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Research paper

A Discrete Imperialist Competitive Algorithm for WSN Deployment

Kamal Jadidy Aval*, Masumeh Damrudi

Department of Computer Science, Firoozkooh Branch, Islamic Azad University, Firoozkooh, Iran
**Corresponding author E-mail:k.jadidy@yahoo.com*

Abstract

The WSN deployment problem is addressed in this paper. The problem applies to the monitored areas with different detection needs at different points. In this problem, every point of the terrain is assigned with a predefined minimum probability of event detection. The objective is providing the best position for the network nodes and at the same time assuring event detection, detection message delivery, and reducing deployment cost. We have formulated the problem as an optimization problem with three objectives, which is NP-complete. Because of the huge solution space for the problem and the exponential computational complexity, none of the exact methods known yet can solve the problem unless for a pretty small scaled case. To battle the complexity of the solution, a new scalable solution is proposed based on imperialist competitive algorithm namely imperialist competitive deployment algorithm (ICDA). We compare the proposal to the related deployment strategies, and the results show that ICDA outperforms them.

Keywords: *Deployment;Evolutionary Algorithms;ICA;ICDA;WSN.*

1. Introduction

Detection of the physical phenomena in an area and reacting accordingly is a problem of hundred years old. After a long time, all the theoretical applications are becoming real. Various tiny devices are being invented and produced to detect and measure changes in the environment parameters like temperature, humidity, pressure, vibration, and many others. Wireless networking combined with these tiny sensors are collaborating to build wireless sensor networks (WSNs). Adding the wireless functionality, the detections and measurements could be sent to some digital centres for further analysis and reaction. Upon detection of an event and/or measurement, a message is sent from the sensor node to a base station, namely sink node, for informing the user-level application and performing the pre-defined action (if any).

The main research issues that were firstly addressed by the researchers of the area were routing protocols, node localization, time synchronization, energy minimization, data gathering, etc. [1,2]. Unlike other wireless networks like MANets, the network topology is playing the main role in the performance of WSNs. Along with the studies that assume an unknown environment and inaccessible deployment area (i.e. a disaster field) with random deployment, some other works specifically target a node deployment problem where nodes are placed by hand or by a robot using a predefined topology. However, unlike the real world applications, these studies usually consider the occurrence of the events to be uniform. While the points of interest are known, the deployment will not be uniform and the nodes will be placed according to the points of interest. A fire fighting application which relies on a fire detection system is one of the common examples of such real applications. The accuracy of the detection assigned to a point in this application is highly dependent to the importance of that point, i.e. high importance is assigned to the area near habitats and low importance is assigned to less important area like rock-ground.

Usually, in the manual deployment strategies, the communication range of the sensor node is not considered. In these cases the focus is on monitoring quality and the communication range is assumed to be large enough to provide network connectivity. Although this assumption simplifies the problem, it leads to the depletion of the nodes because of high energy consumption that results in both less monitoring quality and network fragmentation.

In this paper the issue of WSN deployment in presence of an irregular detection plane is addressed. The main goal is deploying a wireless sensor network considering network cost optimization, ensuring network connectivity, monitoring quality, and finally ensuring the accumulated path reliability rate (APRR). After the deployment of the network, the event detection probability for any point of the environment is expected to be greater than a predefined threshold for that point. The APRR can be addressed in detail for each node of the network that should also be greater than a predefined value or as general evaluation factor that is average of APRR for network nodes.

The problem is formulated as a multiobjective optimization problem. We have proposed a strategy to deploy a wireless sensor network based on the imperialist competitive algorithm (ICA) [3] which is a novel evolutionary algorithm for complex problems. The algorithm is initially proposed for solving continuous optimization problems and while the problem of finding the optimized network topology is a discrete one, we had to make some changes in the main algorithm. The cross over function from genetic algorithm is exploited for this reason. Like some other evolutionary algorithms, ICA is starting with an initial solution set that is produced pseudo-randomly in this case. We have introduced repulsion force for every deployment to evolve the initial solutions towards the optimal solution. There will be an origin and magni-

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tude for this force in the terrain. According to the location of each node, the resultant force will make it to move in each of the iterations of the algorithm. Once the new location of more than one node is overlapping, there will be a merge which will result in network cost reduction. While the difference between the requested coverage and the provided coverage is a main parameter in computing this force, the solutions will evolve to provide the requested monitoring quality with lower cost. Figure 1 illustrates an example of the requested event detection probability for a terrain.

