Multiple Target Discovery and Coverage with Mobile Wireless Sensors

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Environmental monitoring has become a typical application of wireless sensor networks. The concept of monitoring certain points in the sensor field instead of the whole field area helps in reducing the costs of the deployment and improving the performance in terms of coverage. However, the problems of environment exploration, multiple target coverage and connectivity preservation are still solved separately and there are no works that combine the aforementioned problems into a single deployment scheme. In this work, we present a novel approach for mobile sensor deployment, where we combine the environment exploration with with network connectivity preservation and multiple target coverage. We examine the performance of our scheme through extensive simulation campaigns.

Keywords: wireless sensor networks, deployment, distributed algorithm, target coverage

1 Introduction

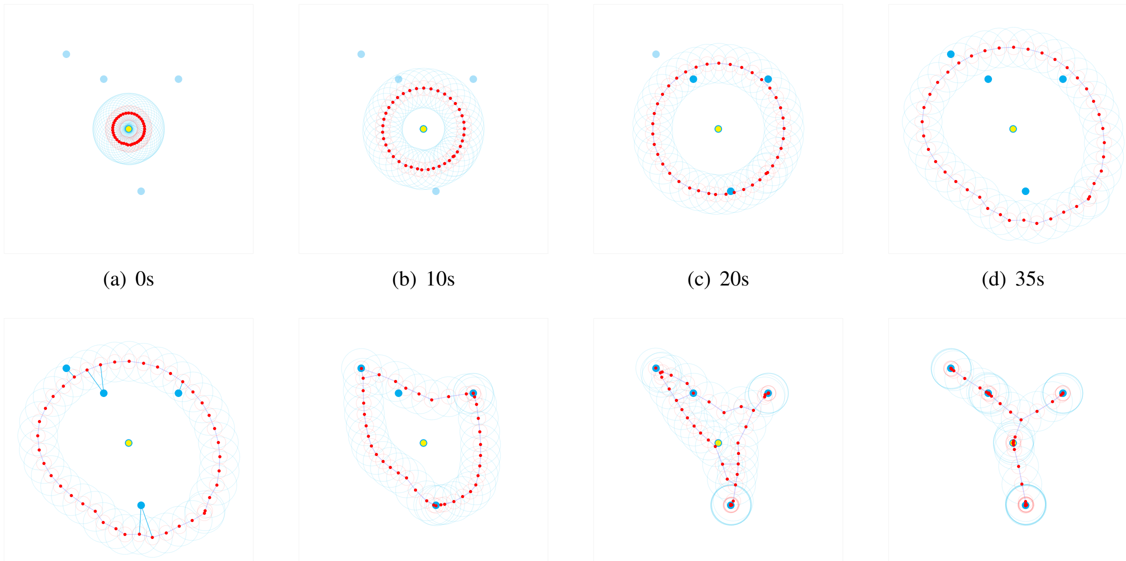
A typical application of wireless sensor networks is environmental monitoring. The sensors have to be deployed and placed on strategic locations to monitor the area of interest. In many cases, monitoring the whole area might be unnecessary. Therefore, monitoring some points of interest increases the sensing performance and reduces the deployment cost.

Obtaining all the necessary information about the environment is not an easy task, especially if the dynamic nature of the observed processes is taken into account. Furthermore, combining target coverage with the connectivity of each sensor with the data sink is a challenging problem in mobile sensor deployment. Therefore, target coverage and environment exploration are opposing demands if the same set of devices is used for both operations, and in order to cover the targets in the field of interest, mobile sensors have to self-deploy in a certain manner and to adjust their positions according to the positions of the targets that have to be covered, which excludes the application of any standard environment exploration technique.

The coverage and monitoring of a point, an area of interest or the whole sensor field is a subject covered from both the ad hoc and sensor and the robotics community by using different approaches and by focussing on different aspects. In [YA08] and [WLM09], authors survey and a classify strategies and techniques for node placement and movement strategies for improving network coverage, respectively. The work from the robotics community that considers exploration and coverage of the network is [BS03]. The exploration phase is performed by mobile robots and driven by a network of radio beacons which assists the robot(s) also during the coverage. One of the works that introduces the concept of virtual forces and potential fields to achieve the environmental exploration is [HMS02]. However, in this works, authors do not consider the network connectivity issues.

In this work, we propose a novel approach that integrates the three mentioned objectives into one simple distributed sensor deployment scheme without considering any additional pre-deployed hardware. Our approach is based on virtual force driven network expanding in order to cover the largest area possible while preserving connectivity and network collapsing in a specific manner that connects the discovered targets with the base station. The algorithm that we propose is distributed in nature and runs on all the sensors using only the one hop information from their neighbors.

