Neighborhood Tracking and Location Estimation of Nodes in Ad hoc Networks Using Directional Antenna: A Testbed Implementation

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***Abstract*--This paper explores the advantage of using directional antenna in estimating approximate location of nodes without using any additional hardware like GPS. We have set-up a testbed of ad hoc network using directional antenna and demonstrated the effectiveness of directional tracking of neighborhood of each node. Subsequently, a method for estimating the location of each node in the network using a pair of reference nodes and the angle of arrival (AOA) of best signal from each reference node are discussed. This neighborhood tracking and location estimation not only help us in implementing directional MAC and directional routing protocols like location-aided routing, but also help us in applications involving location-based services or location aware applications where each node needs to know the approximate locations of other nodes in the network. We have also proposed a multi-hop extension of our location estimation method which enables us to estimate the location of a node that is multi-hop away from the fixed reference nodes. One hop neighbors of the fixed reference nodes which have already estimated their location using angle-of-arrival(AoA) may be used as secondary reference for two-hop away nodes. In this way, by using different levels of reference nodes, the location of all the nodes in the network may be progressively estimated.**

***Index Terms*—Adhoc Networks, Directional Antenna, Location Tracking, Location estimation**

I. Introduction

The recent progress in wireless communication and personal computing leads to the research of ad hoc wireless networks, which are envisioned as rapidly deployable, infrastructure-less networks with each node acting as a mobile router, equipped with a wireless transceiver. However, ad hoc networks with omni-directional antenna uses RTS/CTS based floor reservation scheme that wastes a large portion of the network capacity by reserving the wireless media over a large area. Consequently, lot of nodes in the neighborhood of transmitter and receiver has to sit idle, waiting for the data communication between transmitter and receiver to finish. To alleviate this problem, researchers have proposed to use directional antennas that direct the transmitting and receiving beams toward the receiver and transmitter node only. This would largely reduce radio interference, thereby improving the utilization of wireless medium and consequently the network throughput [1-3]. Additionally, use of directional antenna conserves the power, since it is possible to access a neighboring node directionally with less power compared to omni-directional antenna. In this paper, we will explore another advantage of directional antenna in estimating approximate location of nodes without using any additional hardware like GPS. We have set-up a testbed of ad hoc network using directional antenna and demonstrated the effectiveness of directional tracking of neighborhood of each node and subsequently location estimation of each node with respect to two reference nodes. This neighborhood tracking and location estimation not only help us in implementing directional MAC and directional routing protocols like location-aided routing, but also help us in applications involving location-based services where each node needs to know the approximate locations of other nodes in the network.

In order to implement effective MAC and routing protocol in this context, a node should know how to set its transmission direction to transmit a packet to its neighbors [3]. So, it becomes imperative to have a mechanism at each node to track the locations of its neighbors. Moreover, our test-bed experience indicates that accurate location tracking and location estimation based on single beaconing is not possible due to fluctuating channel characteristics. Usually, the simulation-based studies do not address this issue [4]. In this paper, we have shown that use of multiple beacons and multiple observations on location data are required for location tracking and location estimation. This limits the applicability of our mechanism in highly mobile scenarios. However, in semi-static scenarios (where mobility is infrequent or only a few nodes are mobile), this scheme works well. Area of applications includes sensor networks for remote environment monitoring (forest, mine, natural disaster-prone area, etc.) or community networks in remote area (e.g. geographic exploration or hiking and tracking in remote area).

II. Related Work

Several location estimation techniques have been proposed by the contemporary researchers that do not rely on GPS (Global Positioning System.

Existing location discovery techniques typically use distance or angle measurements from a fixed set of reference points and apply lateration or triangulation to solve for unknown location [6,7]. The distance or angle estimates may be obtained from received signal strength (RSSI) measurements, time-of-arrival, time-difference-of arrival measurements (ToA, TDoA), Angle-of-arrival (AoA) measurements. It was argued that non-uniform propagation environments make RSSI methods unreliable and the due to the high propagation speed of wireless signals, a small error cause a large error in the distance estimate in case of ToA, TDoA. So, the localization techniques using ToA, TDoA needs to use a signal with smaller propagation speed than wireless such as ultra sound and this in turn can gives accurate result but requires additional hardware to receive ultrasound signal. A combination of RSSI and other measurements are suggested in [8,9] for a reliable estimation. The RADAR system [8] is designed for indoor localization, which uses extensive RF signal strength measurements that are performed offline to design signal strength maps. ToA location sensing system includes GPS and the Active Bat Location System. The BAT system [10] uses an array of ultra sound receivers for processing received signals from a user of unknown location. In Cricket location support system [11] fixed beacons broadcast local geographical information to the listener nodes to increase accuracy of distance estimation from ultrasound signals. The SpotON ad hoc location system [12] and Active Campus [13] implements signal attenuation based measurement instead of distance measurements to calculate the position of an object.

