Algorithms on Improving End-to-End Connectivity and Barrier Coverage in Stochastic Network Deployments

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Abstract. When a wireless network is randomly deployed on a region, there is only a certain degree of probability that the connectivity and/or barrier coverage between two sites will be provided. Therefore, it is important to develop mechanisms that will assure the high probability for these two QoS parameters to be provided when the gaps appear in the network. This paper involves the mobile nodes in order for the connectivity and/or barrier coverage gaps to be filled. The simulation results aim to evaluate the network deployment parameters (i.e., density of stationary and mobile nodes with respect to the communication or sensing radii, the size of the deployment area, and the deployment manner) in order the end-to-end (EE) connectivity (and, in similar manner, barrier coverage) to be provided with the probability close to one. By finding the most appropriate paths between two sites, two algorithms presented in this paper provide the directions on using mobile nodes for the EE connectivity and the barrier coverage to be improved in stochastically deployed networks.

Keywords: Algorithms, Barrier coverage, Connectivity, Wireless Sensor Networks.

1 Introduction

One of the most demanding implementations of the wireless sensor networks (WSNs) is related to military surveillance of the large inaccessible regions. When these networks are needed to be installed in order to detect the events, it is expected that their nodes wake up, organize themselves as a network, and start sensing the area for a phenomenon. There are many parameters that define the deployment quality. But, the main issue regarding the QoS is related to the ability of the network to cover the area of interest (i.e., sense the events) and transmit the information between the two accessible sites by either using single-hop or multi-hop communications. On top of these issues, other challenges are considered, such as: energy-efficiency of the media access and routing protocols, redundancy, security, etc. When dealing with deterministic network implementations, all of these issues can be more or less optimized. But, in practical stochastic deployments, there is no way for the connectivity and barrier coverage between a specific node of the network and the

D. Simplot-Ryl et al. (Eds.): ADHOCNETS 2011, LNICST 89, pp. 81–92, 2012.

accessible sites to be assured. Instead, regarding the connectivity, by using the theoretical observations such as the one given in [1], as well as the practical experiments such as the ones given in [2] and [3], by increasing the number of nodes and the communication radius, the connectivity can be improved to the probability near 1. But, due to the energy constraints, the communication radius is a very limited value, while the increase in the number of nodes is constrained by practicality. In addition to the application cost and the impracticality of placing the number of nodes (n) where $n \rightarrow \infty$, it has been observed in practice that a sensor network cannot be too dense because of spatial reuse; specifically, when a particular node is transmitting, all other nodes within its transmission radius must remain silent to avoid collision and corruption of data [4]. Therefore, other mechanisms on improving the connectivity should be explored.

In this work, we refer to the EE connectivity as the network ability to transfer the information from one site (end) to another in multi-hop manner using at least one path. Similarly, a belt region is considered to be barrier covered if there is at least one chain-like structure (formed by sensors) along the length of the belt that assures no object can cross the width of the belt without being detected by the network. Unlike the EE connectivity, where two sensors are considered to be connected if their distance is smaller than the smaller communication radius among them; when dealing with the barrier coverage, two nodes (u and v) are considered to be connected if their sensing ranges intersect, i.e., if the distance between them is smaller than the sum of their sensing radii. Building this structure between two parallel edges of the rectangle makes impossible for the object to remain undetected while crossing the region between two other perpendicular edges of the rectangle.

This paper covers the possibility of using robot-nodes (i.e., the nodes with incorporated mobility) for the lengthwise EE connectivity or barrier coverage to be improved across the rectangular area.

