Range-free Localization Algorithm for Anisotropic Wireless Sensor Networks

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Abstract—**In this paper, we propose a novel range-free localization algorithm tailored for anisotropic wireless sensors networks (WSN)s. Using the proposed algorithm, each regular or position-unaware node estimates its distances only to reliable anchors or position-aware nodes. The latter are properly chosen following a new reliable anchor selection strategy that ensures an accurate distance estimation making thereby our localization algorithm more precise. Indeed, simulations suggest that it outperforms the best representative range-free localization algorithms currently available in the literature in terms of accuracy.**

Index Terms—**Anisotropic wireless sensor networks, localization algorithms, range-free, anchor selection.**

I. Introduction

Due to their reliability, low cost, and ease of deployment, wireless sensor networks (WSNs) are emerging as a key tool for many applications such as environment monitoring, disaster relief, and target tracking [1]-[2]. A WSN is a set of small and low-cost sensor nodes with limited communication capabilities. The latter are often deployed in a random fashion to collect some physical phenomena from the surrounding environments such as temperature, light, pressure, etc. [3]. Due to their limited transmission ranges, the sensor nodes are often not able to directly communicate with a remote access point (AP). For this reason, they recur to multi-hop communication through several intermediate nodes that successively forward their gathered data to the AP. However, the sensing data are very often meaningless if the location from where they have been measured is unknown which makes, their localization a fundamental and essential issue in WSNs. So far, many localization algorithms have been proposed in the literature and mainly fall into two categories: range-based and range-free.

To properly localize the regular or position-unaware nodes, range-based algorithms exploit the measurements of the received signal characteristics such as the time of arrival (TOA), the angle of arrival (AOA), or the received signal strength (RSS) [4]-[6]. These signals are, in fact, transmitted by nodes having prior knowledge of their positions, called anchors (or landmarks). Although the range-based algorithms stand to be very accurate, they are unsuitable for WSNs. Indeed, these algorithms require high power to ensure communication between anchors and regular nodes which are small battery-powered units. Furthermore, additional hardware is usually required at both anchors and regular nodes, thereby increasing the overall cost of the network. Moreover, the performance of these algorithms can be severely affected by noise, interference, and/or fading. Unlike range-based algorithms, range-free algorithms, which rely on the network connectivity to estimate the regular node positions, are more power-efficient and do not require any additional hardware and, hence, are suitable for WSNs [7]- [16]. Due to these practical merits, range-free localization algorithms have garnered the attention of the research community. Unfortunately, in anisotropic environments where obstacles and/or holes may exist, range-free algorithms do not provide sufficient accuracy due to large errors occurring when mapping the hops into distance units. Indeed, in such environments, it is very likely that the shortest path between an anchor and a regular node is curved, thereby resulting an overestimation of the distance between these two nodes. The more obstacles and/or holes there are, the larger are distance estimation errors and, consequently, less accurate is localization.

In this paper, we propose a novel range-free localization algorithm tailored for anisotropic WSNs. Using the proposed algorithm, each regular node estimates its distances only to reliable anchors. The latter are properly chosen following a new reliable anchor selection strategy that ensures an accurate distance estimation thereby making our localization algorithm more precise. Simulations suggest indeed that it outperforms the best representative range-free localization algorithms currently available in the literature in terms of localization accuracy.

The rest of this paper is organized as follows: Section II describes the system model. Section III proposes a novel localization algorithm while section IV and V introduce a new reliable anchor selection strategy and a novel distance estimation technique, respectively. Simulation results are discussed in Section VI and concluding remarks are made in section VII.

II. Network model

Fig. 1 illustrates the system model of N WSN nodes uniformly deployed in a 2-D square area S in the presence of a rectangle obstacle which makes the network topology C-shaped. All nodes are assumed to have the same transmission capability (i.e., range) denoted by R. Each node is able to directly communicate with any other node located in the disc having that node as a center and R as a radius, while it communicates in a multi-hop fashion with the nodes located outside. Due to the high cost of the global positioning system (GPS) technology, only a few nodes commonly known as anchors are equipped with it and, hence, are aware of their

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positions. The other nodes, called hereafter position-unaware or regular nodes for the sake of simplicity, are oblivious to this information. As shown in Fig. 1, the anchor nodes are marked with red triangles and the regular ones are marked with blue circles. If two nodes are able to directly communicated, they are linked with a dashed line that represents one hop. Let N_a and $N_u = N - N_a$ denote the number of anchors and regular nodes, respectively. Without loss of generality, let (x_i, y_i), $i = 1, \ldots, N_a$ be the coordinates of the anchor nodes and (x_i, y_i), $i = N_a + 1, \ldots, N$ those of the regular ones. In what follows, we propose an efficient anchor-based

