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An Efficient Anchor-Free Localization Algorithm for all Cluster Topologies in a Wireless Sensor Network

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Abstract

A wireless sensor network is a type of network, which has many application domains such as military, civil security, industrial and environmental. Localization of fixed or mobile wireless sensors in wireless sensor networks is a delicate issue that has attracted the attention of many researchers. Indeed, a good estimation of the distances between different wireless sensors allows to derive their precise locations in the network. An ideal solution for locating these wireless sensors is to equip them with localization devices such as GPS. However, this solution is not an energy-efficient. Indeed, GPS is very energy-consuming, and the deployment environment is not easily accessible to humans. So, it is not possible to replace the batteries of these wireless sensors when they are discharged. Therefore, it is necessary to propose an energy-saving anchor-free localization algorithm. Despite the grouping of nodes into clusters (or sub-networks), existing anchor-free localization algorithms suffer from a low rate of node localization, low localization accuracy, and high energy consumption. To improve the proposed solutions in the literature, an Efficient Anchor Free Localization Algorithm (EAFLA) was proposed. Regardless the topology of each cluster, our algorithm allows localization of all wireless sensors with a very low localization error rate and consumes less energy.

Keywords: Anchor-free localization, Wireless sensor networks, Localization algorithm, Cluster topology.

1 Introduction

Advances in telecommunication networks have enabled the development of small devices called wireless sensors. A wireless sensor is a small electronic component, with limited resources than can be used to measure various physical quantities present in its environment. The physical architecture of a wireless sensor is generally composed of acquisition, processing, transmission, and energy control units. Indeed, when a set of wireless sensors are deployed in an area to monitor natural phenomena according to the user's needs, they form a network infrastructure called a Wireless Sensor Network (WSN) [3]. A WSN has many applications such as target tracking in military operations and health monitoring [17]. Wireless sensor networks have emerged in recent decades as powerful tools to connect the physical and digital worlds. However, when the data that must be collected are in an uncontrollable and potentially hostile environment (environments that are difficult to access by humans), wireless sensors are deployed randomly in these networks.

The problem of determining the physical position of wireless sensors in a wireless network also called the wireless sensor localization problem is a very important and topical research area. This is because many applications and services of WSN rely directly on location information. In these applications, an event detected without localization information is not useful. An ideal way to obtain the physical positions of wireless sensors is to equip each wireless sensor with a localization system such as a Global Positioning System (GPS), which is one of the best-known and most widely used location systems in the world [8]. Owing to the limitations of wireless sensors in energy resources and GPS (i.e., high energy consumption), equipping each wireless sensor in the network with a location system is not an energy-efficient solution, particularly for wireless sensor networks deployed in hostile environments. Hence, it is necessary to have an energy-efficient localization algorithm, which allows each wireless sensor in the network to be located without the intervention of any localization system such as GPS.

In this work, we proposed an Anchor Free Localization Algorithm in a network deployed in a hostile environment, which allows the localization of all wireless sensors with a very low localization error rate and consumes less energy, regardless the topology of each cluster formed. Our anchor-free localization algorithm comprises three phases. The first phase consists in electing a cluster leader and grouping all wireless sensors in the network into a cluster considering the one-hop neighbourhood (1-cluster). The objective of the first phase is to limit the number of communications between the wireless sensors to minimize their energy consumption. In this phase, one-hop node grouping reduces the impact of noise on the signals and minimizes the error in the distances estimated by Received Signal Strength Indicator (RSSI) technique. The second phase consists in estimating only the distances between the wireless sensors which are necessary to compute the node's position in its cluster. The third phase allows position derivation of the wireless sensors in each cluster using the Al-Kashi's theorem [2]. The particularity of our algorithm is that, for a 1-hop cluster topology, all the wireless sensors in each cluster have a very high rate of localized nodes with good localization accuracy while consuming less energy.

The main contributions of our work are summarised as follows:

- The proposed algorithm computes only the useful inter-node distances required to compute the position of the wireless sensor in each cluster with RSSI.
- The Kleinrock and Sylvester model [9] allows wireless sensors that are not in communication range to compute the distance between them.
- The proposed algorithm computes the position of all wireless sensors in each cluster, regardless the cluster topology.

The remainder of this paper is organized as follows. Section 2 presents a review of existing localization algorithms. Section 3 gives a problem formulation. Section 4 describes in detail our localization algorithm. Section 5 presents simulation results and Section 6 gives a conclusion and perspectives.

