This full text paper was peer reviewed at the direction of IEEE Communications Society subject matter experts for publication in the ICC 2008 proceedings.

On the Effect of Localization Errors on Geographic Routing in Sensor Networks

B. Peng, R. Mautz, A. H. Kemp, W. Ochieng and Q. Zeng

***Abstract*—Recently, network localization systems that are based on inter-node ranges have received significant attention. Geographic routing has been considered an application which can utilize the location information from these localization systems. In this paper, we firstly recognize that sensor network localization algorithms generate positioning data with different error patterns compared to those networks where node positions are determined directly from GNSS measurements. Secondly, by simulating practical sensor network scenarios using data from our localization algorithm, we observe that existing geographic routing algorithms in wireless sensor networks (WSNs) adopt very simplistic methods in the treatment of position error, without due consideration of error distribution. Additionally, an insight is given into localization algorithms for WSNs with inhomogeneous error environments. Our observations represent an initial step toward a detailed understanding and design of efficient geographic routing algorithms in location aware WSNs.**

***Index Terms*—geographic routing, inhomogeneous location errors, sensor networks, wireless positioning**

I. Introduction

Geographic routing [1], also referred to as location-based routing, utilizes the geographical location information of each sensor node to deliver packets over a network. Since routing decisions at the nodes rely on the destination's location information and the location of the forwarding nodes, geographic routing does not require the establishment or maintenance of a specific route. Hence, the communication overhead is relatively small. In addition, geographical routing eliminates the need for route setup time. The combination of these features makes geographical routing an attractive application for wireless sensor networks (WSNs). Since location is the only information for geographical routing to deliver packets from the source to the destination node, the availability and accuracy of the obtained locations are crucial. Previous work [2], [3], [4] assumes that each node in a network is equipped with a Global Navigation Satellite System (GNSS) receiver and consequently is able to independently obtain its own geographic location. However, for many WSN applications GNSS is still too costly, has relatively high power requirements and does not cover indoor environments.

These limitations of GNSS have motivated the search for complementary methods in addition to those depending on satellites. Recently, a large number of wireless positioning systems have been proposed and evaluated, e.g. [5], [6], [7], [8]. Network positioning based on graph theory has been investigated extensively using a set of range measurements between network nodes, e.g. by [9], [10], [11]. Wireless devices enjoy widespread use in numerous diverse applications including sensor networks. The near future scenario consists of countless tiny embedded devices, equipped with sensing capabilities, deployed in all environments and organizing themselves in an ad-hoc fashion.

Network localization systems that are based on inter-node ranges, however, show different error patterns compared to those networks where all node positions are determined directly from GNSS measurements. These effects have been largely neglected in studies on the performance of geographic routing in WSNs. In this paper, we investigate the performance of geographic routing as a function of several sensor network characteristics, such as the number of anchor nodes (i.e. devices with known reference coordinates), the maximal radio range, node density etc. The key parameter of the performance tests is the deviation between input coordinates and the computed coordinates from our localization algorithms. To our knowledge, this is the first study on how position errors whose characteristics are driven by several parameters affect the performance of geographic routing. Our simulation results characterize the impact of several parameters and provide valuable insights into the underlying behaviour of the WSNs under a range of practical parameters.

The rest of the paper is organized as follows. Our positioning strategy and the related error models are introduced in Section II. Section III discusses geographic routing in the presence of location errors. Section IV contains simulation design and results. Section V discusses our findings. Section VI concludes the paper and gives possible directions for future work.

II. Positioning Strategies

A. Geodetic Positioning Mode

The precise or geodetic mode makes use of available distance observations between devices that have direct line of sight. A geodetic network is created with each node having unique error variance of the position coordinates. These

Bo Peng, Andrew H. Kemp and Qinghua Zeng are with the School of Electronic and Electrical Engineer, University of Leeds, LS2 9JT, UK. (phone: +44(0)113 343 2078; Fax: +44(0)113 343 2032; e-mail: b.peng@leeds.ac.uk).

Rainer Mautz is with the Institute of Geodesy and Photogrammetry, ETH Zurich, 8093 Zuerich, Switzerland. (phone: +41(0)44 633 78 27; Fax: +41(0)44 633 11 01; e-mail: mautz@geod.baug.ethz.ch

Washington Ochieng is with Centre for transport studies, Department of Civil and Environmental Engineering, Imperial College London, SW7 2AZ, UK.

