{12}	b_{13} d_{13} t_{13}	b_{14} d_{14} t_{14}	....
b_{21} d_{21} t_{21}	b_{22} d_{22} t_{22}	b_{23} d_{23} t_{23}	b_{24} d_{24} t_{24}	....
b_{31} d_{31} t_{31}	b_{32} d_{32} t_{32}	b_{33} d_{33} t_{33}	b_{34} d_{34} t_{34}	....
b_{41} d_{41} t_{41}	b_{42} d_{42} t_{42}	b_{43} d_{43} t_{43}	b_{44} d_{44} t_{44}	....
....	....	....	....	....

Fig.6. Structure of Localization table (LT)

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Let the bearing of node j estimated by node i is denoted by b_{ij} and the distance of node j estimated by node i is denoted by d_{ij}. The location of node j estimated by node i is denoted by $N_{ij}(b_{ij}, d_{ij}, t)$ or $N_{ij}(x, y, t)$ where x, y is the coordinates of N_j in the network graph estimated by N_i and t is time of distance and bearing calculation. Immediately after this measurement node i updates the corresponding table entry in LT which is $LT_{i,j}$ by putting $N_{ij}(b_{ij}, d_{ij}, t)$ in $LT_{i,j}$. The process is shown in Procedure 1.

The localization table is used for constructing network coordinate graph (NCM) and NCM can be used for constructing the routing table. A node can also use NCM for making various tactical decisions such as mobility decision.

Procedure 1:

```
OnReceivePacket (Packet)
//At Physical Layer:
D = CalculateDistance()
A = CalculateAoA()
T = CurrentTime
i = MyID(Receiver ID)
j = TransmitterID

HandlePacket (Packet)
//At Network layer:
LT(i,j)->Distance = D
LT(i,j)->AoA = A
LT(i,j)->Time = T
```

The nodes periodically broadcast localization request. This may be done in the network layer. They can also broadcast localization request on demand. Whenever a node wants to send a data packet to another node, first it consults the routing table built using NCM to find the minimum and unexpired route to the receiver. A route expiration time threshold can be used based on the mobility parameters of the nodes. A route is called expired route if the lifetime of a corresponding entry in the transmitter's NCM of any node in the route exceeds that threshold time. If no route is found, then the node broadcasts a localization request in the network. Upon receiving a localization request from a node, the receiving node replies to the transmitting node with localization reply packet which conveys the receivers LT. Upon receiving a localization reply packet, the receiver unwraps the LT from the packet. Then it does an element by element comparison of the received LT with its own LT. If any element of the received LT is more recent than the corresponding element in the node's own LT, then it replaces the element in its LT with the received element. The process is described in procedure 2.

Procedure 2:

Update LT() //At Network Layer

```
RLT = Received LT
LT = My LT
for  i  = 1 to nmax
for j = 1 to nmax
if RLT(i, j)->Time > LT(i, j)->Time // More Recent
LT(i, j)->Distance = RLT(i, j)-> Distance
LT(i,j)->AoA = RLT(i, j)->AoA
LT(i, j)->Time = RLT(i, j)->Time
end
end
end
```

Now each node constructs a network coordinate graph using the information it estimates itself and receives from the neighbors. Any node in the network N_i constructs the coordinate map using the following algorithm:

Algorithm for creating NCM from LT:

1. n_i plots itself in the (0, 0) coordinates i.e. center of the graph.
2. n_i then averages the distance and angle estimation of each node pairs (n_p, n_q) using

