# An Efficient Calibration Method for RSSI-based Location Algorithms

Rafael Pereira Pires
Lucas Francisco Wanner
Antônio Augusto Fröhlich

LISHA - Laboratory for Software and Hardware Integration
UFSC - Federal University of Santa Catarina
PO Box 476 – 88049-900 – Florianópolis, SC, Brazil
Email: {rafaelpp, lucas, guto}@lisha.ufsc.br

*Abstract*— **Position awareness is a desirable feature for many applications of Wireless Sensor Networks. The Received Signal Strength Indication of a radio channel provides a feasible way of estimating distance between nodes because its use doesn't require any additional hardware but a radio transceiver. The main drawback of using RSSI is its instability and interference susceptibleness noticed in real environments. This work shows an evaluation of a location algorithm for wireless sensor networks and presents a new calibration approach that substantially improves the trustworthiness in its results. The results show that adequately adjusted RSSI measurements can be successfully used for localization in Wireless Sensor Networks.**

## I. INTRODUCTION

Several wireless sensor networks applications, such as tracking of objects, habitat monitoring, environmental observation and forecasting, battlefield surveillance and enemy tracking, take into account the geographic position of the nodes. Hence, these applications need a system that provides them some kind of location information. Attaching a GPS (Global Positioning System) device to each sensor node could provide applications with precise location coordinates. The GPS system yields good precision, but has limitations for indoor environments, and is based on a considerable satellite infrastructure, as is thus not suitable for low cost devices in ad-hoc sensor networks. For this kind of network, the location system should be self-contained (not dependent on a fixed infrastructure), robust to failing nodes and to errors in range measurements. The system should also be implemented considering the restricted power, processing and communication resources in the nodes.

HECOPS (Heuristic Environmental Consideration Over Positioning System) [1] is a distributed location algorithm for Wireless Sensor Networks where every node estimates its own position after interacting with other nodes. Only a limited number of nodes have exact knowledge of their position coordinates. HECOPS establishes a ranking system to determine the reliability of each estimated position, and uses heuristics that are used to reduce the effects of measurement errors, including a scheme to calibrate range measurements by comparing, whenever possible, the estimated distance with the actual distance between a pair of nodes. This work presents an implementation and evaluation of the HECOPS algorithm, and several adaptations to its calibration system. This new calibration system considerably improves the quality of location results, and could be used in any RSSI-based location algorithm.

The main problem of location algorithms that use RSSI as range measurement for distance estimation is its instability noticed in practice, due to signal reflection, diffraction, and scattering [2]. By collecting data in the field and running large-scale simulations of the algorithm, we were able to observe this characteristic and its effect on the behavior of the calibration scheme. We then realized that some alterations in the way that the distances are corrected could considerably improve position estimations reliability, enabling its deployment in real-world applications. In this article we present this new calibration scheme, and compare it with original results of the HECOPS location system.

The rest of this paper is organized as follows: In Section II we present the related works and highlight the differences to our method. Section III describes the HECOPS algorithm. Section IV presents the infrastructure used for testing, and considerations about the implementation of the algorithm. Section V presents our new calibration approach. Finally, section VI presents our conclusions.

## II. RELATED WORKS

There is a broad range of proposed location algorithms, varying the range measurement, e.g., ultrasound [3], optical [4], difference time of arrival of radio and sound signals [5], angle of arrival [6] and even algorithms that do not use distance estimation at all [7], [8] (usually coordinates average - centroid - of neighboring anchor nodes is used); and the analytical method for position estimation, e.g., lateration, min-max [9] and iterative multilateration [5]. So, we will focus on calibration and refining methods of similar approaches, i.e., anchor-based algorithms that apply some kind of improvement on distance estimation or on the estimated position.