The main contributions of this paper are as follows. We design two algorithms namely: greedy path construction algorithm (GPCA), and run-based path construction algorithm (RBPCA). Using GPCA, we evaluate the influence the network density and the nodes' transmitting ranges on the ability of the network to transfer data from one site to another or to create the barrier in the same direction. We experimentally derive the values of the deployment parameters (the number of stationary nodes and the sensing/communication radii) that assure the barrier coverage and/or lengthwise EE connectivity between two sites and we additionally estimate the number of the mobile sensor nodes (and their positions) that would fill the EE connectivity and barrier coverage gaps when the network parameters deviate from these values. These results can also help in assessing the economical feasibility in implementations where the addition of few mobile nodes is economically comparable with deploying the much greater number of stationary nodes in order for the higher degree of the deployment quality to be provided.

The reminder of this paper is organized as follows. Section 2 reviews previous work on topic. The analysis framework with the basic definitions and problem formulation is given in section 3. In section 4 the designed algorithms are described. Section 5 contains the simulation results derived using GPCA algorithm. Conclusions and discussions, and future work are contained in section 6.

2 Related Work

In literature, connectivity issue is often treated together with the coverage. This is due to the fact that the models for the sensing and communication ranges are similar.

Critical conditions for the existence of barrier coverage along with an algorithm to construct sensor barriers are presented in [5]. Authors of [6] estimate the density needed to achieve coverage and connectivity in thin strips of finite length for four models of coverage, using the uniform deployment manner. A network model for barrier coverage, along with an algorithm to construct barriers is proposed in [7]. The authors compare line-based normal distributed vs. uniformly distributed networks in terms of barrier coverage. Similar work is presented in [8], where a probability analysis of barrier coverage is additionally conducted.

The methodology of relocating the mobile sensors with limited moving range, with the aim to minimize the variance in the number of sensors among the regions is presented in [9]. The construction of the maximum number of barriers with minimum sensor moving distance along with the effects of the number of mobile nodes on the barrier coverage are also covered in [10]. An algorithm similar to the one used in this paper was presented in [11]. However, this algorithm is designed specifically for finding and mending gaps in a network where there is a high probability for the next neighbor node toward the destination to be the one which also leads to the connected graph with the largest carry towards the destination. This is not the case in uniformly distributed network neither in some specific situations that we address in this paper.

3 The Analysis Framework

In this work, we experimentally evaluate the gap filling process in order for the EE connectivity and the barrier coverage to be improved. These two issues are treated together because the process of gap filling is the same for the both issues. Here, only the definition of a connection link differs depending on context being used.

In context of connectivity, we consider two nodes u and w to be in each other communication range (i.e., connected) if the distance between them is smaller than communication radius, that is $d(u,v)<Rc$. Generally, two nodes have different communication radii (because of various environmental factors). In that case, the upper inequality involves the smaller communication radius. In our analysis, we will consider the sensors have the same communication radii.

In the context of barrier coverage, the aim is for the sensor nodes to create the barrier, i.e., to be connected in the sense that their sensing ranges intersects. If a number of sensors create a barrier while connected this way, they provide the barrier coverage.

Given the above reasons, we will refer to the Rc as the connection radius. This parameter has different meaning depending on the context. It represents the communication radius (that is used for the connectivity issue) between two nodes u and w, with the nodes considered connected if $d(u,v)\leq Rc$. In context of barrier coverage, it presents the sensing radius with the nodes considered “connected” if $d(u,v)\leq 2Rc$. Therefore, even though the proceeding analysis is related to the EE connectivity, the gap filling algorithm works in the same manner for the case of the barrier coverage, with the only difference in the way the two nodes are considered to be connected.

In Fig. 1 we consider the left vertical edge of the rectangle to be the source (S) and the right edge to be the destination (D). The aim is for the most efficient connection path from S to D to be provided. The path is considered to be efficient if it involves the smaller number of gaps and the smaller number of mobile nodes that would be necessary to fill these gaps. The nodes that are in certain proximity to the S are the only candidates to construct the paths. In Fig. 1 two connection paths from source to destination are provided: S1-D and S2-D. These paths are constructed by using stationary and mobile nodes. Among them, path S1-D is more efficient since it needs a smaller number of additional mobile nodes for the EE connectivity to be provided. Red lines present the connection links among stationary nodes that are in each others' communication radius, while black lines (also marked with X) show the possible position of the gaps (i.e., virtual connections).

