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Localization in Wireless Sensor Networks Based on the Compromise betweenRange-Based and Range-Free Methods

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Abstract: *localization demonstrates one of the most important research scope in terms of the wireless sensor networks since much of the information distributed by the sensors are important when including the localization problem. In the present study, two new methods for sensor localization have been proposed, which are indeed a compromise between range-based and range-free techniques. In the proposed methods, the sensors make use of omnidirectional antenna for transmission of their usual information, and information processing is performed only through some sensors called landmark. The lack of need for complex processing, reduction in the energy consumption, and high precision in locating the geographical coordinates are among the most important features of the suggested protocols. Simulation results show that the proposed methods are highly efficient while reducing system's complexity.*

Keywords**:** *localization, wireless sensor network, landmark sensor, mother landmark.*

1. Introduction

Wireless sensor networks have been introduced as an important tool for diverse applications such as search and rescue, target tracking, and intelligent environment creation due to their reliability, precision, profitability, and ease of expansion [1]. A wireless sensor network is composed of a set of small, inexpensive, and low-power sensors, in which no especial infrastructures are needed and the sensors are required to receive the data, process them, and finally transmit the information to the basis station directly or through multi hop [2]. The wireless sensor networks are highly dependent on their surrounding physical environment. Knowing their location is an innate feature of such networks, and indeed their received data is only important in case the location of measurement is determined, and hence in many applications it is essential that the sensors know their location [3, 4, 5]. Unfortunately, not all sensors can be equipped with GPS due the costs of the equipment.

The research studies conducted on the sensor localization can generally be divided into the rage-based and range-free algorithms [6]. For the proposed algorithms in range-based section, it is required that the sensors should be equipped with the lateral hardware, while in the range-free techniques, the corresponding sensors are not required to be equipped with additional hardware, and resultantly the total cost of the system, especially in networks with numerous sensors, decreases. Among the most common range-based localization methods are the received signal strength (RSS), which is based on measuring the received signal strength by each sensor and requires the knowledge of the transmitter strength and scattering losses model, and time of arrival (TOA), which is based on the estimation of the data arrival angle by all sensors [7]. The proposed method in range-based part have a high precision but are not cost-effective. For example, one requirement for the localization based on the AOA method is the capability for estimation of the signal arrival angle by all of the sensors. Consequently, any given sensor determines its position based on the information about the transmitted signal arrival angle through three landmarks. In a wireless sensor network, the landmarks are sensors with known location, through which the location of other sensors is determined. As shown in Fig. 1, sensor S with unknown location receivesthe signals from the landmark sensors A, B, and C with known locations. Through the estimation of the received signal's angle of arrival from each of the said landmarks, sensor S thus calculates its own location. On the contrary, the proposed methods in range-free part are inexpensive and straightforward, compared to the range-based techniques [8]. The developed methods in the range-free section include RAE [9], distance vector hop (DV-Hop) [10], and localization algorithm using expected hop progress (LAEP) [2]. Estimation of the distances in such techniques is usually based on measuring the number of hops between the original sensor and distance estimation through numerical or statistical methods using the information concerning the number of connections for each sensor. As an example, in RAW method, the distance between the origin and the destination is estimated in terms of the equation$d = h^{*}r_0$, where h stands for the number of hops between the origin node and destination node and r_0 shows the coverage radius of the sensors. Obviously, if the sensors array is sparse (Fig. 2), then the distance estimation error is much greater than the real amount. Besides, the DV-Hop method [8], due to its ruling relations, demonstrates a proper performance in the networks over which sensors distribution is thoroughly homogenous. However, in the non-homogeneous environments, DV-Hop shows a lot of estimation errors. Localization precision in this group is lower than the range-based method. On the other hand, the range-free methods are more cost-efficient than the range-based methods.

In this paper, two new methods for sensor localization have been proposed, which represents a compromise between the range-based and range-free methods. In these methods, much lower costs are imposed on the network than the costs imposed by the range-based algorithms. However, similar to the range-based methods, here the precision in estimation of the sensors location is very high.