Savarese et. al. [10] proposed a location system based in two phases: Hop-Terrain, for estimating distances to landmark nodes and so calculating the position through lateration; and Refination, to improve the estimated positions. They do not make assumptions about the range measurement to be used. The Refination algorithm gives confidence values based on properties such quality (anchors or not) and number of directly connected neighbors and normalized residue of the estimated position related to distance of neighbors. Therefore, their approach differ from ours because we, besides giving confidence values on estimated positions, also improve the RSSI estimated distances, yielding a greater precision on position estimation. Considering the error in the same units, that is, the ratio between distance error and radio range, using our calibration system, we got about 10% of error with 15% of anchor population and connectivity of 30 nodes in contrast to about 25% of error with anchor population between 10% and 20% and connectivity of 25 nodes reported by them. Note that no propagation model is used in their simulations, but an artificially random error limited to 5% of the radio range for those results.

Savvides et. al. [9] proposed the "N-hop Multilateration Primitive", for estimating and refining initial rough estimations based on selected neighbors. That selection is made in a way that the system of equations have a unique solution. Afterwards, the bounding box method is used to find the first estimates. Then, the refining process is made by applying the Kalman Filter, a method whose purpose is to reduce the global residue considering the estimated positions and distance estimations. They present a centralized solution, that is computation-intensive that wouldn't fit in low processing power nodes and an alternative distributed solution, that considers only local and neighbor information. The main difference in the refining process is that we act on the distance estimation, the main source of errors for RSSI-based location algorithms. Our refining in position estimations is similar, although we use least squares method and do not consider multihop estimations. Other works also deal with corrections on estimated position, accepting the raw range measurement data [11].

An approach based on signal strength and that improves the estimated distances is the RADAR system [12]. This work focuses on indoor environments, such localizing people using PDAs inside a building. The measurements are made in two phases. The first phase intends to create maps of the signal strengths inside the deployment environment by sampling the signal transmissions to fixed base stations. In the second phase the users' locations can be estimated by observing the signal from their stations and matching with the measurements from the first phase. Although good results are achieved, as the signal propagation at the specif deployment environment is considered, their system wouldn't be suitable for dynamic environments, where signal propagation changes along the time, even by mobility or intense interference (that is usual in low frequency radios).

## III. THE HECOPS LOCATION ALGORITHM

The HECOPS location algorithm aims at solving the following problem: given a set of nodes with unknown position coordinates, and a mechanism by which a node can estimate its distance to a few nearby (neighbor) nodes, determine the position coordinates of every node via local node-to-node communication [1]. Hence, some nodes need to have an a priori knowledge of their position based on some global coordinates system. These nodes are called *anchors*. Based on its coordinates, all other nodes will estimate their position. The position information of the anchor nodes can came from GPS devices installed in just a small amount of nodes, pre-established in the source code or by other methods of self establishment of coordinates executed before the location service [13].

An important factor in distributed algorithms of localization is how to estimate distances between pair of nodes directly connected. There are techniques based on time propagation of messages like ToA (Time of Arrival) and TDoA (Time Difference of Arrival), but they need high resolution timers. Other techniques, like AoA (Angle of Arrival) and distance estimation based on optical and ultrasound devices are additional hardware dependent. In order not to depend on any other devices but a radio transceiver, already required for wireless communication, the HECOPS system uses as range measurement the RSSI (Received Signal Strength Indication). The estimated distance is inversely proportional to signal strength received.

The main problem of RSSI is its variation, which is non-uniform in all directions and is easily affected by electromagnetic interferences and physical barriers. These characteristics bring much imprecision into the position estimation system, and must be treated in an efficient way.

Previous studies [14] show that, event with the instability of RSSI, its variation is related to the direction of the radio transmission signal. This means that nodes position in the same direction of a transmitter will present similar signal degradation patterns, and similar RSSI readings. Based on that, in HECOPS, the distances to anchor nodes estimated by nodes with unknown position are calibrated by correction factors obtained by other nodes in the same direction. This factor, called *deviation*, is defined by the the actual distance, calculated by nodes that already know their positions, multiplied by the signal strength of a message sent by one of them.

