Self-adaptive Localization using Signal Strength Measurements

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***Abstract*—The paper treats the problem of localization in Wireless Sensor Network (WSN). In our work, we present and evaluate the localization system that can be used to calculate the geographical positions of network nodes. The search for the accurate positions of nodes is performed using a signal strength measurements and known positions of a set of selected sensors equipped with GPS system. Our scheme uses node to node distance estimates calculated based on RSSI (Received Signal Strength Indicator). The proposed solution is self-adaptive, since the transformation of RSSI measurements into distances is done automatically using information about strength of signals received by nodes equipped with GPS. We focus on the performance of our approach to localization, and discuss the accuracy of position calculation for various methods of inter-node distances estimation. The use and efficiency of the proposed localization system is illustrated by numerical examples performed in our WSN Localization Simulator.**

***Keywords*-wireless sensor networks; localization; Received Signal Strength Indicator; RSSI; signal measurements; optimization; simulated annealing; simulator**

I. INTRODUCTION

The goal of localization is to assign geographic coordinates to each node in the sensor network in the deployment area. Wireless sensor network localization is a complex problem that can be solved in different ways [1]. A number of research and commercial location systems for WSNs have been developed. They differ in their assumptions about the network configuration, distribution of calculation processes, mobility and finally the hardware's capabilities, [2], [3], [4].

Recently proposed localization techniques consist in identification of approximate location of nodes based on merely partial information on the location of the set of nodes in a sensor network. An anchor is defined as a node that is aware of its own location, either through GPS or manual pre-programming during deployment. Identification of the location of other nodes is up to an algorithm locating non-anchors. Considering hardware's capabilities of network nodes we can distinguish two classes of methods:

- range based (distance-based) methods,
- range free (connectivity based) methods.

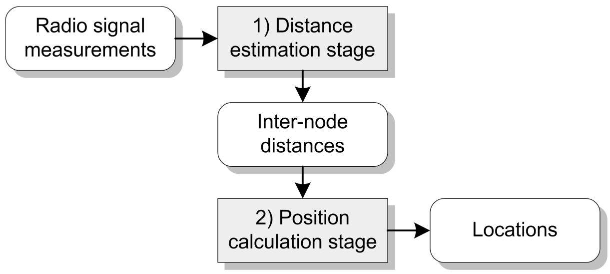


Figure 1. The scheme of localization process

The former is defined by protocols that use absolute point to point distance estimates (ranges) or angle estimates in location calculation. The latter makes no assumption about the availability or validity of such information, and use only connectivity information to locate the entire sensor network. The popular range free solutions are hop-counting techniques. Distance-based methods require the additional equipment but through that much better resolution can be reached than in case of connectivity based ones.

In general, to solve the distance-based localization problem it is necessary to combine two techniques: signal processing and algorithms transforming measurements into the coordinates of the nodes in the network. Hence, distance-based localization schemes operate in two stages, as shown in Fig. 1:

- *Distance estimation stage* – estimation of inter-node distances based on inter-node transmissions.
- *Position calculation stage* – calculation of geographic coordinates of nodes forming the network.

The paper is structured as follows: We formulate the localization problem in Section II. In Section III, we provide a short overview of popular radio signal measurement techniques and discuss the signal propagation modeling. In Section IV, the localization process using our localization system is described. The results of numerical experiments are summarized in Section V. In Section VI, we present conclusions.

II. Distance-based localization techniques

We are concerned with the distance-based approach to localization. Let us consider a WSN formed by M sensors (anchor nodes) with known position expressed as l-dimensional coordinates $a_k \in \mathbf{R}^l,\ k = 1, \ldots, M$ and N sensors (non-anchor nodes) $x_i \in \mathbf{R}^l,\ i = 1, \ldots, N$ with unknown locations. Our goal is to estimate the coordinates of non-anchor nodes. We can formulate the optimization problem with the performance measure J considering estimated Euclidean distances of all neighbor nodes