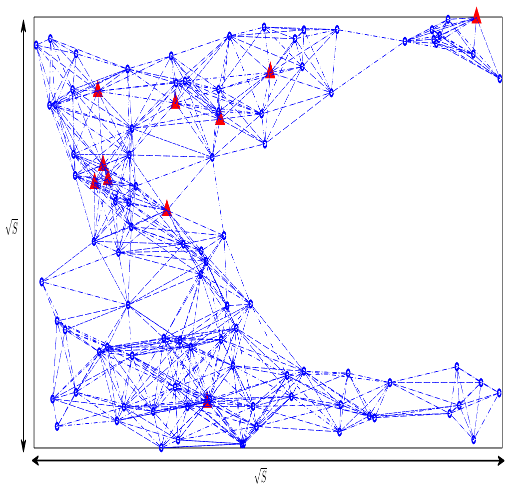

Fig. 1. Network model.

localization algorithm aiming to accurately estimate the regular nodes' positions in the anisotropic WSN (AWSN) of interest. In such type of networks, however, it is very likely that the shortest paths between one regular node and some anchors are not straight lines due to the presence of an obstacle, as can be observed from Fig. 2. This unfortunately causes an overestimation of the distances between the regular node and these anchors, when mapping the number of hops into distance, thereby hindering localization accuracy. In the example of Fig. 2, the regular node 1 communicates with the anchor node $A1$ through $N_h = 6$ hops. Since node 1 requires the knowledge of its distances to all anchors in the network to be able to locate itself, this node estimates its distance to $A1$ as follows

$$d_e = N_h \times \bar{h}_s, \tag{1}$$

where $\bar{h}_s$ is the average hop size which should be carefully derived to ensure accurate distance estimation. As can be seen from Fig. 2, if the blue obstacle does not exist, N_h would be much less than 6 and, hence, the distance from 1 to $A1$ is overestimated. Thus, using d_e when performing multilateration will undoubtedly result in an imprecise localization.

An interesting approach to circumvent this issue is to properly select the anchors so that overestimation stemming from situations similar to the one illustrated in Fig. 2 is avoided or minimized. The selected anchors shall be called hereafter as reliable anchors. In the following, we develop our novel localization algorithm based on this new reliable anchor selection strategy.

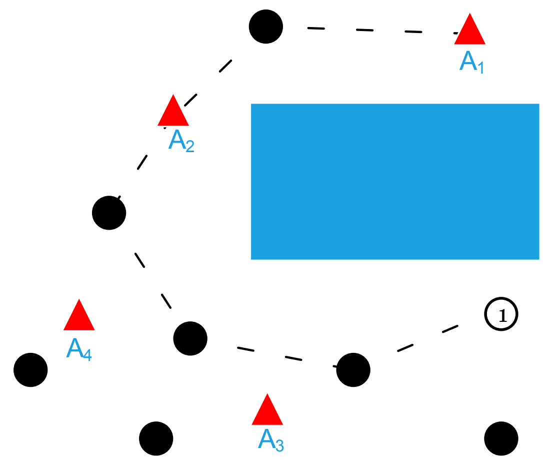

Fig. 2. Motivation scenario.

III. Proposed Localization Algorithm

As a first step of any anchor-based localization algorithm, the k-th anchor broadcasts through the network a message containing (x_k, y_k, n) where n is the hop-count value initialized to one. When a node receives this message, it stores the k-th anchor position as well as the received hop-count $n_k = n$ in its database, adds one to the hop-count value and broadcasts the resulting message. Once this message is received by an another node, its database information is checked. If the k-th anchor information exists and the received hop-count value n is smaller than the stored one n_k, the node updates n_k to n, increments it by 1 then broadcasts the resulting message. If n_k is smaller than n, the node discards the received message. However, when the node is oblivious to the k-th anchor position, it adds this information to its database and forwards the received message after incrementing n by 1. This mechanism will continue until all nodes become aware of all anchors' positions and their corresponding minimum hop counts. In order to avoid the situation illustrated in Fig. 2, we propose a reliable anchor selection phase in the second step of our algorithm. In the next section, we introduce a new selection strategy where the k-th anchor properly selects a set of reliable anchors among all of those in the network denoted by s_k. The k-th anchor then broadcasts s_k over the network. Upon reception of all (x_k, y_k, n_k, s_k), $k = 1, \ldots, N_a$, each regular node estimates its distance only to its nearest anchor (i.e, $k_0 = \arg\min_k n_k$) and to the reliable anchors in the set s_{k_0}. The regular nodes finally compute their own positions exploiting their available distances' estimates by performing multilateration [17].