For example, in Figure 1 [14], nodes B and X, by being positioned at the same direction related to A, are supposed to be affected by the same deviation. Considering A and B anchor nodes, the deviation would be given by equation 1, where $dev_{AB}$ is the deviation, $d_{AB}$ the Euclidean distance between A and B, and $RSSI_B$ the RSSI reading of the node B of a message sent by A. Therefore, the estimated distance between A and X would be given by $d_{AX} = \frac{dev_{AB}}{RSSI_X}$. Node D wouldn't be affected by $dev_{AB}$ because it's not in the same direction.

$$dev_{AB} = d_{AB} \times RSSI_B \tag{1}$$

We expect the required anchor proportion be as small as possible, without compromising the results accuracy. For that reason, the HECOPS allows nodes with estimated positions

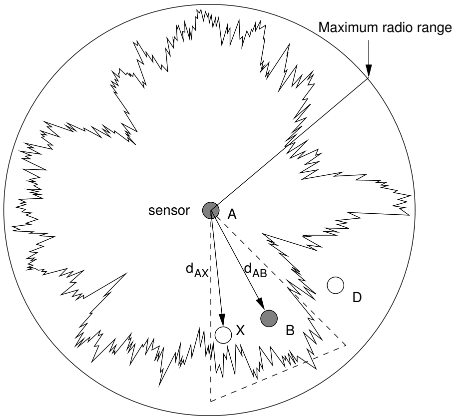

Fig. 1. Irregular radio pattern of a sensor and calibration system based on direction.

to be chosen as landmarks. In order not to let this characteristic compromise the system's performance, HECOPS uses a heuristic scheme that gives a value to the confidence on location information given by nodes. Each node, when calculating its position, defines a confidence value on the result obtained. This value ranks the nodes that should be chosen by a node that has to estimate its location.

Confidence calculation is based on the confidence value of the nodes chosen as landmarks and on the confidence of the nodes used in distance calibration related to that landmarks. In a scale varying from 0 to 1.0, anchor nodes have maximum confidence on its position, equal to 1.0. The other nodes have confidence limited by 0.8, given by equation 2, where $C_x$ is the confidence on position that is being calculated by a node X, $C_i$ the confidence on each landmark chosen by X ($n$ in total) and $C_{ix}$ the confidence of the node that, together with the node $i$, have defined the deviation applied to the distance between the nodes $i$ and X, if any (In Figure 1, $C_{ix}$ would be the confidence on node B, considering $i$ the node A).

$$C_x = 0.8 \times \frac{\sum_{i=1}^{n}(C_i \times 0.75 + C_{ix} \times 0.25)}{n} \tag{2}$$

Location information received from anchors is very trustworthy. But, if the distance estimation of that node has been calibrated by another node, the confidence is even greater. For this reason, the weights of 0.75 and 0.25 were attributed for the confidence on a chosen landmark and the confidence of the node used to calibrate the distance between them, respectively. Thus, when a node that has to estimate its position has already chosen its landmarks and have the estimated distances to all of them, it's enough to apply some method to calculate coordinates, like lateration or min-max [9].

In the beginning, only anchor nodes know their positions. They start by broadcasting their identification (ID), coordinates (x,y) and confidence values (Figure 2(a)). The nodes that receive this message store the information together with the RSSI reading. If the receiving node already knows its position, it calculates the distance and deviation between itself and the sending node, and broadcasts this information (Figure 2(b)). This information is in turn stored by the nodes who wish estimate their positions.

<table>
<tr><td colspan="2">ID</td></tr>
<tr><td>x</td><td>y</td></tr>
<tr><td colspan="2">Confidence</td></tr>
</table>

(a) Position information message.

<table>
<tr><td>$ID_A$</td><td>$ID_B$</td></tr>
<tr><td colspan="2">$deviation_{AB}$</td></tr>
<tr><td colspan="2">$distance_{AB}$</td></tr>
</table>

(b) Deviation information message.

Fig. 2. Content of exchanged messages

When a message with deviation information is received by a node that doesn't know its coordinates, it checks if it's in the same direction than the transmitter, related to the third node described in the message. If it is, it calibrates the RSSI reading of a message sent by that third node with the deviation.