2 Related Work

Depending on the technique used to estimate distances in a localization algorithm, the localization algorithms can be divided into two main groups [18]: Range-based localization algorithm and Range-free localization algorithms. Range-Based localization algorithms [19] are those algorithms that use distance or angle measurements techniques such as RSSI [19], [23], Time Difference of Arrival (TDoA) [11], Time of Arrival (ToA) [22], and Angle of Arrival (AoA) [14]. While range-free localization algorithms use connectivity information [7], i.e. the number of hops to convert them into distance [9], [13]. Both categories of algorithms can run with an anchor (anchor based) or without an anchor (anchor-free). Here, an anchor is a wireless sensor equipped with a localization device. In the following, we present a state of the art of anchor-free localization algorithms that exist in the literature.

Chen Liu et al., in [10] proposed an anchor free localization protocol that uses the node with high connectivity as a virtual anchor and relies on the asynchronous change of learning factor adaptive weights particle swarm optimization algorithm to estimate the positions. To obtain an accurate position, they use the Taylor algorithm. The algorithm resulting from this protocol reduces the accumulated error and increases the localization accuracy.

Qu et al., in [15] proposed an energy-efficient anchor-free localization algorithm, which uses a single well node whose transport capacity and energy is not limited. This well node is taken as a reference position for a global localization of the system by sending an active packet throughout the network. Each sensor that receives this packet is activated to calculate the angle and distance between it and the well node. This algorithm requires that all wireless sensors in the network must be equipped with an angle measuring device and is less accurate for networks with a hostile environment.

Wang Ming et al., in [12] proposed a distributed cluster-based anchor-free node localization algorithm that is performed in three steps. The first step is based on the clustering of single-hop nodes according to the technique used by ICAND (1-hop node selection method) and uses the ToA technique to estimate the distances between nodes. The second step is the cluster synchronisation phase, in this phase all nodes of a cluster are synchronised, and the local coordinates are established using the angle and distance information. The third step is the global localization phase. This approach only considers scalability and accuracy.

Du et al., in [5] proposed an anchor free localization algorithm called LDLA (Ladder Diffusion node Localization Algorithm) in which each node calculates its relative position with the sink node based on the principle of the algorithm proposed by Zhe et al. However, only the nodes located at one hop are activated to calculate the angles and distances between him to the sink nodes, iteratively until all the sensors discover their position. LDLA algorithm optimises the energy management of the sensors but does not consider the scalability of the network and requires all to be equipped with an angle-measuring device.

Qiyue et al., in [21] proposed an anchor-free localization scheme for large-scale wireless sensor networks called the ranging and multidimensional scaling–based localization scheme (RMDS). They use ranging and non-line-of-sight error mitigation techniques to estimate accurate distances between each node pair and attempt to find inflection nodes using a novel flooding protocol to correct transmission paths that have become deviated by a coverage hole. The RMDS algorithm improves only the localization error and the energy consumed.

Shah et al., in [16] proposed an anchor-free localization algorithm for 1-hop nodes. This algorithm computes the inter-node distances based on RSSI technique. The average of the inter-node distances is used to locate the reference nodes. Their solution improves the error on the position of the nodes in the network but does not consider the topology of the different clusters.

Although, the existing anchor-free localization algorithms solve the localization problem without anchor nodes, there are still some shortcomings such as low localized node rate, low localization accuracy, high deployment cost, and network scalability over time. Most of the existing research focuses either on improving the location accuracy, on the energy consumption problem, or the position error. But they do not consider several criteria at the same time and especially the topologies of clusters formed which could impact the rate of nodes located. Therefore, in the following section, we give a formulation of the localization problem (see Section 3), which considers several criteria before presenting our method to solve this problem (see Section 4).

3 Problem specification

3.1 Assumptions

We assume that all wireless sensors in the network:

- Are deployed randomly;
- have the same characteristics (communication radius, communication range, storage capacity, energy capacity...);
- are static after deployment;
- have sufficient energy to perform the localization task;
- have an omnidirectional antenna;
- have a unique identifier (ID).