$$\min_{\hat{x}} \Big\{ J = \sum_{k=1}^{M} \sum_{j \in N_k} (||a_k - \hat{x}_j||_2 - \tilde{d}_{kj})^2 + \sum_{i=1}^{N} \sum_{j \in N_i} (||\hat{x}_i - \hat{x}_j||_2 - \tilde{d}_{ij})^2 \Big\}, \tag{1}$$

where $\hat{x}_i$ and $\hat{x}_j$ denote estimated positions of nodes i and j, $\tilde{d}_{kj}$ and $\tilde{d}_{ij}$ distances between pairs of nodes (k, j) and (i, j) calculated based on radio signal measurements, $N_k = \{(k, j) : d_{kj} \le r\}$, $N_i = \{(i, j) : d_{ij} \le r\}$ sets of neighbors of anchor and non-anchor nodes $(j = 1 \ldots, N)$, and r maximal transmission range.

The stochastic optimization algorithms can be used to solve the problem (1). Kannan, Mao and Vucetic in [5] present the results of location calculation for simulated annealing method. We propose the hybrid technique that uses a combination of the trilateration method, along with simulated annealing (TSA: Trilateration & Simulated Annealing). TSA was described in details in [6]. It operates in two phases:

- *Phase 1* – the auxiliary solution (localization) is provided using the geometry of triangles.
- *Phase 2* – the solution of the phase 1 is improved by applying stochastic optimization.

III. Range estimation

As it was mentioned in Section I using range based methods we can reach much better resolution than in case of range free ones. However in order to do that the additional equipment is usually required. Each of popular techniques – widely described in literature [2], [1] – such as Angle of Arrival (AoA), Time of Arrival (ToA), Time Difference of Arrival (TDoA) needs an additional stuff such as antennas or accurately synchronized clocks. The only exception from these requirements is a Received Signal Strength Indicator (RSSI) technique.

RSSI is considered as the simplest and cheapest method amongst the wireless distance estimation techniques, since it does not require additional hardware for distance measurements and is unlikely to significantly impact local power consumption, sensor size and thus cost. Main disadvantage of using RSSI is low accuracy. In respect to wireless channel models (Section III-A) received power should be a function of distance. However, the RSSI values have a high variability and they cannot be treated as a good distance estimates [7], [8]. On the other hand some authors indicate that new radio transceivers can give RSSI measurements good enough to be a reasonable link estimator [9], [10].

A. The radio signal propagation modeling

Propagation models are generally focused on predicting the average received signal strength at a given distance from the transmitter, as well as the variability of the signal strength in close spatial proximity to a particular location. Propagation models that predict the mean signal strength for an arbitrary transmitter-receiver separation distance are useful in estimating the radio coverage area of a transmitter and are called *large-scale* propagation models, since they characterize signal strength over large distances (hundreds or thousands of meters). On the other hand, propagation models that characterize the rapid fluctuations of the received signal strength over very short travel distances or short time durations are called *small-scale* models [11].

In this paper we concentrate on the stationary networks and do not consider small fluctuations of the signal strength in time. Hence the large-scale model is used further. Both theoretical and measurement based propagation models indicate that average received signal power decreases logarithmically with distance, whether in outdoor or indoor radio channels [11]. The mean large-scale path loss can be expressed as a function of distance:

$$PL(d)[dB] = PL(d_0)[dB] + 10n log \left(\frac{d}{d_0} \right), \tag{2}$$

where d is the transmitter-receiver distance, d_0 is a reference distance (for IEEE 802.15.4 radio typically the value of d_0 is taken to be 1 m) and n is the path loss exponent (rate at which signal decays). The value of n depends on the specific propagation environment and should be obtained through curve fitting of empirical data. An empirical experiment is also the best way to select an appropriate path loss for the reference distance d_0 [12].

The received signal strength P^r at a distance d is:

$$P^r(d)[dBm] = P^t[dBm] - PL(d)[dB], \tag{3}$$

where P^t denotes the power of transmitter.

IV. Localization process

As it was mentioned in Section I our localization system operates in two stages: the distance estimation stage and the position calculation stage.