The checking of a node to discover if it's in the same direction of another one related to a sending node is made according to proximity between them. In Figure 3, the node C receives a message from B about the deviation between A and B. So, node C verifies if its distance to node B is lower than the half of the distance to A. In a positive case, node C calibrates the RSSI reading of the last message received from A with the deviation between A and B. When these conditions are met, hereinafter we will refer as the "tri" occurrence.

Position information messages are stored by the nodes that will estimate its coordinates in a list ordered by the confidence value. When the list size reaches 3 it's already possible to execute the position calculation. The 3 nodes of the list with greatest confidence in their positions are chosen as landmarks.

## IV. SIMULATIONS AND EVALUATION

In order to evaluate the location system implemented in this work, and to allow tweaking of parameters in the location algorithm, RSSI measurements were collected in the field, and stored for offline execution. For this, a wrapper was developed to allow running the same code developed for the sensor platforms with EPOS [15], a deeply-embedded operating system, and in UNIX workstations. Through this wrapper, the same code that would run in a sensor node runs in a thread, and message exchanging is performed through memory copies, using the data collected in the field.

In order to allow this execution scenario, RSSI measurements were collected between every pair of nodes in a $3 \times 3$ sensor grid, with nodes $5m$ apart. These measurements served as input for the workstation wrapper. Three nodes from the nine in total were selected as anchors, and three other nodes estimated their positions. Figure 4 illustrates the geographical disposition of the nodes after stabilization of the estimated positions. The arrows indicate the distance between the estimated positions of nodes A, B and C, and the actual position were they were located. This figure shows that the relative disposition of the nodes' estimated position was maintained from the actual position, which encourages the use of this system in applications which require this characteristic, such as geographical routing [16] or location based acquisiotional queries [17].

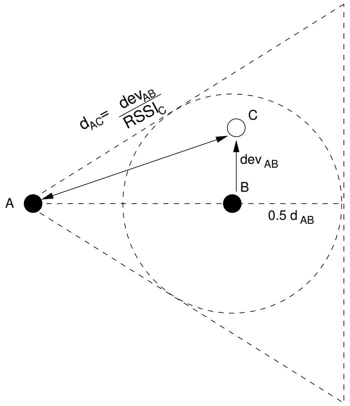

Fig. 3. Determining if two nodes are in the same direction, in order to use calibration

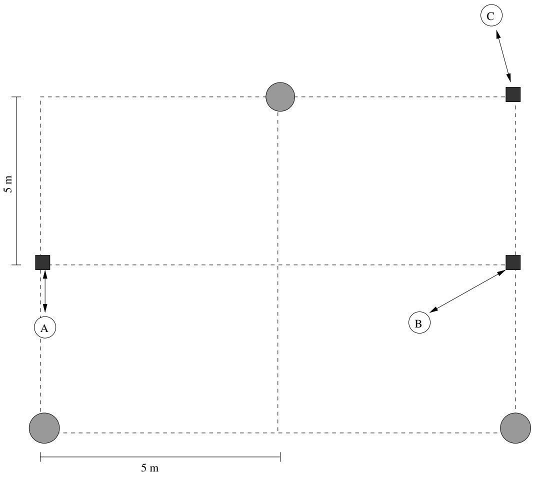

Fig. 4. Graphic disposition of the nodes after stabilization

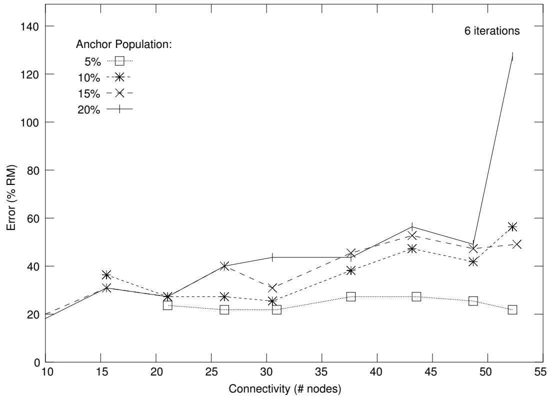

Fig. 5. Average Position Error for different anchor populations in our simulations (with a nonlinear signal propagation model)

In previously published results [1], [18], we used a simulation model based on the one used to evaluate the Hop-Terrain [10] location algorithm. This model allowed direct comparisons of the two algorithms, but was later found to be oversimplified. When our actual implementation showed considerable improvements through the use of a historical average, we found it necessary to evaluate the influence of calibration in the algorithm through more realistic radio propagation models, as the ones found in the Network Simulator (ns-2) [19].