2.1 if d_{pq} and d_{qp} is not zero then
$d = (d_{pq} + d_{qp})/2$
$b_{pq} = \mathrm{mod}(b_{pq} + 2\pi, 2\pi)$
$b_{qp} = \mathrm{mod}(b_{qp} + 2\pi, 2\pi)$
$b_{pq} = b_{pq} + (\mathrm{mod}(b_{qp} + 3\pi, 2\pi) - b_{pq})/2$
$b_{qp} = b_{qp} + (\mathrm{mod}(b_{pq} + 3\pi, 2\pi) - b_{qp})/2$
else if d_{pq} is not zero then
$d = d_{pq}$
$d_{qp} = d_{pq}$
$b_{pq} = \mathrm{mod}(b_{pq} + 2\pi, 2\pi)$
$b_{qp} = \mathrm{mod}(b_{pq} + 3\pi, 2\pi)$
$b_{pq} = b_{qp} + (\mathrm{mod}(b_{qp} + 3\pi, 2\pi) - b_{pq})/2$
$b_{qp} = b_{qp} + (\mathrm{mod}(b_{pq} + 3\pi, 2\pi) - b_{qp})/2$
else if d_{qp} is not zero then
$d = d_{qp}$
$d_{pq} = d_{qp}$
$b_{qp} = \mathrm{mod}(b_{qp} + 2\pi, 2\pi)$
$b_{pq} = \mathrm{mod}(b_{qp} + 3\pi, 2\pi)$
$B_{pq} = b_{pq} + (\mathrm{mod}(b_{qp} + 3\pi, 2\pi) - b_{pq})/2$
$B_{qp} = b_{qp} + (\mathrm{mod}(b_{pq} + 3\pi, 2\pi) - b_{qp})/2$
end

2.2 Set the primary estimation of NCM coordinates for the node pair as

$$NCM_{pq}(x,y) = (d*\cos(b_{pq}+\frac{\pi}{2}), d*\sin(b_{pq}+\frac{\pi}{2}))$$

$$NCM_{qp}(x,y) = (d*\cos(b_{qp}+\frac{\pi}{2}), d*\sin(b_{qp}+\frac{\pi}{2}))$$

3. Let $N_{one\_hop}(i)$ denotes the one hop neighbors of node n_i. $\mathbf{K}$ is the set of nodes which are one hop neighbors of both n_i and n_j. $|\mathbf{K}|$ denotes the number of such nodes. Node n_i sets the NCM coordinates of its one hop neighbors as:

foreach $j \in N_{one\_hop}(i)$ do

$$NCM_{ij}(x) = (NCM_{ij}(x) + \sum_{k=K_1}^{K_n} (NCM_{ik}(x) + NCM_{kj}(x)) / (|\mathbf{K}|+1)$$

$$NCM_{ij}(y) = (NCM_{ij}(y) + \sum_{k=K_1}^{K_n} (NCM_{ik}(y) + NCM_{kj}(y)) / (|\mathbf{K}|+1)$$

```
end
4.n_i plots the coordinates of any other
node n_j using the following procedure:
Let N_no_hop(i) denotes the set of nodes
of which n_i has no NCM entry
for iteration = 1 to |N|-1
foreach j ∈ N_no_hop(i) do
```

$$NCM_{ij}(x) = \sum_{k=K_1}^{K_n} \left(NCM_{ik}(x) + NCM_{kj}(x)\right) / |\mathbf{K}|$$

$$NCM_{ij}(y) = \sum_{k=K_1}^{K_n} \left(NCM_{ik}(y) + NCM_{kj}(y)\right) / |\mathbf{K}|$$

```
end
end
```

Realization of the above algorithm reveals that a node compensates the measurement error of AoA and RSS by the hardware (or the measurement system used) by means of error propagation. First a node calculates the location of its one hop neighbors. For ease of understanding, let i be the node of which we are constructing the NCM. Let, j is a one hop neighbor of i. To find the relative location of j, i finds the approximations of distance and bearing of j. The first approximation of bearing and distance is done by averaging the measurements of node i and j. Let d'_{ij} and b'_{ij} are the first approximation of distance and bearing respectively of node j by node i. Then

$$d'_{ij} = (d_{ij} + d_{ji})/2$$

$$b'_{ij} = (b_{ij} + b_{ji} + \pi)/2$$

(d'_{ij}, b'_{ij}) can be thought as a polar coordinate in a polar coordinate system. This approximation is done for all node pairs (p, q); $p \in \mathbf{N}$, $q \in \mathbf{N}$, $p \neq q$, $d_{pq} \neq 0 \parallel d_{qp} \neq 0$. These coordinates are then transformed into Cartesian coordinates i.e. to (x, y) from. The first approximation of j with respect to node i in a Cartesian coordinate system can be represented by $j_i'(x, y)$.

Further, i finds all the neighbors k of i, of whom j is a one hop neighbor. Then i approximates the location of j by averaging the endpoints of each route ($i \to k \to j$). This two approximations are then averaged to find the final approximation of $j_i(x, y)$.

