Anchor-Free Localization Algorithm Using Controllers in Wireless Sensors Networks

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Abstract. Localization of wireless sensors is a very important aspect of Wireless Sensors Networks (WSNs) as it determines the proper functioning and lifetime of the wireless sensors that constitute the network. The precise localization of fixed or mobile sensors in the network is a challenging problem that has attracted the attention of many researchers. Indeed, due to the constraints of wireless sensors, and the limitations of localization systems such as GPS, equipping each sensor with a localization system is an unviable solution. To solve the localization problem, several localization algorithms have been proposed in the literature. These algorithms fall into two broad categories, namely range-based algorithms, and range-free algorithms, which are either anchor-based or anchor-free. However, these algorithms are energy intensive, less accurate, and suffer from a low rate of localized nodes. To improve the existing solutions in the literature, a localization algorithm called AFLAC (Anchor Free Localization Algorithm using Controllers) has been proposed. Regardless of the communication range between wireless sensors, AFLAC allows estimating the distance between them to derive their position with low energy consumption and good localization accuracy.

Keywords: Localization algorithm · Wireless sensor network · Anchor-free · Controllers

1 Introduction

The emergence of new technologies, wireless communications, and advances in networking have enabled the development of small devices called wireless sensors. These sensors can communicate with each other via radio waves. However, when they are deployed in an area, they form an infrastructure called a Wireless Sensor Network (WSN). Typically, WSNs have a very large number of nodes and are considered a special type of ad hoc network where the nodes of this type of network are made up of many micro-sensors capable of collecting, processing, and transmitting environmental data in an autonomous

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way. WSNs are deployed randomly in hostile environments (places where human presence is undesirable) and allow to substitute the processing that humans could bring on local data. In recent years, WSNs have been used in several application areas: military, civil security, transportation, industrial, environmental, and many others. These networks have emerged with many challenges, such as security, routing, localization, etc.

Although in the literature there are several localization systems such as GPS (Global Positioning System) [1]. Because of the energy constraints of wireless sensors and the limitations of these localization systems, equipping each sensor with a localization system is an economically unviable solution. Hence the need to develop a localization algorithm without any localization system.

In this work, we proposed an anchor-free localization algorithm that aggregates the wireless sensors in a cluster network and uses a controller to estimate the distances between intra-cluster nodes that are not within the communication range. A controller is a Cluster Head that is elected among the set of Cluster Heads and it's able to communicate with all the wireless sensors of its adjacent clusters.

Our algorithm is executed in three steps:

- The first step is to partition the network into clusters considering the 1-hop neighborhood. To do so, we based on the work of C. Lin et al., [2]. The objective of this step is to reduce the number of communications to minimize energy consumption, it also reduces the impact of environmental factors on the signals when the sensors estimate the distances between them.
- The second step is the intra-cluster position derivation phase using Cluster Head as a reference.
- The third step is to group the clusters into zones and elect a controller among the Cluster Heads to manage the zones to support distance calculations between wireless sensors that are not in communication range.

The rest of our work is organized as follows. Section 2 presents a review of existing anchor-free range-based localization algorithms. Section 3 gives the problem specification. We describe in detail our anchor-free localization algorithm in Sect. 4. Section 5 presents the evaluation criteria, the results of the simulation and discussions are presented in Sect. 6 and ended in Sect. 7 with a conclusion and some perspectives.

2 Literature Review

In this section, we survey the different approaches of anchor-free localization that exist in the literature. But first, it is necessary to specify the different step of executing localization algorithm.