In our original MatLab model [1], the signal propagation model was in the same scale as the coordinates system, and its variation was considered linear with relation to distance. Medium interference was simulated by adding a random value limited to a percentage of the actual distance. As observed in our field experiments and in recently published research results [2], [20], using a constant relation between distance and RSSI for different distances is too far from reality, thus not being a good model.

In our new simulations, we used the ns-2 "Two Ray Ground" propagation model, which considers node heights (1m above ground in our simulations), and has pass loss exponent (that indicates the rate at which the signal strength attenuates with distance) equal to 4. Signal intensity calculation is given by equation 3, where $P_r$ is the received signal power at distance $d$ from the transmitter, $P_t$ is the transmitted signal power, $G_t$ and $G_r$ are the antenna gains of the transmitter and the receiver respectively and $h_t$ and $h_r$ are the heights of the transmit and receive antennas respectively. In this model, signal intensity is inversely proportional to $d^4$, and notably non-linear. As in our previous simulations, we used a 10 × 10 nodes grid. Maximum node range was based on field experiments with Mica2 nodes [21], and equal to 80 meters. In our model, we use the term "connectivity" as the average number of nodes within reach of each node. For different connectivities, we varied the distances between nodes.

$$P_r(d) = \frac{P_t G_t G_r h_t^2 h_r^2}{d^4} \tag{3}$$

We ran different simulations, and came to some unexpected results. In our previous simulations, an increase in anchor population considerably decreases location errors. With a non-linear propagation model and with a large anchor population, the deviation average (used when no "tri" is found), produces an average that does not suit most distance calibrations. This happen because, when there is a high anchor density, there will be several different distances between them, and thus a great variation in deviation, which causes the error in estimated position to grow even when anchor population increases. Figure 5 presents a graph showing that behavior. Positioning error is defined as the ratio between the distance of the actual and estimated position to the maximum reach of the radio signal. In this graph, a smaller anchor population yields smaller error ratios. However, if anchor population is small, only a small quantity of nodes will be able to estimate its position, as many nodes will not be able to connect to any anchors.

In the previous model, deviation average was unnecessary, as the signal intensity was in the same scale as the coordinates system. When no "tri" was found, it was enough to use the RSSI reading as the estimated distance. As this does not occur in practice, we decided to evaluate the impact of introducing the average deviation when “tri” conditions are not met. According to our simulations, the number of “tris” grows with increased connectivity and anchor proportion, but remains close to 30%. Therefore, the number of times when deviation average must be used is approximately 70% of the total number of distance estimations. Enhancements in deviation average calculation methods would probably introduce significant improvement in position estimations errors.

The use of a confidence system, that is, using nodes with estimated positions as anchors, allows the use of a smaller anchor populations, without compromising the ability of nodes to estimate their positions, albeit with smaller precision. However, such a system introduces further error into estimated distances. This error grows when we decrease the landmark eligibility threshold. In our simulations, we ignored the confidence system, in order to avoid interference in other metrics relevant to the current work.

## V. NEW CALIBRATION APPROACH

Our new simulations and field experiments showed that our calibration approach was incorrect in its disregard of the disproportionality between distance and signal strength values. The method proposed to verify if two nodes are in the same direction is based on the relation between the distance of the estimating node and a nearby anchor, and the distance between this anchor and the node whose direction relationship one wishes to verify. According to Figure 3, if the $d_{BC}$ distance is smaller than $0.5 \times d_{AB}$, C would be considered to be in the same direction as AB, and the $dev_{AB}$ deviation would be applied by node C to the signal intensity of a message received from node A to estimate the distance between A e C. The $d_{BC}$ must be minimal in order for the same signal interference between AB and AC to be considered in the calibration process. However, when a multiplication factor (0.5) is used, this distance may be wide, when $d_{AB}$ is also wide.