978-1-4244-2075-9/08/$25.00 ©2008 IEEE

position errors are typically in the magnitude of the range measurements (e.g. 1 dm to 1m). Where the network has an inter-nodal connectivity of c > 3 (or c > 4 in 3D), the precise geodetic network can be initialized. The positioning strategy is based on the creation of a rigid structure. The key issue is to find a globally rigid graph, or in other words, a structure of nodes and ranges which has only one unique embedding, but still can be rotated, translated and reflected. In 2D, the smallest graph consists of four fully connected nodes in general position, (five nodes in 3D). If such an initial rigid cluster passes statistical tests, additional vertices are added consecutively using a verified multilateration technique. Most applications require the network nodes to be tied in a coordinate system of higher order. With a minimum availability of three anchor nodes (four in 3D), the local coordinates can be transformed unambiguously into the relevant target system. This can be achieved by a 3D-Cartesian coordinate transformation. A closed form solution for the determination of transformation parameters using the 3D-Helmert transformation is given by Horn [12]. Subsequent to the transformation, a fully constrained Least Squares (LS) network adjustment is performed that permits all of the available anchor nodes and all range measurements to be processed together in order to refine all position approximates simultaneously. Further details of the positioning algorithm can be found in [13].

B. Coarse Positioning Mode

Coarse positioning exploits connectivity information between nodes when sufficient range measurements are not available. The uncertainty of coarsely located nodes is in the magnitude of the maximal transmission range (e.g. 10m to 50m). If a node cannot measure a sufficient number of ranges to its neighbors, but is able to receive data from neighboring nodes, its position can be roughly estimated by intersecting the circles (or spheres in 3D) with the maximal radio range. The more connections a node has and the smaller the maximal transmission range is, the more precise the location estimation of the node.

C. Error model

All nodes that participate in the precise mode get refined coordinates as a result of the rigid geodetic network adjustment. This kind of adjustment is based on the linearization of the equation system that involves all range observations and all coordinate unknowns. The linearization of the observation equations is based on the Gauss-Markov model. If an a priori error variance of the range measurements is known, the standard deviation of the estimated coordinates can be easily and reliably propagated. The error estimation of the coarse positioning mode cannot be done by using the Gauss-Markov model, because the errors involved do not follow a normal distribution. The deviation of nodes located by the coarse mode is systematic errors that are driven by the maximal transmission range. However, in order to allow a rough error estimation of all nodes in the network, the errors of the coarsely located nodes are estimated by simple geometric considerations and propagated in a simple straight-forward way; e.g. the mean point error of a node that has only one range measurement to an anchor node will get

$$\hat{\sigma} = \sqrt{r^2 + s_1^2 + s_2^2}, \quad (1)$$

where r is the measured range, s_1 is the mean standard deviation of the range observation and s_2 the mean standard deviation of the anchor node position.

III. Geographic Routing in the Presence of Location Errors

Many geographic routing protocols have previously been proposed and most of them consist of two operations: greedy forwarding and recovery procedure. Greedy Perimeter Stateless Routing (GPSR) [1] is one of the well known geographic routing protocols that proposed using perimeter or face routing to route around voids or obstacles when greedy forwarding fails. However, geographic routing protocols are inevitably vulnerable to location errors. Previous studies [2], [3], [4] have shown that location errors can lead to a substantial degradation in the performance of geographic routing in terms of packet delivery ratio and energy consumption. In [2] the authors studied the impact of location error on greedy forwarding by modelling four location inaccuracy metrics: absolute location accuracy, relative distance accuracy, absolute location inconsistency and relative distance inconsistency. They observed severe performance degradation and even protocol correctness violations for greedy forwarding even in the presence of reasonable (relatively small) location errors, and even without considering mobility. The effect of localization errors on recovery procedures have also been studied in [3], where the authors focused on the perimeter forwarding (also known as face routing) in GPSR. Their results showed that even for realistic and relatively small location errors (≤10%), the effects of location errors on perimeter forwarding are noticeable. Another study in [4] showed the effect of localization errors on the performance of greedy forwarding and a geographic routing protocol that uses flooding to route around obstacles. The results indicated that the throughput and energy consumption performance in the network deteriorates considerably for localization errors of more than 20% radio range. Based on the above findings, there is a need of a geographic routing protocol which can tolerate location errors and achieve better energy consumption. There are also proposals [14] based on Virtual Coordinate Systems (VCS) to address some of the shortcomings of geographic routing, such as vulnerable location errors. However, a relatively large setup overhead is required to setup this logical coordinate structure, especially when the topology changes.