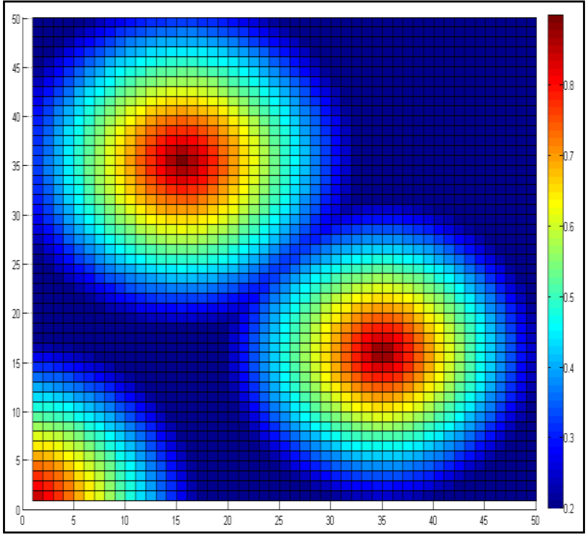

Fig. 1: Requested event detection probability distribution

The remainder of this paper is structured as follows: the next section introduced the existing wireless sensor network deployment issues. Afterwards, the proposed algorithm is demonstrated followed by a discussion on the performance evaluation. Then the contributions are discussed. And finally the conclusion is drawn.

2. Related Works

We have classified the research on the deployment of nodes in a wireless sensor network into two main classes, mobile node strategies and fixed position node strategies. The following subsections summarize the research in these two classes.

2.1. Mobile Nodes

The researchers in [4] have studied the problem of covering an unknown area using mobile sensor nodes. Their main objective is covering all of the area. In the initial phase, they have the entire sensor nodes focused in the start point. By execution of the algorithm, virtual forces are guiding nodes toward their final positions. The concept of potential field has been exploited to compute the virtual forces moving nodes. They have not considered the communication requirement.

The virtual force algorithm is proposed in [5]. The sensors are distributed over the deployment area after a random initial deployment. In this algorithm, sensor nodes are forcing surrounding nodes to move. If the distance between two nodes is greater than a predefined threshold, they attract each other and if this distance is less than the threshold the resulting force make them apart. Every node moves toward the net force resulting from its neighbours.

The problem of providing coverage using the mobility of the nodes is targeted in [6]. The authors have designed two distributed protocols to control the movements of the sensor nodes based on the Voronoi diagrams.

The aim of the research in [7] is to provide the area coverage in presence of both stationary and mobile sensor nodes. While the position of the stationary nodes is fixed, virtual forces cannot provide the solution itself. On the other hand an improved particle swarm algorithm (CPSO) cannot solve the problem itself in a reasonable time. Mixing these two techniques, the authors have benefited from the ability of virtual forces for local optimization and from co-evolutionary particle swarm as a global optimizer.

It should be reminded again that all of the above algorithms are considering the requested detection to be uniformly distributed all over the sensing area. Once there is an irregularity in the probability of detecting the events, the threshold for each point of the area should be provided by the algorithm.

2.2. Fixed Nodes

The non-uniform coverage requirement and fixed sensor nodes are two main properties for the following pieces of research.

In [8], two deterministic algorithms were proposed by the authors to solve the deployment problem where the event detection model is probabilistic. The problem area is broken into the coverage of grid points. The MAX_AVG_COV is trying to maximize the average coverage of the grid points in the area, while the MAX_MIN_COV is trying to maximize the coverage at the grid points with minimum effective coverage. Although the algorithms are designed for uniform event distribution, but they can easily cover the problem of non-uniform event detection. The main drawback for both algorithms is their high time complexity.