In Figure 6, supposing A, B, and C are anchors, and X wishes to estimate its position, it would verify that its distance to the B node is larger than $0.5 \times d_{AB}$, and would discard the $dev_{AB}$ deviation. It would then verify that $d_{CX} < 0.5 \times d_{AC}$, and would use $dev_{AC}$ in order to calibrate signals from A. Using $dev_{AC}$ in this case would introduce considerable error into the distance estimation between A and X. As signal intensity does not varies linearly to distance, and $d_{AB}$ is closer to $d_{AX}$, the best deviation factor to be used in this calibration would be $dev_{AB}$. Although the distance $d_{BX}$ should be considered in order to deal with interference caused by physical barriers or electromagnetic waves, the relation between the $d_{AB}$ and $d_{AX}$ distances should also be considered, in order to allow deviations of a similar distance to be used in the calibration. In addition to the proposed restriction ($d_{BX} < 0.5d_{AB}$), we also ran simulations that excluded calibration factors when the distance between $d_{AX}$ and $d_{AB}$ was too large, that is, $\frac{|d_{AX} - d_{AB}|}{d_{AB}} > 0.15$, which would exclude $dev_{AC}$ in Figure 6.

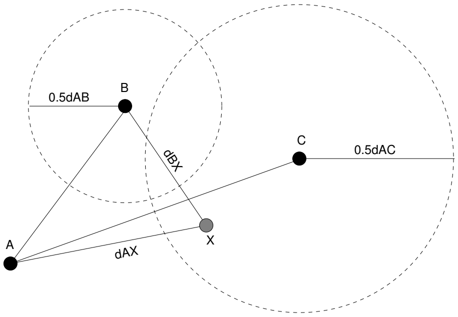

Fig. 6. Problem with previously proposed tri

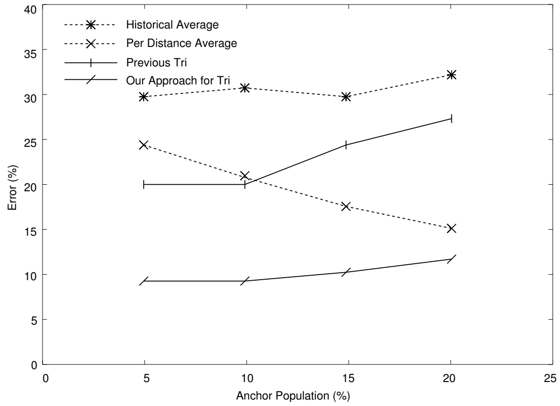

Fig. 7. Comparison of distance estimations errors (previous and new approach)

Additionally, we’ve considered RSSI readings as an inversely proportional function to distance, i.e., $P_r(d) = \frac{dev}{d}$, with $dev$ being the deviation. For similar distances, deviation is very similar, independently of the radio signal propagation model. Based on that, we decided to keep an average of deviations according to the distance of the nodes used in its calculation, instead of the average of all deviations. This alteration considerably reduced errors in estimated distances. Alternatively, based on the propagation models *free space* and *ground reflection*, where the pass loss are equal to 2 and 4, respectively [22], the calibration of RSSI could be done by extracting the square or fourth root of $\frac{dev}{RSSI}$.

Figure 7 presents the error obtained in the distance estimations using the previous approach, and the one proposed in this work. Both the “tri” alteration, and the separation of averages by classes of distances considerably reduced errors in estimated distances. Error, in this figure, corresponds to the relation of absolute difference between the estimated distances and the actual distance.