All the above studies assume that the errors of each node in a network follows the same probability distribution (e.g. Uniform distribution in [4]). These independent location error models are probably fine if the position information of each node in a

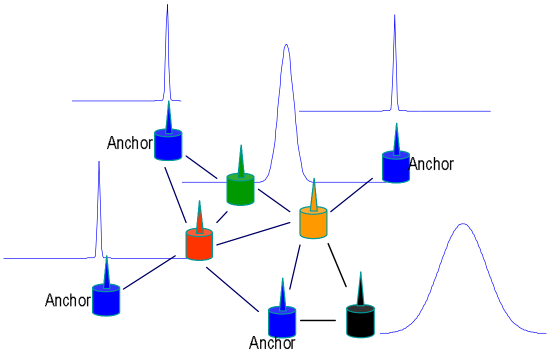

Fig. 1 Error distribution in a WSN

network is directly obtained from a node equipped with a GPS receiver. However, localization errors from network localization systems (e.g. our algorithm in section II) that use inter-node ranges show different error patterns compared to those networks where all node positions are determined directly from GNSS. In reality, localization in sensor networks typically requires a certain number of fixed anchor nodes which are aware of their own location and that are used as reference points to locate other network nodes with unknown location. These fixed anchor nodes require direct sight to the GNSS satellites, capability to read and process satellite ephemeris and sufficient power supply for data reception. Therefore, the location of these nodes has a relatively clear defined level of accuracy compared to sensor nodes that are using local range measurements. As described in section II, two modes of positioning quality for each node in a network need to be clearly distinguished: one mode we define as “geodetic” when the node is part of a rigid cluster of nodes. The other mode is the “coarse” mode, where the location information is roughly estimated by connectivity or a few ranges that don’t allow for the establishment of a rigid cluster. Fig.1 gives an example that different types of node have different level of accuracy. The latter group is extremely poor in its coordinate position quality and expected to have more significant impact on routing performance. Moreover, nodal positions that are a result of local inter-nodal ranges introduce different error characteristics into the network depending on several factors such as the quality of range measurements, availability and fraction of anchor nodes, the localization algorithms used and networks density and connectivity etc.

IV. Simulation Study

To verify the impact of various parameters on routing performance, a detailed simulation study is carried out in this section. Our network model consists of a set of sensor nodes, where each node position is determined by our localization the number of anchor nodes. Varying the number of anchor nodes algorithm and the GPSR routing protocol is evaluated based on these location data. We also assume that nodes have consistent location information about other nodes, so we do not include the location inconsistency previously studied in [2].

TABLE I
VALUES OF AVD FOR DIFFERENT NUMBERS OF ANCHOR NODES

Anchor	4	8	12	16	18	20	22
AVD (20m)	30.9	17.4	13.8	9.6	6.1	6	5.1
AVD (30m)	12.6	1.4	2.4	0.8	1	1	0.9

