Distributed Recognition of Reference Nodes for Wireless Sensor Network Localization

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Abstract. *All known localization techniques for wireless sensor and ad-hoc networks require certain set of reference nodes being used for position estimation. The anchor-free techniques in contrast to anchor-based do not require reference nodes called anchors to be placed in the network area before localization operation itself, but they can establish own reference coordinate system to be used for the relative position estimation. We observed that contemporary anchor-free localization algorithms achieve low localization error, but dissipate significant energy reserves during the recognition of reference nodes used for the position estimation. Therefore, we have proposed an optimized anchor-free localization algorithm referred to as BRL (Boundary Recognition aided Localization), which achieves a low localization error and mainly reduces the communication cost of the reference nodes recognition phase. The proposed BRL algorithm was investigated throughout the extensive simulations on the database of networks with the different number of nodes and densities and was compared in terms of communication cost and localization error with the known related algorithms such as AFL and CRP. Through the extensive simulations we have observed network conditions where novel BRL algorithm excels in comparison with the state of art.*

Keywords

Recognition, reference nodes, wireless sensor networks, localization, communication cost, simulation.

1. Introduction

To acquire information about a monitored area is the fundamental task of the wireless ad-hoc sensor networks. This task involves more specific actions. Sending message towards a node or set of nodes at the specific position, an area discovery, where the monitored data has exceeded the predefined threshold or to retrieve data from a specific region are the often representatives of tasks that can not be accomplished without employing node position information. Position aware nodes are a condition ensuring the basic network functions in applications such as Location Aided Routing [1], Multicast Routing [2], Perimeter Discovery [3] or patient tracking [4].

Localization, often referred to as positioning, is a process of coordinates estimation for a given node in a network. To estimate a node position, most recently proposed localization algorithms for wireless ad-hoc networks engage two following assumptions:

1. Each node is able to estimate the distance to all nodes within its radio range.
2. An appropriate set of location aware nodes called reference nodes (or anchors) are established within the network.

Regarding to the first assumption, the localization algorithms are classified as *range-free* and *range-aware* algorithms. In range-free algorithms a distance between two nodes can be expressed simply as the sum of the hops, referred to as Hop-Count (number of intermediate nodes in a shortest path), between a pair of nodes. Neighbor nodes thus have distance $d_{\mathrm{HC}} = 1$ and number of hops $h = 1$. The second distance estimation method uses DV-Hop (Distance Vector) metric [5], where the Euclidean distance of two location aware nodes is divided by their hop-count. DV-hop metric results in the correction value that express the average length of one hop. The range-aware localization algorithms employ techniques for the distance estimation between nodes expressed in meters. The distance between pair of nodes can be expressed as a sum of the distances between adjacent nodes constituting the shortest path; this method is denoted as DV-distance. The range-aware algorithm localizes nodes with higher accuracy comparing to range-free algorithms, but its efficiency is influenced by the accuracy of the measurement techniques employed. The impact of different distance estimation methods on the accuracy of WSN (Wireless Sensor Network) localization is reported in [6].

The way how the position is assigned to the reference nodes defines two different sets of localization algorithms. Localization techniques exploiting nodes with position known prior to deployment belong to the set of *anchor based* localization algorithms. The anchor based algorithms produce an absolute position of nodes since the position assigned to the anchors reflects their placement with regard to the local coordinate system. The anchors obtain the position information either prior to deployment by the manual configuration or by employing a certain external coordinate system such as GPS. However, the efficiency of the anchor based algorithms is considerably restricted. First, the anchors configuration has to be realized prior to deployment with user intervention through manual configuration. This factor restricts the application area of anchor based localization since it does not make the wireless sensor network automated. Second, Hoffmann-Wellenhof and Collins [7] proved that GPS is an effective and robust solution for global positioning, but its restriction of outdoor utilization, considerable energy consumption and high cost of appropriate equipment make this system inapplicable for low-power and modest wireless sensor nodes.

Problem that should be addressed by the anchor-free localization can be defined as follows:

"Given a set of nodes with unknown position to which the relative coordinates are to be assigned by using only local processing capabilities of nodes without any anchor nodes deployment".

According to the approach, how the nodes select and exploit the reference nodes, the anchor-free localization is classified as i) *One-Hop Incremental* and ii) *N-Hop Concurrent* localization. The one-hop incremental algorithms build the system of reference nodes inside of the network. The position of nodes forming a coordinate map is incrementally calculated, while unlocated nodes take advantage of the nodes position calculated in previous localization steps. Once the unlocated node has minimally three located nodes within its radio range (justification of One-Hop name), the position can be estimated. The incremental localization algorithms consume a slight amount of energy, since only one-hop transmissions within the networks are realized. However, the localization error exponentially grows with the network size. On the other hand, the N-hop concurrent algorithms are almost twice as accurate as incremental, but suffer from the high communication cost, meaning that number of packets transmitted during their operation is enormous [8]. Problem of the high communication cost is caused by the selection of the reference nodes. These are established on the periphery of the network and thus to reach them, the messages are passed through the number of intermediate nodes and thus significant energy reserves are affected. For this reason, we have proposed and simulated a novel localization algorithm referred to as BRL (Boundary Recognition aided Localization) that aims to optimize the communication cost by employing the optimized boundary recognition algorithm denoted as BRC (Boundary Recognition using Cset). The knowledge of the boundary nodes in the network can significantly decrease the number of packets transmitted within the network, since only these boundary nodes generate traffic during reference node selection phase. The accuracy of correct boundary nodes recognition greatly affects the number of transmissions realized. Therefore, we have investigated and compared the proposed boundary recognition algorithm in terms of False and Success detection ratio. Matlab simulations showed that implementation of introduced ideas can bring the significant optimization of number of packet transmitted during the localization process performed in wireless sensor network.