2.1 The Steps Involved in Executing a Localization Process

As shown in Fig. 1 below, a localization process is executed in three steps:

- Distance estimation phase
- Position computing phase

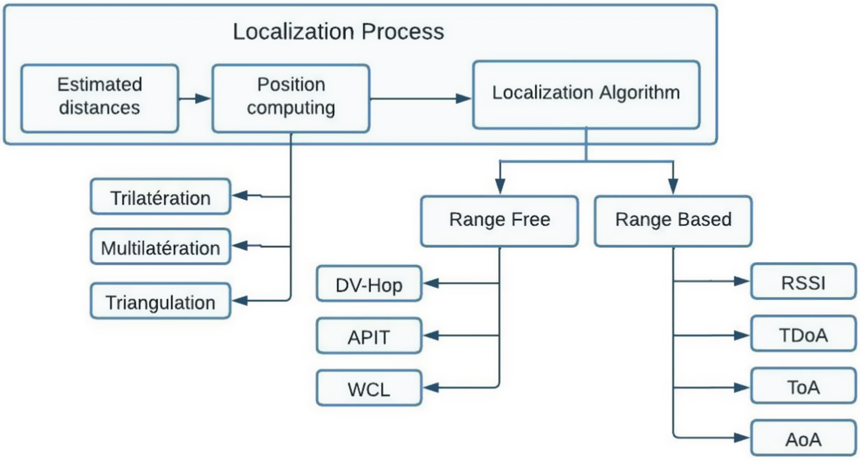

Fig. 1. Localization process

- Localization algorithm phase

The distance estimation phase is very important because the calculation of the position depends on the estimated distance. Indeed, an accurate estimation between nodes allows to derive the position of the nodes with less error. However, the methods used by localization algorithms to estimate distances can be divided into two groups:

– Methods based on distance such as AoA (Angle of Arrival), ToA (Time of Arrival) [3], TDoA (Time Difference of Arrival) [4], RSSI (Received Signal Strength Indicator) [5, 6].
– Methods based on connectivity information such as DV-Hop (Distance Vector Hop) [7], WCL (Weighted Centroid Localization) [8], APIT (Approximate Point in Triangulation) [9]. Methods based on connectivity information generally require anchor nodes, although they have the advantages of being cheaper, simple to implement but less accurate than distance-based methods and therefore not suitable for applications where the localization of a node is very critical.

Among the distance-based methods, AoA, TDoA, ToA can achieve better localization accuracy compared to the methods using RSSI because of the environmental factors that greatly affect the amplitude of the RSSI signal which is very sensitive to noise and obstacles. However, the RSSI method is the most common, least expensive and simplest technique as it does not require additional equipment (e.g. infrared or ultrasound) [6]. This method is suitable for networks with a high density of nodes.

The RSSI method uses the received signal strength to estimate the distance between two nodes (sender and receiver nodes). There are several channel models for RSSI signal transmission, the most popular of which is the log-normal shadowing [5].

Depending on the method used in the distance estimation phase, they can be distinguished into two main groups of localization algorithm: range-based localization algorithms and range-free localization algorithms [9]. These algorithms can be either anchor-based or anchor-free.

In the most hostile environments, anchor-free approaches are preferred for three reasons. First, the deployment of anchors in the network is done manually, which can be difficult or impossible. Secondly, the numerical stability of the estimated positions of anchor-based approaches is questionable as the accumulated errors of the anchors have a very high weight, which could considerably affect the overall solution. Finally, anchor-based approaches are less scalable because to combat the instability described above, many anchors would be needed to configure a working area that can evolve over time.

2.2 Anchor-Free Localization Algorithms

The anchor-free localization algorithm problem has been widely explored in the literature. To solve this problem, Youssef et al., [10] proposed an anchor-free localization algorithm called AAFL (Accurate Anchor-free Localization) which is based on clustering, all nodes are grouped into clusters and each cluster has an edge node which provides communication with other edge nodes although the distributed nature of AAFL reduces the computational complexity, but its localization accuracy is very low, moreover the network needs high connectivity to make the network more flexible and also the communication load of the edge nodes is too high which affects the lifetime of the network.

Moore et al., [11] proposed an anchor-free distributed localization algorithm called RODL (RObust Distributed network Localization with noisy range measurements) based on distance measurement. It adopts a cluster-based localization technique that uses quadrilaterals to avoid inconsistencies. The formation of clusters optimises communication costs and therefore energy; this makes their algorithm scalable.