In what follows, we develop our proposed reliable anchor selection strategy as well as our distance estimation technique.

IV. Reliable anchor selection strategy

After receiving all anchors' information, the k-th anchor becomes aware of its own position as well as those of all other anchors in the network and, hence, is able to compute all true distances separating it from the latter. On the other hand, this anchor could also compute the estimate of the distance to any other anchor j and the corresponding estimation error e_{k-j} stemming from the use of (1). Nevertheless, due to the anisotropic topology of the WSN considered here, error could be too large if we fall in a situation such as in Fig. 2. Consequently, a threshold on e_{k-j} is required to guarantee some reliability of the j-th anchor with respect to the k-th anchor. If the topology of the WSN was isotropic, e_{k-j} would be

$$\begin{aligned} e_{k-j} &= \hat{d}_{k-j} - d_{k-j} \\ &= \lceil \frac{d_{k-j}}{R} \rceil \bar{h}_s - d_{k-j}, \end{aligned} \quad (2)$$

where $\lceil x \rceil$ is the ceiling function. Thus, a distance estimation error higher than the right hand side (RHS) of (2) occurs only if the shortest path between the k-th and the j-th anchors is curved, due to the presence of obstacles between the two nodes. In such a case, in fact, the number of hops between the latter is much larger than d_{k-j}/R and, hence, we should have $e_{k-j} \gg T_1 = \lceil d_{k-j}/R \rceil \bar{h}_s - d_{k-i}$. Therefore, we chose T_1 as a threshold below/above which an anchor is deemed reliable or not, respectively. Finally, in order to ensure an accurate distance estimation, each regular node will estimate its distance only to the nearest anchor and to those rated reliable by the latter.

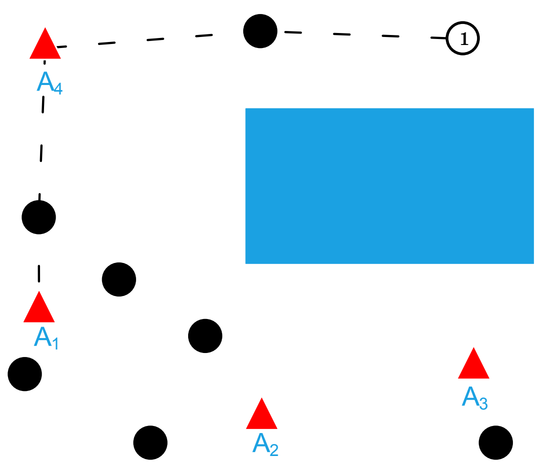

Fig. 3. Reliable anchors.

However, some anchors deemed reliable by the nearest anchor could be found unreliable by the regular node, since the shortest path from the latter to these anchors may be curved as shown in Fig. 3. To circumvent this issue, we implement a finer selection at the regular node that discards each anchor having a number of hops larger than $T_2 = \lceil \sqrt{2S}/R \rceil$. Note that T_2 is the maximum number of hops that may occur if the shortest path is not curved. Processing steps at the anchors and regular nodes are summarized by localization algorithms 1 and 2 listed in Algorithms 1 and 2, respectively.

Algorithm 1 Localization algorithm for anchor nodes

```
% k refers to the k-th anchor node %
s_k = {}
for j=1 to N_a and j ≠ k do
    d̂_{k-j} = n_k × h̄_s
    e_{k-j} = d̂_{k-j} − d_{k-j}
    if e_{k-j} ≤ T_1 then
        s_k = s_k ∪ {j}
    end if
end for
Broadcast the set s_k of reliable anchors
```

Algorithm 2 Localization algorithm for regular nodes

```
% i refers to the i-th regular node %
% s_{k_i} is the set of the reliable anchors at the nearest anchor
node from the i-th regular node%
% s_i is the new set of reliable anchors at the i-th regular
node %
s_i = {}
c = 0
for k ∈ s_{k_i} do
    if h_{i-k} ≤ T_2 then
        s_i = s_i ∪ {k}
        c = c + 1
    end if
end for
for j = 1 → c do
    d̂_{j_i} = n_{j_i} × h̄_s
end for
% j_i denotes the j-th reliable anchor node index in the set
s_i %
% x̂_i, and ŷ_i can be estimated by multilateration %.
```