To find the relative location of non-one hop neighbors of node i, i uses the following procedure. Let j be a non-one hop neighbor of i. i finds all the nodes k, for whom $k_i(x, y)$ is approximated and j is a one hop neighbor of k. Then i approximates the location of j by averaging the endpoints of each route ($i \to k \to j$). For non-one hop neighbors this is the final approximation. This procedure is repeated until all possible node locations are approximated.

Using the above algorithm a node can find the relative position of any other nodes in the networks to which a route exists from that node. For this algorithm we assume that no entry in the LT has been expired. The algorithm has a complexity of $O(n^2)$.

D. Limitations of the system

The proposed system has some limitations. The accuracy of the system roughly depends on the accuracy of the hardware or system used for AoA and RSS measurement and the fading condition of the environment. The size of the network has an impact on the proposed system. If the network size is huge then the localization table size also gets huge as the localization table size is proportional to square of the size of the network. As the MAC body size in IEEE 802.11 systems is limited (≤2312 bytes), the bigger the localization table size is, the more packets are needed to transmit the localization table of a node. To resolve this issue, the nodes may only transmit partial LT containing recently updated entries only. Again the NCM creation algorithm has a complexity of $O(n^2)$. Thus the bigger the network size is, the more computational power is needed by the nodes to construct the NCM. The above stated algorithm works only for nodes in a two-dimensional plane.

E. Metric estimation

The measurement of Angle of Arrival requires highly accurate and precise directional antenna which has not yet became an available technology. For random shadowing condition, the RSS is not quite dependable. Some available technology such as Bluetooth provides another metric called link Quality. So we can see that the efficiency of our proposed system depends on the accuracy of the measurements of AoA and RSS.

F. AoA measurement

In our proposed system all the nodes should be equipped with smart antenna with which the nodes can measure the bearing of the received signals. Angle of arrival (AoA) measurement is a method for determining the direction of propagation of a radio-frequency wave incident on an antenna array. AoA determines the direction by measuring the Time Difference of Arrival (TDOA) at individual elements of the array - from these delays the AoA can be calculated.

Generally this TDOA measurement is made by measuring the difference in received phase at each element in the antenna array. This can be thought of as beam-forming in reverse. In beam-forming, the signal from each element is delayed by some weight to "steer" the gain of the antenna array. In AoA, the delay of arrival at each element is measured directly and converted to an AoA measurement.

There is a number of AoA estimation methods available e.g. MUSIC [16], ESPIRIT [17], CA-MUSIC [18], correlation and maximum likelihood techniques etc.

G. RSSI

RSSI (Received Signal Strength Indicator) is circuit to measure the strength of incoming signal. The received signal strength is a function of the transmitted power and the distance between the sender and the receiver. The received signal strength will decrease with increased distance as equation shows.

$$rssi = (10n\log_{10} d + A + \sigma_{offset})$$

Where n is signal propagation constant, also named propagation exponent or path loss exponent, while d and A are distance from sender to received signal strength at a distance of 1 meter and measuring the RSS value, respectively. σ_{offset} is the standard deviation which is a random value of measured RSSI that ranges from 0 to 1 dBm.

RSS measurement is corrupted by two types of errors: Non-Line of Sight (NLOS) error and measuring error. The measurements in cellular systems taken by Nokia [19] shows that NLOS error dominates the standard measurement noise and tends to be the main cause of the error in range estimation. They also show that the location estimation error linearly increases with the distance. Following these measurements, Wylie and Holtzman propose a method for the detection and correction of NLOS errors [20]. They show that it is possible to detect a NLOS environment by using the standard deviation of the measurement noise and the history of the range measurements. They propose a method for LOS reconstruction and they show that the correction is only possible if the standard measurement noise dominates the NLOS error. A different approach is presented in [21] by Chen. Chen shows that if the NLOS measurements are unrecognizable, it is still possible to correct the location estimation errors, if the number of range measurements is greater than the minimum required. The algorithm is referred to as the Residual Weighing Algorithm (Rwgh).

V. Simulation Model

For the simulation of our proposed localization system, we coded an event driven simulation model using MATLAB.

