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On the optimal random deployment of wireless sensor networks in non-homogeneous scenarios

J. Vales-Alonso [a,*], F.J. Parrado-García [a], P. López-Matencio [a], J.J. Alcaraz [a], F.J. González-Castaño [b]

[a] Department of Information Technologies and Communications, Technical University of Cartagena, Spain
[b] AtlantTIC, University of Vigo, Spain

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ABSTRACT

Random scattering of WSNs is needed in many practical cases due to the large scale of the network required or to the inaccessibility of the terrain. However several important features of deployments of this type have been neglected due to their analytical complexity. Node placement must guarantee correct operation: if nodes are too separated many would be isolated and data would not reach the sinks. Besides, if the nodes are too close, the area covered would be small and little information would be retrieved. Moreover, the target area cannot be considered homogeneous since in real-life situations some zones are more important than others. This paper addresses these constraints by proposing and solving an optimization problem which maximizes network sensing coverage. In our model several clusters of nodes are spread over the target area following Gaussian random distributions, and the goal is to decide the optimal launch point and the dispersion for each cluster. This corresponds to real situations where clusters are dropped in an airborne launch in which dispersion is controlled by the release altitude. The problem is solved by considering iterative steps where single cluster deployments are addressed. Several tests validate our approach and indicate that our method outperforms previous approaches, especially in deployments with a low number of nodes, which are more challenging from the optimization perspective.

1. Introduction

Wireless Sensor Networks (WSNs) offer new capabilities to study large-scale physical world phenomena, leading to unprecedented observation abilities. Despite the continuous development of WSNs, there still exists a number of open research challenges. Network deployment, for example, remains a critical challenge from an operational and efficiency perspective [1]. Deployment planning requires consideration of account several objectives such as energy consumption, sensing coverage, network lifetime, network connectivity, and so forth. Often these objectives are conflicting, and operational trade-offs must be established during network design.

The two major types of deployments are *deterministic* placement and *random* scattering of nodes. In the former, the positions of sensors can be accurately selected. This is possible for small or medium-scale networks where node cost is a constraint or where only a specified set of sensor locations is available. In other realistic applications, due to the large-scale of the network (which may contain thousands of nodes), or the inaccessibility of the terrain (*e.g.* Martian exploration), random scattering is the most convenient or perhaps the only option.

In this paper, a special *integrated coverage and connectivity* problem [2] is addressed for random deployments. The goal is to find the optimal network deployment scheme that maximizes the joint sensing coverage of the

* Corresponding author. Address: Campus Muralla del Mar, 30202 Cartagena, Spain. Tel.: +34 968 326 588; fax: +34 968 325 973.
E-mail address: javier.vales@upct.es (J. Vales-Alonso).

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nodes, while satisfying connectivity conditions. Our system model considers the following major features:

1. Node placement is inherently random, due to airborne sensor deployment, for example. Nevertheless, it is assumed that the network designer can select certain placement parameters, which allows some control over the position of the nodes.
2. The nodes are grouped in one or more *clusters*, and each cluster placement can be independently controlled. In this work, Gaussian random distributions are assumed for the clusters, since they correspond to actual observed distributions in airborne seeding [3–5]. For each cluster two parameters can be selected: the *target point* (i.e. where the nodes are aimed) and the *dispersion* (i.e. the standard deviation). The latter controls how the nodes are spread from such points and may be easily controlled in airborne placements since it is related to the altitude at which the cluster is released (see [3]).
3. Some zones in the target area are more "important" than others (*non-homogeneous* scenario), distinguishing our model from many previous models which assume a uniformly distributed importance across the target area (see Section 2). In our model a map describes the importance of each point in the operational region. It is assumed that sensors collect information from a small area (sensing coverage), and that overlapping does not provide additional information. Therefore nodes must be spread to avoid overlapping of sensing areas.
4. Sensed data must be delivered to a control node (*sink* node in WSN terminology), otherwise data will be lost. The routing capabilities of WSN make multi-hop transmissions possible, so sensed data can be delivered whenever a path is available. However, some nodes may be isolated (due to random scattering), and the information they gather cannot reach the sink.

Therefore, the challenge is to select suitable target points and dispersions which provide a trade-off between sensing overlapping and the number of isolated nodes. This leads to a complex stochastic optimization problem. As will be discussed later in Section 4, this problem can be efficiently addressed by dividing the optimization into several steps (one per cluster), where simplified placement problems are addressed separately.

Let us remark that, although energy constraints are important in the design of a WSN, this work focuses exclusively on sensing coverage; other constraints are beyond the scope of this paper.

Without loss of generality, this model is inspired by planetary exploration scenarios such as those proposed in [6,7], where the operational region is notably larger than the sensing range of a node. So far, inter–planetary exploration probes and rovers have only been able to land in and explore small areas in a few solar system bodies such as Mars or Saturn's moon Titan. In this scenario the "important areas" may be, for instance, places where the best chances of finding traces of water exist, as has been the goal of NASA's Mars Sojourn rovers Spirit and Opportunity [8].

Within this context, WSN may become a feasible alternative for extending monitoring range. Clusters can be deployed over large important areas, and simple nodes would be in charge of data monitoring. Besides, these nodes, rather than deliver the data directly to Earth (which would require complex communication hardware) would relay it via the sink (a special node with such capability). In addition, the Gaussian distribution, selected to model the network placement, also fits with this scenario. During the terminal descent phase of the probe, the expulsion mechanism can be adjusted to release the nodes at a specific altitude above the surface [7].

1.1. Major contributions of this work

As far as we know, this is the first work to analytically solve the optimality of a WSN random deployment considering Gaussian clusters. Previous works have mainly focused on network connectivity issues in non-clustered WSNs. Moreover, we also integrate the effect of non-homogeneous importance in the target scenario, unlike previous works which have largely ignored it. Let us remark that our analysis can be also applied to homogeneous scenarios (which is a particular case of the non-homogeneous problem). Section 2 discusses these related works.

In summary, the main contributions of this paper are:

- We obtain a mathematical optimization problem from the system model (Section 3). This problem fully integrates both coverage and connectivity issues for clustered networks.
- We demonstrate how the global problem naturally decomposes into smaller problems, each related to the deployment of a single cluster. These problems can be solved simultaneously, leading to a *global optimization* strategy. As will be discussed later, analytical solutions in this field are still unknown. In this paper we develop an approximation to characterize the joint sensing coverage of a cluster. Several tests have been performed on this approach and the results (Section 5) clearly validate it.
- We show that an approximate *iterative optimization* achieves solutions close to the global optimization solutions in complex scenarios while being computationally feasible for any number of clusters, unlike the global optimization which does not scale up well.
- Finally, we have tested this methodology in complex scenarios, including the lunar Tycho crater as the target scenario (see Fig. 4) for our validation tests. Providing coverage to such an extension is a challenging project as will be shown in Section 5.

2. Related work

Deployment optimization focused on either deterministic or random scenarios is a field of increasing interest in WSNs. The problems addressed are related to both communication connectivity and sensing coverage. Optimization of deterministic deployments are surveyed in some