3.2 Problem Formulation

A wireless sensor network (see Figure 1 as an instance) is represented by a geometric and random graph $G = (V, E)$, with $V = \{v_1, v_2, \ldots, v_n\}$ the set of wireless sensors deployed in a 2-dimensional Euclidean space, where n represent the total number of nodes and $E = \{(v_i \ ; v_{i\prime}) \in V^2 \mid d_{i,i'} \leq r_i + r_{i'}\}$. with $i \neq i'$ the set of radio communication links where $r_i, r_{i'}$ and $d_{i,i'}$ denote respectively, the communication range of node v_i, the communication range of $v_{i'}$ and the distance between nodes v_i and $v_{i'}$

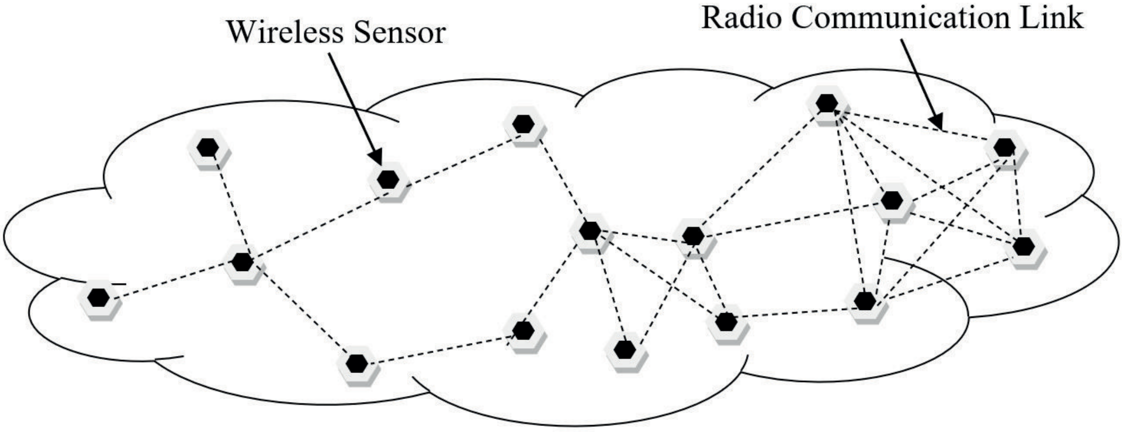

Figure 1: Wireless sensor network

The localization problem studied here is formulated as follows:

- Given: a wireless sensor network represented by the graph $G = (V, E)$.
- Goal: compute the accurate position of each wireless sensor while reducing energy consumption, regardless the topologies of the cluster that will be formed.

4 Proposed Algorithm

4.1 Useful notation in our algorithm

In this section, we describe the symbols used in the EAFLA localization algorithm.

- C_k : the k-th cluster with $1 \leq k \leq m$ (m the number of clusters formed in the network).

- CH_k : the k-th Cluster Head of the cluster C_k.
- v_j^k : the wireless sensor belonging to cluster C_k located at the smallest distance from CH_k.
- v_i^k : the i -th wireless sensor with $(i \neq j)$ belonging to cluster C_k.
- $d_{k,j}^k$: the distance between the Cluster Head CH_k and the wireless sensor v_j^k in the cluster C_k.
- $d_{k,i}^k$: the distance between the Cluster Head CH_k and wireless sensor v_i^k in the cluster C_k.
- $d_{i,j}^k$: the distance between the wireless sensors v_i^k and v_j^k in the cluster C_k.

4.2 Description of proposed algorithm

We have proposed a localization algorithm that consists of three phases:
1- Election of cluster heads and formation of clusters;
2- Distance estimation;
3- Computation of the relative position for all sensors in each cluster;