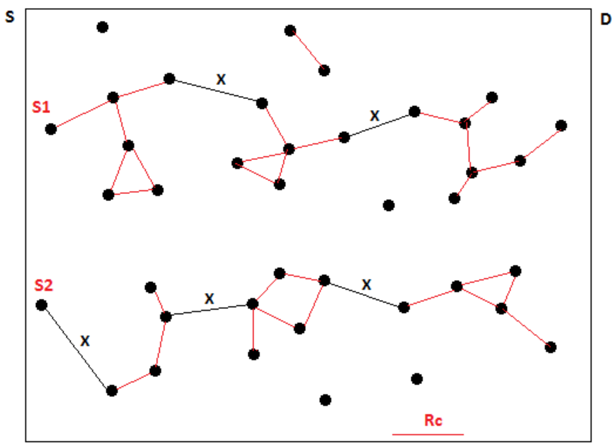

Fig. 1. Finding and mending connectivity or barrier gaps using mobile nodes
Description: In this example, GPCA algorithm is used. It is obvious that the path S1-D is more efficient than S2-D because it involves the smaller number of mobile nodes.

In the case when the density and the communication/sensing radius are constant values, we propose GPCA algorithm. The framework includes networks that are randomly distributed across the square region where starting and ending nodes have to be on the parallel edges of the square. We consider two deployment styles on the area, namely uniform and line-based.

First case refers to the network deployed across the square region randomly with the density $\rho = \frac{n}{A}$, where n is the number of nodes and A is the area of the region. The starting point of the analysis (S) is the proximity (smaller than Rc) to one edge of the square, while the ending point is the proximity (smaller than Rc) to another parallel edge.

The process of dropping the nodes out of a plane is often approximated using so-called line based deployment. It is defined as a combination of the uniform distribution along one axis and the normal distribution along other. Depending on the variance σ^2, the deployment can be wider or narrower in width, which corresponds to the deployment occasions (such as the influence of the wind, the height of the flight, the influence of the terrain, etc.). Both uniform and line based distributions are simulated using GPCA algorithm. This algorithm begins from the points of the accessible site, constructs communication paths (or builds the barriers) by using the stationary nodes, and proposes the positions of the mobile nodes until the created chain-like structures reach the destination site.

Our third scenario is (only theoretically) covered by using a designed RBPCA algorithm. This algorithm aims to overcome the observed weakness of the GPCA algorithm in situations where the density of the network and the communication/sensing radius vary on two-dimensional space. For example, the expected range of the transmitting radii for the free-space environment is different comparing to the range of the devices when the network is deployed in a forest. The examples of analysis regarding the differences in propagation patterns due to the type of the environment can be found in [12] and [13]. This means that, in a region, when designing the coverage and connectivity issues, the environment factor should be included. Therefore, the critical network density for achieving the connectivity and coverage varies over the same region. Furthermore, for example, in the case of airdropped sensors on the small hill, a greater number of sensor nodes are expected to be positioned on the bottom of the hill. These sensors now are more likely to get connected in a non-uniform manner resulting in some sub-graphs having the greater reach to the destination. Consequently, there is a higher probability that the connectivity and barrier coverage will be more efficiently addressed using the designed RBPCA algorithm.

4 The Algorithm Description

4.1 The Greedy Path Construction Algorithm (GPCA)

Let's denote the coordinates of the node *i* with X*i* and Y*i, respectively*. The left and the right edges of the region (i.e., square) will generally be denoted by S and D, respectively. This algorithm firstly finds the nodes that can be accessed from an accessible site. These nodes communicate with other nodes in their radii and the connecting process continues until the graph created that way reaches the destination or maximum run on the direction of the destination. The node of the created graph that is closest to the destination now virtually connects to the nearest node toward the destination. This is registered as a gap, and the needed number of mobile nodes to mend this gap is calculated. The algorithm continues till the connection path reaches the destination.