A. Distance estimation stage

The signal propagation model outlined in Section III-A allows us to estimate the distance if we know the power of received signal. Hence, in our research we used RSSI measurements. The objective of the distance estimation stage is to tune parameters of propagation model (2-3) wrt a given network technology and deployment area. Calibration procedure achieves this goal automatically – by exploiting information (pair o values: RSSI and true physical distance) obtained for the links connecting anchor to anchor node. Therefore the localization can be called self-adaptive since the algorithm is capable of calibrating own parameters without additional information about the environment.

Consider WSN with M anchor nodes with known coordinates $a_k \in \mathbf{R}^l$, $k = 1, \ldots, M$ as defined in Section II. For each pair (i, j) of anchors which is in transmission range we can measure received signal strength P^r_{ij} . The set of such pairs is as follows:

$$\Psi = \{(P^r_{ij}, d_{ij}) : ||a_i - a_j||_2 < r\}, \tag{4}$$

where d_{ij} is known true physical distance between anchors i and j, and r transmission range.

Using (2) and (3) we can estimate the average distance between nodes i and j as a function of received signal strength P^r_{ij}:

$$\tilde{d}_{ij} = d_0 \cdot 10^{\frac{P^t - \overline{PL(d_0)}}{10n}} \cdot 10^{-\frac{1}{10n} P^r_{ij}}, \tag{5}$$

where d_0 denotes the reference distance, $\overline{PL(d_0)}$ the path loss at the reference distance, n the path loss exponent and P^t output power of the transmitter. It should be pointed that the goal of the calibration procedure is only to predict a value of the distance d for known value of P^r_{ij}, not to find the exact value of the parameters $n, P^t, d_0, \overline{PL(d_0)}$. Hence, we can simplify the equation (5) introducing parameters α and β:

$$\tilde{d}_{ij} = \alpha \cdot 10^{\beta \cdot P^r_{ij}}, \tag{6}$$

where $\alpha = d_0 \cdot 10^{\frac{P^t - \overline{PL(d_0)}}{10n}}$ and $\beta = -\frac{1}{10n}$. It seems to be reasonable to fit the RSSI-distance curve based on two parameters not four.

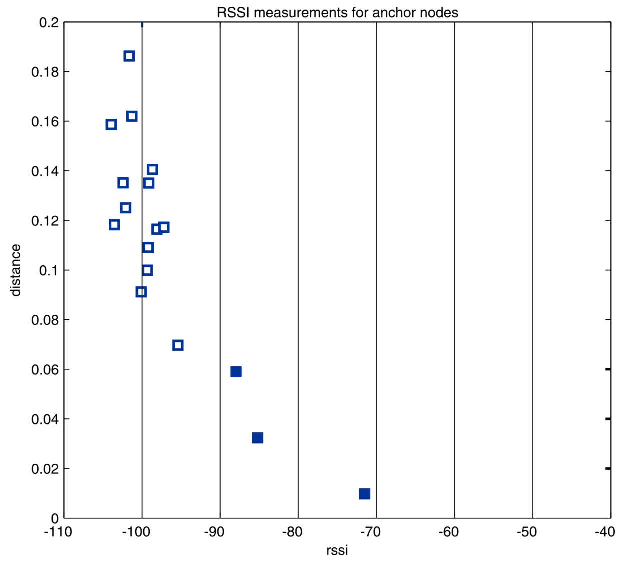
It is obvious that this average distance differs vastly from the true physical distance between selected nodes, but there is no chance to fit the curve describing signal propagation to all samples from Ψ. An ordinary least square (OLS) method can be used to calculate values of parameters α and β that minimize the error between the true physical and estimated distances:

$$\min_{\alpha_{ols}, \beta_{ols}} \sum_{(P^r_{ij}, d_{ij}) \in \Psi} \left(\alpha_{ols} \cdot 10^{\beta_{ols} \cdot P^r_{ij}} - d_{ij} \right)^2. \tag{7}$$

The set Ψ contains distances and RSSI measurements for anchor to anchor connections. It should be pointed here that errors caused by the signal diffraction, reflection and scattering are very high and increase with distance. For anchors distributed randomly it is very probably that they are not very close to each other and because of errors RSSI measurements are similar for different distances, see Fig. 2. In (7) all samples have the same significance (both empty and filled boxes in Fig. 2).