Teijiro Isokawa et al., [12] proposed an anchor-free localization algorithm in which no geometric information of the sensors is required, it relies on a link quality indicator and the number of hops to estimate the distances between the nodes using Kalmann filter to reduce the errors induced by the link quality indicator. The performance of their protocol is limited only to a network with only four wireless sensors and requires all sensors to be equipped with an angle measurement device.

Zhe Qu et al., [13] proposed an Energy Efficient Anchor-Free Localization Algorithm, which uses a single well node so the 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 sink node. This algorithm requires all sensors in the network to be equipped with an angle measuring device and is less accurate for networks with a hostile environment.

Chen Liu et al., [14] proposed an anchor-free localization algorithm 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 (SAAPSO) to estimate the positions and to obtain an accurate position, they use the Taylor algorithm. The resulting algorithm reduces the accumulated error and increases the localization accuracy.

Wang Ming et al., [15] proposed a Distributed Cluster-based Anchor-free node localization algorithm (CDAP) which is executed in 3 steps. The first step is based on the clustering of one-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 synchronization phase, in this phase all nodes of a cluster are synchronized, and the local coordinates are established using the angle and distance information. The third step is the global localization phase. Although this approach is scalable and accurate, all sensors need to be equipped with an angle measuring device.

Tao Du et al., [16] proposed an anchor-free localization algorithm called LDLA (Ladder Diffusion node Localization Algorithm) in which each node calculates its relative position with the well node based on the principle of the algorithm proposed by Zhe et al., but only the nodes located at 1- hop are activated to calculate the angles and distances to the well nodes iteratively until all the sensors discover their position. Their algorithm optimizes the energy management of the sensors but does not take into account the scalability of the network and requires all of them to be equipped with an angle measuring device.

Although the existing anchor-free localization algorithms solve the localization problem without anchor nodes, but there are still some shortcomings such as high computational complexity, low localization accuracy, high deployment cost and network scalability over time. Most of the existing research focuses either on improving the localization accuracy or on the energy consumption problem of the nodes.

3 Problem Specification

3.1 Assumption

We assumed that all wireless sensor in the network:

- Are not equipped with a localization system,
- are deployed randomly in an area of interest,
- after deployment are static,
- have sufficient energy to perform the localization task,
- have an omnidirectional antenna,
- have a unique identifier (ID).

3.2 Problem Formulation

In general, a wireless sensor network is represented by a random geometric graph $G = (V, E)$ with $V = \{v_1, v_2, ..., v_n\}$ the set of wireless sensors deployed in a Euclidean space and the set of links and $E = \left\{ \left(v_i; v_j\right) \in V^2 | d_{i,j} \leq r_i + r_j \right\}$ where r_i, r_j denote the communication ranges of the sensors v_i and v_j and n denote the number of wireless sensors in the network.

The localization problem we are solve is to make a good estimate of the distances $d_{i,j}$ between the wireless sensors v_i and v_j in order to derive their position $P_i(x_i, y_i)$ and $P_j(x_j, y_j)$ in a 2D Euclidean plane where no element in V has knowledge of its position, i.e. no element in V is equipped with a localization system.

3.3 Objectives

Coverage, complexity, scaling, robustness, cost (in energy and hardware) and localisation accuracy are the major challenges that existing localization algorithm in the literature have difficulty in meeting. Indeed, a good localization algorithm must consider these performance criteria. However, the specific objective we set ourselves in this work is to propose a localization algorithm that is good:

- rate of localized nodes,
- less energy consumption,
- localization accuracy.

4 Contribution

Network Model
Consider a wireless sensor network represented by the architecture below (Fig. 2):

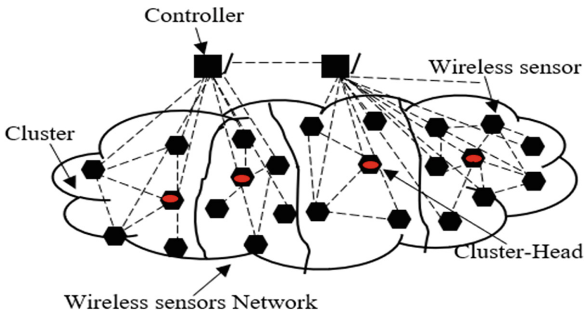

Fig. 2. Cluster and zone network architecture

Let us designate all the components of the network by the following parameters:

- CH_k: the k-th cluster head of the network ($k \in \{1, \ldots, m\}$) with m the number of clusters in the network.
- $Cont_p$: p-th controller of the network ($p \in \{1, \ldots, q\}$) with q the number of controllers in the network. A controller is a Cluster Head that is elected among the set of Cluster Heads. It's able to communicate with all the wireless sensors of its adjacent clusters.
- $P(x_i, y_i)$: the position of a sensor v_i in a 2D Euclidean plane.
- r_i: the communication range of a wireless sensor v_i.
- $d_{k,i}$: the distance between a Cluster Head CH_k and a wireless sensor v_i with $k \in \{1, \ldots, m\}$ and $i \in \{1, \ldots, n\}$.

4.1 Proposed Localization Algorithm

In this section, we describe our proposed anchor-free localization algorithm. This localization algorithm called AFLAC (Anchor Free Localization Algorithm using Controllers) is executed in 4 steps:

Clustering Phase of the Network

- Nodes are deployed randomly in the network
- Election of a group leader and cluster formation considering 1-hop sensors.

Each node v_i has a unique identifier $id(v_i)$ and knows the identifiers of its 1-hop neighbors, all stored in a set $\Gamma(v_i)$. If a node has the lowest identifier in, $\Gamma(v_i)$ then it becomes Cluster Head and the Cluster Head ID $id(CH)$ is set to $id(v_i)$. It then broadcasts a CLUSTER $(id, id(CH))$ message to inform its neighbours of its decision and removes $id(CH)$ from the set Γ. If the node does not yet know its cluster head, $id(CH)$ is set to *unknown* each node v_i executes a series of instructions until Γ becomes the empty set.

Distance Estimation Phase

Use of the log-normal Shadowing model (RSSI) to estimate the distances between all nodes in a cluster that are in communication range.

And when two nodes in a cluster are not within communication range, the controller steps in to calculate the distance between these wireless sensors.

Position Calculation Phase

Cluster Heads (CH) are taken as the coordinate reference position $CH_k(0, 0)$. Each Cluster Head chooses one sensor v_i and a sensor v_j in its cluster from among its peers to form its reference axes (the x-axis and y-axis). Assuming that the position sensors $CH_k(0, 0)$, $S_i(d_{ki}$,0) and $S_j(0, d_{kj})$ are taken as reference, the relative position of all wireless sensors for all clusters that constitute the network is determined iteratively by the trilateration method.

When the position of a sensor is calculated, it is taken as a reference.

Global Localization Phase

- Division of the network into zones (a zone consists of a set of clusters)
- The Cluster Head who has more energy and can communicate with all the wireless sensors of its adjacent clusters is taken as the zone leader (controller). Each zone is managed by a controller who has a global view of the zone assigned to him.
- Each cluster head communicates its cluster ID to its dedicated controller.
- Each controller can communicate with its nearest neighbouring controllers for global localization.

Figure 3 summarises the steps of our localization algorithm call AFLAC.