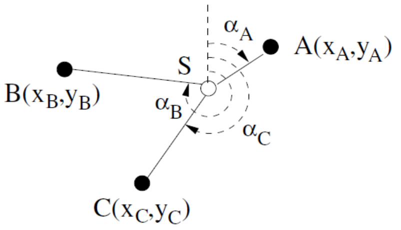

Fig. 1: the calculation of the angle of arrival for three landmark sensors A, B, and C using sensor S with unknown location [4].

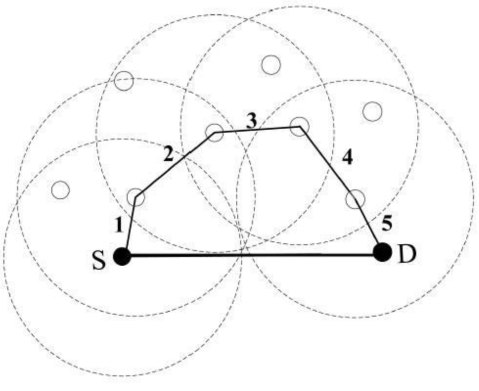

Fig. 2: Sparse array in the wireless sensor network [2].

2. Network Model

Generally speaking, when the wireless sensor network is randomly distributed, no especial order can be assumed for how the sensors are arrayed and distributed. However, the landmarks (i.e., sensors that know their position through GPS or a manual program), which help in the estimation of the location of the sensors, might have a determined order. The structures that can usually be considered for the landmark installation are in quadratic, triangular, and hexagonal forms [2, 3]. In our considered network, the number of sensors is N and each sensor is defined by its number (n) in such a way that $n \in \{1,2,\dots,N\}$. Furthermore, each landmark is defined by its number (l) so that $l \in \{1,2,\dots,L\}$ and $L \ll N$.

In the first scenario, it has been assumed that only the landmarks are capable of estimating the angle of arrival for the transmitted data by the sensors around them (the data within the coverage radius of the landmarks) and each sensor is linked to at least one landmark. Distribution of the sensors in the two-dimensional space is modelled by the Poisson model with the average of $\lambda = \frac{N}{D\times D}$ in a square with dimensions of $A = D \times D$. Besides, it has been supposed that all sensors have omnidirectional antenna [12] and similar coverage radius r_0. Therefore, if sensor n_i is in the coverage radius of sensor n_j, then sensor n_j is also within the coverage radius of sensor n_i [2] and each sensor is regarded as the center of a circle which can be in connection with the other sensors within r_0. Besides, in the network under study, at most two sensors, called mother landmarks, exist that all the other existing sensors in the network can receive their data. The information disseminated through the mother landmark's omnidirectional antenna can be modelled as $I_M(ID_M, X_M, Y_M)$ where ID_M signifies the identification number and (X_M, Y_M) shows the coordinates of the mother landmark. A schema of how the sensors are distributed in the considered network model is provided in Fig. 3. In this figure, the central green sensor is the same as the mother landmark, while the red points also show the landmarks.

3. Sensors Localization

3.1. First method: Localization through a Mother Landmark.

In the first scenario for localization of the sensors, in eachnetwork only one mother landmark and a limited number of landmarks with thoroughly known locations (according to Fig. 3). The mother landmark transmits the information $I_M(ID_M, X_M, Y_M)$, described in Section 2, at moment t_0 and the said information is received by all sensors. For t^n, or time of arrival by the nth sensor, we have:

$$t^n = t_0 + t_{dis}^{M,n} \qquad ,n = 1,2,\dots,N \tag{1}$$

In this equation, $t_{dis}^{M,n}$ is the time period required for data transmission from the mother landmark to the nth sensor. Number of times for transmission and the time span for iteration of the information transmission, due to the environmental conditions, are different. However, under the ideal conditions, just one single transmission by the mother landmark is sufficient. After the mother landmark data are received by the nth sensor at moment t^n, the set of $I_n(ID_n, t_{dn})$ is distributed by the omnidirectional antenna of the nth sensor. The landmark of number l receives the information package of the nth sensor, which is in its coverage range, at the moment of t_l^n. The time of arrival for these packages by the landmarks can be expressed by Eq. 2.