The rest of the paper is organized as follows: Section 2 brings the related work in the field of concurrent localization anchor-free algorithms together with the algorithms devoted to the boundary recognition. In Section 3, we introduce the novel algorithm BRC used for the recognition of the network boundaries. Within this section, a comparison with the CRP and HNT algorithm is realized. Section 4 introduces the novel localization algorithm BRL. Its efficiency is compared with AFL and CRP algorithms considering a localization error and communication cost metrics. Section 5 concludes the presented work.

2. Related Work

In contrast to incremental algorithms, nodes running concurrent algorithms perform localization independently of other nodes in the network. Error propagation is thus suppressed to the minimum since nodes do not rely on the position of nodes previously calculated.

Priyantha et al. [9] proposed algorithm called AFL (Anchor-Free Localization) that exploits five nodes acting as a reference coordinate set.

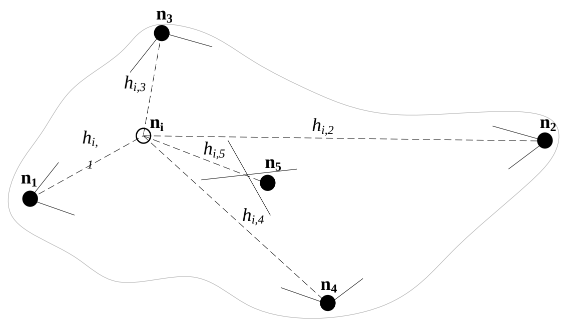


Fig. 1. Fundamentals of AFL.

The reference nodes selection policy defines the four nodes depicted in Fig. 1 as $n_1 \dots n_4$, to be placed on the periphery of the network while being far apart from each other and placed roughly in the edges of the imaginary quadrilateral. Once the reference set is established (this process is performed in a distributed manner) each node (consider node n_i in Fig. 1) knowns distances to all edge nodes and to one central node n_5 and calculates own polar coordinates (ρ, θ) using hop count metric h and radio range R as the input parameters:

$$\rho_i = h_{i,5} \times R, \qquad (1)$$

$$\theta_i = \tan^{-1}\left(\frac{h_{i,1} - h_{i,2}}{h_{i,3} - h_{i,4}}\right). \qquad (2)$$

It was already proved that reference nodes are selected in the cost expensive manner [10]. Considering a network of 100 nodes, each applying the AFL algorithm, simulations show that each node is overloaded by the 462 messages that were processed. It was also found in the same network that maximum number of the messages that were processed by one node exceeds the value of the 1000 messages. Considering the fact that node's position can be changed due to the maintenance or the topology reconfiguration reasons, the entire network is often relocated. The relocation process floods the entire network with 5 broadcast and $5 \times N$ unicast rounds that significantly drain the energy reserves.

Nawaz and Jha [11] proposed CRP algorithm that exploits also the AFL principles. They proposed an algorithm for the energy-aware reference selection phase that induces $O(n)$ packet transmissions, less than the original AFL proposed by Priyantha et al. [9]. The idea of CRP is based on maintenance of a hierarchical tree rooted at a randomly selected node, where each node during reference query diffusion maintains a list of descendants, simply referred to as children. Nodes having no child (leaf nodes) transmit distance query messages including measured distance and ID towards their parents. The given parent retransmits only response with the highest distance value while adding its own distance estimation to the upstream transmitted message. This process is repeated by every parent until all responses are received by originator. This principle is depicted in Fig. 2

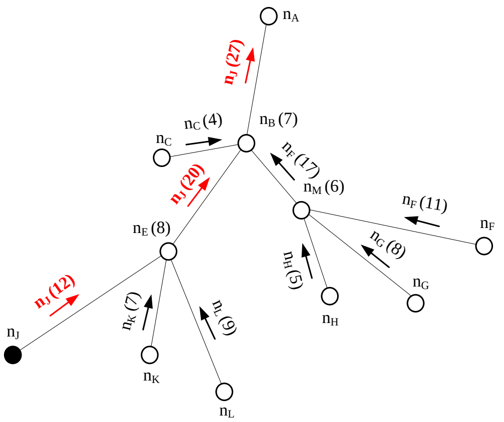


Fig. 2. Reference nodes selection in CRP.