Capkun et. al. have proposed a distributed infrastructure-free positioning algorithm for the nodes in ad hoc networks that does not rely on GPS [5]. Their algorithm uses the distance between nodes to build a relative coordinate system in which node positions are computed in two dimensions. However, it has been shown [7] that location estimation using angle *(angulatio*n) performs better than location estimation using distance *(lateratio*n), because angle measurement noise is much smaller than distance measurement noise based on signal strength.

In [14], the authors have proposed a location estimation technique for sensor networks based on the angle-of-arrival of beacons from three or more fixed beacon nodes whose positions are known. In [7], Lee et. al. also supported the fact that the location estimation protocols should have the capability of multi-hop based location computing and they proposed a location sensing protocol utilizing the directional antenna system and the direction of arrival (DOA) estimation algorithm.

III. Location Tracking using Directional Antenna

There are basically two types of smart antennas used in the context of wireless networks: switched-beam or fixed beam antennas and steerable adaptive array antennas. In a steerable adaptive array antenna which is more advanced than a switched beam antenna, the beam structure adapts to Radio Frequency (RF) signal environment and directs beams towards the signal of interest to maximize the antenna gain.
We have used the ESPAR(Electronically Steerable Passive Array Radiator) antenna, which is a low cost smart directional antenna in our Testbed experiments. The application which we developed for carrying out the various tasks like steering the antenna, forming the neighborhood information is named as Adhocnet Communicator.

In order to effectively communicate with a neighbor using directional antenna, a node needs to know the exact direction of each of its neighbors to set its antenna-beam to talk to that neighbor. Each node does this directional location tracking periodically. Normally, each node waits in omni-directional-receive-mode while idle. To initiate location tracking, a node, say, n, broadcasts 12 directional beacons sequentially, using its 12 directional beam-pattern in the ESPAR Antenna. Each beacon contains node-id and corresponding direction of transmission. This is done sequentially in all direction at 30 degree interval, covering a span of 360 degree. Thus each node will record the received signal strength and the direction from which it receives the packet. So that each node can record its neighborhood information in a table known as Neighborhood Link State Table (NLST). In Figure 1 NLST is shown graphically using Adhocnet Communicator.

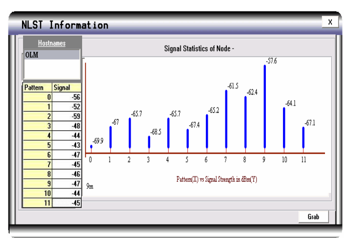

Figure 1. NLST as shown in the Adhocnet Communicator

After the formation of NLST, a node i will calculate the beam pattern of n at which it has received strongest signal from n and the corresponding value of the received signal strength from n and send this information back to n. On receiving that, node n will record this information in its Angle Signal Table (AST). In a similar fashion, node n will receive similar information from all of its neighbors and update its AST. Thus, an Angle Signal Table (AST) at any node n essentially contains the neighbors of node n and the best possible direction to access each neighbor of n and the signal strengths as perceived by each neighbor in the corresponding best directions. Graphical representation of AST using Adhocnet communicator is shown in Figure 2

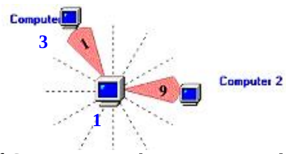

Figure 2. AST of Computer 1 with computer 2 and computer 3 as its neighbors, using Adhocnet Communicator