The GPCA now works as follows:

1) Initialize the minimum number of gaps g=0 and the minimum number of needed mobile nodes m=0.
2) Find the nodes that are connected to the leftmost edge. If there are no such nodes, the network is deployed unsuccessfully. In simulation, the deployment is repeated.
3) Perform a routine that constructs a connectivity graph for each of these nodes, i.e., find the nodes that are situated in radius *r*, add them to the

appropriate sub-graph, and continue searching for their neighbors. Repeat the searching routine for each newly included neighbor until there are no more neighbors to be added. The output from this routine will be a number of connected or trivial graphs G1 (V1, E1), G2 (V2, E2)… Gn (Vn, En). Each of these graphs have at least one node reaching the S edge.

4) If any of the nodes that belong to G1, G2,..Gn has reached the distance Rc from the right edge, than the EE connectivity is considered to be provided and the program terminates returning minimum number of gaps g = 0 and minimum number of needed mobile nodes m = 0.
5) If not, find the rightmost node *i* from graph G1.
6) From the rest of the nodes (that do not belong to any of the graphs) find the node *j* which is closest to *i* and where X*j*>X*i*. This node will be positioned at a distance larger than *r* from node *i*, otherwise it would be reached by some of the graphs. Now connect *i* and *j* (in GUI depicted by black line). Increment *g, a*nd find the parameter m

   If: $(d_{ij} - r)\bmod(r) = 0$

$$m = \frac{d_{ij} - r}{r} + m \ . \tag{1}$$

   else:

$$m = \frac{d_{ij} - r}{r} + 1 + m \ . \tag{2}$$

   In equation (2), the whole number part of the quotient (d_{ij} -r)/r is returned. Then 1 is added along with the previous value of the parameter m. In simulation program, the distance d_{ij} is approximated to the integer value.

7) Perform the routine (such as one in step 3) to construct the connected graph starting from the point j.
8) If the new rightmost node *i* (of the new graph) has not reached the distance smaller than *r* from D, then repeat from step 6. Otherwise return the values *g1* and *m1*.
9) Repeat from step 5 for the graphs G2,…Gn.
10) Return *g = MIN (g1, g1,…,gn)* and *m = MIN (m1, m2,.., mn).*

When the algorithm terminates, only one of the graphs G1, G2,… Gn will be selected to provide the full barrier coverage from S to D (Fig. 7). It will contain the additional links created from the potentially added mobile nodes.

In analyzing the barrier coverage, only instead of using r (which in the above algorithm refers to the communication radius), the *2r* value is used, with *r* representing the sensing radius.

4.2 The Run-Based Path Construction Algorithm (RBPCA)

The RBPCA algorithm differs from the previous one in fact that, in the process of finding and mending the gaps, instead of looking for the next closest node (in the direction of D), it observes the trivial graphs and connected sub-graphs as a whole, while the main criterion in making the decision on which of them to use is the balance between their distance from a given graph and the run they provide toward the destination.

A simplified situation that describes the way the RBPCA functions is depicted in Fig. 2.

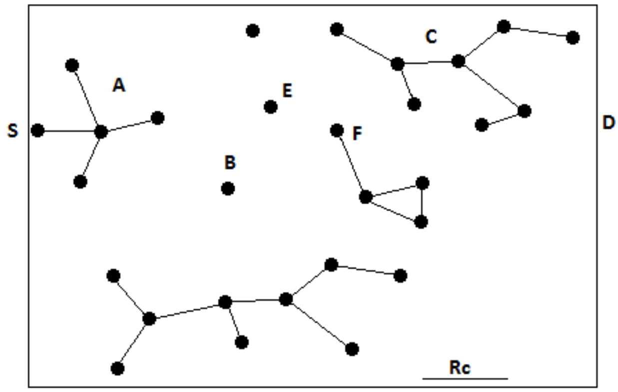

Fig. 2. An example when RBPCA over performs the GPCA

Description: In order to bridge the gap, GPCA would first choose the node B. In proceeding, according to GPCA, nodes E and graph F would be chosen successively. In the end, one of the nodes of graph F will bridge the gap with the graph C. This results in at least four additional mobile nodes. Using RBPCA, graph A directly bridge the gap with graph C, by using only two mobile nodes.