The coordinates of the reference nodes are also calculated in distributed manner by the reference nodes themselves. Once the coordinates of reference nodes are disseminated through the network, the nodes employ one of the multilateration algorithms described in many recent works such as Savvides et al. [12], Hou et al. [13]. As authors reported, the observed number of messages processed during localization was C = 27, 29, 30 messages for network sizes of N = 49, 100, 196 nodes. However, the authors did not consider problem of the overhearing transmission that must be considered during a wireless communication.

Jianquan and Wei [14] enhanced the AFL algorithm and tried to propose a solution that decreases the communication cost of the reference selection phase and generates a more accurate initial layout by smoothing the distance measurements to the reference nodes. The reference nodes are selected in the manner similar to the one used in AFL. To minimize the communication cost, they applied the condition that ensures that the distance query message is transmitted only by the nodes complying with the condition:

$$m_{\mathrm{i}} < 0.5R^2\rho + \varepsilon \tag{3}$$

where the parameter m_{i} stands for the number of neighbors of the node i, R stands for the uniform radio range of the nodes, ρ is equal N/S where N represents the number of nodes and S represents total area of plane. This condition ensures that responses are sent only by nodes placed on the boundary of the network since these nodes should have (as Jianquan and Wei [14] claimed) approximately half the number of neighbors than nodes placed inside the network. The authors assume that the nodes are aware of a $(\rho + \varepsilon)$ parameter meaning that nodes need to be preconfigured with the parameters defining the number of nodes N, the occupied area (m^2) and the optimization constant referred to as ε. Parameter ε is in paper [14] chosen empirically in dependence on the network configuration. However, once the user changes the deployment strategy, the mentioned approach fails.

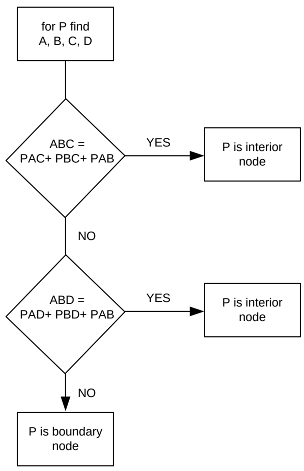


Fig. 3. Flowchart of the CGN and the IP algorithm.

Some earlier works were devoted to the boundary nodes recognition in wireless ad-hoc networks, not exactly devoted to the localization issue. Some algorithms estimate boundary nodes in geometric manner [15] some of them rely on the topology construction [11], [16]. Deogun et al. [15] proposed distributed algorithm, which we refer to in the text as CGN (Choose Good Neighbors). The CGN algorithm forms two suitable triangles from the neighbors of the evaluated node. Having node P that is to be evaluated, the algorithm finds the four suitable nodes A, B, C, D around the P node and calculates areas of the triangles ABC, PAC, PBC and PAB. If the P node is not identified as the boundary node, the same areas are calculated considering the D node instead of C node. The flowchart of the mentioned algorithm is illustrated in Fig. 3.

Wang et al. [16] worked on the topological method for boundary recognition based on the shortest path trees construction. The topological method can discover holes in the network by detecting a separation and a subsequent junction of the tree branches. This bifurcate path thus encloses the network hole. All nodes involved in the *inner boundaries set* of holes are merged into one path. The boundary set simultaneously floods the network to detect the nodes having maximum hop counts from them. The resulted nodes are then identified as the boundary nodes. This approach has several shortcomings. First, the topological method is based on the repeated floods of the network that induce the excessive communication cost and secondly, the algorithm's performance significantly decreases in the sparse networks containing a large number of holes.

Khedr et al. [3] used Barycentric technique for perimeter discovery in the network constituted by location aware nodes. Since authors assume location aware nodes, the proposed approach is behind the localization issue.

Nowak and Mitra [17] focused on the boundary recognition in a sense of detecting variations or gradients of measured parameters in the entire sensor field. However, the boundary recognition is rather defined as the process of discovering the delineation between homogeneous regions and thus does not reflect the requirements of network boundaries detection.

3. Boundary Recognition Algorithm

Our work is focused on the design of an algorithm capable to recognize boundary nodes in distributed manner without any redundant communication being realized through the entire network. Nawaz and Jha [11] and Jianquan and Wei [14] used the semi-centralized approach, where the boundary recognition is controlled by certain node. We have focused on the fully distributed approach and proposed novel algorithm that is partially inspired by [15].