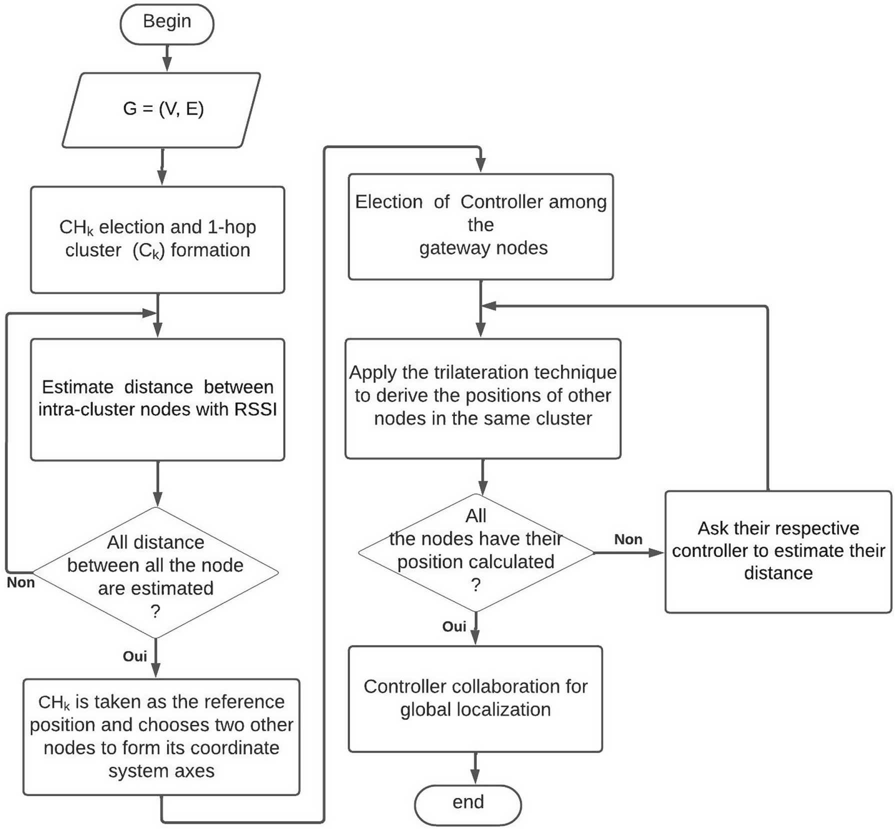

Fig. 3. Flowchart of the AFLAC algorithm

5 Performance Evaluation

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 50 * 50 m^2. At the beginning of the simulation, all nodes have the same energy.

To evaluate the performance of our algorithm, we considered certain criteria such as:

5.1 Positioning Accuracy

Equation (1) allow to compute the position error of a wireless sensor v_i.

$$e_i = \sqrt{\left(x'_i - x_i\right)^2 + \left(y'_i - y_i\right)^2} \quad (1)$$

where (x_i, y_i) and $\left(x'_i, y'_i\right)$ define respectively the actual and estimated position of a wireless sensor v_i.

5.2 Rate of Localized Node

The Eq. (2) calculates the ratio of localized nodes to the total number of nodes deployed in the network.

$$\%N = \frac{Number\ of\ nodes\ located}{Total\ number\ of\ nodes} * 100 \tag{2}$$

5.3 Energy Consumption Model

The energy expended to transmit and to receive a message of β – bits at distance d are defined respectively by Eq. (3) and Eq. (4):

$$E_{TX}(\beta, d) = \begin{cases} \beta * E_{elec} + \beta * \in_{fs} * d^2, & if\ d < d_0 \\ \beta * E_{elec} + \beta * \in_{amp} * d^4, & if\ d \geq d_0 \end{cases} \tag{3}$$

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

$$E_{RX}(\beta) = \beta * E_{elec} \tag{4}$$

6 Results and Discussions

The localization algorithm we proposed has a very high localized node rate. However, Fig. 5 shows that when we vary the nodes between 10 and 50 AFLAC keeps its performance in terms of localized node rate unlike that of Wang Ming et al. This performance is due to the controller nodes which have this ability to calculate the distance between nodes that are not in communication range (Fig. 4).

It can be seen from Fig. 6 that during the localization process, the AFLAC localization algorithm gives an estimated low error rate on the position of the nodes compared to the proposed CDAP.

Figure 6 shows that as the number of nodes in the network increases, the rate of energy consumed by CDAP localization algorithm increases sharply while the rate of energy consumed by the proposed AFLAC algorithm remains almost constant regardless of the number of nodes in the network.