A. Enabling technologies

For the simulation of the proposed system, we choose the IEEE802.11g as the enabling technology. IEEE 802.11g-2003 or 802.11g is an amendment to the IEEE 802.11 specification that extended throughput to up to 54 Mbit/s using the same 2.4 GHz band as 802.11b. This specification under the marketing name of Wi-Fi has been implemented all over the world [22]. The carrier frequency of the nodes is 2.4 GHz. For simplicity of the model, no channel allocation scheme is deployed. Suppressing the reality, all the nodes use the same frequency for transmission. The channel bandwidth is taken as 22 MHz. DSSS is used as the spread spectrum technique.

For the simulation of positioning and routing, we simulate the various layer and layer task of 802.11g. Though we mostly implemented real parameter values for the simulation, we also chose some arbitrary values of some parameters such as various slot times. On the transmitter side, the packets move from upper layer (Application layer) to lower layer (Physical layer) through Network and MAC layer, and on the receiver side, the packets are received at physical layer and go through upper layers consequently. The routing tasks are implemented at network layer. Besides RREQ (Route Request) and RREP (Route Reply), two new network layer packets are introduced for adding the capability to implement our proposed system. The packets are LOCREQ and LOCREP. LOCREQ is a broadcast packet, while LOCREP is a unicast packet. The nodes requests for the LT of other nodes in the network by broadcasting a LOCREQ. Each node receiving a LOCREQ from another node, replies with LOCREP to that node. LOCREP is a data packet which conveys the LT of the transmitting node. The LT can have a size greater that max MAC body size; we simply avoid this fact for the sake of simplicity of the simulation.

B. Space model

Ad-hoc networks are infrastructure-less networks, i.e. there is no fixed base station. They have the convenience to be deployed on the fly, any place, and any time. So the environment of the space of deployment may be diverse. It may be an open playground, or a lightly dense suburban area or a highly dense urban area. For the sake of simplicity of our simulation we assume that the space is a 2-D plane, so we focus on 2-D positioning of the nodes.

C. Node distribution model

In the simulated system, we assume that the nodes in the network are randomly distributed in a two dimensional space of area A according to a uniform distribution. The nodes have associated paths which may be random or predefined. For a time instance, the node density is denoted as ρ, so the total number of nodes is $N = \rho A$. The probability of a node located in a smaller area A' is given by $p = AA'$.

D. Node mobility model

We added the capability to the nodes to move within the topology boundary. The speed of the node is limited by a value. We implemented two methods of mobility: random waypoint and projected path.

E. Transmission model

In the simulated system, the nodes are lightweight and power constrained devices. The average height of the nodes is assumed to be approximately 1 meter. No height gain factor as stated in Okumura model is considered. The transmission power of each node is assumed to be equal. The transmission antenna is isotropic and has omni-directional radiation patterns. The antenna has a unit gain. We simulate virtual carrier sensing for sensing the channel.

F. Channel model or Link model

We used three different link models for the simulation.

1. Friis free space path loss model
2. Two ray model
3. Log normal shadowing.

Each of the models also consists of an AWGN (Additive White Gaussian Noise) channel.

To implement the randomness of the link model we primarily used Log normal shadowing. Log normal shadowing is attributed by the following equation:

$$PL(d) = PL(d_0) + 10n\log\left(\frac{d}{d_0}\right) + X_\sigma$$

Here PL(d) is the path loss at a distance d, d_0 is a reference distance from the transmitter for which $PL(d_0)$ is known. X_σ is zero mean Gaussian distributed random variable with standard deviation σ. n is the path loss exponent of the environment. The nodes assume the value of n of the environment, which is not necessarily same as the actual value. The value of σ is changed to different values to simulate fading in the environment.

G. Reception model

We assume that smart antennas are implanted in each of the nodes. Though we did not actually implemented any

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technique to calculate AoA, which is a difficult task to simulate. We simply used some codes that output the AoA with a random error. The error variance is changed to different values to see the effect.

VI. Simulation Results

We simulated the proposed system a number of times with different parameters. We simulated the system with and without node mobility to see the systems performance and measure the effect of mobility on the system. We also changed the standard variance of error of metric calculations to see how the algorithm mitigates the error through error propagation. We found the result quite satisfactory.

A. Simulation without node mobility

First we simulated the system without node mobility, i.e. the nodes were fixed at their position throughout the simulation. The simulation parameters are shown in table 1.