3.1 Boundary Recognition using C set Algorithm

Novel algorithm referred to as BRC (Boundary Recognition using Cset) differs from CGN in the following. Instead of attempting to form the quadrilateral ABCD around the investigated node and thus to analyze only the two adjacent triangles ABC and ABD respectively, the BRC algorithm works with the set of all adjacent triangles having AB basement to increase probability of boundary node identification. The BRC algorithm constitutes two sub-algorithms. First, a node referred to as P running a first `createCset` algorithm selects two neighbors A, B forming two vertices (baseline) of all eventual adjacent triangles defined by the set of third vertices referred to as Cset, see Fig. 4a). The A node has the minimum distance $r_{\mathrm{P,A}}$. The P node then sends unicast message requesting the neighbor table referred to as NBT from the A node. From the intersection of $\mathrm{NBT_P} \cap \mathrm{NBT_A}$ it selects the B node that complies with the condition: B = $\arg[\max(r_{\mathrm{A,B}} - r_{\mathrm{P,A}} - r_{\mathrm{P,B}})]$. Meaning that the B is the farthest from the A and the difference between distances $r_{\mathrm{P,A}}$ and $r_{\mathrm{P,B}}$ is minimal, see Fig. 4 a). By means of this condition, the P, A, B nodes should have maximal number of the intersect neighbors $\in \mathrm{C_P}$. Here, $\mathrm{C_P}$ is a set containing all the intersect neighbors: $\mathrm{C_P} = \mathrm{NBT_P} \cap \mathrm{NBT_A} \cap \mathrm{NBT_B}$. Considering that the $\mathrm{C_P}$ has size of l, then, $\mathrm{C_P} = \{\mathrm{C_1}, \dots, \mathrm{C}_l\}$ and $\mathrm{T_P} = \{\mathrm{ABC_1}, \dots, \mathrm{ABC}_l\}$. $\mathrm{T_P}$ represents the set of all the triangles adjacent to the node P. A pseudocode of the `createCset` algorithm is illustrated in Fig. 5a). The second `compareAreas` algorithm analyses all the triangles $\in \mathrm{T_P}$ by estimating, whether the node P is enclosed by at least one triangle from $\mathrm{T_P}$, see Fig. 4b). The algorithm assumes in advance that the investigated node is placed on the boundary of the network (parameter *isBoundary* = true in the pseudocode illustrated in Fig. 5b)).

Algorithm: **createCset(P)**

isBoundary=false
A, B, $\mathrm{C_P}$ = 0
select neighbor **A** with $\min(r_{\mathrm{P},A})$
create $\mathrm{NBT_{P,A}} = \mathrm{NBT_P} \cap \mathrm{NBT_A}$
if ($\mathrm{NBT_{P,A}}$ is empty) then
  return *isBoundary*=true → **break**
select neighbor **B** with $\max(r_{\mathrm{A,B}})$ AND $\min(r_{\mathrm{P},A} - r_{\mathrm{P},B})$
create $\mathrm{NBT}_{\mathrm{P},A,B} = \mathrm{NBT}_{\mathrm{P},A} \cap \mathrm{NBT_B}$
if ($\mathrm{NBT}_{\mathrm{P},A,B}$ is empty) then
  return *isBoundary*=true → **break**
else
  $\mathbf{C_P} = \mathrm{NBT}_{\mathrm{P},A,B}$

(a) createCset algorithm

Algorithm: **compareAreas(P)**

isBoundary=true
[A, B, $\mathrm{C_P}$, *isBoundary*]=createCset(P)
if (*isBoundary*==false) then
  for $\forall\, \mathrm{C_j} \in \mathrm{C_P}$ do
    calculate $\mathrm{S_{A,B,C}}$, $\mathrm{S_{P,B,C}}$, $\mathrm{S_{P,A,C}}$, $\mathrm{S_{P,A,B}}$
      if $\mathrm{S_{A,B,C}} \neq \mathrm{S_{P,B,C}} + \mathrm{S_{P,A,C}} + \mathrm{S_{P,A,B}}$ then
        isBoundary=false → **break**
return *isBoundary*

(b) compareAreas algorithm

Fig. 5. Pseudocodes describing the fundamentals of novel BRC algorithm.

The algorithm then step by step compares an area of each triangle $S_{\mathrm{A,B,C}} \in \mathrm{T_P}$ with an area $S_{\mathrm{P,A,C}} + S_{\mathrm{P,B,C}} + S_{\mathrm{P,A,B}}$, see Fig. 4b). The area of the investigated triangles $S_\triangle$ is calculated using a modified Heron's formula:

$$S_\triangle = \frac{1}{4}\sqrt{(a^2+b^2+c^2)^2 - 2(a^4+b^4+c^4)}. \tag{4}$$

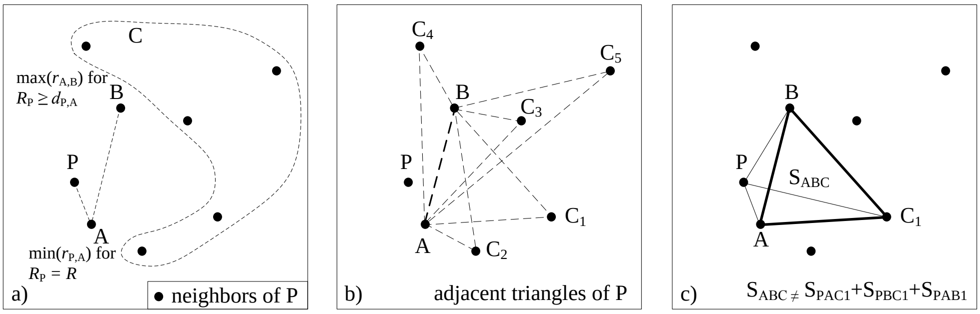


Fig. 4. Description of the BRC algorithm fundamentals

In the case that one triangle complies with condition of $S_{A,B,C} = S_{P,A,C} + S_{P,B,C} + S_{P,A,B}$, the boolean value of the *isBoundary* parameter is changed to "false" and the P node is identified as the inner node. If no triangle complies with the mentioned condition, the P node is identified as the boundary node (Fig. 4c). It is necessary to mention that the algorithm breaks when the P node is once identified as the inner node and thus it does not need to processes the rest of adjacent triangles. In the worst case, the number of evaluated triangles of one node equals to the size of T_P. The performance of BRC algorithm is depicted on the network layout illustrated in Fig. 6.

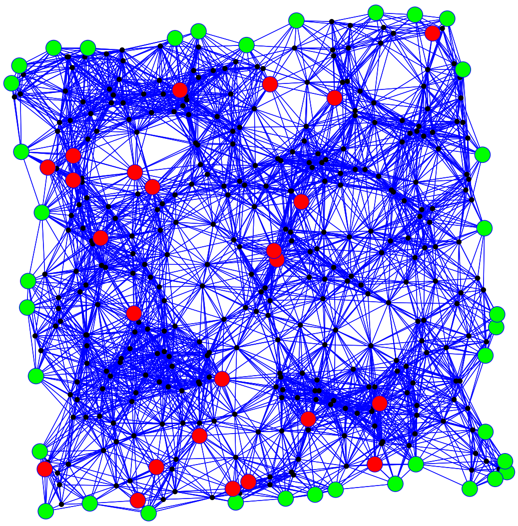


Fig. 6. Boundary recognition performance of the proposed BRC algorithm.

The green points represent successfully recognized boundary nodes, on the other hand, the red points show the nodes that were marked as boundary even they are placed inside of network.

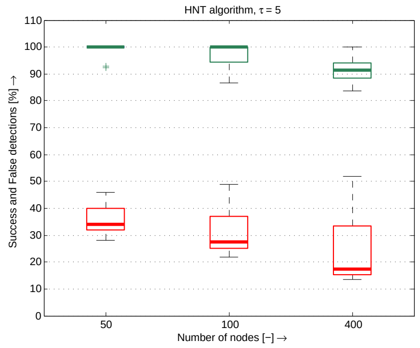
3.2 Recognition Efficiency of BRC Algorithm

The proposed BRC algorithm was studied on the created database of the 30 network models with size of $N = 50$, 100, 400. It's performance was measured by *SuccessDetections* and *FalseDetections* metrics describing the ratio of the successfully or incorrectly identified nodes respectively. The nodes selected as the boundary nodes, while being located inside of the network, are thus qualified as the incorrectly identified nodes.

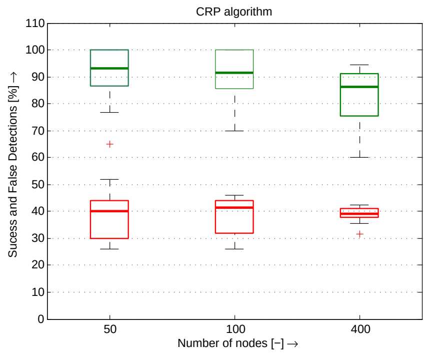
$$\begin{aligned} SuccessDetections\,[\%] &= \frac{\Lambda_{est} \cap \Lambda_{real}}{\Lambda_{real}}, \\ FalseDetections\,[\%] &= \frac{\Lambda_{est} - (\Lambda_{est} \cap \Lambda_{real})}{N}. \end{aligned} \tag{5}$$

In (5) Λ_{real} stands for the number of the real boundary nodes, the Λ_{est} parameter stands for the number of the nodes that algorithm identified as the boundary nodes.

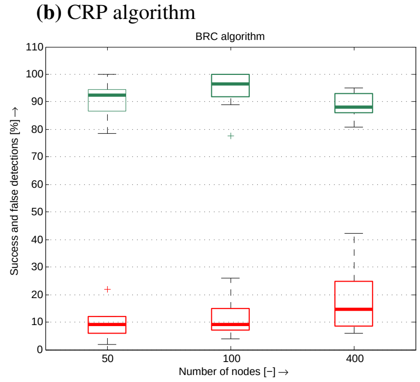
The recognition performance of the BRC algorithm was compared with the CRP algorithm and the one proposed by Jianquan and Wei [14] that is in the further text referred to as HNT (Half Neighbors Threshold). The authors of HNT algorithm use the optimization value ε that is not specified in more details in the author's text. Hence, the performance of the HNT configured with the ε parameters varying from 1 to 10 was studied in order to find out the optimal ε value. A difference between the success detections and the false detections was taken as the metric for the ε parameter investigation. From the results it implies that the biggest performance of the HNT algorithm was achieved with the $\varepsilon = 5$, hence this value was chosen for the further work. The HNT, the CRP and the BRC algorithms were investigated under the same conditions on the created database of the 30 network models. The results from the simulations are depicted in Fig. 7. It is obvious that all the algorithms achieve a high success detection ratio (green upper boxes). The HNT algorithm detects in the networks with N = 50, 100 all the boundary nodes, see Fig. 7a). However the price for this efficiency is the high number of the false detections (red bottom boxes) that is significantly higher than the BRC achieves, see Fig. 7c). The CRP algorithm achieves almost the similar ratio of the success detections as the BRC does, but it suffers from the highest ratio of the false detections in comparison with the HNT and the BRC. Here it can be summarized that the BRC algorithm outperforms both the HNT and CRP algorithms, because it reaches the high ratio of success detections while achieves the lowest ratio of false redundant detections. The results from the the simulations show that the BRC algorithm achieves about 90 % of detection success in average. Furthermore, the BRC algorithm incorrectly detects about 13 % of all the nodes in the network. Causing that 13 % of the nodes needlessly will unicast their own distance reports.