V. Distance estimation technique

We propose in this work to estimate each regular-anchor distance using (1). To this end, one should accurately derive the average hop size $\bar{h}_s$ between any two consecutive nodes on the shortest path between any regular and anchor nodes. Let us first denote by Z the random variables that represent the distance between any consecutive two nodes. In order to derive

$$\bar{h}_s = \mathrm{E}\{Z\}, \quad (3)$$

we start by deriving the cumulative distribution function (CDF) of Z defined as

$$F_Z(z) = P(Z \leq z), \quad (4)$$

where z is a realization of the random variable Z. Since, according to Fig. 4, $Z \leq z$ is guaranteed only if there are no nodes in the dashed area F, we obtain

$$F_Z(z) = P(\mathrm{F}_0), \quad (5)$$

where $P(F_0)$ is the probability that the event $F_0 = \{$no nodes in the dashed area $F\}$ occurs. As the nodes are uniformly deployed in S, the probability of having K nodes in F follows a Binomial distribution $\text{Bin}(N,p)$ where $p = \frac{F}{S}$. For a relatively large N and small p, it can be readily shown that $\text{Bin}(N,p)$ can be approximated by a Poisson distribution with $\lambda = N/S$ being the nodes density in the network. Then, the probability of having K sensors in F can be obtained as [13]:

$$P(K,F) = \frac{(\lambda F)^K}{K!} e^{-\lambda F}. \qquad (6)$$

Injecting (6) in (5) and substituting K with 0 yields

$$F_Z(z) = e^{-\lambda F}. \qquad (7)$$

Exploiting some geometrical properties and trigonometric transformations, it is straightforward to show that

$$F = R^2 \left(\left(\theta - \frac{\sin(2\theta)}{2} \right) + \left(\theta' - \frac{\sin(2\theta')}{2} \right) \right), \qquad (8)$$

where $\theta = \arccos\left(\frac{x}{2R}\right)$ and $\theta' = \arccos\left(\frac{x}{2r}\right)$. The average hop size $\bar{h}_s$ is then given by

$$\bar{h}_s = \int_0^R (1 - F_Z(z))\, dz. \qquad (9)$$

Finally, each regular node estimates its distance to the anchors using (1) and (9).

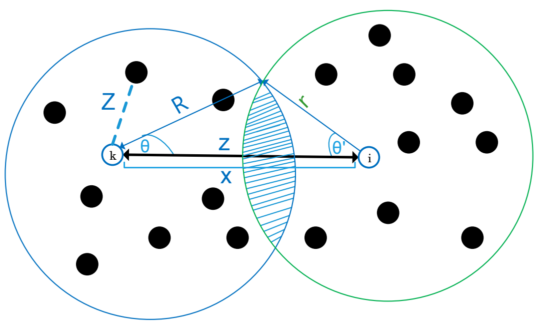

Fig. 4. Distance analysis.

VI. Simulations Results

In this section, we evaluate the performance of the proposed algorithm in terms of localization accuracy by simulations using Matlab. These simulations are conducted to compare, under the same network settings, the proposed algorithm with some of the best representative localization algorithms currently available in the literature, i.e., DV-Hop [7] and RAL [19]. All simulation results are obtained by averaging over 100 trials. In the simulations, nodes are uniformly deployed in a 2-D square area $S = 2500\ m^2$. As an evaluation criterion, we propose to use the normalized root mean square error (NRMSE) defined as follows

$$e = \frac{\sum_{i=1}^{N_u} \sqrt{(x_i - \hat{x}_i)^2 + (y_i - \hat{y}_i)^2}}{N_u R}. \qquad (10)$$

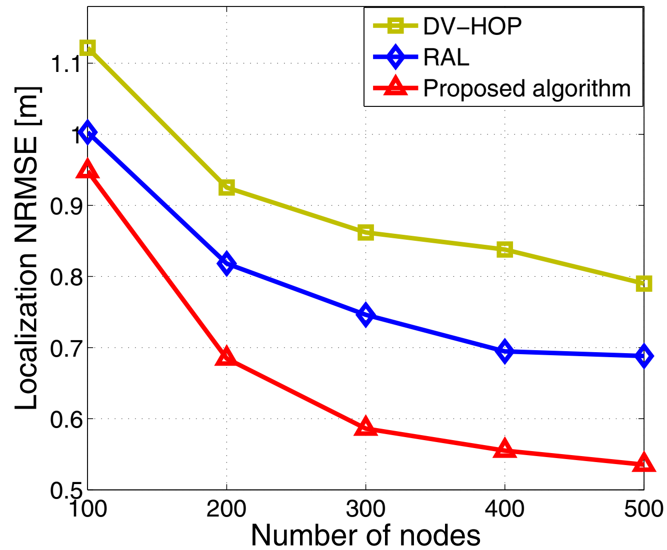

Fig. 5. Localization NRMSE vs. number of sensor nodes with 10% of anchors' percentage.