The rest of the paper is organized as follows : the approach for target discovery and coverage, together with the algorithm that combines them, are analyzed in Section 2). The performance of our approach is evaluated in Section 3. Conclusions are drawn in Section 4.



(a) 0s (b) 10s (c) 20s (d) 35s

(e) 0s (f) 15s (g) 30s (h) 47s

FIGURE 1: Target discovery and coverage with 30 sensors.

2 Deployment algorithm

In this section we present our approach to target discovery and coverage with networks connectivity preservation. We assume that all the targets are located at different unknown positions. The approach in general is divided into two parts : *target discovery* and *target coverage*. In the first part the goal is to discover the largest area possible in search for targets while preserving the network connected. In the second part, sensors create the multi-hop link between the targets and the base station. The objective is to minimize the number of relaying sensors in order to maximize the number of covering sensors.

During the discovery phase, each sensor calculates the resulting repulsive virtual force direction and magnitude, referring to the base station position and the positions of Relative Neighborhood Graph (RNG) neighbors in the neighborhood table. Resulting virtual force is the sum of the forces exerted by the base station and RNG neighbors $\overrightarrow{F} = -(C_B\overrightarrow{j_B} + \sum_{i=1}^{n_{RNG}} \frac{C_N}{d_i^2}\overrightarrow{j_i})$, where $\overrightarrow{j_B}$ and $\overrightarrow{j_i}$ are unit vectors pointing to the base station and RNG neighbors, respectively. The RNG neighborhood of the node u is referred to as $RNG(u)$, while n_{RNG} represents the number of sensors in $RNG(u)$. After the virtual force is known, each sensor calculates its maximal allowed movement distance (d_{max}) that guarantees network connectivity preservation. The distance d_{max} is calculated as expressed in Equation 1 by using sensors' communication range (R), distance to the i^{th} RNG neighbor (d_i) and the angle between sensor's heading and direction towards the i_{th} RNG neighbor (α_i).

$$d_{max} = \min\{(R\cos\alpha_i + \sqrt{d_i^2 - R^2\sin^2\alpha_i})/2, i \in RNG(u)\} \quad (1)$$

In the beginning (Figure 1(a)), all the sensors are located in the vicinity of the base station. When the deployment starts, all the sensor react to the virtual forces and the network is spread, shown in 1(b), 1(c) and 1(d). If a target is detected during the network spreading, the information regarding the target is shared with the RNG neighborhood. The details about the communication protocol are out of the scope of this work. Due to the connectivity preservation condition, all the sensors eventually stop with their movement, forming an approximate to the circle. The discovery phase ends after $35s$.

In order to achieve the maximal target coverage with minimized number of sensors used for the connectivity, a sensor applies the virtual force which is the sum of the forces towards the target and neighbors in the RNG table $\overrightarrow{F} = (C_T/d_T^2)\overrightarrow{j_T}$ if it covers the target, or $\overrightarrow{F} = (C_T/d_T^2)\overrightarrow{j_T} + \sum_{i=1}^{n_{RNG}} C_N d_i \overrightarrow{j_i} + C_B\overrightarrow{j_B}$ otherwise.

After the force calculation is finished, the sensor moves accordingly, respecting the Equation 1.

The starting configuration of the coverage phase is the network that is maximally spread (Figure 1(e)). In this phase, a sensor includes all known targets in its neighborhood table and in the RNG neighborhood reduction. Therefore, only certain sensors will have the target in its RNG neighborhood and in the virtual force component as well (the links to the targets are shown in Figure 1(e)). By applying the virtual force driven movement, sensors achieve the target coverage as shown in Figures 1(f) to 1(h). The coverage phase is finished after 47*s* seconds.

Algorithm 1: Target Discovery and Coverage Algorithm (TDCA) for target discovery and deployment that is run on a sensor u.

Phase = discovery
repeat
  Calculate the $RNG(u)$
  if *Phase == Discovery* **then**
    $\overrightarrow{F} = -(C_B\overrightarrow{j_B} + \sum_{i=1}^{n_{RNG}} \frac{C_N}{d_i^2}\overrightarrow{j_i})$
    if *Target is discovered* **then**
      Add $T_i(x,y)$ in the neighborhood table
  else
    if *Covering the target* **then**
      $\overrightarrow{F} = \frac{C_T}{d_T^2}$
    else
      $\overrightarrow{F} = \frac{C_T}{d_T^2}\overrightarrow{j_T} + \sum_{i=1}^{n_{RNG}} C_N d_i \overrightarrow{j_i} + C_B\overrightarrow{j_B}$
  $d_{max} = \min\{(R\cos\alpha_i + \sqrt{d_i^2 - R^2\sin^2\alpha_i})/2, i \in RNG(u)\}$
  if $d_{max} == 0$ **then**
    Phase = Coverage
until *Target is covered*

Details about the Target Discovery and Coverage Algorithm (TDCA) that runs on each node and uses only locally available information regarding the targets and neighboring sensors are shown in Algorithm 1.