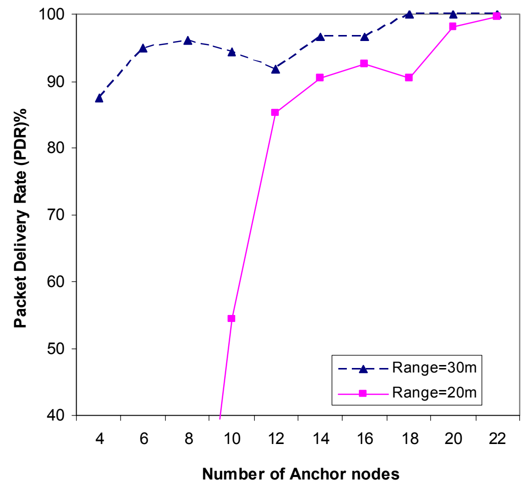

Fig. 2 Impact of the number of anchor nodes on the packet delivery rate

A. Simulation setup

While studying the impact of errors induced by various parameters on geographic routing, we choose GPSR as the routing protocol in the simulation study. The choice of GPSR is to make our results directly comparable to those previously published. We study positioning performance using a variety of different network parameters and evaluate their impact on geographic routing. In our simulations a static and stable network (no mobility and no failures) without obstacles and with nodes having accurate and symmetric radio ranges is assumed. 100 nodes are uniformly and randomly placed within a 100m × 100m network, and the results are computed as the average of 10 runs. All scenarios are simulated in two steps: (1) The localization algorithm calculates the coordinates of all sensor nodes in the network; (2) The routing algorithm uses the location information to perform packet delivery. For all simulation runs, 20 Constant Bit Rate (CBR) messages are generated uniformly from 20 pairs of sending and receiving nodes. Each CBR flow sends at 8kbps, and uses 32-byte packets. Each simulation lasts for 250 seconds of simulation time.

B. Impact of number of anchor nodes

In this section, we investigate the impact of the number of anchor nodes on packet delivery rate (PDR). The noise level is set to 1m and number of anchors is varied from 4 to 22. Two different radio ranges, 20m and 30m, are shown. Table I lists the AVD (Average Mean Deviation) of all nodes, which can be used as an indication of the average error on all nodes in the network. Fig. 2 shows the packet delivery rate as a function of the number of anchor nodes which varies from 4 to 22 (i.e. 4% to 22%). This results in an increase of the PDR for both ranges. Clearly, more anchor nodes improve the localization performance, and therefore, PDR increases accordingly. However, when the range is 20m, the PDR drops very quickly

TABLE II
VALUES OF AVD FOR DIFFERENT NOISE LEVELS

Noise (m)	0	0.4	0.8	1.2	1.6	2
AVD (30m)	0	0.6	2.9	6.9	2.2	7.9
AVD (25m)	0.5	1	2.4	8.7	66	15

TABLE III
VALUES OF AVD FOR DIFFERENT CONNECTIVITIES

Connectivity	10	12	14	16	18	20	22
AVD (Noise=0m)	1.8	0.5	0.4	0.4	0.2	0.2	0
AVD (Noise=1m)	11.6	8.1	3.7	2.6	1.9	1.2	1.1

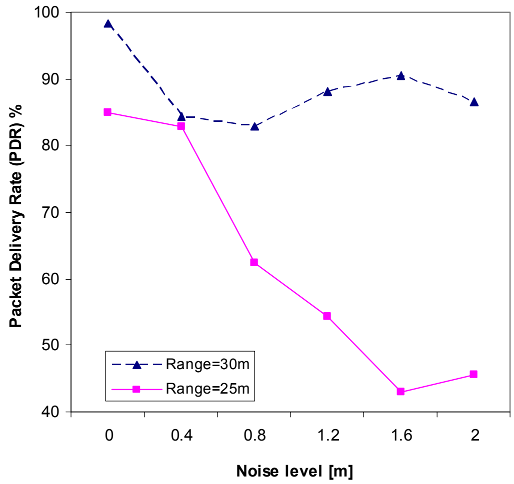

Fig. 3 Impact of noise level on the packet delivery rate

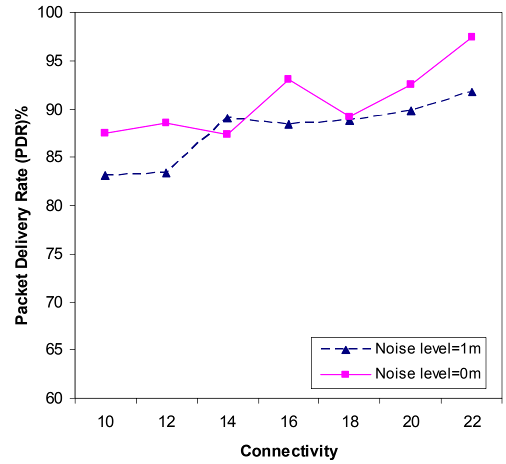

Fig. 4 Impact of the connectivity on the packet delivery rate

(<40%) if the number of anchors is less then 10%. However, this is not the case when the range is 30m. This finding confirms our previous expectations that the required minimal number of anchor nodes also depends on the other parameters, such as connectivity. Hence, the radio range has a strong effect on PDR in this scenario. Larger radio ranges make nodes "see" more direct neighbours, which increase the connectivity of the network. We also observe that PDR can achieve nearly 90% when radio range is 30m with only a small number of anchor nodes (>5). This is because those 30m ranges provide quite a high connectivity, which improves not only the accuracy of the localization algorithm, but also routing performance.