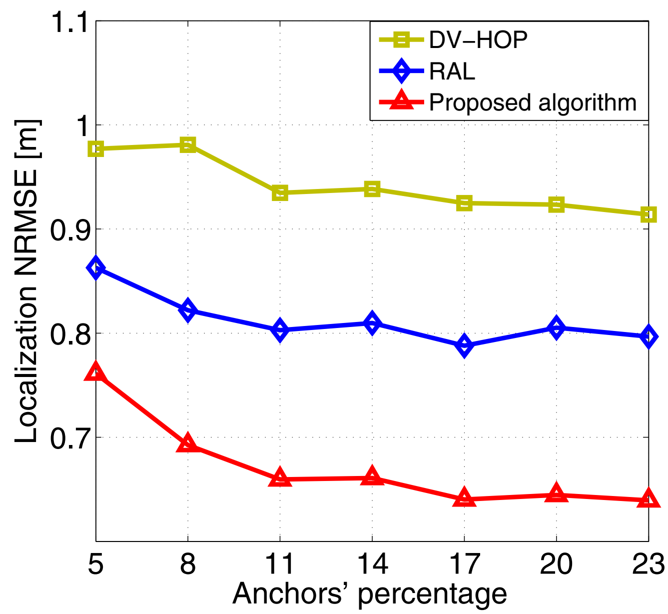

Fig. 6. Localization NRMSE vs. anchors' percentage with 200 sensor nodes.

Fig. 5 plots the localization NRMSE achieved by DV-Hop, RAL and our proposed algorithm for different numbers of nodes with a constant anchors' percentage of 10%. As can be shown from this figure, the proposed algorithm is until about 15% and 30% more accurate than DV-Hop and RAL, respectively.

Fig. 6 illustrates the localization NRMSE for different anchors' percentages with a constant number of nodes equal to

200. Our proposed algorithm achieves the lowest localization NRMSE, more so when the number of anchors in the network increases. This is hardly surprising since the number of potential reliable anchors increases as well thereby resulting in more accurate localization.

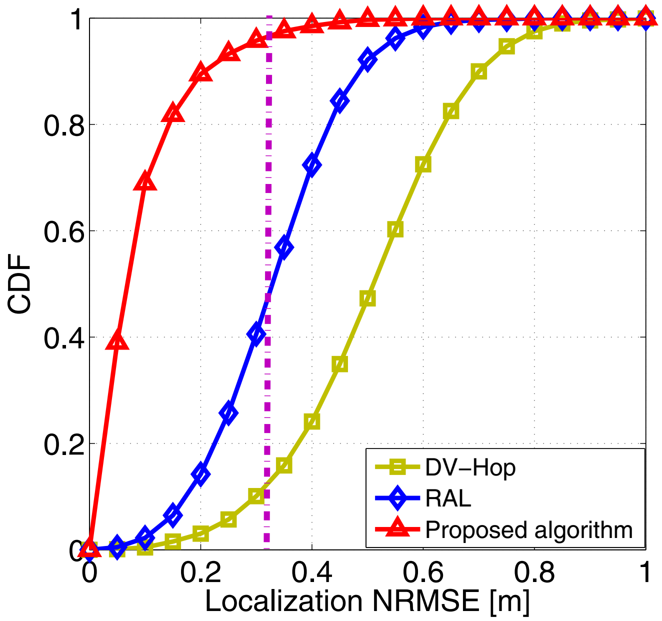

Fig. 7. CDF of localization NRMSE with 200 sensor nodes and 10% of anchors' percentage.

Fig. 7 illustrates the CDF of the localization NRMSE with a constant number of sensor nodes equal to 200, and 10% of anchors' percentage. Using the proposed algorithm, 97% of the regular nodes could estimate their position within one third of the transmission range. In contrast, 50% of the nodes achieve the same accuracy with RAL and about only 14% with DV-Hop. This further proves the efficiency of our new algorithm.

VII. Conclusion

In this paper, a novel range-free localization algorithm tailored for AWSNs is developed where each regular node estimates its distances only to reliable anchors. The latter are properly chosen to ensure an accurate regular-to-anchor nodes distance estimation thereby making our localization algorithm more precise. Simulations confirm indeed that it outperforms the best representative range-free localization algorithms currently available in the literature in terms of accuracy.

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