The decision (on which virtual link to use) is made based on maximum value among the ratios that satisfy:

$$\frac{RUN\ (Gi)-RUN(G_0)}{d_{ij}-Rc} > 1. \tag{3}$$

$$\text{While, } d_{ij} \leq 3Rc\ . \tag{4}$$

Where, RUN (G_i) and RUN (G_0) present the closest points the graphs G_i and G_0 can provide toward destination, respectively, while d_{ij} is the distance between the closest nodes of the graphs G_i and G_0. We refer to the node u that belongs to the sub-graph G_k , and that is closest to the D as RUN-node. This construction should overcome the problem of great number of small runs that can appear in GPCA algorithm. Great number of small runs can be expensive in the sense that they involve the greater number of mobile nodes. On the other hand this algorithm obviously introduces an extra communication and computation operations (because it does not search for only the nearest node in the direction of destination), which makes it more resource-hungry compared to the GPCA.

We have chosen maximum two mobile nodes for the depth of this algorithm, since we consider that a higher degree would degrade the performance, especially when the nodes are uniformly scattered, hence they would need more energy to cross the paths in order to mend larger barriers. For the case of d_{ij}>3Rc, the GPCA subroutine (i.e., finding the closest node toward the D) is simply performed.

The RBPCA works as follows: Initialize the minimum number of gaps g=0 and the minimum number of needed mobile nodes m=0.

1) Perform a routine that constructs connectivity graphs by connecting the neighbor nodes of each of the deployed nodes, i.e., find the nodes that are situated in radius Rc, and continue searching for their neighbors. Repeat the searching routine for each newly included neighbor until there are no more neighbors to be added. Group the nodes that can reach each other (in multi-hop communication) into sub-graphs and identify them by the sub-graph number. We choose for the sub-graph number to be the lowest ID of the node. The output from this routine will be a number of connected or trivial graphs G1 (V1, E1), G2 (V2, E2)… Gn (Vn, En).
2) Calculate the RUNs for each of the sub-graph (i.e., calculate the closest point to the D each sub-graph can reach to). At this point, besides its ID and the absolute position, each node knows the number of sub-graph it belongs to as well as the common RUN for that sub-graph.
3) Find all the sub-graphs Gsi that have at least one node situated in the proximity Rc from the S. If there is no such a sub-graph or trivial graph, the algorithm is terminated.
4) Given a Gsi (starting from i=0), from all the graphs Gj find the one that satisfies the condition given by inequality (4) and afterward calculate:

$$Max\,\{\frac{RUN\,(Gj)-RUN(Gsi)}{d_{ij}-Rc} > 1\}\ . \quad (5)$$

5) IF there is no such a sub-graph, find the RUN-node of the Gsi and treat the path between that node and the closest node toward D (ni) as the optimal one, i.e., perform a routine of the GPCA algorithm. Now let let Gj=Gsi.
   ELSE Gj=Gsi.
6) Increment g and find the parameter m:
   If: $(d_{ij}-r)\,\mathrm{mod}(r)=0$
   Then use equation (1), else use equation (2).
   Here d_{ij} is the distance between the RUN-node of the sub-graph i and graph Gj
7) IF the RUN-node of the sub-graph Gj did not reach the destination, repeat from step 4.
   ELSE: i++, repeat from step 4.
8) Return g = MIN (gs1, gs2,…,gsn) and m = MIN (ms1, ms2,.., msn).

