Snap and Spread: a self-deployment algorithm for mobile sensor networks [*]

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Abstract. The use of mobile sensors is motivated by the necessity to monitor critical areas where sensor deployment cannot be performed manually. In these working scenarios, sensors must adapt their initial position to reach a final deployment which meets some given performance objectives such as coverage extension and uniformity, total moving distance, number of message exchanges and convergence rate.

We propose an original algorithm for autonomous deployment of mobile sensors called SNAP & SPREAD. Decisions regarding the behavior of each sensor are based on locally available information and do not require any prior knowledge of the operating conditions nor any manual tuning of key parameters. We conduct extensive simulations to evaluate the performance of our algorithm. This experimental study shows that, unlike previous solutions, our algorithm reaches a final stable deployment, uniformly covering even irregular target areas. Simulations also give insights on the choice of some algorithm variants that may be used under some different operative settings.

1 Introduction

The necessity to monitor environments where critical conditions impede the manual deployment of static sensors motivates the research on mobile sensor networks. In these working scenarios, sensors are initially dropped from an aircraft or sent from a safe location, so that their initial deployment does not guarantee full coverage and uniform sensor distribution over the area of interest (AOI) as would be necessary to enhance the sensing capabilities and extend the network lifetime. Mobile sensors can dynamically adjust their position to reach a better coverage and more uniform placement. Due to the limited power availability at each sensor, energy consumption is a primary issue in the design of any self-deployment scheme for mobile sensors. Since sensor movements and, to a minor extent, message exchanges, are energy consuming activities, a deployment algorithm should minimize movements and message exchanges during deployment, while pursuing a satisfactory coverage.

The impressively growing interest in self-managing systems, starting from several industrial initiatives from IBM [2], Hewlett Packard [3] and Microsoft [4], has led to various approaches for self-deploying mobile sensors. The virtual force approach (VFA) proposed in [5–7], and its variants proposed in [8–10], model the interactions among

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[*] The full version of this paper is [1].

sensors as a combination of attractive and repulsive forces. This approach requires a laborious and off-line definition of parameter thresholds, it presents oscillatory sensor behavior and does not guarantee the coverage in presence of narrows. The Voronoi approach, detailed in [11], provides that sensors calculate their Voronoi cell to detect coverage holes and adjust their position. This approach is not designed to improve the uniformity of an already complete coverage and does not support non convex AOIs.

The main contribution of this paper is the original algorithm for mobile sensor self-deployment, SNAP & SPREAD, with self-configuration and self-adaptation properties. Each sensor regulates its movements on the basis of locally available information with no need of prior knowledge of the operative scenario or manual tuning of key parameters. The proposed algorithm quickly converges to a uniform and regular sensor deployment over the AOI, independently of its shape and of the initial sensor deployment. It makes the sensors traverse small distances, avoiding useless movements, ensuring low energy consumption and stability. Furthermore, it outperforms previous approaches in terms of coverage uniformity.

2 The SNAP & SPREAD algorithm

The deployed sensors coordinate their movements to form a hexagonal tiling, that corresponds to a triangular lattice arrangement with side R_{S}, where R_{S} is the *sensing radius*. This deployment guarantees optimal coverage (as discussed in [12]) and connectivity when $R_{\mathsf{S}} \leq \sqrt{3}R_{\mathsf{TX}}$, where R_{TX} is the *transmission radius*. To achieve this arrangement, some sensors snap to the centers of the hexagonal tiling and spread the others to uniformly cover the AOI. These snap and spread actions are performed in an interleaved manner so that the final deployment consists in having at least one sensor in each tile.

One sensor, $s_{\mathtt{init}}$, is assigned the role of starter of the tiling procedure, while others may also concurrently act as starters, for fault tolerance purposes. The starter sensor gives rise to the **snap activity** selecting at most six sensors among those located in radio proximity and making them snap to the center of adjacent hexagons. Such deployed sensors, in their turn, give start to an analogous selection and snap activity thus expanding the tiling. This process goes on until no other snaps are possible, either because the AOI is completely covered, or because all the sensors that are located at boundary tiles do not have any further sensor to snap.

The **spread activity** provides that un-snapped sensors are pushed toward low density zones. Let $S(x)$ be the number of sensors located in the same hexagon as sensor x. Given two snapped sensors p and q located in radio proximity from each other, if $|S(p)| > |S(q)|$, p and q can negotiate the movement (push) of a sensor from the hexagon of p to the hexagon of q. Cyclic sensor movements are kept under control by imposing a *Moving Condition*, that we detail in [1].

The combination of these two activities expands the tiling and, at the same time, does its best to uniformly distribute redundant sensors over the tiled area.