The authors of [9] have proposed an approach to optimize the number of nodes to determine the locations of node. The two algorithms namely MIN_MISS and MAX_MISS are deploying one sensor in each step of the iteration. The nodes are placed in the grid points that miss the coverage and are more in need to event detection. Just like the previous research, the main drawback of this algorithm is also its computational complexity which is even worse.

The problem of providing coverage for a non-uniform event detection requirement is addressed in [10]. The event detection model used in the research is probabilistic and the problem is formulated as an integer linear programming deployment problem that is proved to be NP-Complete. The time complexity of the Diff_Deploy proposed in this paper is $O(4/3n^6)$. Although the proposed method is deterministic, the time complexity is even worse compared to the results of [9].

The authors of [11] have proposed a pseudo-random deployment strategy based on the Tabu search. They have used the Bernoulli distribution for adding or removing a sensor to or from a location. The idea is extended in their other work [12] to provide a connected network. While the approach is using a pseudo-random strategy there is no guarantee that the required coverage will be provided for all of the paints of the terrain.

In [13, 14], the authors have proposed an approach to provide network coverage and connectivity while minimizing the network cost and the network lifetime. The authors have proposed two heuristic algorithms as the solution namely PFDA and MODA based on the tabu search. They have conducted simulations using NS2 to prove the performance of the approach in terms of network lifetime.

2.3. Coverage and Connectivity Models

We have assumed the sensing model of the network to be the probabilistic sensing model where the results are more close to the results from real experiences. A quantity R_u is defined in this model, such that $R_u < R_s$. The probability of detecting an event happening at a distance not less than $(R_s + R_u)$ is zero, and at a distance not greater than $(R_s - R_u)$ is one. Finally at a distance between $(R_s - R_u)$ and $(R_s + R_u)$ the probability of detection is p. R_u is the uncertainty factor of sensor detection. The sensing behaviour of ultrasound, infrared and other similar devices are reflected by this probabilistic model as illustrated in Fig. **2**. Based on this model, the *probabilistic coverage* notion of a point $P(x_i, y_i)$ by node s_i is defined as [15]:

$$c_{x_i y_i}(s_i) = \begin{cases} 0, & R_s + R_u \leq d(s_i, P) \\ e^{-\omega a^{\beta}}, & R_s - R_u < d(s_i, P) < R_s + R_u \\ 1, & R_s - R_u \geq d(s_i, P) \end{cases} \quad (1)$$

where $a=d(s_i,P)-(R_s-R_u)$, and ω and β are sensing parameters related to the sensor node. The points at a distance not greater than (R_s-R_u) from sensor are 1-covered and the coverage for other points of the area is less than one. There is no coverage for the points at a distance greater than (R_s+R_u) from node. According to the assumptions of this paper, event detection capability of all of the sensor nodes in the vicinity of a point p are considered in computing the generated event detection probability in point p. However, no collaborative event detection model is considered in this paper which needs a predefined protocol to decide on the event detection based on the information exchanged by the nodes in the vicinity. The decision is made individually by each node without considering the results from other neighbours. The event detection probability at point p is calculated as

$$\mathrm{P}_p = 1 - \prod_{s \in V_p} \left(1 - P_p^s\right), \quad (2)$$

where P_p^s is the detection probability of a sensor s at point p that is calculated by Eq. (1). V_p represents the set of sensor nodes deployed in the vicinity of p. According the coverage model introduced earlier, for any point on the terrain, V_p consists of the sensor nodes located within $R_s + R_u$ or less distance from p.

We have classified the research on the deployment of nodes in a wireless sensor network into two main classes, mobile node strategies and fixed position node strategies. The following subsections summarize the research in these two classes.

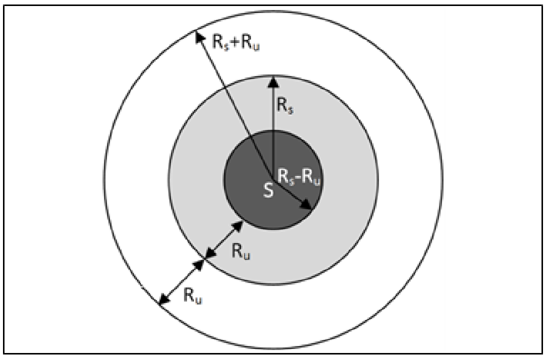

Fig. 2: Probabilistic sensing model

In the communication model, the shadowing model is utilized in this paper. Unlike the binary disk model which is far from the real world, it is shown that the results of considering the shadowing effect are more close to the real world results by choosing the proper parameters.