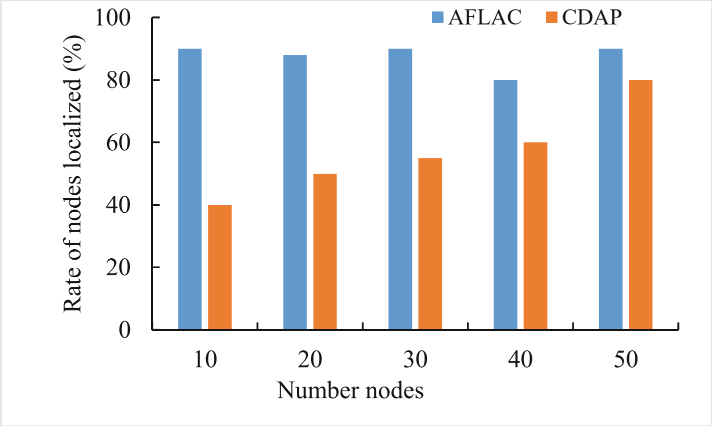

Fig. 4. Rate of localized nodes

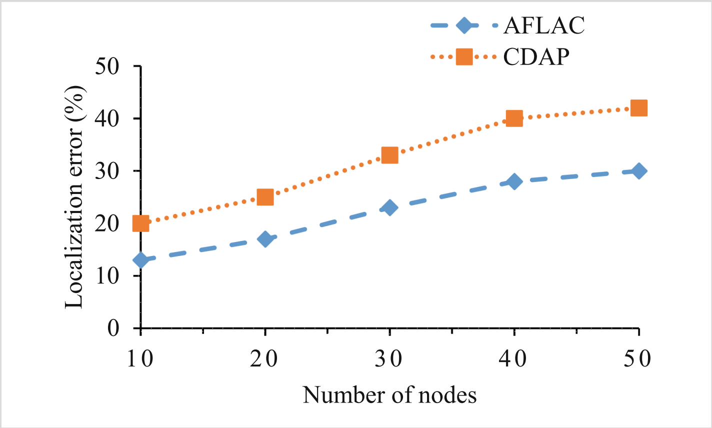

Fig. 5. Error in the estimated position of nodes

Our experiments have shown that, when there are more nodes within communication range, the possibility of calculating distances between nodes favors a good rate of nodes located by the AFLAC and CDAP localization algorithms, which results in an estimated low error rate on the position of nodes. When there are fewer nodes within communication range, the AFLAC localization algorithm keeps its performance and the CDAP algorithm decreases in performance.

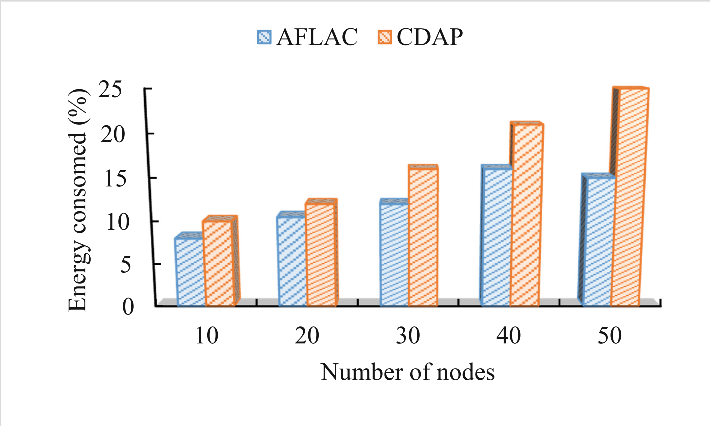

Fig. 6. Energy consumed as a function of the number of nodes

7 Conclusion and Perspective

In this work, we have addressed the problem of anchor-free localization in wireless sensor networks. Major challenges such as scalability, energy consumption, robustness, accuracy is still to be addressed by existing localization algorithms. This inspired us to propose a localization algorithm called AFLAC (Anchor Free Localization Algorithm using Controllers), which use a controller to compute the distance between two sensors which are not in communication range. To evaluate the performance of our algorithm AFLAC compared to one proposes by Wang et al., we based ourselves on some performance criteria such as the rate of located nodes, the error on the positioning accuracy and energy consumed in the localization process. The results of our experiment showed that the AFLAC localization algorithm has a good performance compared to the CADP algorithm.

The clusters formed in the first phase can have different topologies. In our future work we plan to propose a localization algorithm that considers the topology of the clusters.

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