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A novel method for probabilistic coverage estimation of sensor networks based on 3D vector representation in complex urban environments

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Abstract

Wireless Sensor Networks (WSNs) are widely used for monitoring and observation of dynamic phenomena. A sensor in WSNs covers only a limited region, depending on its sensing and communicating ranges, as well as the environment configuration. For efficient deployment of sensors in a WSN the coverage estimation is a critical issue. Probabilistic methods are among the most accurate models proposed for sensor coverage estimation. However, most of these methods are based on raster representation of the environment for coverage estimation which limits their quality. In this paper, we propose a probabilistic method for estimation of the coverage of a sensor network based on 3D vector representation of the environment.

1. Introduction

Nowadays, WSNs have found various applications in industry, security, agriculture, military and disaster management. Efficient monitoring and management of dynamic phenomena in the real world necessitates its efficient and accurate coverage. The efficiency of the coverage of a sensor network depends on optimal position of each sensor node within the network. An individual sensor covers only a limited area, which depends on its sensing capacity, range of communication as well as the environment's complexity. The total area covered by a WSN is obtained from the union of the regions covered by individual sensors. Therefore, efficient deployment of sensors in a WSN is a critical issue that affects the coverage as well as communication between sensors.

Several optimization methods (i.e., global or local, deterministic or stochastic, etc.) have been proposed to detect and eliminate coverage holes and hence increase the coverage of sensor networks (Argany et al. 2015). One of the key issues of all deployment optimization algorithms is accurate estimation of the coverage of an individual sensor. Sensing model of individual sensors ─which could be binary or probabilistic, omnidirectional or directional─ has significant impact on the precise coverage estimation of a sensor network using diverse optimization algorithms. Most of the sensor coverage estimation methods use a raster representation of the environment (Akbarzadeh et al. 2013) for optimization purposes that limits their precision and efficiency. This is because raster representations are constrained by their spatial resolution, and their regular shapes result in redundant data for unoccupied areas. Few vector-based optimization algorithms are proposed in the literature, which are mostly based on 2D vector-based representation of the environment and do not adequately consider the presence of manmade and natural obstacles in the sensing areas (Wang and Cao 2011).

To overcome these limitations, in this paper we propose a probabilistic sensor coverage estimation method based on precise 3D vector-base representation of the environment and we present some results of an ongoing research project that aims at better optimization of a sensor network in a 3D complex urban area.

2. Probabilistic sensing models

Akbarzadeh et al. (2013) presented an improvement to optimization models by proposing a probabilistic sensing model for individual sensors that considers not only the impact of distance on sensing capacity, but also the impact of angle between the sensor direction and the line connecting the sensor to a given target (Figure 1). However, this model is still limited in accurately optimizing and estimating the coverage of a sensor network as it is based on a raster representation of the environment.

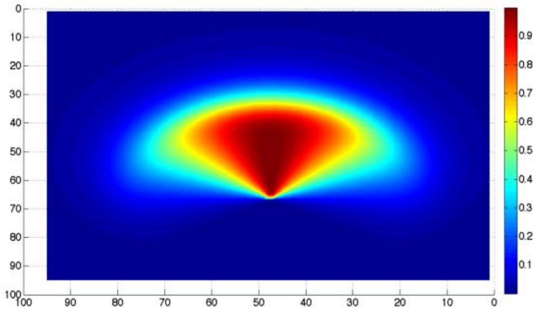


Figure 1: Probabilistic sensing model of a sensor with limited distance and angle range (Akbarzadeh 2013)

Advances in geospatial methods and technologies provide precise and timely collection of 3D spatial data allowing the creation of multi-resolution and multi-purpose 3D vector model of the environment that can significantly improve the efficiency and accuracy of optimization and coverage estimation of a sensor network in a 3D urban environment.

3. 3D vector-based Probabilistic sensor coverage estimation

Consider a representation of the environment as a set of polygons that form buildings, terrain and obstacles, and a sensor that has a limited range in distance and field of view. Then, in a 3D probabilistic sensor coverage model, quality of detection of a polygon depends on its distance to the sensor as well as the angle between the polygon and the sensor. In Figure 2, for example, polygon **A** is further from sensor **S** compared to polygon **B**, thus polygon **A** is detected with a lower quality than polygon **B**. On the other hand, although polygons **B** and **C** are, in average, located at the same distance to the sensor **S**, polygon **C** has a lower detection quality than polygon **B** as it has a more oblique direction respect to the sensor **S**. Even, as the distance and direction differ from point to point on an individual polygon, each point on a polygon may have a different detection quality.

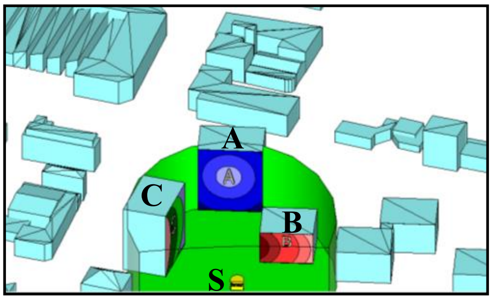


Figure 2: Detection quality of target based on distance and direction.

To practically implement the proposed methodology, the polygons, or the fraction of polygons, that are visible by the sensor are determined (Afghantoloee *et al.* 2014). Then, these visible polygons are discretized to a grid (Figure 3) and the detection quality of cells is estimated and finally categorized to certain classes.

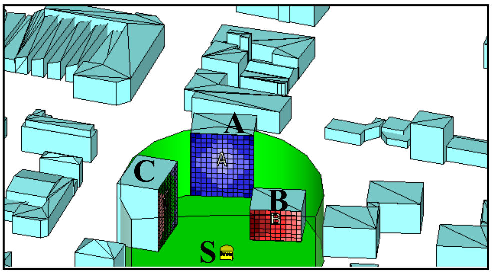


Figure 3: Surface rasterizing in 3D space.