Figure 3 illustrates the communication model between two sensor nodes. The nodes in this example are called one-hop neighbours and they are connected in the connectivity graph. the log-normal shadowing model [16] can capture the effect of multiple paths that uses the following formula:

$$PL(d) = PL(d_0) + 10\eta \log_{10}\left(\frac{d}{d_0}\right) + X_{\sigma} \quad (3)$$

where *PL(d)* is the signal strength loss at distance *d* from sender, d_0 is a predefined value as distance reference, η is the path-loss exponent, and $X\sigma$ is a zero-mean Gaussian random variable with standard deviation of σ. The strength of received signal at a *d* distance is the transmission power of sender minus *PL(d)*. The σ parameter for this model is calculated by curve fitting experimental data, and $PL(d_0)$ can be either obtained from experiment or analysis.

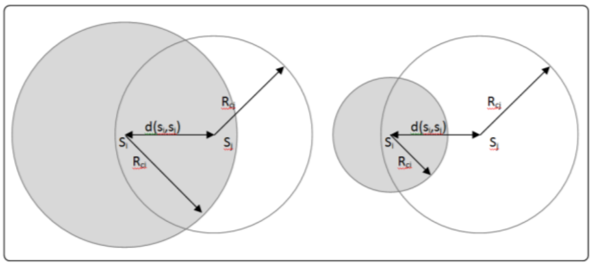

Fig. 3: Model of Communication

3. Discrete Imperialist Competitive Algorithm for Node Deployment

In this section the proposed approach on the WSN will be discussed. At first the original ICA algorithm will be described that will be followed by another subsection describing the changes that has been proposed.

3.1. Imperialist Competitive Algorithm

The ICA [3] was introduced in 2007 as an optimization algorithm to help solving NP-hard problems. The idea of ICA comes from the centuries of governing behaviour around the world. Almost all of the countries that become powerful start to invade the other countries with less power that are full of natural resources. The competition between these imperialist countries on having more resources through their colonies around the world is the base theory behind ICA.

In this algorithm at first, during the initialization phase, a random solution set for the problem is created. Each of these solutions is representing a country in the world. Then, the algorithm chooses a number of these solutions namely countries to become imperialists. Just like the real world, the countries with more power which is represented by less cost have higher priority to become an imperialist. The author of the algorithm is recommending 10% of the whole countries to become imperialists in the initialization phase. Once the imperialists are chosen, the remaining countries are all labelled as colonies and assigned to the imperialists proportional to the imperialists’ cost. The imperialists with lower cost will have more colonies under their ruling.

After the initialization phase, every colony is developed towards its imperialist. Once this development results in a colony which has lower cost than its imperialist, the imperialist and the colony exchange their positions. Then, the competition starts where the cost of the empires is calculated with both the imperialist’s cost and the cost of its colonies. Referred to the original ICA [3], the total cost of an empire is calculated by adding the cost of the imperialist to a number coming from multiplication of an impact factor to the mean of its colonies’ costs. The impact factor is recommended to be 0.1. During every iteration of the competition, the weakest colony is disjoined from the weakest empire and is joined to one of the remaining empires proportional to their total cost. Once there is no colony left for an empire, it collapses and the imperialist of the empire is joined to the other empires. This iteration is done until there is only one empire or a predefined finish condition in met. The original ICA is designed for continuous problems with a single objective.

3.2. Node Deployment Algorithm

The node deployment algorithm proposed in this paper is getting the main idea from the original ICA. As defined in the above, there are two objectives in the problem with two criteria. The preferred solution for the defined problem should provide a better deployment cost which is represented by the number of nodes and a better APRR for assuring packet delivery form nodes to the sink. The solution must provide the requested coverage along with a connected network. The coverage and connectivity models used in this approach are described earlier.