3 Approach evaluation

In this section we analyze the discovery and coverage quality of proposed algorithm. We run 1000 simulations with different number or sensors and different number of targets on unknown locations. All the simulation parameters that we use are listed in Table 1. The simulator used in this work is WSNet[†].

We compare the total area discovered by mobile sensors applying the TDCA with the ideal case where mobile sensors form a circle. Each sensor in ideal case is placed on the circle edge and has two neighbors at distance $2r_S$, where r_S represents the sensors' sensing range. Ideal discovered area (when sensors form a circle) depending on the number of sensors n is therefore $A_n = (nr_S)^2/\pi$. Figure 2(a) presents the results regarding the area discovery after 1000 simulation runs. The deviation in the discovered area are present

†. Event-driven simulator for large scale wireless sensors networks, http ://wsnet.gforge.inria.fr/

TABLE 1: Simulation parameters

Area	Sensors	Targets	Speed	Sensing range, r_S	Comm. range, r_C	C_B	C_T	C_N
$100x100m$	20-40	1-5	$1m/s$	$5m$	$10m$	10^4	10^4	10^2

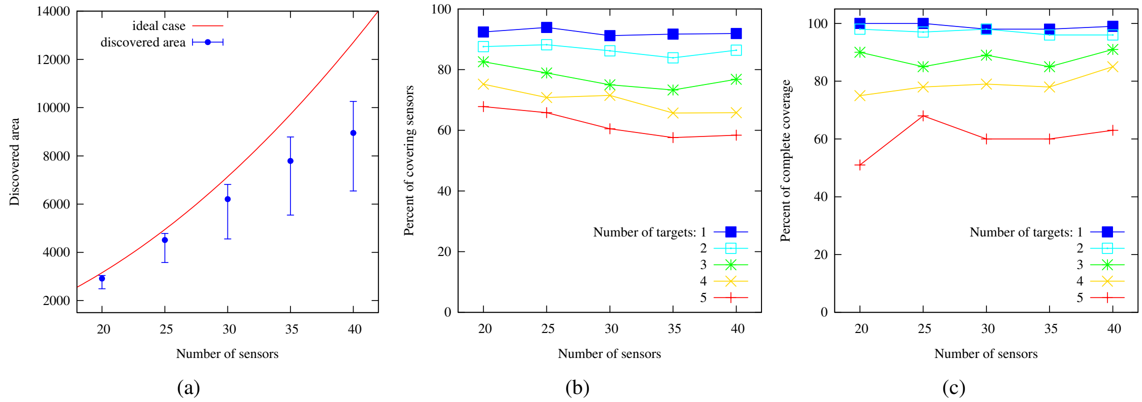


FIGURE 2: Total discovered area in relation to the number of sensors (a), complete coverage evaluation (b) and the percent of sensors used for the target coverage(c) in 1000 different simulation runs.

due to the boundaries of the deployment area that prevent the circle formation. However, it is worth noting that, applying TDCA allows the target discovery in irregularly shaped areas.

The coverage quality expressed with the percent of sensors used for the target coverage is presented in Figure 2(b). Simulation results show that in the case of 1 target that has to be covered, minimum of 92% of sensors in the field is used for the target coverage(83%, 73%, 66% and 58% of sensors for the case of 2, 3, 4 and 5, respectively). Figure 2(c) presents the results for the percent of complete coverage with varied number of sensors used and different number of targets.

4 Conclusion

In this work, we presented the distributed approach for multiple target discovery and coverage with mobile sensors. Target location are unknown in the beginning of the deployment and, therefore, we introduced two separated phases of deployment : target discovery and coverage. Both deployment phases are integrated into our multiple Target Discovery and Coverage Algorithm (TDCA). The algorithm relies on the virtual force calculations based on the target, base station and Relative Neighborhood Graph neighbors' locations. Unlike other works in this field, we integrate the network connectivity preservation technique that ensures that the connectivity is preserved all throughout the deployment procedure. The performance of our approach is examined through extensive simulation campaigns. Future work in this field will include communication and energy consumption aspects of our proposed approach.

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