IV. Location Estimation by a Node using a Pair of Reference Nodes

1. First of all, two nodes are selected as two primary reference nodes [manually one is placed at (0, 0) and the other is placed at (x, 0) with their 0^{th} beam-patterns aligned across X-axis for the sake of simplicity]. It is possible to get the information about the best beam-pattern to access a node from the NLST kept at each node. From the beam-patterns it is possible to get the corresponding angles of arrival (e.g. angle of arrival of beam 0 is 0, beam 1 is 30˚, beam 2 is 60˚ and so on). So, the AoA of best signal to a node coming from reference nodes can be decoded from the corresponding beam-patterns stored in NLST of that node. We have used that in our coordinate calculation process.
2. Each reference node will periodically transmit its coordinate through directional beacons so that other nodes in the neighborhood of each of the reference nodes can collect that information for their coordinate calculation purpose.
3. If a node (say P in Figure 3) can manage to collect the coordinates of two reference nodes (that is possible only if it lies within the transmission range of both the reference nodes R1 and R2) then it will immediately

$$p = ((y2 - y1) + x1 \tan\alpha - x2 \tan\beta)/(\tan\alpha - \tan\beta)$$
$$q = ((x1 - x2) \tan\alpha \tan\beta + (y2 \tan\alpha - y1 \tan\beta))/(\tan\alpha - \tan\beta) \quad (1)$$

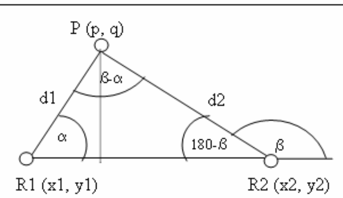

Figure 3. Illustration of Coordinate calculation using 2 reference nodes

calculate the coordinate of itself (p, q) using four parameters available to it -

a. Coordinates of reference node R1 (x1,y1) which is (0,0) in this case,
b. Coordinates of R2 (x2,y2) which is (x, 0) in this case,
c. AoA of signal from R1 (α) and
d. AoA of signal from R2 (β). Using the process described below we can easily calculate the coordinate of P. The general equation of line PR1 and PR2 will be,

$$(y - y1) = \tan\alpha\,(x - x1) \quad \text{and} \quad (y - y2) = \tan\beta\,(x - x2)$$

Now, P (p, q) is the point of intersection of both PR1 and PR2. So, substituting (x, y) by (p, q) in both the equations, we have the coordinate of P as shown in eq(1).

4. A node which is two-hop away from primary reference nodes can not calculate its coordinate from the above parameters as there is no direct link between the reference nodes and that node. So, in that case, a two-hop away node should use nodes like P as its reference nodes to calculate its coordinates. Thus, P will act as a secondary reference node in this case. But before that, the secondary reference nodes like P has to orient its antenna with primary reference nodes so that they can share the common or unified frame of reference and help other distant nodes to calculate their location with respect to the same frame of reference. So, after unification of orientation of antenna, P can volunteer itself as a secondary reference node.

V. Unification of Orientation of Antenna by a non-primary Reference Node

We will illustrate this problem and its possible solution considering ESPAR antenna which has 12 predefined patterns, identified by beam-pattern 0 to 11 along counter clock-wise direction. Let us assume that a reference node R1 has aligned its 0^{th} beam towards East and the 0^{th} beam of another node say P is set at an angle 120˚ with respect to the

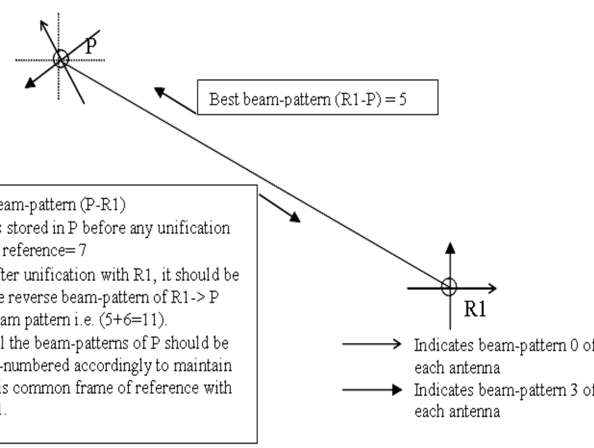

Figure 4. Illustration of Unification of orientation of antenna using reference

0^{th} beam of R1 (Figure 4). Now, the beam-pattern of R1 to access P is say 5. So, ideally, in the common frame of reference, P should access R1 at its reverse beam pattern 11 (=5+6). But initial alignment of the 0^{th} beam of P is at an angle 120˚ in the counter-clock-wise direction with respect to that of R1. So according to P, the best beam pattern to access R1 is recorded as 7 in its AST instead of 11 (Figure 4). This conflict of beam pattern occurs because the initial alignments of antennas in P and R1 are different.