The underlying algorithm of the proposed approach is the ICA. The APRR of a colony is used as the objective to choose the imperialists of the empires, which converges the final solution to a better APRR. The discrete nature of the objective functions for sensor deployment has led to using the crossover operation from genetic algorithm for the development of colonies towards their imperialist. During the development, two random numbers are generated as x and y to divide the terrain into four regions. During the crossover operation, each region of the imperialist has 50% chance to replace the same region of the colony. At the end of the crossover, the resulting terrain is checked for providing coverage and connectivity. If it is connected and provides coverage, the terrain is used as the new terrain for the colony.

The other objective of the proposed algorithm is the network cost. Derived from the gas molecules theory that the molecules are intended to move from the high pressure area to a lower pressure area, the repulsion force is defined. This force repels the nodes from over-covered areas. During the movement of the nodes, two situations will help to reduce the number of nodes in the network. At first when a node is moving to a location where there is another node will merge with it. On the other hand, the nodes on the border lines could be moved outside of the terrain which again reduces the cost of the network. During each development phase the resultant over-coverage and its location is calculated for the terrain. Then the nodes are moved according to distance and angle parameters.

4. Performance Evaluation

The performance evaluation of the DICA is performed in this section. DICA and the related deployment strategies are implemented using MATLab®. The proposed deployment strategy is run and the results are compared to two other most related deployment strategies found in the literature namely NSGAII[17], and PFDA [13]. DICA execution results in less sensor nodes where the same QoM distribution is used for three of them.

We have set the number of countries in the initial phase to 100 and we have assumed 10 empires accordingly. Each country which is representing a terrain is initialized during the initialization phase. Bernoulli distribution is used as the base decision to deploy a sensor in any cell assigned with a random-bernoulli strategy. The required event detection probability threshold of each terrain cell is used as the Bernoulli parameter.

4.1. Environment Settings

For running the algorithms, we have used the following settings to calculate the coverage provided at each terrain cell: $\omega = 1, \beta = 1$, rs = 1, ru = 5. The communication quality between nodes has been calculated using the physical layer settings listed in Table 1.

Table 1: Physical Layer Parameters

Parameter	Value
Transmission power	281.83815 mW
Transmitter antenna gain	1
Receiver antenna gain	1
Frequency	914 MHz
System loss	1
Path loss exponent	2
Shadowing deviation	2.8
Reference distance	1
Receiver threshold	3.3e-8 W

4.2. Simulation Results

Figure 1 illustrates the non-uniform distribution of the requested event detection probability used for obtaining the simulation results. Figure 4 shows the resulting deployment from the DICA. Using the number of nodes to evaluate the cost objective of the problem, DICA has the best result compared to the other two methods. The number of nodes in the proposed method is 196 while the resulting deployment from NSGAII and PFDA are 284 and 221 respectively. The same communication and coverage settings are used for all three runs of algorithms. For all three algorithms the solutions providing the requested coverage are considered as the acceptable results. It worth noting that there is no dependency to the relationship between coverage and connectivity in DICA.