$$t_l^n = t^n + t_d^n + t_{dis}^{n,l} \quad ,l = 1,2,\ldots,L \tag{2}$$

In the above relation, $t_{dis}^{n,l}$ is the time length needed for distribution of the package of the sensor n to the landmark l, while t_d^n is the random delay produced by the sensor n in distribution of its characteristics. The reason why the random delay is used by the sensors is, in fact, provision of different delays in the receivers of the landmarks so that the interference among the equidistant sensors to the landmarks can be avoided. This random delay can be modelled as follows.

$$t_d^n = \frac{d_M + r_0}{v}(D+1) \quad ,D \in \{0,1,\ldots,E_C\} \tag{3}$$

In the above relation, dM shows the maximum range of the mother landmark per meter and $\boldsymbol{v}$ represents the signal emission speed. $\boldsymbol{E_c}$is the average number of the sensors associated with each landmark, which depends on the statistical features of the sensors distribution. Each sensor, after reception of the mother landmark data, might randomly choose a number within the range of D. Subsequently, with regard to its corresponding delay, the sensor releases its information. One of the most important advantages of this method is its prevention from the sensors data interference in the landmarks receiver. Fig. 4 represents a schema for application of the random delay feature by the assumed sensors, which results in the non-interference of the data from the two sensors. The experimental data extracted from the environment have been analyzed using the software Cool Edit 20002.1 Build 3097.0. Moreover, the landmarks receive the datasent by the mother landmark at moment of $\boldsymbol{t_l^M}$, thus:

$$t_l^M = t_0 + t_{dis}^{M,l} \quad ,l = 1,2,\ldots,L \tag{4}$$

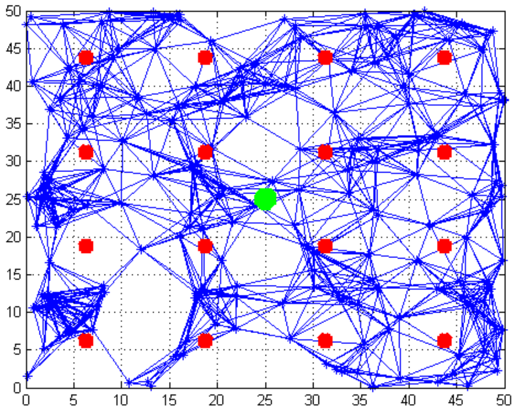

Fig. 3: schema of network model and sensors distribution.

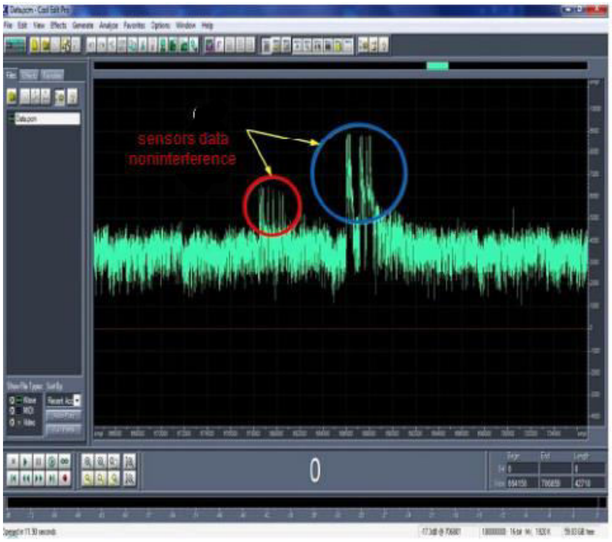

Fig. 4: non-interference of the data from assumed sensors using random delay.

In the aforementioned equation, $t_{dis}^{M,l}$ stands for the time length needed for transmission of information package from the mother landmark to the landmark l. Therefore, two different times of $t_l^M$and t_l^n, the lth landmark receives the information packages from the mother landmark and the nth sensor within the range of r_0. If the time difference between t_l^M and t_l^n is called $t_l^{M.n}$, then the relation can be written as follows.

$$\begin{aligned} &t_l^{M,n} = t_l^n - t_l^M = t_{dis}^{M,n} + t_d^n + t_{dis}^{n,l} - t_{dis}^{M,l} \\ &\Rightarrow t_{dis}^{M,n} + t_{dis}^{n,l} = \sigma_{n,M,l} = \text{constant} \end{aligned} \tag{5}$$

In Eq. 5, only the values of $t_{dis}^{M,n}$ and $t_{dis}^{n,l}$ are unknown, the sum of which is indeed available. Therefore, summation of the distances of the nth sensor from the two mother landmark and the lth sensor is known. In this context, Eq. 5 shows the geometric position of some spatial points on a unique ellipse, of which the corresponding foci are established on the points where the mother landmark and landmarks are located.