So, the best beam-pattern from R1 (or R2) will be extracted by a node P from the beacon sent by R1 (or R2) according to their antenna alignments. But the original alignment of P may differ from the alignment of node R1 (or R2). So, P has to map that beam-pattern according to the alignment of reference nodes R1 (or R2) in order to unify the orientation of its frame of reference with primary reference nodes. But this does not mean that P has to ensure the similar physical alignment of antennas as in R1. So, P has to map its current beam-patterns to unified beam-patterns through some mechanism so that from then onwards it can send beacons specifying the unified beam-patterns instead of its original alignment of beam-pattern. In other words, P renames its beam-patterns without physically changing the orientation of its antenna. This renaming is done through a mapping table. Thus, instead of physically aligning the antenna of a node, the mapping table logically aligns its original beam patterns to a common reference frame.

VI. Formation of Mapping Table After Unification of Antenna Orientation

1. A node say P will first find out the beam-pattern from which it is getting the strongest beacon signal from a neighboring reference node R1. This is the best beam pattern to access P by R1. This information is obtained from the NLST of P. Let this be x.
2. Then N1 will derive the reverse pattern of x. It can be done as follows.
   Since ESPAR has 12 beam patterns,
   Reverse beam-pattern of x = x + 6, if $0 \le x \le 5$
   Reverse beam-pattern of x = x - 6 if $6 \le x \le 11$
3. P will now consult its AST to find out its best recorded beam pattern to access R1. Let this be y.
4. P will now match the reverse beam pattern with y to form its *Post- unification Mapping* Table (PM table) after logical reorientation of antenna as follows.
   a. P will first find out the difference obtained from calculated value of reverse beam-pattern (from P to R1 as calculated using step 2) and the best beam pattern to access R1 as mentioned in its AST (y). This difference is called *offset*.
   b. For each beam pattern, P will then add this offset value to get corresponding post-unification beam-pattern as follows.
      I. If the resultant value is less than or equal to 11 then the resultant value will be stored in PM table as the post-unification beam pattern of a corresponding pattern.
      II. But, if the resultant value is greater than 11 then (resultant value - 11) will give us the actual post-unification beam pattern of a corresponding pattern as already illustrated in section V with an example figure 4.

So, after formation of PM table and calculation of self coordinates, any node (say P) may act like a secondary reference node for the nodes which are physically located far away from fixed reference points R1 and R2.

VII. Estimating Location of a Node Multi-hop away from Reference nodes

A node (say Q) that is multi-hop (say two-hop) away from primary reference nodes R1 and R2, can not calculate its coordinate directly using the process described in section IV because there is no direct link between the reference nodes R1, R2 and the node Q. In that case, Q should use nodes like P and S as shown in figure 5. Reference nodes like P has to logically map its antenna with primary reference nodes using

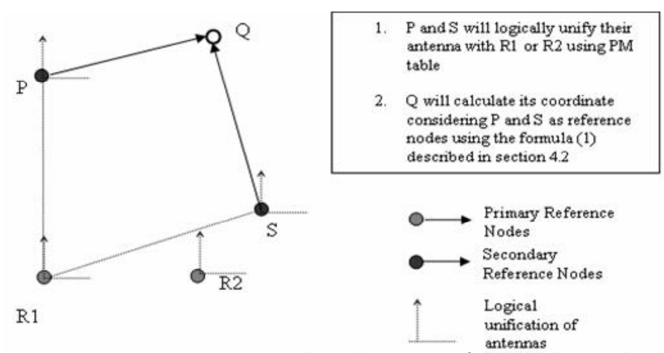

Figure 5. Location estimation by node Q using reference nodes P and S

the scheme described in section V so that they can share the common frame of reference and help other distant nodes like Q to calculate their location with respect to the same frame of reference. So after the formation of Post-unification Mapping Table at P, it can volunteer itself as a secondary reference node. Then Q can use the position of two neighboring secondary reference nodes (like P, S) and the corresponding angle of arrival (AOA) of signals from them to calculate its coordinate as per formula 1 shown in section IV.