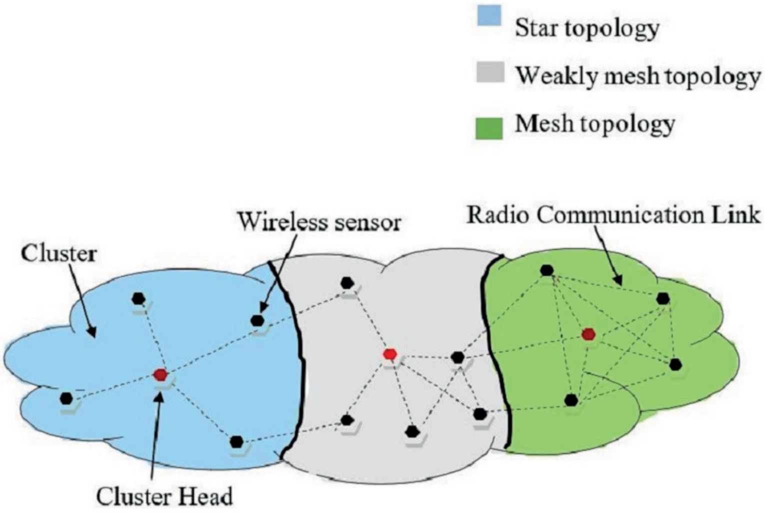

Figure 2: Wireless sensor network grouping in 1-hop cluster

The first phase of our localization algorithm consists in electing cluster heads and forming clusters considering the 1-hop neighbourhood (refer to line 2 of Algorithm 1) as shown in Figure 2. This first phase is based on Low Energy Adaptive Cluster Hierarchical (LEACH) Protocol [6]. With LEACH, each node chooses random number q $(0 \leq q \leq 1)$. This value (i.e., q) is compared to the threshold T which depends on the desired percentage of clusters. If the number q of a node is less than T, this node is selected as a cluster head. Then, in this first phase, for each cluster head, our algorithm groups the wireless sensors in its 1-hop neighborhood to form the clusters.

In the second phase (refer to lines 4 to 14 of Algorithm 1), the distances separating all peer nodes in each cluster are estimated using the RSSI signal transmission model. A node x is a peer node of node y if they are in the same cluster and within communication range. Note that x is a peer node of y means also that y is a peer node of x. However, the more nodes there are in a cluster, the more communications there will be, which would lead to high energy consumption. To avoid high energy consumption, we propose to reduce the amount of communication in the distance estimation process by using a two-step process in this second phase:

– The first step (refer to lines 4 to 9 of Algorithm 1) consists in estimating only the distances between each Cluster Head CH_k and its peers. Then, each CH_k chooses the node v_j^k among its peers located at the smallest distance from it and communicates its identifier to all other nodes of the same cluster. If there is more than one node located at the smallest distance from the cluster head CH_k, then choose the node that has the most energy. And if there are also at least two nodes among these nodes that have the the smallest energy, then choose the one with the smallest ID. All other nodes in the same cluster that are within communication range of v_j^k estimate the distances $d_{i,j}^k$ between them with RSSI transmission model represented by Equation (1):

$$P_r\left(d_{i,j}^k\right) = P_t - PL(d_0) - 10\ \eta\ log_{10}\left(d_0\right) + X_\delta \tag{1}$$

where $P_r(d_{i,j}^k)$ is the received signal power, P_t is the transmit power, $PL(d_0)$ is the path loss for reference distance of d_0, η is the attenuation constant and is the uncertainty factor due to multipath $X_\delta = N(0, \delta^2)$ and shadowing. Generally, the typical value of parameters is as follows: $P_t \in [0, 4]$ (dBm), $PL(d_0) = 55$ dB ($d_0 = 87{,}7$m), $\eta \in [2, 4]$ and $\delta \in [4, 10]$.

– In the second step (refer to line 11 of Algorithm 1), if one node is not in communication range with v_j^k; the Kleinrock and Sylvester model [9] represented by Equation (2) is used to compute the distance $d_{i,j}^k$.

$$d_{i,j}^k = R^k(1 + e^{-l} - \int_{-1}^{1} e^{\frac{l}{\pi}*\arccos(t) - t\sqrt{1-t^2}})dt \tag{2}$$

where R^k and l are respectively the cluster radius and the number of nodes in the cluster C_k. This model expresses the distance between two nodes as a function depending on the number of hops between these two nodes. Once all distances necessary for the computation of the positions are known, EAFLA can compute the nodes position.

In the third phase (refer to line 16 of Algorithm 1), the relative position of each wireless sensor is computed according to Al-Kashi's theorem represented by Equation (3). Figure 3 is an exemple of computing position of the node v_i^k.

$$\begin{cases} \widehat{x_i^k} = d_{k,i}^k * cos(\theta_{i,j}^k) \\ \widehat{y_i^k} = d_{k,i}^k * sin(\theta_{i,j}^k) \end{cases} \tag{3}$$

where $\theta_{i,j}^k = arccos(\frac{{d_{k,i}^k}^2 + {d_{k,j}^k}^2 - {d_{i,j}^k}^2}{2 * d_{k,i}^k * d_{k,j}^k})$; $\theta_{i,j}^k \in [0, 2\pi]$ and $\theta_{i,j}^k = \angle(v_i^k, CH_k, v_j^k)$ the angle formed by v_i^k, CH_k and v_j^k.