In order to overcome this property and improve the significance of ”outliers” the weighted least square (WLS) approach was incorporated. The RSSI values scope was divided into a few ranges (indicated by a vertical lines in Fig. 2), which have the same impact on the minimized performance function. The set of anchor to anchor measurements can be given by a sum of separate subsets:

$$\Psi = \Psi_1 \cup ... \Psi_k ... \cup \Psi_n. \tag{8}$$



Ψ_1	Ψ_2	Ψ_3	Ψ_4	Ψ_5	Ψ_6	Ψ_7
7	7	2	1	0	0	0

Figure 2. Samples from the set Ψ for random topology.

The optimization problem for WLS approach is formulated as follows:

$$\min_{\alpha_{wls}, \beta_{wls}} \sum_{\Psi_k \in \Psi} \left[\frac{1}{|\Psi_k|} \sum_{(P^r_{ij}, d_{ij}) \in \Psi_k} \left(\alpha_{wls} \cdot 10^{\beta_{wls} \cdot P^r_{ij}} - d_{ij} \right)^2 \right]. \tag{9}$$

Finally, in order to make calibration stage more robust the geometric combined least square method (GCLS) is proposed. In this approach parameters α_{gcls} and β_{gcls} are expressed as:

$$\alpha_{gcls} = \sqrt{\alpha_{ols} \cdot \alpha_{wls}}, \quad \beta_{gcls} = \frac{\beta_{ols} + \beta_{wls}}{2}. \tag{10}$$

The parameters α and β obtained as a solution of optimization problems OLS (7), WLS (9) and GCLS (10) are used to transform the RSSI measurements characterizing the whole network into the matrix of appropriate distances, which is used in the next stage.

B. Position calculation stage

In the position calculation stage the measurements of inter-node distances are used to estimate the coordinates of non-anchor nodes in the network. We propose two-phase method – TSA to solve the optimization problem (1). We describe its performance in case of WSN placed on a plane.

1) Phase 1 (trilateration): In the first phase the initial localization is provided using the geometry of triangles. To determine the relative location of a non-anchor on a 2D plane using trilateration alone, generally at least three neighbors with known positions are needed. Hence, all nodes are divided into two groups: group **A** of nodes with known location (in the beginning only M anchor nodes) and group **B** of nodes with unknown location (in the beginning N non-anchor nodes). In each step of the algorithm node i from the group **B** is chosen. Next, three

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nodes from the group **A** that are within node i radio range are randomly selected. If such nodes exist the location of node i is calculated, node i is moved to the group **A**. Otherwise, another node from the group **B** is selected and the operation is repeated. The first phase stops when there are no more nodes that can be localized based on the available information about all nodes localization. It switches to the second phase.

2) Phase 2 (stochastic optimization): Due to the distance measurement uncertainty the coordinates calculated in the first phase are estimated with non-zero errors. In addition the position of nodes that have less than three localized neighbors can not be estimated. Hence, the solution of the first phase is modified by applying stochastic optimization method. A Simulated Annealing (SA) was considered in our research [13].

From the numerical experiments it was observed that the increased value of the location error is usually driven by incorrect location estimates calculated for a few nodes. The additional functionality (correction) was introduced to remove incorrect solutions involved by the distances measurement errors. The additional constraints were introduced to the optimization problem. The detail description of the correction algorithm can be found in [6].

V. Experimental Results

In [6], we presented performance evaluation of TSA method in case of simplified model for distances approximation. We estimated the nodes' locations for known values of distance measurements, and focused only on localization phase. It is obvious that in real application inter-node distance have to be calculated based on radio signals measurements. Therefore, in this work we focus on self-adaptive distance calculation based on signal strengths and calibration of propagation models.