C. *Impact of the noise level*

The random measurement noise in the ranges is a key factor in location determination. In order to asses the impact of noise, we created a simple scenario. We place 100 nodes uniformly and randomly in a three-dimensional cube with 100 m edge length. The range length is recorded only between nodes that are within a maximum ranging distance $r_{\max}$. For a later comparison, the positions are recorded as true positions $\mathbf{P}_i$ and error free ranges d_i. Furthermore, a fraction of nodes are randomly selected to serve as control points and saved separately. Then, normally distributed random noise with mean $\mu = 0$ and standard deviation σ_r is added to the observations, now recorded as $r_i = d_i + \sigma_r z_i$, where z is a function that generates normally distributed random numbers with a standard deviation of 1. We also study two different maximal transmission ranges among the nodes. Figure 3 shows the impact of the noise level on the PDR. Generally speaking, the packet delivery rate of both ranges decreases when the noise level increases. With an increase of the noise level, the number of accurately located nodes decreases, hence more nodes are only located with the coarse positioning mode. The number of nodes that participate in the precise geodetic network decreases because a higher noise level causes an increase of the rate of failure of the volume and ambiguity check (Table II). However, this trend is not exactly monotonic because the networks were created independently and randomly. With each created network, a new random deployment of the nodes is created. Furthermore, the maximum radio range is also crucial to PDR in this scenario. With an increase of the maximum radio transmission range, the number of inter-node ranges also increases. The positional error is clearly driven by the maximum radio range, e.g. using Bluetooth it is 10m or 20m. Larger radio ranges will not only increase the inter-node connectivity for localization, but also be beneficial for routing performance.

D. *Impact of the network connectivity*

In this section, we investigate the impact of the connectivity on PDR using two different noise levels. The radio range is fixed to 30m and the number of anchor nodes that are randomly deployed in the network is 10. We vary the connectivity from 10 to 22, where the connectivity is defined as the average number of ranges a node in the network can measure to its neighbouring nodes. Table III shows the influence of the connectivity to the average deviation (AVD). At low connectivity below 10, only anchor nodes can be located precisely. How the PDR increases with higher connectivity can be seen in Figure 4. The more ranges available the better the positioning accuracy, and therefore, the routing algorithm can deliver more packets with smaller location errors. Higher connectivity also increases the success rate of GPSR because GPSR can use the greedy method to forward the majority of packets in denser networks. As expected, an added noise level of 1m degrades the PDR about 10% independently from connectivity.

TABLE IV
VALUES OF AVD FOR DIFFERENT RANGES

Range (m)	15	20	25	30	35
AVD	19	16	4	1	0.7

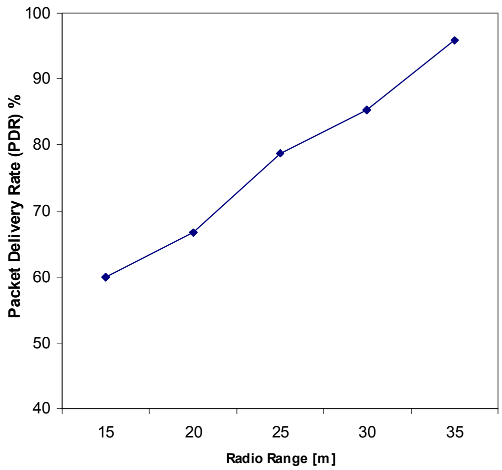

Fig. 5 Impact of the radio range on the packet delivery rate

E. Impact of radio range

In this scenario, we simulate maximum radio ranges between 15m and 35m in order to investigate their impact on the packet delivery rate (at 1m noise level and 10 anchor nodes). As shown in Figure 5, the radio range has significant effect on the routing performance, due to a change in the AVD from 19 down to 0.7, see Table IV. A longer radio range increases the connectivity, and hence more nodes can be located precisely and more packets can be delivered successfully. This also confirms our findings in section C.