5 Simulation Results

In order to generalize the observations, we deploy a number of stationary nodes on the square areas. By running the GPCA, we derive the number of additional mobile nodes needed for the EE connectivity to be provided with the probability close to one. The simulation results are shown in Figure 3. Here, the number of robots needed to mend the network gaps is presented with respect to the number of the stationary nodes and the ratio a/r, where *a* is the length of the edge, while *r* is the communication radius.

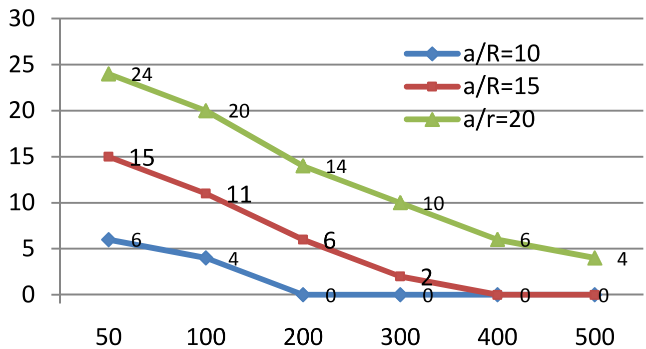

Fig. 3. The minimum number of additionally needed robots for the EE connectivity to be achieved with high probability (near one)

Description: Given the communication radii, one can determine the minimum number of mobile nodes needed to mend the connectivity gaps. The results can also be applied for the strip-like regions when the length of the region is an integer multiple of the region width. In the case of barrier coverage, the 2Rs parameter is used instead of Rc. As can be noted, the communication or sensing radius, greatly impacts the issues of EE connectivity and barrier coverage, respectively.

An important conclusion from the simulation is that, for a given number of stationary nodes deployed on a square region, numbers *g* and *m* depend only on ratio a/R. For typical communication radii of 10m, 20m, and 50m, our simulations now include the square regions 100x100, 150x150, 200x200, 300x300, 400x400, 500x500, 750x750, and 1000x1000. Another important conclusion is that these results can also be applicable for the strip-like regions where the area is *S=a x (ka)*, precisely, if the length of the region is a *k* (integer) multiple of the area width, the number of additionally needed robots is *k x m,* where m is the number of additional robots in the case of a square with dimensions *a x a*. If the number of stationary nodes is *p* for the *axa* region, than this parameter would be *xp* for the area S. For example, from the Fig 3, one can conclude that, in a region of dimensions 600x300 = 2x300x300, when 400=2x200 stationary nodes are uniformly deployed across the region, with the communication range of 20 m (i.e., a/r=15), on average, 12 robot nodes will be necessary to mend the connectivity gaps with high probability.

Line-based deployment relies on uniform distribution along one axis and the normal distribution along other axis. In our case, sensors are uniformly distributed along the horizontal axis and normally along the vertical axis. According to the 68-95-99.7 rule for the Gaussian distribution, 99.7% of number of nodes is expected to fall within the distance $\pm 3\sigma$ from the mean value, i.e., the horizontal line. Hence, the width of the region is not important as long as it is greater than 6σ. In this implementation, the network density cannot be expressed a constant value. Therefore, we find more appropriate to evaluate the minimum number of mobile nodes that can assure connectivity for different communication radii. In Fig. 4, the results are obtained using following values: σ=10, $\sigma = 20$, r=10, and r=20. The dimensions of the region are 400x400.