Fig. 5 represents the above schematic for two assumed sensors 1 and 2, the sum of which is equidistant from the two involved foci.

Obviously, in order to uniquely determine the nth sensor's position on the above ellipse, another feature as the angle of arrival of information to the landmark (θ_i in Fig. 5) is required. Note that in this method, sensors are equipped with omnidirectional antennae and only the landmarks (which are too few in number) can find the direction. Besides, all calculations have been done by the landmarks while the sensors do not need to perform any complicated and cumbersome calculations to know their geometric position. The final coordinates of the sensors $(x_n\ ,\ y_n)$ can easily be obtained by Eq. 5 and the ruling ellipsoid relations [13] and by solving the introduced system in Eq. 6 – which is indeed the intersection of the two equations through the unknown parameters x_n and y_n.

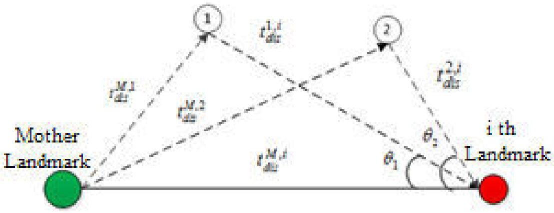

Fig. 5: overall schematic representation of the first scenario.

$$\frac{((x_n-\bar{x}_{Ml})\cos(\theta)+(y_n-\bar{y}_{Ml})\sin(\theta))^2}{a_{nl}^2}+\dots$$
$$\frac{((y_n-\bar{y}_{Ml})\cos(\theta)-(x_n-\bar{x}_{Ml})\sin(\theta))^2}{b_{nl}^2}=1 \qquad (6)$$
$$d_{Mn}^2=d_{\ln}^2+d_{Ml}^2-2d_{\ln}d_{Ml}\cos(\theta_n)$$

$$\bar{x}_{Ml}=\frac{x_M+x_l}{2} \quad , \quad \bar{y}_{Ml}=\frac{y_M+y_l}{2}$$
$$a_{nl}=(\sigma_{n,M,l})v \qquad (7)$$
$$c_{nl}=\sqrt{(x_M-x_l)^2+(y_M-y_l)^2}$$
$$b_{nl}^2=a_{nl}^2-c_{nl}^2$$

In Eq. 6 and 7, d_{Ml}, d_{Mn}, and d_{ln} are the distance between mother landmark and landmark l, mother landmark and the *n*th sensor, and landmark l and sensor, respectively. Furthermore, (x_M, y_M) and (x_l, y_l) are the coordinates of the mother landmark and the lth landmark in Cartesian coordinate system, whereas parameter θ shows the angle of the line connecting the mother landmark and the lth landmark to the horizontal axis. One significant advantage of the proposed method is that it does not rely on the statistical calculations and the synchrony of the sensors is not required. Besides, the location of each sensor is independently and precisely calculated. Moreover, since all calculations are performed in the landmark, each sensor is thus able to know the geographical coordinates of the other sensors.

After calculation of the sensors location through the landmarks, the landmarks can distribute the geographical coordinates of the sensors in their coverage range so that each node in the network can be aware of not only its own geographical coordinates but also of the geographical coordinates of its adjacent nodes. This capability can be important in some applications. Table 1 represents the summarized pseudo code from the aforementioned process.

3.2. The Second Method: Localization Using Two Mother Landmarks

In the proposed method in Section 3.1, the landmarks make use of the information about the angle of arrival and the signal time difference received from two paths and determine the coordinates of unknown placement, which are, by the next phase, disseminated for all the sensors within the coverage range. In the second localization method, only the information regarding the time difference of the received packages at the point where the landmarks are located, and no need for estimation of the angle of arrival by the landmarks is felt in practice. Here, as in the previous method, the sensors are informed of their location through the landmarks. Fig. 6 provides a schematic representation of the proposed scenario. In this figure, the mother landmarks, the landmark, and the investigated sensor are shown in green, red, and black, respectively.