In order to evaluate our two-phase method extended by the calibration procedure many numerical tests were performed using our new software tool – *WSN Localization Simulator* (Fig. 3). All the calculations were carried out on the machine Intel Core2 Duo E6600 – 2.4GHz, 2GB RAM. The average results obtained during five runs of each localization task are presented in tables and figures. In this paper we present the results for the centralized TSA algorithm (each sensor node gather the measurements of distances between its and all the neighbors and pass them to a central station for analysis, after which the computed positions are transported back into the network).

A. Network topology generation

Network models considered in this work were created using generator built in our simulator, which is based on *Link Layer Model for MATLAB* provided by M. Zuniga and B. Krishnamachari [14]. This tool allows to generate link layer models for wireless sensor networks. In our software we focus on wireless channel modeling. No radio modulation and encoding were considered. The sample network topology – presented in Fig. 4 – was generated using parameters collected in Table I. The sensor network

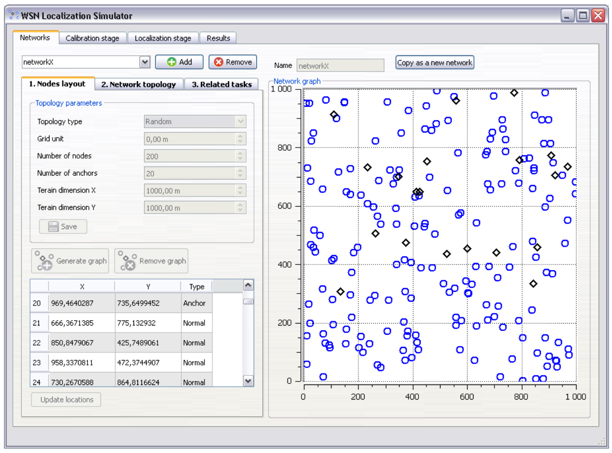

Figure 3. WSN Localization Simulator

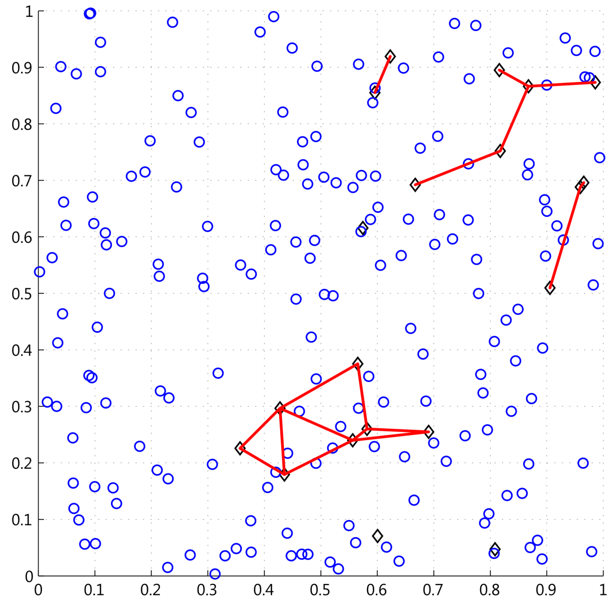

Figure 4. Sample network topology. Anchor nodes marked with diamonds and non-anchor nodes marked with circles. Connections between anchor nodes used for model calibration are marked by lines.

consisting of 200 nodes – 20 anchor nodes (marked with diamonds) and 180 non-anchor nodes (marked with circles) was considered.

B. Distance estimation stage evaluation

The comparative study of different methods of inter-node distances estimation was performed. Fig. 5 depicts the relationship between the RSSI measurements and the true physical distances for the considered task. In Fig. 5a the RSSI measurements only for anchors are presented – these data are used for signal propagation model calibration. The Fig. 5b depicts the measurements for all connections. The fitting curves obtained during calibration process are marked with the red line for the ordinary least square method, with the green line for the weighted least square method and with the blue line for the geometric combined least square method. As we can see the propagation model for the ordinary least square method