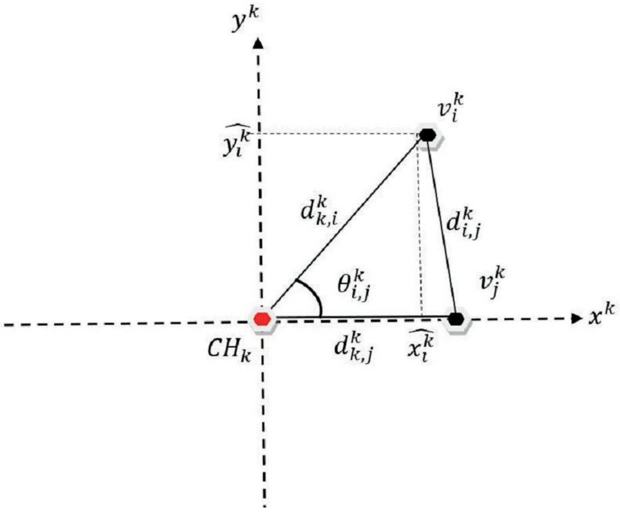

Figure 3: position computing based on Al-Kashi's theorem in the cluster C_k

The position of the cluster head is assumed to be known because the cluster head is taken as the reference position.

4.3 Proof of our algorithm total correctness

EAFLA (see Algorithm 1) takes as input the wireless sensor network represented by a graph G and provides as output the set of nodes positions of the network regardless the topology of each cluster

Algorithm 1 Efficient Anchor Free Localization Algorithm (*EAFLA*)

```
Input: $G(V, E)$                                   // $G$ : Graph of wireless sensor network
Output: $P$                                        // $P$: Set of accurate positions of wireless sensors
 1: $P = \emptyset$
 2: Election of the set Clusters Heads $CH$ and formation of the set of clusters $C$ ;    // $CH = \{CH_1, ..., CH_m\}$ the set of Clusters Heads; $C = \{C_1, ..., C_m\}$ the set of clusters.
 3: for each $C_k \in C$ do
 4:     $D^k$ = the set of distances between each node (belonging to $C_k$) and Cluster Head $CH_k$ such that each distance is obtained using Equation (1);    // $D^k = \{d^k_{k,1}, ..., d^k_{k,l}\}$, $l$ = number of nodes belonging to $C_k$
 5:     Select a node $v^k_j$ such that $d^k_{k,j} = \min D^k$ ;    // $v^k_j$ is the j-th wireless sensor belonging to cluster $C_k$ which have the smallest distance among $D^k$
 6:     $\overline{D}^k = \emptyset$ ;    // $\overline{D}^k$ : the set of distances between $v^k_j$ and each node except $CH_k$
 7:     for each $v^k_i \in V^k \setminus \{v^k_j, CH_k\}$ do    // $V^k$: set of nodes belonging to $C_k$
 8:         if RANGE $(v^k_i, v^k_j)$ == True then    // RANGE $(v^k_i, v^k_j)$: a function that tests whether $v^k_i$ and $v^k_j$ are in a communication range
 9:             Estimate distance $d^k_{i,j}$ using Equation (1);    // $d^k_{i,j}$ the distance between the wireless sensors $v^k_i$ and $v^k_j$ in the cluster $C_k$
10:         else
11:             Estimate distance $d^k_{i,j}$ using Equation (2) ;
12:         end if
13:         $\overline{D}^k = \overline{D}^k \cup \{d^k_{i,j}\}$;    // $\overline{D}^k$ is updated
14:     end for
15:     for each $v^k_i \in V^k \setminus \{v^k_j, CH_k\}$ do
16:         Compute the position $(\widehat{x^k_i}, \widehat{y^k_i})$ of $v^k_i$ using Equation (3), with $d^k_{k,i} \in D^k$, $d^k_{k,j} \in D^k$ and $d^k_{i,j} \in \overline{D}^k$;
17:         $P = P \cup \{(\widehat{x^k_i}, \widehat{y^k_i})\}$;    // $P$ is updated
18:     end for
19:     Set the position of $v^k_j$ to $(d^k_{k,j}, 0)$ and add this position to $P$
20:     Set the position of $CH_k$ to $(0, 0)$and add this position to $P$
21: end for
22: Return $P$
```

formed while generating low energy consumption. LEACH is the most robust protocol for cluster head election and cluster formation. Its correctness was proven by the authors. This implies that LEACH provides a finite set of clusters and thus a finite set of cluster heads (*i*). Each cluster contains a finite number of nodes. Thus, the for loop starting at line 7 (and ending at line 14) always stops (*ii*). Similarly, the for loop starting at line 15 (and ending at line 18) always stops (*iii*). From (*i*), (*ii*) and (*iii*), it follows that the for loop starting at line 3 (and ending at line 21) always stops (*iv*). From (*ii*), (*iii*) and (*iv*), it follows that EAFLA always ends (*v*). Let G be an instance of graph, for each cluster instance formed:

1) Equations (1) and (2) allow an estimation of all inter-node distances useful to compute the position of any node in a formed cluster (refer to lines 4, 9, 11, and 13 of Algorithm 1).

2) Equation (3) representing the Al-Kashi theorem (refer to line 16), lines 19 and 20 of Algorithm 1 allow to derive the positions of the nodes of this cluster.

5 Performance Evaluation

5.1 Localization evaluation metrics

To confirm the effectiveness of our algorithm (EAFLA), we compared it with the one proposed by Shah et al., [16]. This performance was evaluated mainly according to the following metrics:

- The rate of localized nodes for a given topology of cluster

$$\%N_k = \frac{Number\ of\ nodes\ located\ \ in\ a\ cluster}{Total\ number\ of\ nodes\ in\ a\ cluster} * \ 100 \tag{4}$$

with $\%N_k$ the rate of nodes located for a given cluster C_k. A node is located if phases 1 and 2 are successfully performed.

This criterion allows to evaluate the ability of an algorithm to locate the nodes for a given cluster.

- The average error on the location position

$$e_r = \sqrt{\sum_{i=1}^{n} \frac{\left(x_i - \hat{x}_i\right)^2 + \left(y_i - \hat{y}_i\right)^2}{n}} \tag{5}$$

$(x_i^k,\ y_i^k)$ the actual position and $(\widehat{x_i^k}, \widehat{y_i^k})$ the estimated position of the wireless sensor.

- Energy consumption model

The energy expended to transmit and to received a message of β-bits at distance d are respectively defined by Equation (6) and Equation (7) :

$$E_{TX}\left(\beta, d\right) = \begin{cases} \beta * E_{elec} + \beta * \in_{fs} * d^2,\ if\ \ \ d < d_0 \\ \beta * E_{elec} + \beta * \in_{amp} * d^4,\ if\ \ \ d \geq d_0 \end{cases} \tag{6}$$

where E_{elec} is the energy consumed by the radio, $\in_{fs}$ and $\in_{amp}$ are used to amplify the signal, with $d_0 = \sqrt{\frac{\in_{fs}}{\in_{amp}}}$

$$E_{RX}\left(\beta\right) = \beta * E_{elec} \tag{7}$$

5.2 Simulation set up

MATLAB software was used as a simulation tool to evaluate the performance of the proposed localization technique. MATLAB has a large library of functions particularly those that manipulate vectors and matrices. We assume that the wireless sensor nodes are randomly deployed in an area of 100 *100 m^2. At the beginning of the simulation, all nodes have the same energy. Table 1 lists the parameters and their values used during simulation.

Table 1: Simulation parameters

Parameters	**Values**
Deployment surface	100 m * 100 m
Number of wireless sensors deployed	50 à 350
The initial energy of wireless sensors	1 J
$\in_{fs}$ (Signal in free space)	10 pJ/bit/m^2
$\in_{amp}$ (Multi-path fading coefficient)	0.0013 pJ/bit/m^4
E_{elec} (Electronic circuit energy)	50 nJ/bit
d_0 (Threshold distance)	87,7 m

5.3 Results analysis and discussions

- The rate of localized nodes for a given cluster topology

Figure 4 shows that for fully meshed topology of cluster, EAFLA (i.e., our algorithm) and the one proposed by Shah et al., [16] have a localized node rate that is very high (98%), these two algorithms behave in almost the same way, i.e., their ability to localize nodes in a fully meshed topology of cluster is almost identical. This is because in a fully meshed topology of cluster, each node in this cluster is within communication range with all other nodes in that cluster.