Naturally, the improved distance estimations is reflected in the estimated position. As previously stated, as about 70% distances are estimated through deviation averages, the change in deviation average calculation alone brings considerable improvements. Figure 8 presents errors considering instant deviation variation, historical deviation average combined with original “tri” determination, and finally, the new deviation by distance and the new “tri”. Error is the absolute distance in the coordinates system. In this simulation, one unit corresponds to one meter. The instant deviation curve shows the behavior

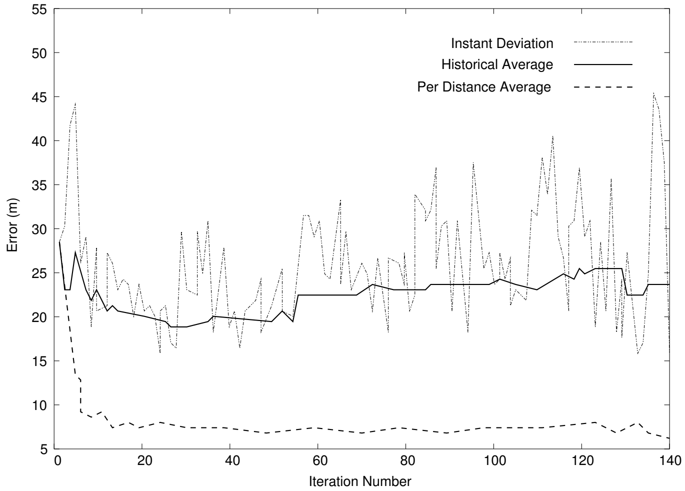

Fig. 8. Absolute Error along iterations with different approaches for deviation averages and tri

of the algorithm in relation to the highly irregular RSSI measurements, which hinder stabilization of the estimated position. In the other curves, a historical average of the RSSI was kept by each node, minimizing the effect of momentary RSSI fluctuations. The "per distance average" curve clearly shows the minimized erros brought by our approach.

## VI. CONCLUSION

This paper described and evaluated the HECOPS location algorithm for Wireless Sensor Networks under extensive simulations, using different models and assumptions than our previous work. We observed that, even with the restrictions of low cost and low computational power devices, it is possible to use an RSSI-based location algorithm, as long as some adaptations for performance and accuracy are introduced in the implementation of the location system for real world deployment.

We have proposed a calibration approach that brought great improvements to the results and could be used to any anchor and RSSI-based location algorithm. This calibration method does not depend on nonlinear propagation models and we've shown that it has a good performance in such environments.

Although RSSI measurements have been discouraged as a reliable distance estimation tool for wireless networks, due to its instability and susceptibleness to noise and interference, we found that with calibration, cooperative position exchanging, and heuristics, we may obtain good location results based on such measurements without the need for additional hardware.

## REFERENCES

[1] R. Reghelin and A. A. Fröhlich, "A decentralized location system for sensor networks using cooperative calibration and heuristics," in *MSWiM '06: Proceedings of the 9th ACM international symposium on Modeling analysis and simulation of wireless and mobile systems*. Terromolinos, Spain: ACM Press, 2006, pp. 139–146.

[2] J. Ma, Q. Chen, D. Zang, and L. M. Ni, *An Empirical Study of Radio Signal Strength in Sensor Networks Using MICA2 Nodes*, Department of Computer Science and Engineering - Hong Kong University of Science ant Technology. Technical Report, Mar. 2006.

[3] N. B. Priyantha, A. Chakraborty, and H. Balakrishnan, "The cricket location-support system," in *6th ACM/IEEE International Conference on on Mobile Computing and Networking (ACM MOBICOM '00)*, 2000.

[4] R. Stoleru, T. He, J. A. Stankovic, and D. Luebke, "A high-accuracy, low-cost localization system for wireless sensor networks," in *SenSys '05: Proceedings of the 3rd international conference on Embedded networked sensor systems*. San Diego, California, USA: ACM, 2005, pp. 13–26.

[5] A. Savvides, C.-C. Han, and M. B. Strivastava, "Dynamic fine-grained localization in ad-hoc networks of sensors," in *MobiCom '01: Proceedings of the 7th annual international conference on Mobile computing and networking*. Rome, Italy: ACM, 2001, pp. 166–179.

[6] D. Niculescu and B. Nath, "Ad hoc positioning system (APS) using AOA," in *INFOCOM 2003. Twenty-Second Annual Joint Conference of the IEEE Computer and Communications Societies*, vol. 3, Mar. 2003, pp. 1734–1743.