(a) HNT algorithm (ε = 5)



(b) CRP algorithm



(c) BRC algorithm

Fig. 7. Comparison of boundary recognition efficiency.

4. Proposed Localization Algorithm Using Boundary Recognition Approach

In the following sections, we introduce the fundamentals of the proposed localization algorithm BRL taking advantage of the boundary recognition algorithm BRC and discuss the results from the performed comparative simulations.

4.1 Fundamentals of Novel BRL Algorithm

A novel localization algorithm referred to as BRL (Boundary Recognition aided Localization) takes advantage of the proposed BRC algorithm. The selection of the reference nodes is realized as follows. The nodes send the distance response messages toward the given nodes that select the appropriate reference nodes. The number of the responding nodes and thus the number of the unicast transmissions is in the proposed approach significantly reduced. Only the nodes identified by the BRC algorithm as the boundary nodes response to the distance query message. For the calculation of the coordinates, the BRL algorithm employs the multilateration technique that performs well if the unlocated nodes lie inside of the reference triangle. Hence, the BRL algorithm establishes the three (eventually four) reference nodes lying on the edges of the network. Their position is estimated by the iterative technique used in the incremental localization algorithms such as ABC (Assumption Based Coordinates) [18].

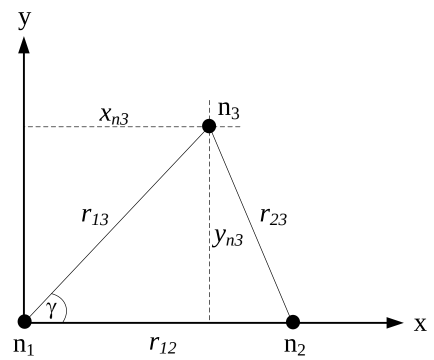


Fig. 8. Position estimation of three reference nodes in BRL.

The position to the reference nodes is assigned as follows. The randomly selected node broadcasts the first distance query message. During the message dissemination, each node receives the number of copies equals to the number of its neighbors. The nodes create the distance-aware neighbor table and launch the BRC algorithm to find out if they are placed on the boundary of network. All nodes recognized as the boundary nodes unicast the distance response message upstream to the initiator. The number of the unicast transmissions is thus many times reduced, e.g. in comparison with the AFL algorithm. The first selected reference node referred to as n_1 self-assigns its own coordinates of [0,0] and thus establishes the onset of the coordinate system. The n_1 node launches the second flood of the reference selection process by broadcasting the distance query message containing the coordinates $p_1 = (0,0)$. Since, all the nodes are already identified as the boundary or as the intermediate nodes, the BRC algorithm is no more launched. The second round of the reference nodes selection process results in the definition of the second reference node referred to as n_2 with the coordinates of $p_2 = (\max(r_{1,2}),0)$, where the $r_{1,2}$ parameter stands for the distance measured between the reference nodes n_1 and n_2 and it is estimated as a sum of the distances on the shortest path between these nodes. Inter-neighbour distances can be derived e.g. from the received signal strength indication [19]. The third round of reference nodes selection results in the definition of the n_3 reference node with the coordinates of $p_3 = (x_3, y_3)$, where x_3 and y_3 are estimated as:

$$\begin{aligned} x_1 &= 0, & y_1 &= 0, \\ x_2 &= r_{1,2}, & y_2 &= 0, \\ x_3 &= r_{1,3}\cos\gamma, & y_3 &= r_{1,3}\sin\gamma, \end{aligned} \quad (6)$$

$$\gamma = \arccos\left(\frac{r_{1,3}^2 + r_{1,2}^2 - r_{2,3}^2}{2r_{1,2}r_{1,3}}\right),$$

$$x_3 = \frac{r_{1,3}^2 + r_{1,2}^2 - r_{2,3}^2}{2r_{1,2}}, \quad y_3 = \sqrt{r_{1,3}^2 - x_3^2}. \quad (7)$$

If four reference nodes are required for the localization, the next reference node can be found by the next round of the distance query message broadcasting by the n_3 node. The coordinate p_4 equals to $(x_3, -y_3)$, since the n_4 node is placed roughly on the opposite side from the n_3 node. The n_4 node then broadcasts its own coordinates within the network. Once the reference node selection process is finished, each node i knows the distances to the reference nodes $r_{i,1}$, $r_{i,2}$, $r_{i,3}$ and $r_{i,4}$ respectively. It also knows the reference coordinates p_1, p_2, p_3 and p_4 respectively. Each node then estimates its own position by performing the multilateration technique that for example can be solved by employing the Gauss-Newton algorithm [12].