The suggested steps in this methods are as follows. First, at moment t_0, each of the two mother landmarks transmits its information package, shown as $I_M(ID_M, X_M, Y_M)$, M = 1, 2. After receiving the information package of the *M*th mother landmark through the *n*th sensor at the moment of t_M^n, as in the first method, all of the sensors, after the random delay t_d^n, transmit an informational package of $I_n(ID_n, t_{dn})$ that involves the identification number and amount of random delay t_d^n. This package is transmitted by the omnidirectional antenna of the sensors. The lth landmark at the moment of $t_{l,M}^n$ receives the informational package of the *n*th sensor (relayed by the *M*th mother landmark) in its coverage range. Therefore, the landmarks have access to (both through a direct path and through the sensors) the time differences between the time of arrival of data from the two mother landmarks. With regard to Eq. 5 and concerning the descriptions provided in Section 3.1 and by multiplying this time difference by the signal emission speed, pair of the summation for the path distances can be calculated as $\beta^n = d^{ni} + d_1^{Mn}$ and $\alpha^n = d^{ni} + d_2^{Mn}$. The distances d^{ni}, d_1^{Mn}, and d_2^{Mn} are shown in Fig. 6. This process is also carried out for the landmarks, that is, after receiving the data from each mother landmark and by a random delay of t_d^i, the *i*th landmark tries to propagate the identification number and amount of its random delay in the informational package of $I_i(ID_l, t_d^i)$.

Table. 1: pseudo code for estimation of the sensors placement in the first proposed method

Stage	Description
1	The *M*th mother landmark releases the information of (ID_M, X_M, Y_M). M = 1
2	The considered *n*th sensor receives I_M and then propagates $I_n(ID_n, t_{dn})$.
3	The lth landmark receives I_M and I_n and estimates the angle of arrival θ_n corresponding to I_n.
4	The landmark calculates $\sigma_{n,M,l}$ in Eq. 5 and measures (x_n, y_n) based on the relations expressed in Eq. 6.

In this case, the investigated sensors also involve the time difference of two different paths of receiving data from the mother landmark (directly and through the landmark). Accordingly, by multiplying this time difference and the signal emission speed together and through rewriting Eq. 5 and the explanations in Section 3.1, the distance difference of the two paths (shown in Fig. 6) can be calculated as $\beta'^{n} = d^{ni} - d_1^{Mn}$ and $\alpha'^{n} = d^{ni} - d_2^{Mn}$. Finally, the investigated sensors propagate these calculations in the informational package $I_n(ID_n, \alpha'^{n}, \beta'^{n})$ for the landmarks in their range.

By performing the aforementioned steps, at each point where a landmark is located, four parameters as α^n, β^n, α'^{n}, and β'^{n} corresponding to the *n*th sensor are available, and hence by solving their corresponding relations, the distance of the *n*th sensor from three known points (two mother landmarks and one landmark) as d_2^{Mn}, d_1^{Mn}, and d_{ni} can be determined.

Therefore, the geometric coordinates of each sensor can be achieved uniquely by substitution of its distance in three known points (d_{ni}, d_1^{Mn},d_2^{Mn}) in Eq. 8.

$$x_n = \frac{CE - BF}{AE - BD} \qquad , y_n = \frac{AF - CD}{AE - BD}$$

$$\begin{aligned} A &= 2(x_{M1} - x_l) \\ B &= 2(y_{M1} - y_l) \\ C &= (d^{nl})^2 - (d_1^{Mn})^2 + x_{M1}^2 - x_l^2 + y_{M1}^2 - y_l^2 \\ D &= 2(x_{M2} - x_l) \\ E &= 2(y_{M2} - y_l) \\ F &= (d^{nl})^2 - (d_2^{Mn})^2 + x_{M2}^2 - x_l^2 + y_{M2}^2 - y_l^2 \end{aligned} \tag{8}$$

The pseudo code of the second scenario is also given in Table 2.