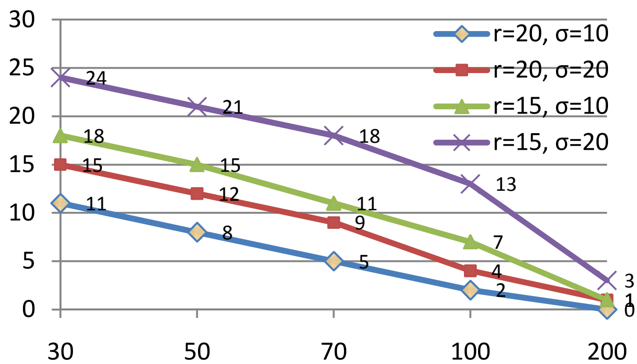

Fig. 4. Number of additionally needed mobile nodes versus number of stationary nodes in a line-based deployment across the 400x400 m2 area

Description: The dependence of value m (for two different radii and two different variances) on the number of stationary nodes across a 400x400 m² region where the network is deployed based on normal distribution along vertical axe.

It is important to note that these results can be generalized for distances shorter or longer than 400m. For example, for the area length of 1200=3x400 m, where r=20 and σ=20, if the network is deployed using 300=3x100 stationary nodes, the number of additionally needed robot nodes would be 12=3x4.

By relying on results in Fig. 4, we notice that the greatest impact on the EE connectivity and the barrier coverage in a line-based deployed network has the communication and sensing radius, respectively. The second parameter ordered by the influence on these issues is the variance, while the last important parameter is the number of stationary deployed nodes. In realistic implementations, the communication and sensing radii cannot be adjusted (primarily due to the energy and the environment constraints). Therefore, the designer should aim to improve the variance by making the width of the deployment area as narrower as possible. Afterward, by using results from Fig. 4, the number of additionally needed robots can be estimated.

6 Conclusions Discussions and Future Work

Stochastic deployment of the WSNs presents the most challenging design space for the network designer. In this environment, all layers of the protocol stack should be carefully planned. In addition, the cross-layer design is the only appropriate approach, especially when the large-scale, long-term WSN applications are meant to be installed on the inaccessible regions.

Connectivity and coverage are two of the basic issues that are to be evaluated at the very beginning of the network implementation. Shortly, without good coverage, network cannot sense the area properly while without network connectivity, it cannot transmit the sensed data. Therefore, these two issues give the meaning of using the WSNs for a given purpose.

The scope of analysis in this paper is limited to the barrier coverage and the EE connectivity issues.

We present two algorithms. GPCA algorithm is simpler and is appropriate when there is no information about the deployment environment. When the deployment is uniform over the region, there is the same probability for the sub-graphs with the same distance between the closest and the farthest position in one direction to be situated in proximity of any of the nodes. Therefore, the choice of the node that belongs to the sub-graph with the higher reach to the destination increases the probability for the most efficient path to be chosen. However, the situation that makes RBPCA more efficient is naturally unlikely to happen in a line-based deployed network, especially if the σ parameter is smaller. On the other hand, if the sensing or communication radii can be estimated, and if the deployment environment is known leading to the creation of the irregular sub-graphs, the presented RBPCA algorithm can perform better than the GPCA.

Since the difference between GPCA and RBPCA has its meaning only in specific situations, we present only the construction of the RBPCA and the situations where the routines of this algorithm can be used. On the other hand, in order to derive the experimental results and generalize them for the situations where environment factors cannot be predicted, a simulation process based on GPCA algorithm is conducted.

The results provide the minimum number of mobile nodes that would be necessary in the gap mending process of a randomly deployed network in a specific region. The results show that the main factor in constructing the EE connectivity and barrier coverage is the communication and sensing range, respectively. When these radii are large enough comparing to the area width (e.g., larger than 1/10), then the number of created gaps becomes similar or equal to the number of the needed mobile nodes to mend these gaps. Another important conclusion is derived on the fact that given the same number of stationary nodes and the same value of the ratio a/r, the number of mobile nodes remains the same.

The simulation results provide values for the various and the most typical WSN's implementations. Relying on these results, the designer can predict network parameters when planning to combine the stationary and mobile nodes in a specific deployment.

Our future work will be focused on building the simulation framework based on the RBPCA. A comparison of the results based on GPCA versus those based on RBPCA will also be the object of follow-up.

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