Figure 1 shows an example of the algorithm execution. Figure (a) depicts the starting configuration, with nine randomly placed sensors and (b) highlights the role of $s_{\mathtt{init}}$, which starts the hexagonal tiling. In (c) the starter sensor $s_{\mathtt{init}}$ snaps six sensors to the center of the adjacent hexagons, according to the minimum distance criterion. Figure

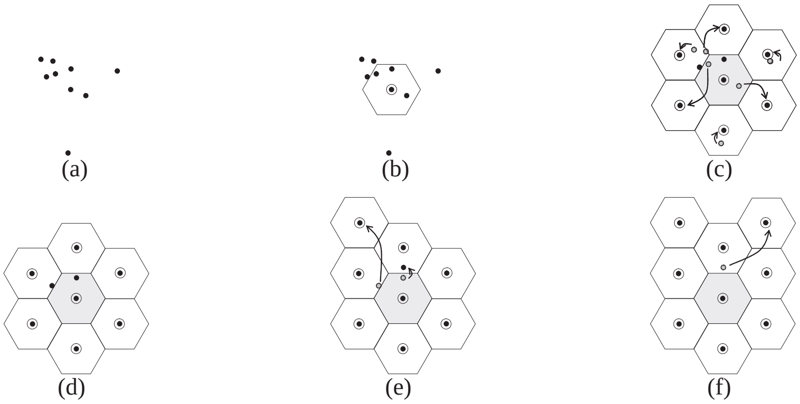
(a) (b) (c) (d) (e) (f)

Fig. 1. Snap and spread actions: an example.

(d) shows the configuration after the snap action of $s_{\texttt{init}}$. In Figure (e) $s_{\texttt{init}}$ starts the spread action sending its redundant sensors to a lower density hexagon, while one of the sensors deployed in (c) starts a new snap action. Figure (f) shows the snap of the last redundant sensor just pushed by the starter, thus reaching the final configuration.

Since some performance objectives such as average traversed distance, network lifetime and coverage extension may be in contrast with each other, we introduce some algorithm variants that specifically prioritize one objective over the others.

According to the Basic Version (BV) of Snap & Spread, the un-snapped sensors that are located in already tiled areas, consume more energy than snapped sensors, because they are involved in a larger number of message exchanges and movements. We introduce an algorithm variant, named Uniform Energy Consumption (UEC), to balance the energy consumption over the set of available sensors making them exchange their roles.

A second variant named Density Threshold (DT), provides that a sensor movement from the hexagon of p to the hexagon of q is allowed if, besides the Moving Condition, the constraint $|S(q)| < T_d$ is satisfied, that is the number of sensors located in the hexagon of q is lower than a *density threshold* T_d. This variant avoids unnecessary movements of sensors to already overcrowded hexagons that certainly exceed the optimal density. Notice that when $T_d \leq 1$, this variant can not be applied as it could limit the flow of redundant sensors to the AOI boundaries, thus impeding the coverage completion.

Due to space limitations we refer the reader to [1] for deeper details.

3 Simulation results

In order to study the performance of Snap & Spread and its variants, we developed a simulator on the basis of the wireless module of the OPNET modeler software [13].

In the following experiments we set $R_{\mathsf{TX}} = 2\sqrt{3}R_{\mathsf{S}}$ with $R_{\mathsf{S}} = 5$ m. This setting guarantees that each snapped sensor is able to communicate with the snapped sensors located two hexagons apart. This choice allows us to show the benefits of the role exchange mechanism (UEC variant) whereas it does not imply significant changes in the qualitative analysis with respect to other settings. In all the experiments of this section we assume that the sensor speed is 1 mt/sec.

The following figures 2 e 3 show how SNAP & SPREAD performs when starting from an initial configuration where 150 sensors are sent from a high density region. In figure 2 the AOI is a square 80 m × 80 m while in figure 3 the AOI has a more complex shape in which a narrows connects two regions 40 m × 40 m. Note that previous approaches fail when applied to irregular AOIs such as the one considered in figure 3.

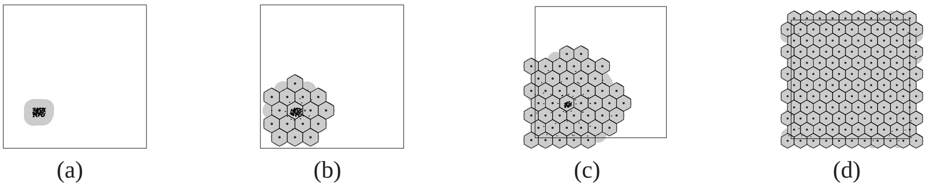
(a) (b) (c) (d)

Fig. 2. Sensor deployment on a square, starting from a dense configuration

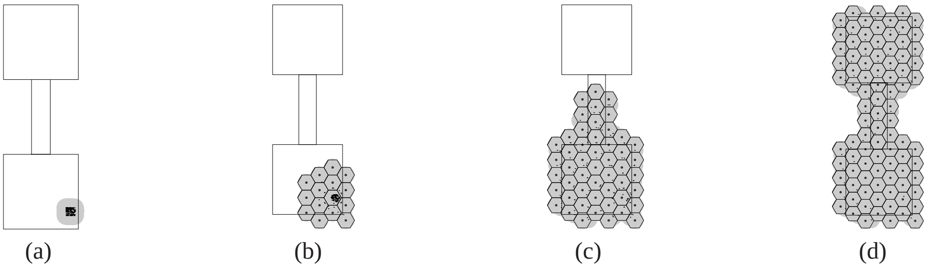
(a) (b) (c) (d)

Fig. 3. Sensor deployment on an irregular AOI, starting from a dense configuration

Figure 4 shows instead how SNAP & SPREAD covers a square 80 m × 80 m starting from a random initial deployment of 150 sensors. Either starting from a high density distribution or from a random one, the algorithm SNAP & SPREAD completely covers the AOI. Of course, the coverage is much faster and consumes less energy when starting from a random configuration.