4. Software Implementation

4.1. Preview

It is clear that the sample rate in the receiver demonstrates the precision in the estimation of time ofarrival (TOA).

The larger the sample rate, $\frac{1}{T_s}$, is, the more exactly the data arrival time can be estimated. Fig. 7 gives aschematic representation of the realtime of arrivalof a practical signal and its estimation in the receiver. The time distance of receiving the signal by the sensor till the last moment of sampling is called t_n, which is assumed to be a random value with homogenous distribution and $0 < t_n \le T_s$. In this case, the worst case error (WCE) and the best case error (BCE) are $WCE = T_s$ and $BCE = 0$, respectively. If the signal arrival distance to the last sampling moment is nominated by βT_s and β is chosen by MMSE criterion, then the following relation can be considered:

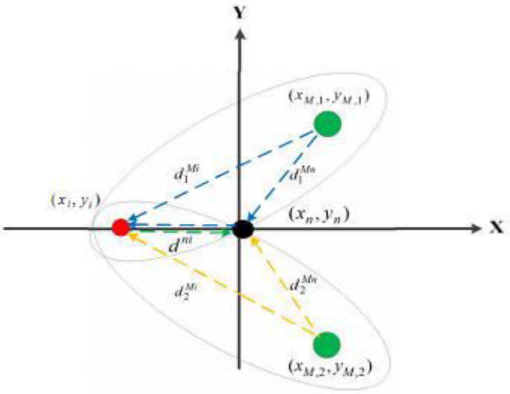

Fig. 6: a schema representation of the introduced scenario in 3.2

Table. 2: pseudo code for sensors place estimation in the second proposed method

Stage	description
1	The *M*th mother landmark releases the information of (ID_M, X_M, Y_M). M = 1,2
2.a	The considered *n*th sensor receives I_M and then propagates $I_n(ID_n, t_{dn})$.
2.b	The investigated *i*th sensor receives I_M and then propagates $I_i(ID_l, t_d^i)$.
3	The landmark I_n and the investigated sensor receive I_i.
4	At the location of the landmark and of the investigated sensor, the values (β^n, α^n) and $(\beta'^{n}, \alpha'^{n})$ are calculated, respectively.
5	The investigated *n*th sensor propagates the package $I_n(ID_n, \alpha'^{n}, \beta'^{n})$.
6	The *i*th landmark receives I_n and calculates (x_n, y_n) using the set of relations in 8.

$$\begin{aligned} &\beta = \arg\min_{\beta} \overline{\|\hat{t}_n - t_n\|^2} ,0 < \beta < 1 \\ &\frac{\overline{\partial MSE}}{\partial \beta} = \frac{\partial}{\partial \beta}[\frac{1}{T_s}\int_0^{T_s} (\beta T_s - t_n)^2 dt_n] = 0 \rightarrow \beta = 0.5 \end{aligned} \tag{9}$$

Consequently, if signal arrival time is defined by the *K*th moment of sampling, then the signal pulse arrival time can be expressed as $(k-1)T_s + 0.5T_s$.

4.2. Simulation Results

For evaluation of the efficiency of the proposed methods, a number of 200 sensors are randomly distributed in a square space with dimensions of $A = 50 \times 50 m^2$. Poisson distribution function with the average of $\lambda = 0.07/m^2$, coverage radius for each sensor as $r_0 = 8.5\, m$,and the sample frequency of $f_s = \frac{1}{T_s} = 1kHz$ and $v = 1500 \frac{m}{s}$ has been considered. Simulation results havebeen obtained using MATLAB software with 40 iterations, while the distance estimation error in each case has been calculated based on the following relation, thus:

$$DEE^{i,j} = \frac{\| D^{i,j}_{estim} - D^{i,j}_{real} \|}{D^{i,j}_{real}} \qquad (10)$$

Here, $DEE^{i,j}$, $D^{i,j}_{estim}$, and $D^{i,j}_{real}$ are distance estimation error, estimated distance, and real distance between the ith and the jth sensors, respectively.