Table I: Simulation Parameters with No Node Mobility

Parameter	Value
Number of nodes	10
Topology area	100 m × 100 m
Max simulation time	100 s
Node transmission power	0.2 watt
Node speed	0 m/s
Rx and Tx gain factor	1
Rx and Tx loss factor	1
Rx receive threshold	-75 dBm

Fig. 7 shows the initial network topology with uniformly distributed nodes and the associated connectivity graph between the nodes.

The Network Coordinate Map (NCM) generated by node 1 at the end of the simulation is shown in Fig. 8(a) and the actual NCM with respect to node 1 is shown in Fig. 8(b). Comparing these two figures we find that the simulated NCM is quite similar to the actual one. The difference between the approximated and actual NCM is obviously the result of AoA and RSS measurement errors. Here we see that node 1 can approximate the location of all nodes connected to the network by the aid of proposed algorithm even though some nodes are not one hop neighbors of node 1.

B. Simulation with node mobility

Next we simulated the system enabling node mobility. During the simulation the nodes moved within the topology boundary towards random directions with random speeds. In this random waypoint simulation the nodes changed their speed and direction randomly and aperiodically. Each node kept their own track of waypoints but for simplicity the node positions were only updated each time a node received a packet from other nodes. The simulation parameters are shown in table 2.

Table II: Simulation parameters with node mobility

Parameter	Value
Number of nodes	10
Topology area	100m × 100m
Max simulation time	100s
Node transmission power	0.2 watt
Rx and Tx gain factor	1
Node speed	Max 1 m/s along random waypoints
Rx and Tx loss factor	1
Rx receive threshold	-75dBm

The simulation started from the initial topology similar to Fig. 7. Other simulation parameters were kept almost unchanged. Fig. 9 shows the network topology and associated connectivity graph at the end of the simulation.

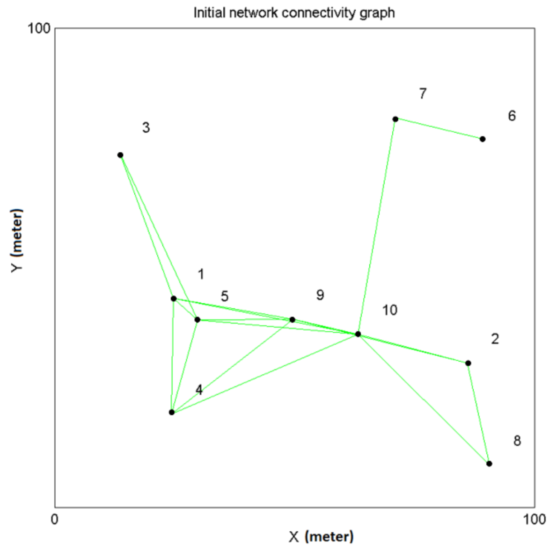
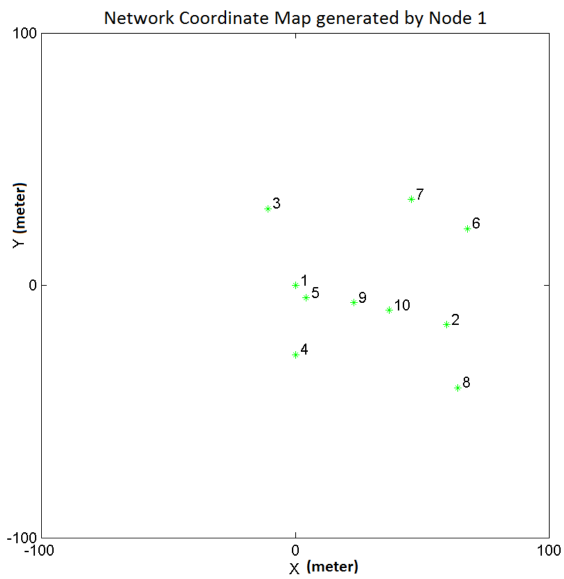
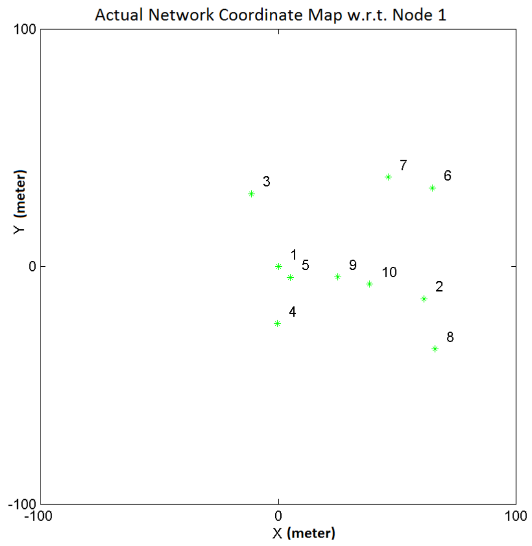