F. Discussions

We have evaluated the impact of the key parameters in WSN on routing performance using node positions with a realistic distribution of errors according to the results of our localization algorithm. Although every parameter influences the routing performance significantly, it is the average deviation (AVD) which actually has the highest impact on the routing performance (PDR) as can be seen in the tables. Taking into account that network localization systems based on inter-node ranges show a different error pattern than those networks where all node positions are directly measured by GNSS, we argue that errors in WSN have two properties: the average deviation of error which has been studied previously and the distribution of the errors across the whole network. This property, however, as far as we know, has not been studied yet. Hence, the existing geographic routing algorithms (e.g. GPSR) do not take inhomogeneous error distribution into their path selecting metrics. We believe that the error distribution cannot be ignored and taking it into account will benefit not only the packet delivery rate but also the energy consumption for geographic routing protocols.

V. CONCLUSIONS

We investigated realistic sensor network scenarios using data from our localization algorithm in order to obtain better understanding of the impact of location errors on geographic routing in WSNs. We observe that various network parameters have a strong influence on geographic routing. Our simulation results show that the number of anchor nodes, noise level, radio range and the respective number of connections each have a significant impact on routing performance in terms of packet delivery rate. The experiments confirm and extend the findings of other studies, and also give insights into the source of location errors. Finally, we have quantified the impact of network parameters which drive the positional errors and as a consequence the packet delivery rate. Our findings represent an important step in understanding and designing efficient geographic routing as well as localization algorithms in WSNs under complex error environments. The simulation experiments provide insights into the performance of wireless sensor networks under different conditions. Future research can exploit these findings and optimize the network settings in order to reduce the impact of location errors on geographic routing. Furthermore, new geographic routing algorithms considering error distribution in practical WSNs seem a promising direction.

REFERENCES

[1] B. Karp and H. T. Kung: GPSR: "greedy perimeter stateless routing for wireless networks". in *MobiCom '00: Proceedings of the 6th annual international conference on Mobile computing and networking*. New York, NY, USA: ACM Press, 2000, pp. 243–254

[2] Y. Kim, J.-J. Lee, A. Helmy: "Modeling and analyzing the impact of location inconsistencies on geographic routing in wireless networks". *SIGMOBILE Mob. Comput. Commun. Rev*., vol. 8, no. 1, pp. 48–60, 2004.

[3] K. Seada, A. Helmy, R. Govindan. "On the Effect of Localization Errors on Geographic Face Routing in Sensor Networks". *USC Technical Report*, July 2003

[4] R. Shah, A. Wolisz, J. Rabaey: "On the performance of geographical routing in the presence of localization errors," in *Communications, 2005. ICC 2005. 2005 IEEE International Conference on*, Seoul, Korea, May 2005.

[5] Niculescu, D and Nath, B, "Ad-hoc positioning system", in*: IEEE GlobeCom*, 2001

[6] Savarese, C; Langendoen, K and Rabaey, J, " Robust positioning algorithms for distributed ad-hoc wireless sensor networks", in: *USENIX Technical Annual Conference*, Monterey, CA, 2002, pp. 317–328.

[7] Savvides, A; Park, H and Srivastava, M, "The n-Hop Multilateration Primitive for Node Localization Problems". *MONET* 8(4): 443-451.

[8] Smith, A; Balakrishnan, H; Goraczko, M and Priyantha N, "Tracking Moving Devices with the Cricket Location System".

[9] Goldenberg D; Krishnamurthy, A; Maness, W; Yang, Y; Young, A; Morse, A; Savvides, A and Anderson B "Network Localization in Partially Localizable Networks". *In Proceedings of IEEE INFOCOM* 2005, Miami, FL, March 13-17, 2005.

[10] Eren, T; Goldenberg, D; Whiteley, W; Yang, Y; Morse, A; Anderson, B and Belhumeur, P, "Rigidity, computation and randomization of network localization". In: *Proceedings of IEEE Infocom '04*, Hong Kong, China, April 2004.

[11] Moore, D; Leonard, J; Rus, D and Teller, S (2004): Robust distributed network localization with noisy range measurements, Proceedings of the ACM Symposium on Networked Embedded Systems, 2004.

[12] Horn, B, "Closed-from solution of absolute orientation using unit quaternions". *Journal of Opt. Soc. Amer*., vol. A-4, pp. 629–642, 1987.

[13] Mautz, R., Ochieng, W.Y., Brodin, G., Kemp, A., "3D Wireless Network Localization from Inconsistent Distance Observations", *Ad Hoc & Sensor Wireless Networks*, Vol. 3, No. 2–3, pp. 141–170, 2007

[14] A.Caruso et al. "GPS free coordinate assignment and routing in wireless sensor networks", *INFOCOM* 2005