The PDF and CDF functions of distance estimation error, obtained from the suggested method in Section 3.1, are shown in Fig. 8 and Fig. 9, respectively. These figures also compare the results from the proposed method with the results of RAW [8] and DV-Hop [9] methods. Fig. 8 shows that, in the suggested method in Section 3.1, if the angle of error (AOE) is equal to 1, 3, and 5 degrees, then the possibility of the sensors distance estimation error being close to zero will be about 0.82, 0.77, and 0.70, which is approximately two times as great as the values in the DV-Hop method. Besides, in this method, as in theRAW method, the estimation is not biased. A goodadvantage of the suggested method is due to its capability for achieving the desired localization error when the estimation error for the signals angle of arrival is up to 5 degrees. Furthermore, Fig. 9 shows that for the angle of errors as 1, 3, and 5 degrees, the possibility for the distance estimation error to be in the range of $\pm 0.1 D_{real}$ is about 0.87, 0.85, and 0.83, respectively, which are yet much more appropriate than the values found by the two other methods. Therefore, the simulation results of the sensor network demonstrate the proper performance ofthe first proposed method in terms of the sensors localization with random distribution. The PDF and CDF distance estimation error functions resulting from the simulations by the second method are given in Figs 10 and 11, respectively.

It should be noted that, here, in comparison with the first method, the capability for estimation of angle of arrival in the landmarks is not required; however, a further stage is here added to the sensors correspondence stages (compare Tables 1 and 2). As seen in Fig. 10, the probability for the distance estimation error to be in the range of $\pm 0.1 D_{real}$, for RAW, DV-Hop, and the suggested method in Section 3.2 are 0.02, 0.56, and 0.95, respectively, which is indicative of the significant superiority of the introduced method in Section 3.2 over the two other methods.

Besides, comparison of Figs. 9 and 10 demonstrates the relative superiority of the second suggested method (i.e., use of two mother landmarks and all antennas being omnidirectional) for estimation of the sensors location over the first suggested method (i.e., use of one mother landmark and capability for estimation of angle of arrival in the landmarks). Fig. 11 compares the probability density functions for the distance error in the RAW [8], DV-Hop [9], and suggested methods, which can also reveal the considerable advantage of the used method in Section 3.2 over the two other methods. In the wireless sensor networks, the probability density functions are used to calculate the degree of probability for the estimation error in sensors localization to be in certain ranges.

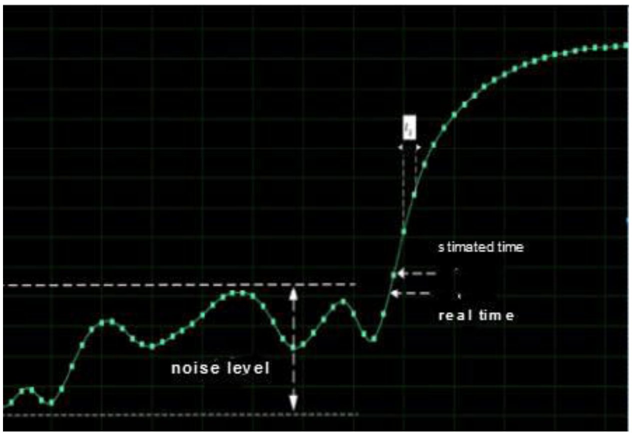

Fig. 7: sampling of the input pulse to the hypothesized sensor.