4.2 Localization Error

We have compared the BRL algorithm with the origin AFL algorithm through Matlab simulations on the set of networks with various number of nodes and network densities. For research purposes, our database with network models is available at [20]. For the evaluation, we have implemented metric referred to as the *GER* (Global Energy Ratio)[9]. Here, the Energy parameter does not present the number of Joules, but it expresses the difference between estimated and real distances between all nodes. The GER metric is calculated according to (8)

$$GER = \frac{2}{N(N-1)}\sqrt{\sum_{i,j:i<j} \hat{e}_{i,j}^2}$$
$$\text{where} \quad \hat{e}_{i,j} = \frac{\hat{d}_{i,j} - d_{i,j}}{d_{i,j}}. \quad (8)$$

The $e_{i,j}$ parameter is the mentioned energy value that expresses difference between the estimated distance $\hat{d}_{i,j}$ and real distance $d_{i,j}$ between all pairs of nodes i and j in the network. The distance $\hat{d}_{i,j}$ is calculated on the geometric base by means of the calculated coordinates $[\hat{x}_i, \hat{y}_i]$, $[\hat{x}_j, \hat{y}_j]$ of two considered nodes i and j. The $e_{i,j}$ parameter is normalized by real distance $d_{i,j}$ to reflect the non-uniform distances between the neighbor nodes. Consider two nodes i, j placed $d_{i,j}$ = 10 meters apart, then certain localization error causes that distance between two coordinates p_i, p_j is estimated as $\hat{d}_{i,j}$. This innacurate estimated distance thus induces the localization error of $GER = 0.2$

We have performed a set of simulations to compare the localization error of the AFL and the BRL algorithms. The BRL algorithm was configured to work only with three reference nodes to show if this configuration can outperform the accuracy of AFL using five reference nodes. The results of the simulation are summarized in Tab. 1.

	$GER(50)$	$GER(100)$	$GER(400)$
BRL(3)	26×10^{-3}	4×10^{-3}	0.7×10^{-3}
AFL	41×10^{-3}	11×10^{-3}	1.6×10^{-3}

Tab. 1. Comparison of the BRL and the AFL algorithm accuracy under the different network size.

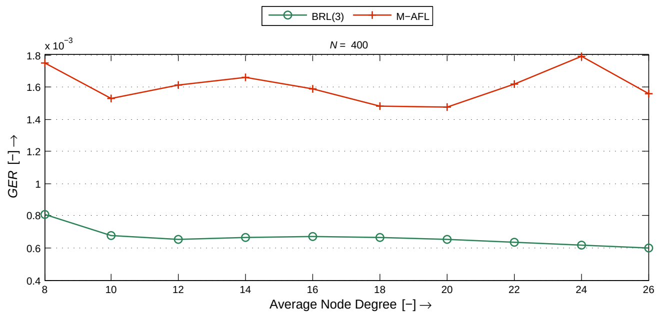


Fig. 9. GER comparison of the BRL and the AFL algorithm in the network with 400 nodes.

It is obvious that the BRL algorithm achieves approximately two times better *GER* results than AFL and thus it can be stated that the three reference nodes are sufficient input configuration for the BRL algorithm. It should be noticed also that *GER* function suffers from the dependency on the network size N, since the N parameter is the denominator of the function and thus *GER* value decreases with the growth of the network size. Hence, the algorithms are compared individually for each network size. Fig. 9 illustrates the progress of *GER* of both the algorithms in the dependency on the node degree for the network with 400 nodes.

4.3 Communication Cost

Furthermore, the efficiency of the BRL algorithm was investigated in terms of the communication cost of the reference nodes selection phase and its results were compared with the results achieved when AFL and CRP were implemented. The CRP algorithm was configured with the four and five reference nodes. Since, it was proved that three reference create the sufficient reference system for the BRL algorithm performance, the BRL algorithm was configured with the three reference nodes and additionally also with the four reference nodes. Fig. 10 shows the mean communication cost versus network size. Red bars represent the communication cost of AFL. It is obvious that the CRP (blue

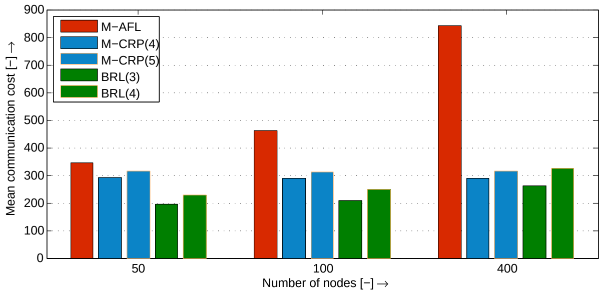


Fig. 10. Dependency of mean communication cost on the network size.