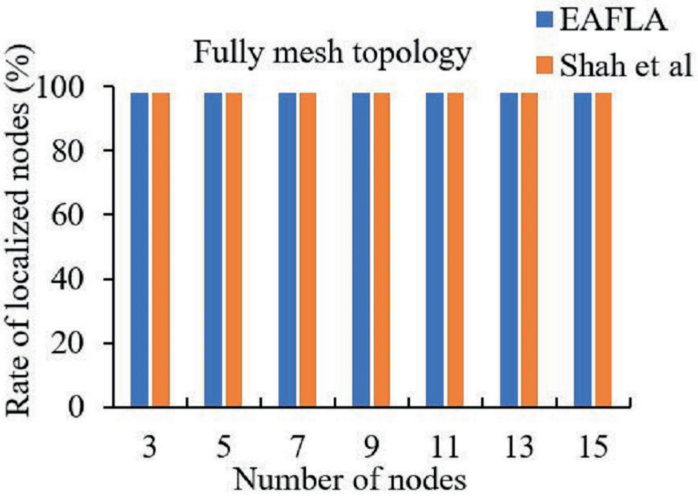

Figure 4: localized node rate for a fully meshed topology of cluster

Figure 5 shows that for a weakly meshed topology of cluster, the localized node rate with EAFLA (i.e., our algorithm) remains unchanged while the localized node rate with the Shah et al.'s algorithm is low. In a weakly meshed topology of cluster, only a few nodes in this cluster are in communication range. This is due to the non-possibility of computing some inter-node distances that could be involved in the position computation.

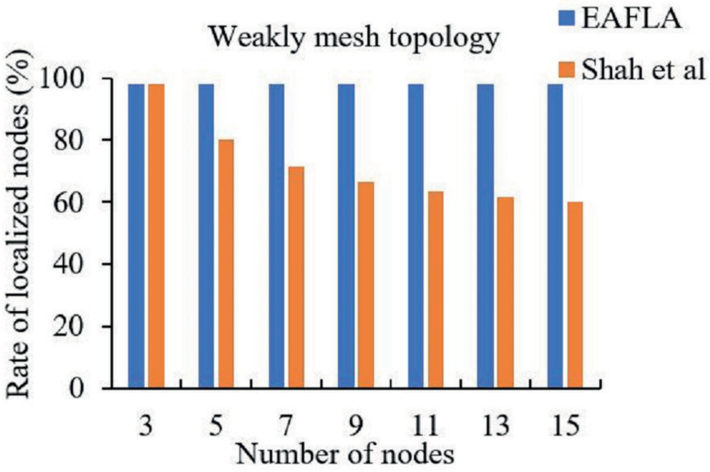

Figure 5: localized node rate for a weakly mesh topology of cluster

Figure 6 also shows that for star topology of cluster, the ability of the EAFLA algorithm to locate the nodes remained the same as that of the other two topologies mentioned above. This is due to the ability of EAFLA to calculate distances between two wireless sensors in the same cluster, even when they are not in communication range. However the Shah et al.'s algorithm locates the nodes of the cluster very weakly. In a star topology, only the cluster head is within communication range with all

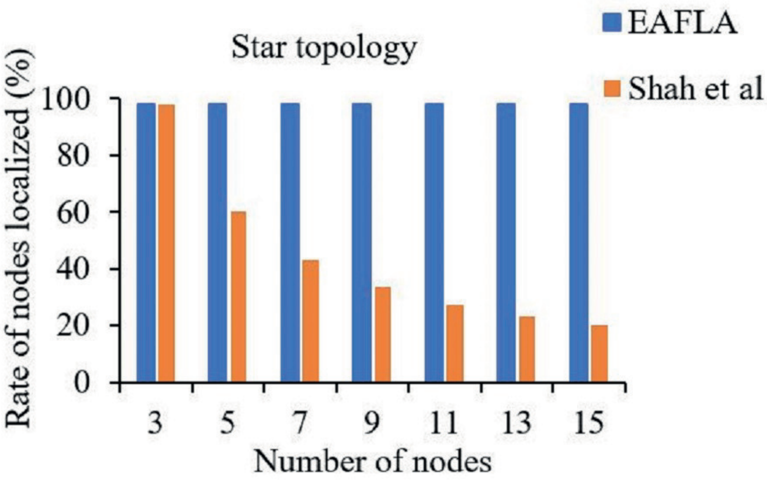

Figure 6: localized node rate for a star topology of cluster

nodes in its cluster. This is because of the low connectivity between nodes. This low connectivity leads to the non-possibility of estimating the distances between certain nodes.