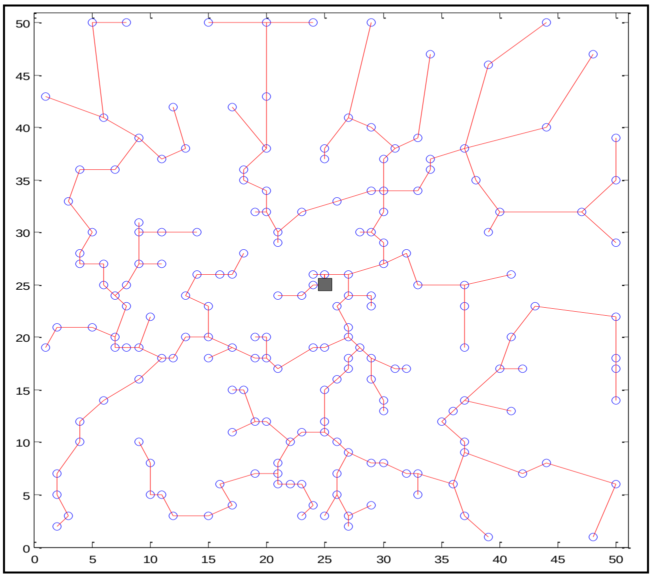

Fig. 4: Node locations resulting from running DICA

From communication quality perspective, the results of three algorithms are illustrated using the APPR for all network nodes in Figure 5 and Figure 6. The APRR diagram for network nodes shows that around 73% of the nodes of the network have an APRR of 70% and above. While the resulting network from PFDA has only 49% of the nodes with 70% and higher value of APRR. On the other hand this value for NSGAII output is 52% of nodes. The only drawback resulting from DICA is the existence of nodes with APRR lower than 50% which covers 16% of network nodes. On the other hand, 5% and 24% of the network nodes for NSGAII and PDFA are assigned with an APRR of 50% and less. This shows that in both 50% and 70% boundaries for APRR, DICA outperforms PDFA while it can only outperform NSGAII for the upper boundary of 70% which is resulting from a much higher density of node deployment in NSGAII.

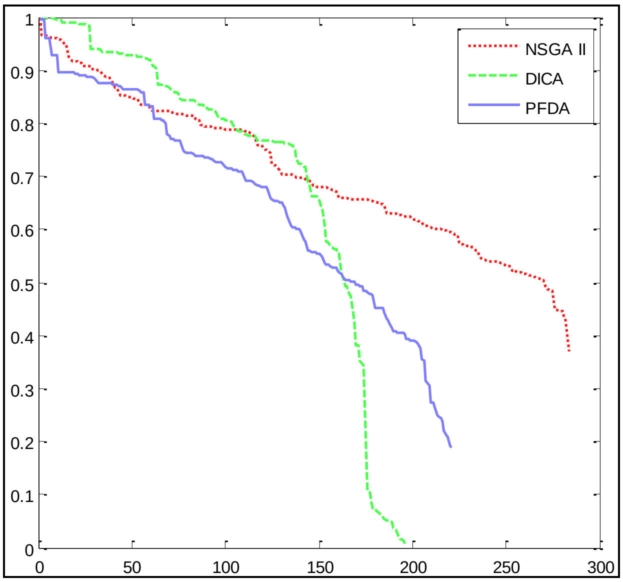

Fig. 5: APRR for network nodes

The density histogram for the APRR of the network nodes is depicted in Figure 6. It can be seen that in comparison to the NSGAII and PDFA, DICA has more nodes with APPR close to 100%.

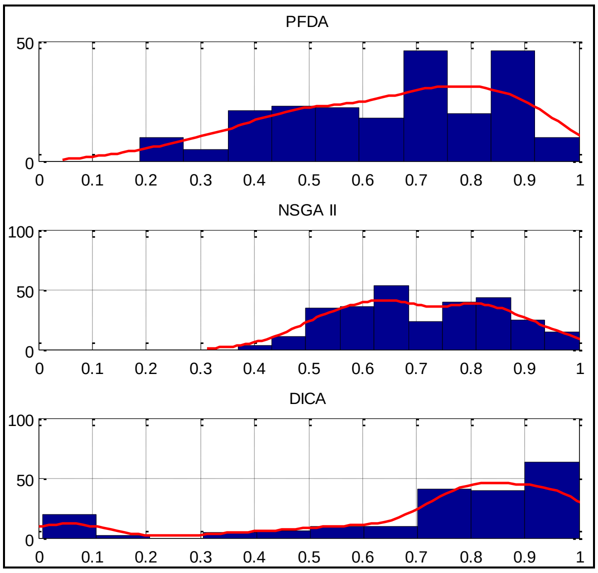

Fig. 6: Density histogram for APPR of the network

5. Conclusion

We have proposed a new deployment strategy based on ICA which can provide the desired coverage while maintaining network connectivity. At the same time the output of the algorithm is utilizing relatively low number of nodes with high APRR parameter. The design of the algorithm enables the network designer to adjust the resulting deployment density to achieve a desired APRR.

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