Fig.7. Initial network topology and connectivity graph of a simulation



(a)



(b)

Fig.8. Network co-ordinate map generated by node 1 at the end of simulation (a) and comparison with actual map (b) in simulation without node mobility

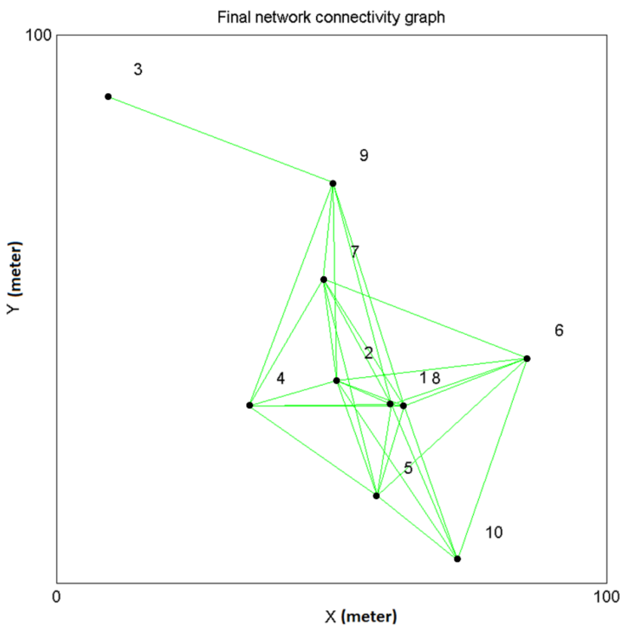
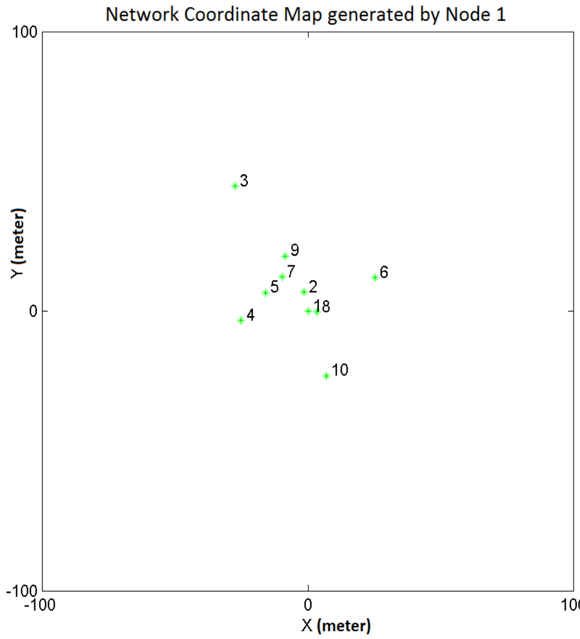


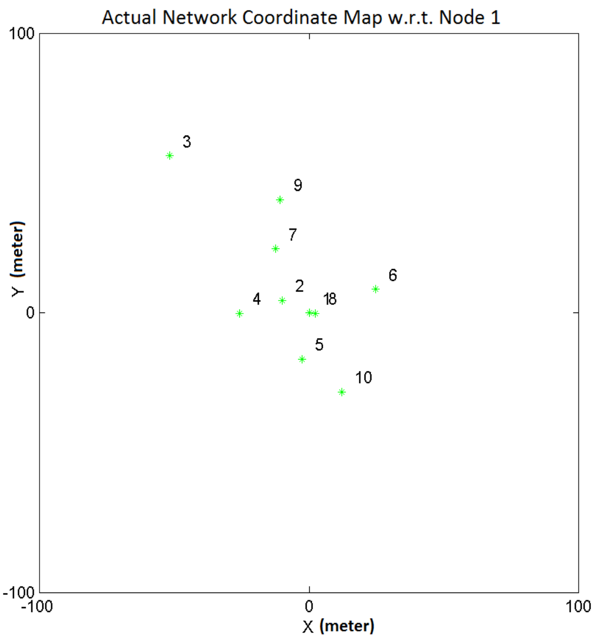
Fig.9. Final Network topology and connectivity graph at the end of simulation with node mobility