VIII. Five-Node Setting: Single-hop Location Estimations with two reference nodes

In our testbed implementation, we have set up a network of five nodes in the lounge as shown in Figure 6. The actual co-ordinates of the nodes are shown in small circles and are as follows (in meters):

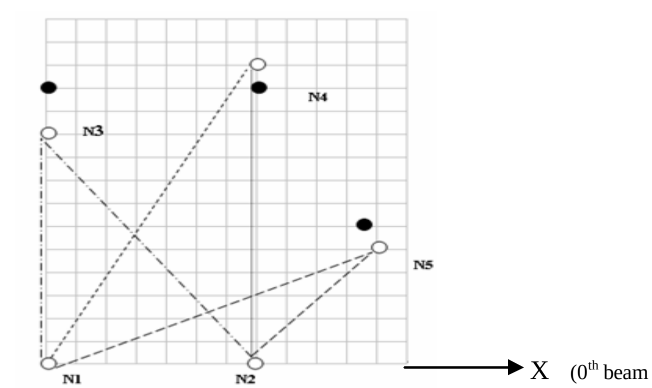

Figure 6. Single-hop location estimations of N3, N4 and N5 with two reference nodes N1 and N2

N1 (Reference node 1) = (0, 0),
N2 (Reference node 2) = (3.5,0), N3 = (0, 5),
N4 = (3.5, 6.5), N5= (5.5, 2.5)

The tracking of N3, N4 and N5 by reference nodes N1 and N2 are shown in figure 6 and the corresponding tracking angles are.

∠N3N1N2 = 90°, ∠N4N1N2 = 60°, ∠N5N1N2 = 30°,
∠N3N2X = 120°, ∠N4N2 X = 90°, ∠N5N2X = 60°

Here, 0^{th} beam pattern of both the reference nodes N1 and N2 are oriented towards X as shown in figure 6.

Based on these, nodes N3, N4 and N5 compute their coordinates. This is done using the formula shown in (1) (where p is the x-coordinate and q is the y coordinates of the target node):

In case of N3, α = 90° and β= 120°, y1=y2=x1=0, x2=3.5; so, N3 (p, q) =N3 (0, 6)

In case of N4, α = 60° and β= 90°, y1=y2=x1=0, x2=3.5; so, N4 (p, q) =N4 (3.5, 6)

In case of N5, α = 30° and β= 60°, y1=y2=x1=0, x2=3.5; so, N5 (p, q) =N5 (5.2, 3)

Here Figure 7 shows the location tracking of node 3,4,5 by node 1 using the proposed algorithm.

We have also implemented the multihop location estimation algorithm for node N4 with respect to two non primary reference nodes N3 and N5. Coordinates of N4 in multihop estimation is (2.6, 7.5)

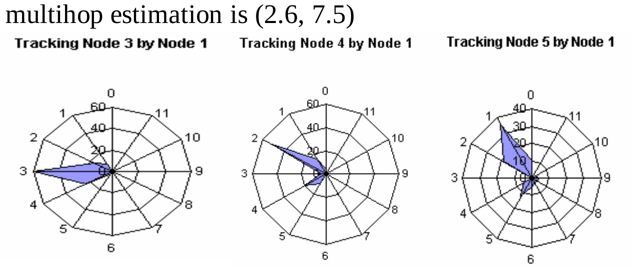

Figure 7. Location Tracking of Node 3,4,5 by node 1

IX. Error in Location Estimation

There will be two types of errors that will occur in location estimation. First, the estimation error due to error in location tracking; and, second, the estimation error due to beam-width which limits the estimation of AOA to discrete values as 30°, 60°, and so on.

The experimental results of location tracking depicts that the accuracy of location tracking is dependent on several external factors like environment, multipath effects and so on. Empirical results indicate that it is possible to get the correct beam pattern to access a node if a considerable number of beacons are observed. In a line-of-sight communication environment, the most frequently occurred beam-pattern will be the correct beam pattern to access a node even in the presence of multipath effects.

Figure 8 shows the estimation error due to beam-width where two reference nodes R1 and R2 are trying to track the location of N. Even if the AOA estimation is correct, the shaded region is the region of error and N may reside anywhere in this region. This region of error is proportional to beam-width and the product of d1 and d2. Reducing beam-width will definitely improve the estimation error. At the same time, if d1 and/or d2 increase, the estimation error increases.