Table I
LINK LAYER MODEL PARAMETERS USED IN EXPERIMENTS

Parameter	Value
PATH_LOSS_EXPONENT	3.2
SHADOWING_STANDARD_DEVIATION	2.8
PL_D0	35.0 dB
D0	1.0 m
OUTPUT_POWER	0.0 dBm
NOISE_FLOOR	-105.0 dBm
ASYMMETRY	0 (NO)
TERRAIN_DIMENSIONS_X	1000.0 m
TERRAIN_DIMENSIONS_Y	1000.0 m
NUMBER_OF_NODES	200
TOPOLOGY	3 (RANDOM)

Table II
COMPARISON OF DISTANCE AND LOCALIZATION ERRORS FOR OLS, WLS AND GCLS METHODS USED IN CALIBRATION STAGE

Method	DE	LE
Ordinary least square (OLS)	19.22%	3.34 (0.65*)
Weighted least square (WLS)	17.65%	4.32 (0.97*)
Geometric combined least square (GCLS)	18.21%	3.95 (0.48*)

* the variance of results obtained from five runs of each task.

is prone to overestimating calculated distances between the nodes.

The differences between the true physical distances and those obtained from propagation model are presented in Fig. 6. The error is defined as $DE = |\frac{d-\hat{d}}{d}|$. It can be observed that WLS and GCLS methods effects in smaller maximum error. The differences in results of considered method increase in case of low density networks with big distances between anchor nodes.

C. Position calculation stage evaluation

The distance estimation stage produces inputs to the localization process. The estimates of inter-node distances are used to compute the coordinates of non-anchor nodes in the network. Due to the measurement uncertainty it is difficult to find a good metric to compare the obtained results. To evaluate the performance of tested algorithms we have used the mean error between the estimated and the true physical location of the non-anchor nodes in the network, defined as follows:

$$LE = \frac{1}{n} \cdot \sum_{i=1}^{n} \frac{(||\hat{x}_i - x_i||)^2}{r_i^2} \cdot 100\%, \qquad (11)$$

where LE denotes a localization error, x_i the true position of the sensor node i in the network, $\hat{x}_i$ estimated location of the sensor node i and r the radio transmission range. The localization error LE is expressed as a percentage error. It is normalized with respect to the radio range to allow comparison of results obtained for different size and range networks. The results of the localization stage are presented in Table II.

It should be underlined that the localization accuracy is more than satisfactory. The localization errors are below