The Network Coordinate Map (NCM) generated by node 1 at the end of the simulation is shown in Fig. 10(a) and the actual NCM with respect to node 1 is shown in Fig. 10(b).

Comparing the generated NCM with actual NCM we see that despite the mobility of nodes, the generated NCM is quite similar to the actual one. The generated NCM seems to be a scaled version of actual NCM. This is because the actual path loss exponent of the link and the assumed path loss exponent by the nodes had different values. From the above simulation result we see that the proposed system has the capability to predict a NCM quite well if the RSS and AoA calculation error is minor.



(a)



(b)

Fig.10. Network co-ordinate map generated by node 1 at the end of simulation (a) and comparison with actual map (b) in simulation with node mobility

Fig. 11 depicts the proposed system's performance when the AoA and RSS measurement error of the hardware (or the measurement systems used) is less than 10%. The figure shows that for hardware measurement error of 10%, a one hop neighbor of the calculating node (node 1 in this case) may have a linear displacement of at most 6 meters. Although this displacement amount depends not only on the hardware measurement error of the calculating node but also on hardware measurement error of all other nodes in the network. Because, for approximation of the relative location of a node, the calculating node uses the measurements of each node in each route from the calculating node to that node. As both RSS and AoA measurement is affected by the environment conditions, for a free space condition, the system has accuracy like any other triangulation based localization systems.

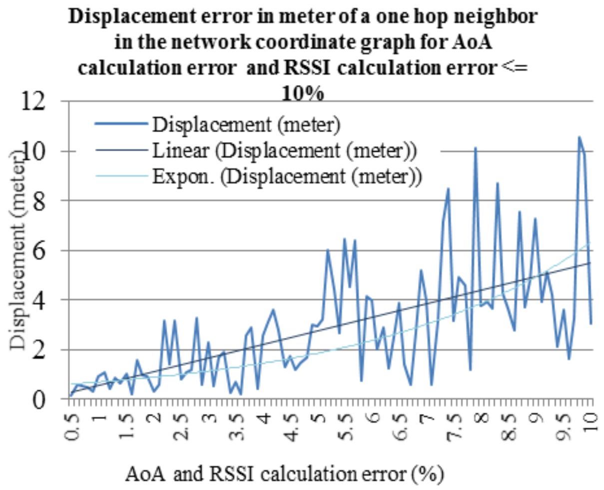


Fig.11. Displacement error in meter of a one hop neighbor in the network coordinate graph for AoA and RSS calculation error <= 10%

VII. Conclusion

From the simulated results presented above, we see that in spite of absence of conditions of triangulation, our proposed localization system can still predict a network coordinate map with reliable accuracy. The system is perceived as robust in conditions where other localization systems can get stuck. Although it is obvious that the hardware measurement errors should be mitigated in order to get higher accuracy, we assume more accurate hardware for AoA and RSS measurement will be available in the near future.

Future Work

The localization model presented here assumes the environment as a 2-D space and provides functionality for positioning of nodes in 2-D coordinate system. However, the model can be easily extended for being capable of positioning in 3-D space. We can simply do this by making the receiving the antenna capable of measuring the 3-D bearing of incoming signal. This makes the proposed localization system more robust than other positioning system. For example to be capable of positioning of nodes using triangulation in a 3-D space any node requires at least three (AoA) or four (RSS/ToA/TDoA) neighbor to exist always. Necessary changes for the capability of 3-D positioning of the system will be examined in later works. In future, we wish to simulate the system in real world scenario and exploit the proposed system's capabilities of positioning of nodes in various environments. Furthermore, the routing protocol based on our proposed system needs further refinement and improvement.

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