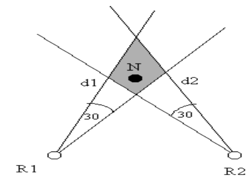

Figure 8. Error Estimation

When we use multihop estimation technique, the error seems to be compounded, since the computed co-ordinates of secondary reference nodes themselves have some error. However, if a node is single-hop away from primary reference nodes with large d1 and d2, it may be better to compute the coordinate of that node in multi-hop, since that would reduce the value of d1 and d2. However it was pointed out in [5] that, in n-hop scenario, since the location estimation at each hop can produce error with the same probability in every direction, the distribution of the direction of estimation error will be uniform. As a result, the error propagation in case of multi-hop location estimation may not be very significant.

X. Simulation of Estimation Error

In this section we present the simulation results and study the nature of estimation error with increasing transmission range and the characteristics of estimation error. In a 1000 X 1000 sq. unit area 100 nodes are placed randomly and the transmission range of each node was initially set to 2500 units and later increased by 2000 each time up to 14500 units. We assume all the nodes have same power and observe the error characteristics based on this.

A. *Error propagation with Increasing Transmission Range*

We have repeated the simulation experiments under 5 different topologies Figure 9 depicts the "Average Error" (Average error is the average of the estimation error where estimation error is denoted by $\sqrt{((X_p-X_c)^2+(Y_p-Y_c)^2)}$, X_p, Y_p

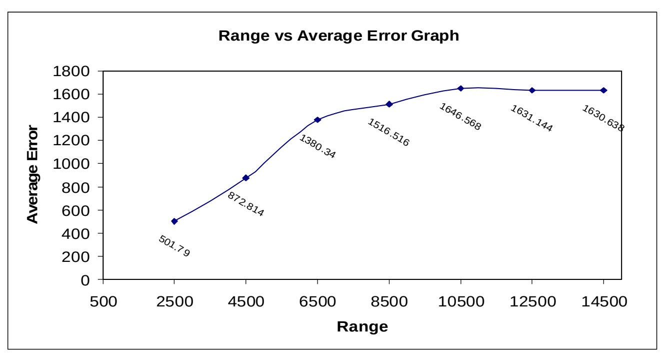

Figure 9. Range vs. Average Error Graph

are the actual coordinates and X_c, Y_c are the estimated coordinates as described in section IX obtained for a particular Transmission range) obtained at different setting of "Transmission Range" and it has been observed that "Average Error" increases with increasing value of transmission range. It is also clearly noticed from the figure (Figure 9) that the error reaches saturation point when transmission range is more than 10,500 units. This indicates that with smaller value of transmission range, our protocol estimates the node positions more accurately. This is the outcome of the fact that the nodes multi-hop away from primary reference nodes will select a suitable pair of neighbors as it reference nodes (may be secondary, tertiary reference nodes or, so on but, not primary reference). If we increase the transmission range sufficiently to cover all the nodes in the network, then, a node, physically located at a long distant from primary reference nodes, will be prone to more error as argued in section IX. So, it may be concluded that it is not always better to estimate the position of node using the primary reference nodes. Positional error of a node increases with its distance from the reference nodes. So, it is better to estimate the position of a node using a pair of reference nodes closer to that node instead of primary reference nodes at long distance.

B. Characteristics of Estimation Error

In this part of our analysis we focus on the cumulative effect of Estimation error. As we have discussed earlier that the estimation error increases with the increase of reference levels, so in that aspect the final value of estimation error seems to be the cumulative sum of the estimation errors in the previous reference levels which contradicts very much with the simulation results and is clearly visible from figure 9 and figure 10.

Estimation error does not increase cumulatively with the increase in reference level and it would imply that the error cannot be expressed as a monotonically increasing function of reference level. For a given range (say 2500 units) figure 10

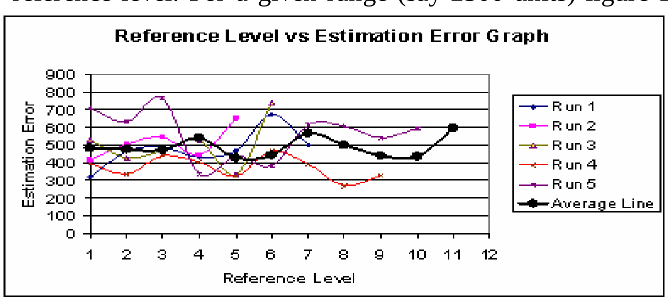

Figure 10. Reference Level vs. Average Estimation Error Graph

represents the estimated error at different reference levels. The Bold black line in Figure 10 shows the average of the Estimation error and it justifies the more or less constant nature of Estimation error which is pointed out in [5].