From the figure 4, figure 5 and figure 6 we can conclude that, whatever the topology presented by all clusters in the network; our algorithm keeps the same localization performance in terms of localized node rate, compared to the one proposed by Shah et al., [16].

- The average location errors

Figure 7 shows that the Shah et al., algorithm gives a very high average location error when the network has a relatively low node density. This error decreases considerably as the number of nodes in the network increases. However, the average error of the proposed localization algorithm (i.e., EAFLA) varies very little regardless of the number of nodes in the networks.

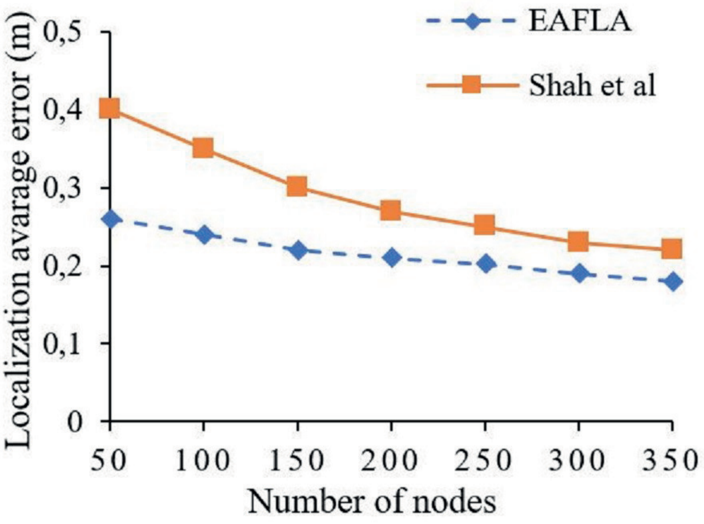

Figure 7: average error as a function of the number of nodes

- The rate of localized nodes Energy consumption

Figure 8 shows that as the number of nodes in the network increases, the rate of energy consumed by the approach proposed by Shah et al.,[16] increases sharply while the rate of energy consumed by the proposed EAFLA algorithm remains almost constant regardless of the number of nodes in the network.

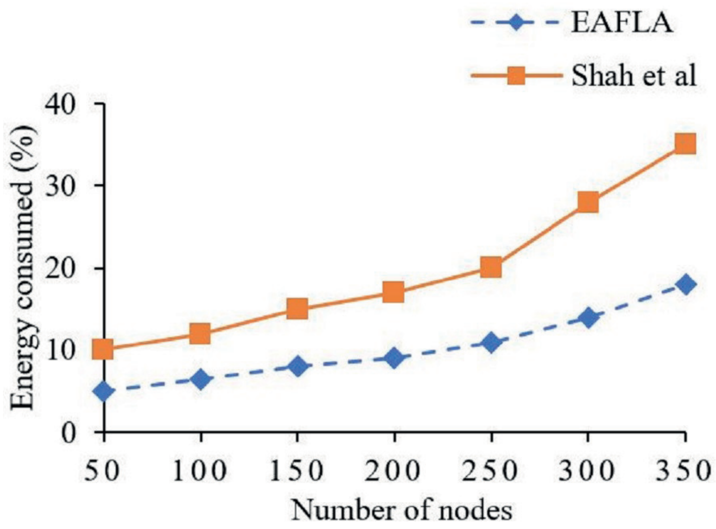

Figure 8: : Energy consumed as a function of the number of nodes

6 Conclusion and Future Work

In this study, we have proposed an anchor-free localization algorithm that helps to find the physical position of nodes, in a wireless sensor network that is deployed in a hostile environment. To do so, we proposed an Efficient Anchor-Free Localization Algorithm (EAFLA) for all topologies of the clusters formed in the wireless sensors network. Our algorithm first groups the nodes into 1-hop clusters and then estimates the distances between the nodes within each cluster using RSSI when they are in communication range, if not we use the Kleincroch model. Finally, we use Al-Kashi's theorem to derive the position of the different wireless sensors in the network. We have shown that our contribution is efficient for any topology that a 1-hop cluster might present and reduces the average error on the position of the nodes with a very low energy consumption rate. That increases the lifetime of the network.

The location of the nodes allows for establishing a path in order to be able to transmit information from a source to a destination. However, it will be interesting to investigate the problems related to geographic routing in wireless sensor networks [1].

Author contributions

The authors contributed equally to this work.

Conflict of interest

The authors declare no conflict of interest

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