[7] N. Bulusu, J. Heidemann, and D. Estrin, "GPS-less low cost outdoor localization for very small devices," *IEEE Personal Communications Magazine*, vol. 7, pp. 28–34, Oct. 2000.

[8] T. He, C. Huang, B. M. Blum, J. A. Stankovic, and T. Abdelzaher, "Range-free localization schemes for large scale sensor networks," in *MobiCom '03: Proceedings of the 9th annual international conference on Mobile computing and networking*. San Diego, CA, USA: ACM, 2003, pp. 81–95.

[9] A. Savvides, H. Park, and M. B. Srivastava, "The bits and flops of the n-hop multilateration primitive for node localization problems," in *Proceedings of the First ACM International Workshop on Wireless Sensor Networks and Applications (WSNA-02)*. New York: ACM Press, Sep. 28 2002, pp. 112–121.

[10] C. Savarese, K. Langendoen, and J. Rabaey, "Robust positioning algorithms for distributed ad-hoc wireless sensor networks," in *USENIX Technical Annual Conference*, Monterey, CA, Jun. 2001, pp. 317–328. [Online]. Available: http://rama.pds.twi.tudelft.nl/ koen/papers/robust-positioning.pdf

[11] J. Arias, J. Lázaro, A. Zuloaga, J. Jiménez, and A. Astarloa, "GPS-less location algorithm for wireless sensor networks," *Computer Communications*, vol. 30, no. 14-15, pp. 2904–2916, 2007.

[12] P. Bahl and V. N. Padmanabhan, "RADAR: An in-building RF-based user location and tracking system," in *INFOCOM (2)*, 2000, pp. 775–784.

[13] H. Wu, C. Wang, and N.-F. Tzeng, "Novel self-configurable positioning technique for multihop wireless networks," *IEEE/ACM Transactions on Networking*, vol. 13, no. 3, pp. 609–621, 2005.

[14] X. Ji and H. Zhaa, "Sensor positioning in wireless ad-hoc sensor networks with multidimensional scaling," in *Poceedings of IEEE Conference on Computer Communications (INFOCOM)*, 2004.

[15] A. A. Fröhlich, *Application-Oriented Operating Systems*, ser. GMD Research Series. Sankt Augustin, Germany: GMD - Forschungszentrum Informationstechnik, Aug. 2001, no. 17.

[16] I. Stojmenovic, "Position-based routing in ad hoc networks," *IEEE Communications Magazine*, vol. 40, pp. 128–134, Jul. 2002.

[17] S. Madden, M. J. Franklin, J. M. Hellerstein, and W. Hong, "The design of an acquisitional query processor for sensor networks," in *SIGMOD '03: Proceedings of the 2003 ACM SIGMOD international conference on Management of data*. New York, NY, USA: ACM Press, 2003, pp. 491–502.

[18] R. Reghelin and A. A. Fröhlich, "RF-based location system using cooperative calibration," in *Proceedings of the 3rd IEEE International Workshop on Wireless Ad-hoc and Sensor Networks*, New York, U.S.A., 2006.

[19] K. Fall and K. Varadhan, *The ns Manual*, Mar. 2007, a Collaboration between researchers at UC Berkeley, LBL, USC/ISI, and Xerox PARC. Source: http://www.isi.edu/nsnam/ns/doc/ns_doc.pdf.

[20] D. Lymberopoulos, Q. Lindsey, and A. Savvides, "An empirical analysis of radio signal strength variability in ieee 802.15.4 networks using monopole antennas," in *Proceedings of the Second EWSN - European Workshop on Sensor Networks*, 2006.

[21] J. Hill, R. Szewczyk, A. Woo, S. Hollar, D. Culler, and K. Pister, "System architecture directions for networked sensors," in *Proceedings of the ninth international conference on Architectural support for programming languages and operating systems*, Cambridge, Massachusetts, United States, 2000, pp. 93–104.

[22] T. S. Rappaport, *Wireless Communications: Principles and Practice*, 2nd ed. Upper Saddle River, NJ: Prentice Hall PTR, 2002.