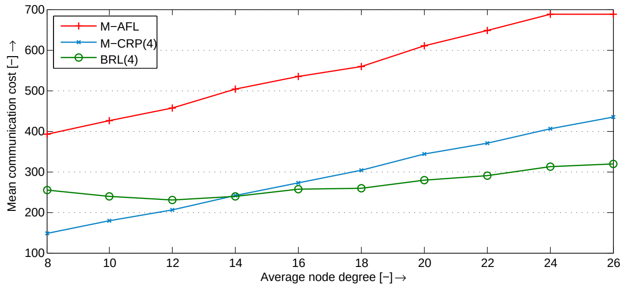


Fig. 11. Dependency of mean communication cost on the node degree.

bars) and the BRL (green bars) significantly reduce the communication cost, mainly in large networks. The BRL algorithm achieves in both configurations (three respectively four reference nodes employed) a less communication cost in the comparison with the CRP(4) and CRP(5). This difference is obvious in the networks with the $N = 50, 100$ nodes. In larger networks, the difference is not so significant and even the CRP(4) has lower communication cost than the BRL(4). The BRL(3) achieves the lowest cost in networks with 400 nodes.

A drawback of the CRP algorithm is presented by the solution in which the position of the reference nodes is estimated after the reference node selection phase. Here the reference nodes must disseminate their own positions into the entire network and thus additively load the nodes. The number of the additive CRP broadcast transmissions is thus equal to the number of the reference nodes established. On the other hand, the communication cost of the CRP algorithm does not depend on the network size and remains almost constant in the whole scale of network size. The greatest advantage of the BRL is presented by the solution in which the position of the reference nodes is estimated after each round of the reference selection process. The estimated reference positions are included in the distance query message and thus no additive broadcast transmissions announcing the reference position are necessary. However, as Fig. 10 shows, the BRL communication cost grows with the network size. This trend is caused by the increasing number of the nodes selected as boundary nodes transmitting the distance response message.

Fig. 11 depicts the communication cost versus the average node degree. The communication cost for each node degree was obtained by averaging the results from the networks with $N = 50, 100, 400$ with the appropriate node degree. Thus, the illustrated graph represents the dependency through the network size scale.

Results show that in the case of AFL and CRP algorithms, the increasing node degree causes the increasing communication cost. This can be explained by the overhearing problem, since in a dense network more node overhear the ambient transmissions. This problem is less obvious in the BRL algorithm that has a slightly increasing trend of communication cost. In the sparse networks, the problem of the BRC false detections overcomes the problem of the overhearing and hence the trend of the BRL algorithm has minimal increasing trend. The cross of the CRP and BRL behavior shows, that the BRL algorithm outperforms the CRP algorithm in a certain portion of the node degree scale. It can be summarized that the BRL algorithm is optimal for the networks with the node degree larger than 14 while the CRP algorithm works more efficiently in sparse networks where the node degree is lower than 14.

5. Conclusion

In this paper we have presented a method for optimization of the communication cost for the anchor free localization algorithms designed for the wireless sensor networks. The valuable research contribution is presented by introducing the novel anchor free localization algorithm that stands on two fundamental ideas. First, sending the response messages only from the nodes placed on the network boundary for reducing the number of unicast transmissions. Second, defining the reference system consisting of three eventually four reference nodes placed on the boundary that are subsequently used for position estimation. An algorithm that can recognize in distributed manner the nodes placed on the network boundaries was proposed. This algorithm is referred to as BRC algorithm. The BRC algorithm performance compared with the known HNT and CRP algorithms achieves the lowest false detection rate of 11,6 % versus 26 % of the HNT and 40 % of the CRP algorithm. It can be summarized that the BRC algorithms outperform the known boundary recognition algorithms more than two times. The last part of the paper introduced the proposed localization algorithm referred to as BRL. The BRL algorithm takes advantage of the proposed BRC algorithm and the multilateration technique for position estimation. The efficiency of the BRL algorithm was investigated in terms of the localization error and mainly in terms of communication cost. It was proved by simulations that BRL algorithm taking advantage of three reference nodes achieves localization error of $GER = 0.7 \times 10^{-3}$, which is two times lower than localization error of the AFL algorithm that equals to $GER = 1.6 \times 10^{-3}$. The communication cost of the localization process incurred by the BRL was compared with the AFL and the CRP algorithm. The results show that both algorithms BRL and CRP significantly outperform the original AFL algorithm. And also that BRL algorithm can outperform the CRP algorithm, but not in the whole scale of the network parameters. The CRP algorithm excels better in large and sparse networks. However, it is worthwhile to mention that novel solution using boundary recognition approach achieves the significant results in a large scale of network parameters. The proposed algorithm can be applied for energy efficient construction of the located network. This network can serve as the reference coordinate system for tracing of a moving object in the warehouses or persons during military missions.

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