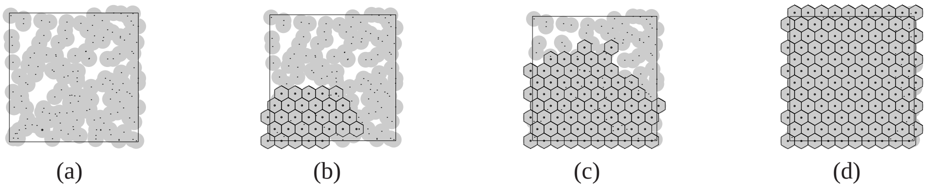
(a) (b) (c) (d)

Fig. 4. Sensor deployment on a square, starting from a uniform configuration

In the figures from 5 to 8, we show some performance comparisons among the basic version BV of SNAP & SPREAD and its two variants DT and UEC. This set of simulations is conducted on the scenario described in figure 2 (a), with a high density zone in the initial sensor configuration. Notice that in all the figures, in the case of variant DT the line starts when the number of sensor is 150. This is because this variant has been designed to work when the number of sensors is sufficient to entirely cover the AOI, i.e. when the threshold T_d can be reasonably set to a value larger than 1.

Figure 5 shows the time to converge to a final deployment when varying the number of available sensors. When the number of available sensors is lower than strictly necessary to cover the area even with an optimal distribution, the time to converge to the final solution increases with the number of sensors because more sensors can cover a wider area. Instead, once the number of sensors is high enough to entirely cover the AOI, redundant sensors are helpful to complete the coverage faster. Notice that the convergence time of UEC is larger than the other ones because this variant incurs some overhead to perform role exchanges. The convergence time of DT is slightly larger than the one of BV because of the additional constraint imposed on redundant sensor movements.

Figure 6 shows the percentage of AOI being covered by SNAP & SPREAD and its variants, when increasing the number of sensors. Note that in most cases an incomplete coverage is due to the lack of the necessary number of sensors and not to a wrong behavior of the algorithm.

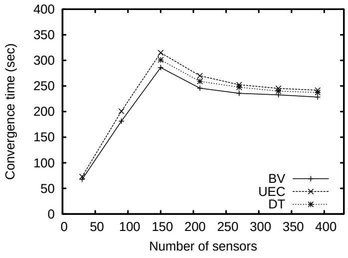

Fig. 5. Convergence Time

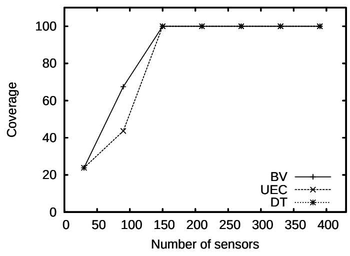

Fig. 6. Coverage

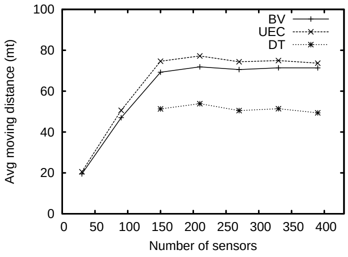

Fig. 7. Average moving distance

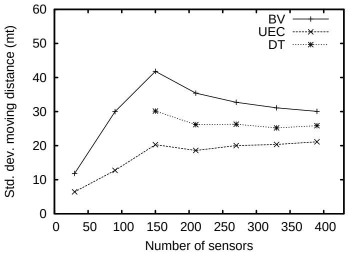

Fig. 8. Std dev of the moving distance

Since both mechanical movements and electronic communications consume energy, of which mechanical motion is the predominant part, we use the average traversed distance as a metric to highlight the energy consumption of the different algorithm variants. Figure 7 shows that variant DT is highly effective in reducing the energy consumed for unnecessary movements.

Figure 8 complements the previous one by showing the effects of the two variants in terms of standard deviation of the traversed distance. Variant UEC significantly reduces the standard deviation with respect to the other variants. Indeed this variant was designed with the purpose to balance the load over all the available sensors and this obviously leads to a lower deviation. This result is important if one of the primary objectives of the deployment is the coverage endurance. The peak in the standard deviation obtained using the basic version of SNAP & SPREAD is due to the snap actions which govern the energy consumption when the number of sensors is less than 150. In the variants without role exchanges (as in BV and DT) the snap actions induce an initially high standard deviation of the traversed distance. Indeed sensors located close to the starter consume less energy than those that have to reach the farthest boundaries of the AOI. As we noticed before, the use of variant DT reduces unnecessary movements and consequently the average energy spent by each sensor. This results in a lower deviation as well.

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