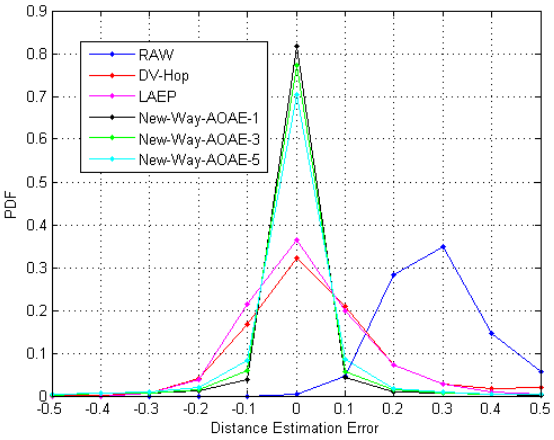

Fig. 8: PDF function of distance estimation error

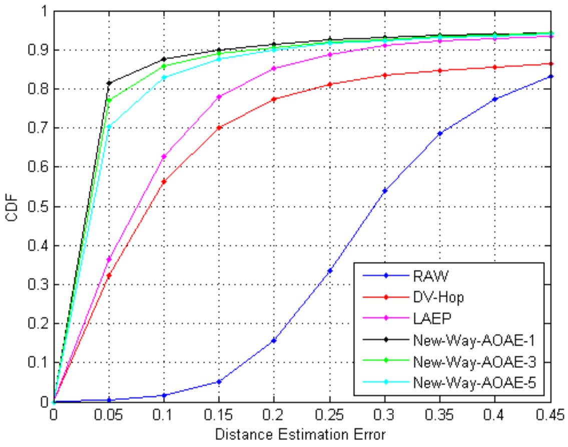

Fig. 9: cumulative distribution function of distance estimation error

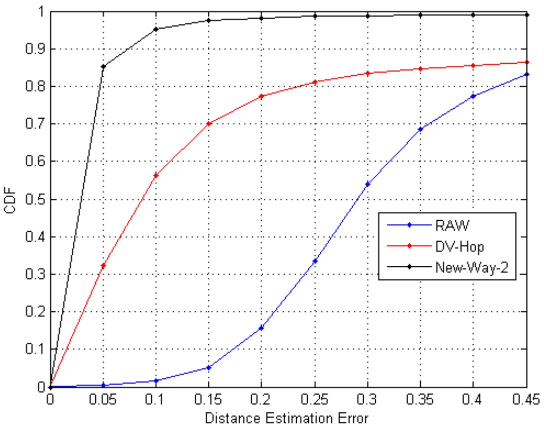

Fig. 10: cumulative CDF function of distance estimation error.

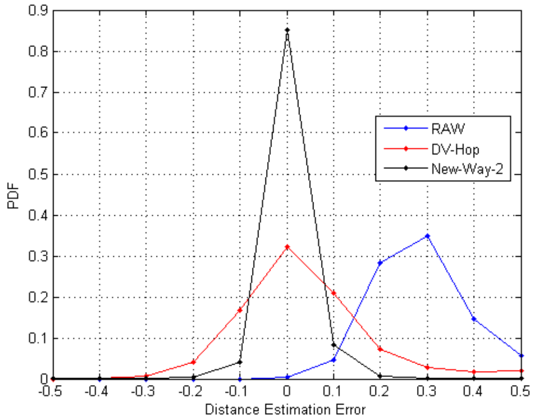

Fig. 11: comparison of distance estimation error PDF function in RAW, DV-Hop, and suggested method

5. Conclusion

In this study, two innovative methods for sensors localization have been developed, which are indeed a compromise between the range-free and range-based methods. In the first method, only one mother landmark is used and estimation of the angle of arrival of the signal is merely performed by the landmarks. Moreover, all calculations are done in the landmarks, in the range of which the considered sensor is placed. In the second method, instead of using one single mother landmark, two mother landmarks are used and the need for estimating the angle of arrival of the signal from the landmarks has thus been removed. Simulation results are representative of the high efficiency of these methods, compared to the range-free methods. In the proposed methods, no process is required for estimation of the sensor location by the said sensors. Due to the fact that a large number of sensors are used in a wireless sensor network, it is of great importance to provide some mechanisms for reducing the energy consumption and finally the network costs. That the sensors themselves are not required to perform the localization process for knowing their location, which is a good advantage of our proposed algorithms, can be considered as a step toward realization of the said aim. Moreover, in terms of the error from localization estimation, the suggested methods significantly outperform the traditional range-free methods, which can be verified by the simulation results. One of the other advantages of the suggested methods is due to their consideration of random delay in sending the informational packages through the sensors. In this context, the interference of the transmitted data by the sensors in the landmark location can be avoided, and thus retransmission of the information and further energy consumption in the sensors, as well as reprocessing of their information at the location of the landmarks, are not required. Concerning the sensors localization, great importance should also be attached to landmarks and mother landmarks placement. Efficient methods for sensors placement with high precision in sensors localization may lead to substantial decrease in the costs of the wireless sensor networks.

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