The detection quality of a cell is determined using the area of each cell multiplied by the probability of coverage respect to its distance and direction from the sensor. This is obtained using the following equations (Akbarzadeh et al. 2013):

$$C = Area(q) * P(\|q - p_s\|) * P(\theta - \angle(q, p_s)) \tag{1}$$

$$P(\|q - p_s\|) = \begin{cases} \dfrac{1}{1 + \exp\left[-\dfrac{\alpha}{\|q - p_s\|} - \beta\right]} & \|q - p_s\| \le d_s \\ 0 & otherwise \end{cases} \tag{2}$$

$$P(\|q - p_s\|) = \begin{cases} (\dfrac{\cos(\theta - \angle(q, p_s)) + 1}{2})^{\omega} & (\theta - \angle(q, p_s)) \in [-\alpha_s, \alpha_s] \\ 0 & otherwise \end{cases} \tag{3}$$

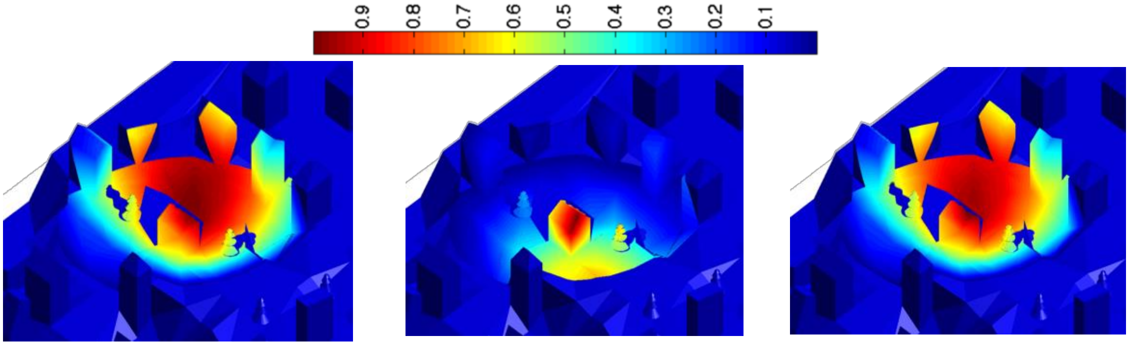
where *Area(q)* is the area of the pixel q; d_s *and* α_s are respectively the distance and angle range of the sensor; $\angle(q,p_s)$ is the pan angle of the sensor relative to the pixel q; $\|q-p_s\|$ is the distance between the sensor and pixel q; θ is pan angle of the sensor; and α, β, and ω are the parameters for configuring the probability function which can be estimated from the observation behavior of the sensor.

4. Case study

In order to evaluate the proposed strategy, a directional sensor with a 3 and 30 meters height and radius, pan angle of 45° and direction of [1,1,-1] was considered in 3D environment. The parameters α, β, and ω are respectively considered as 350, 10, and 3. All features in the 3D vector model are constructed by polygons with 1 cm accuracy, which have a counterclockwise structure. Using perspective based visibility estimation methodology and 3D rasterizing of the polygons, the probabilistic coverage of all cells of the 3D model was calculated. Figure 4 illustrates the probabilistic coverage considering (a) distance, (b) direction and (c) both together. Figure 5 shows the results for the same case in a 2.5 raster dimension model with 20 cm resolution. Comparing the results (Table 1) indicates that the proposed strategy allows a more precise probabilistic coverage estimation compared to a raster model.

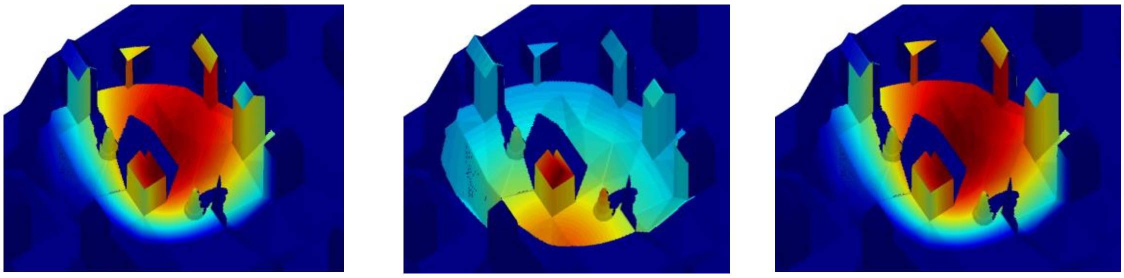
4. Conclusions

This paper proposed a novel method based on 3D urban vector models for estimation of the coverage of wireless sensor networks. This method has more advantages compared to raster-based DSM/DEM models as it considers the coverage of all facets of features like buildings and walls, and even under the features such as bridges and balconies. The proposed method for a probabilistic sensing estimation model led to a more realistic coverage estimation for individual sensors in a sensor network in a 3D complex environment.



(a) (b) (c)

Figure 4: Probabilistic coverage estimation in a 3D vector model: (a) direction (b) distance, and (c) both together.



(a) (b) (c)

Figure 5: Probabilistic coverage estimation in a raster model: (a) direction (b) distance, and (c) both together.

Table 1. The comparison coverage probabilistic estimation in Raster and Vector model.

Coverage probability	Raster_20cm (m^2)	Vector_without wall (m^2)	Vector_with wall (m^2)
Distance	438.66	446.5768	691.6791
Direction	1329.570	1349.364	2073.376
Distance & Direction	364.928	370.363	568.989

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