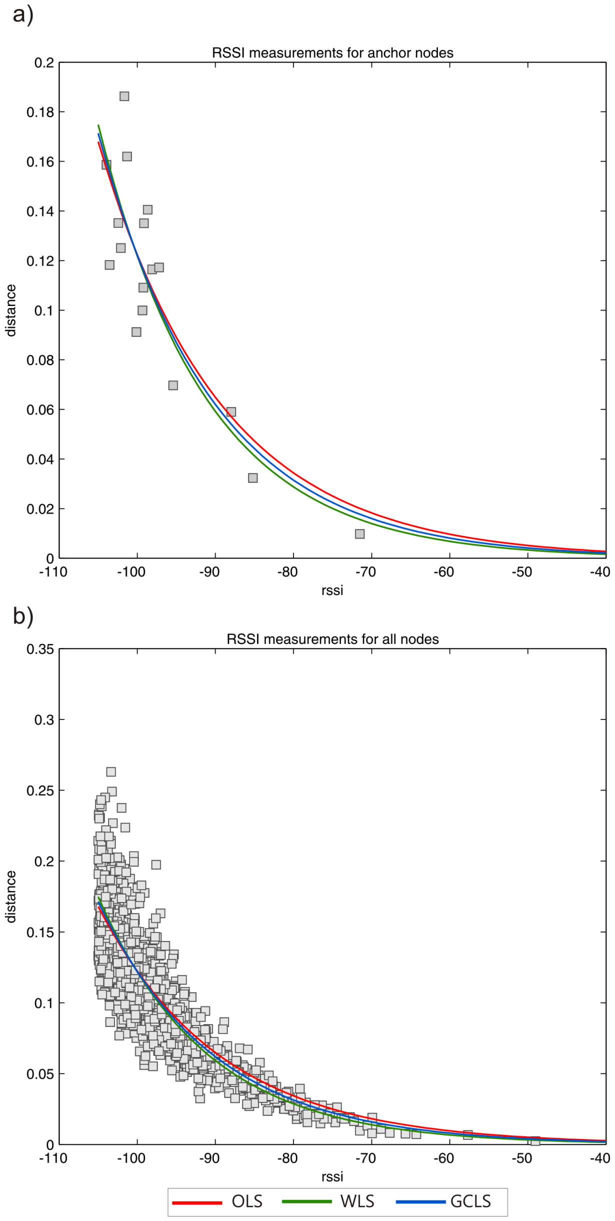

Figure 5. Distance as a function of RSSI measurements.

5% for different calibration methods, while the mean error in distance measurements is about 20%. It means that our approach allows to obtain accurate location estimates even in case of very inaccurate distance measurements.

VI. SUMMARY AND CONCLUSIONS

We have presented the design and evaluation of our hybrid two-phase scheme for estimating the locations of nodes with unknown positions in WSN system. Emphasis was placed on the inter-node distances estimation based on received signal strength indicator. We have evaluated our algorithm, through analysis and simulation. Our evaluation demonstrates that the TSA method provides quite accurate location estimates. In our current research, we apply our algorithm to the testbed network of sensors in the laboratory.

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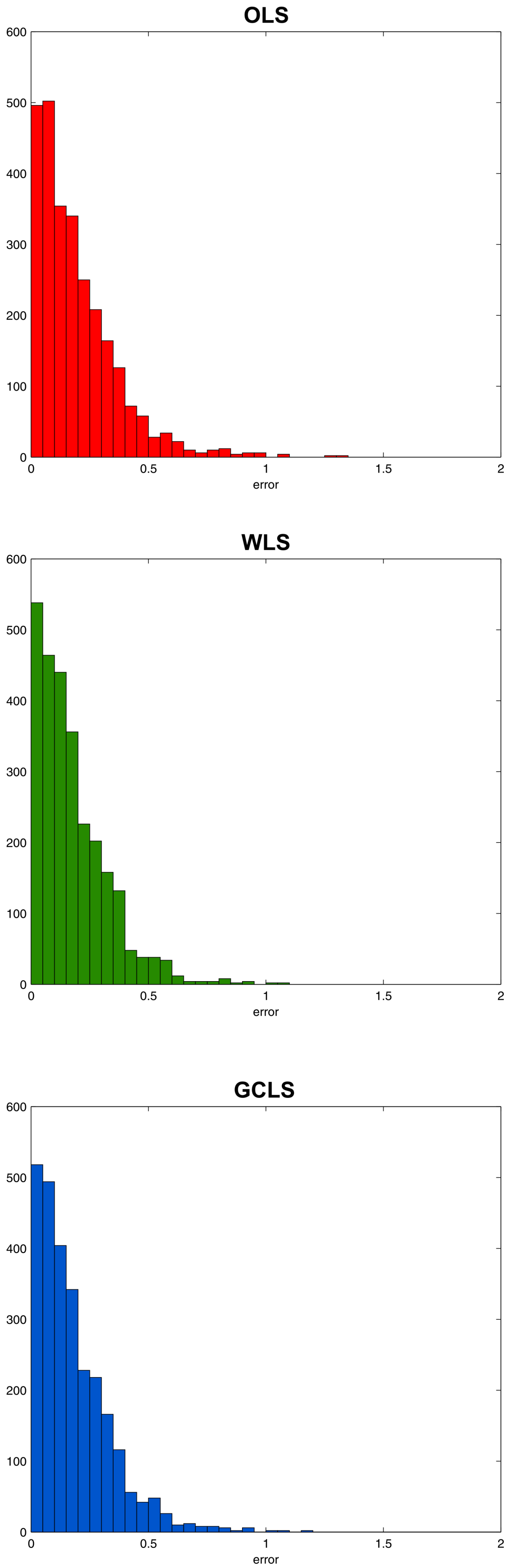

Figure 6. Distance errors histograms.

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