XI. Conclusion

In this paper, we have proposed a mechanism for location tracking and location estimation of nodes in ad hoc networks using directional antenna and evaluated the effectiveness of the scheme on a test-bed. Our focus is not so much on accuracy of location estimation. Each node in the system has to do neighborhood location tracking to implement directional MAC and routing. We have just used this knowledge for approximate location estimation without using additional hardware. Currently, we are investigating the possibility of using multiple reference nodes to more accurately track the location even in Non-Line-of-Sight environment.

XII. References

[1] M. Takai, J. Martin, R. Bagrodia and A. Ren, "Directional Virtual Carrier Sensing for Directional Antennas in Mobile Ad Hoc Networks", ACM MobiHoc, June 2002.

[2] Siuli Roy, Dola Saha, S. Bandyopadhyay, T. Ueda, S. Tanaka, "A Network-Aware MAC and Routing Protocol for Effective Load Balancing in Ad Hoc Wireless Networks with Directional Antenna", ACM MobiHoc,2003, Maryland, USA, 1-3 June 2003.

[3] Tetsuro Ueda, Shinsuke Tanaka, Dola Saha, Siuli Roy, Somprakash Bandyopadhyay, "A Rotational Sector-based, Receiver-Oriented mechanism for Location Tracking and medium Access Control in Ad Hoc Networks using Directional Antenna, Proc. of the IFIP conference on Personal Wireless Communications PWC 2003. September 23-25, 2003 - Venice – ITALY

[4] Martha E. Streenstrup, "Neighbor Discovery among Mobile Nodes Equipped with Smart Antennas" www.wireless.kth.se/adhoc03/ Proceedings/mssession6-1.pdf

[5] *S. Capkun, M. Hamdi, J. Hubaux,* "GPS-Free Positioning in Mobile ad-hoc Networks" Proceedings of the 34th Annual Hawaii International Conference on System Sciences (HICSS-34)-Volume 9 January 03 - 06, 2001 Maui, Hawaii.

[6] A. Nasipuri, Kai Li, "A Directionality based Location Discovery Scheme for Wireless Sensor Networks" Proceedings of the 1st ACM international workshop on Wireless sensor networks and applications, Atlanta, Georgia, USA.

[7] Jeongkeun Lee, Sungjin Kim, Dongkyun Kim, Yanghee Choi, "Location sensing protocol utilizing directional antenna systems in millimeter-wave broadband ad hoc networks" Technical Report, SNU-CSE-MMLAB-LSDA version 1, Sep. 2003.

[8] P. Bahl and V. Padmanabhan RADAR: An in-building RF-based user location and tracking system. In Proceedings of INFOCOM, pages 775–784, March 2000.

[9] N. Bulusu, J. Heidemann, and D. Estrin, GPS-less low cost outdoor localization for very small devices. IEEE Personal Communications Magazine, pages 28–34, October 2000.

[10] A. Ward, A. Jones, and A Hopper, "A new location technique for the active office." IEEE Personal Communications, 4(5):42–47, October 1997.

[11] N. Priyantha, A. Chakraborthy and H. Balakrishnan. "The cricket location support system" In ACM/IEEE International Conference on Mobile Computing and Networking (MOBICOM), August 2000.

[12] J. Hightower, R. Want, and Gaetano Borriello, "SpotON: An Indoor 3D Location Sensing Technology Based on RF Signal Strength," UW CSE 2000-02-02, University of Washington, Seattle, WA, Feb. 2000.

[13] W.G. Griswold, R. Boyer, S.W. Brown, T.M. Truong, E. Bhasket, R.Jay and R.B. Shapiro, "ActiveCampus: Sustaining Educational Communities through Mobile Technology", Technical Report, University of California, San Diego, Department of Computer Science and Engineering, 2002.

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