Systematic Random Deployment for Wireless Sensor Network in Agricultural Sampling-Interpolation Applications

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Abstract. Wireless sensor network can act as a distributed sampling system in precision farming applications which aim at estimating the spatiotemporal variability. Sensor nodes should be deployed referring to the communication range r_c and the sampling range r_s instead of the sensing range. In this paper, a kind of systematic random deployment based on three popular regular patterns-equilateral triangle, square and hexagon is explored to achieve both coverage and connectivity. The efficiency of different regular patterns of systematic random deployment is also compared, thus enabling to make a better deployment decision for different values of r_c/r_s.

Keywords: Precision farming, Wireless sensor network, Sensor nodes deployment.

1 Introduction

Precision farming demands soil, microclimate, crop and other field data for spatial and temporal variability analysis [1]. But limited samples could not explain exactly the variability and support farming decision. The application of Wireless Sensor Network (WSN) technology could provide the optimal and integrated solution for real-time data acquisition, reliable transport, aggregation, in-network processing and statistics [2]. The potential benefits of using the WSN technology resulted in the appearance of a large number of academic and industrial R&D projects in agriculture. Lofar Agro project resulted in an experimental WSN installation in a potato field. The purpose of the WSN is to measure the microclimate factors essential to resist the phytophtora disease [3]. Camalie vineyard currently had an advanced soil moisture monitoring system named Camalie Net. It used twenty Mica2dot motes of Crossbow Inc. to establish the network. These motes sent data of temperature, soil moisture and soil temperature to a central computer once every 10 minutes [4]. It is obvious that wireless

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sensor networks could act as a distributed sampling system in precision farming applications, which aim at estimating the spatiotemporal variability.

Sensor nodes deployment is one of the primary issues for any WSN application. Most researches on deployment concentrate on event detection applications, which aim to detect when and where particular event takes place such as the start of a fire. The communication range and the sensing range are introduced to design the deployment in such applications. However, WSNs in precision farming are mostly kind of continuous sampling-interpolation applications different from event detection. The goal of the network is to carry out continuous spatiotemporal sampling and build field data distribution map by interpolating the values of the field where no sensor reading exist. The sensing range is largely meaningless in this case unlike in the event detection class of sensor networks. In this paper, the sampling range is proposed for WSN deployment instead of the sensing range. A kind of systematic random deployment based on regular patterns to achieve both coverage and connectivity is discussed.

2 Systematic Random Deployment

Wireless sensor nodes could be generally placed in three methods including random deployment, regular deployment and customized deployment [5]. Taking the agricultural scenario, sensors could be mostly possible installed during terrain preparation. It is a good choice for sensor node deployment referring to traditional sampling methods.

The most commonly used sampling design for spatial data is systematic sampling in agricultural experiments because it is easy to implement. A Square grid, an equilateral triangle grid or a regular hexagonal grid is commonly chosen in systematic sampling. Liu et al. show how to deploy sensor nodes in regular patterns in farmland environmental monitoring applications [6]. But Systematic sampling does have a few disadvantages for spatial correlation analysis. There is a danger that the systematic grid might coincide with a systematic feature of the landscape, especially in man made landscapes. Systematic random sampling is another type of sampling spreading the data in space in a similar fashion as systematic sampling. One sampling unit is selected at random in each grid cell. It is more efficient for spatially correlated data than systematic sampling and simple random sampling.

Consequently we present systematic random deployment approach for wireless sensor network in agricultural sampling-interpolation applications. However, it is different from pure sampling that the network connectivity has to be maintained in the sensor nodes deployment at the same time.

Firstly, some definitions and the model description in this paper are as follows.

Definition 1: Let $\{x_0, \cdots, x_{n-1}\}$ be the locations of n sensor nodes spread over a 2-D monitoring area.

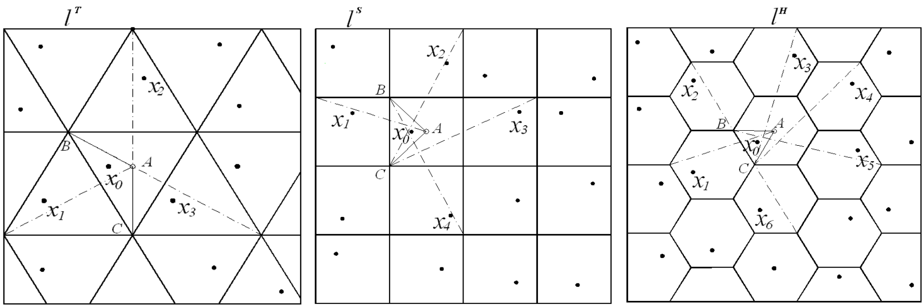
Definition 2: Let there be m environmental variables to be sampled by each sensor node in the monitoring network.

Definition 3: Each environmental variable has the spatial correlation. It has a sampling range r^i_s, which could be determined according to historical data, experience results or some literature. r_s is defined as the sampling range for the whole network. Then

$$r_s = \min(r_s^i) \quad i = 1, \cdots, m \tag{1}$$

Definition 4: Each active node has a communication range of r_c, and two active nodes can communicate reliably at a distance of r_c or less. In addition, all nodes have the same communication ranges.

Systematic random deployment is designed based on three popular regular patterns including an equilateral triangle pattern, a square pattern and a regular hexagonal pattern (shown in Fig.1). We need to address the following two questions. (1) How to determine the optimal grid size for these systematic random deployment patterns? (2) Which is the best pattern on the efficiency among these systematic random deployment patterns? We explained the first question in Section 3 and the second in Section 4.



(a) An equilateral triangle pattern (b) A square pattern (c) A regular hexagonal pattern

Fig. 1. Systematic random deployment

3 Optimal Grid Size of Different Deployment Patterns

Let l^T, l^S, l^H denote the grid side length of regular deployment patterns-triangular, square and hexagon. In terms of sampling requirements, the feasible grid size could be determined by the criterion of system sampling patterns-equilateral triangle, square and hexagon. Then,

$$l^T \le \sqrt{3} r_s \tag{2}$$

$$l^S \le r_s \tag{3}$$

$$l^H \le \frac{\sqrt{3}}{3} r_s \tag{4}$$

To achieve connectivity, the communication range r_c must be also considered. In Fig.1a, x_0 is the sensor node with three neighboring nodes x_1, x_2 ,x_3. Let x_0 locate in $\triangle ABC$. Considering connectivity requirement, at least one of the respective distances from x_0 to x_1 ,x_2 ,x_3 is less than r_c. Hence, we must have

$$\begin{cases} \frac{\sqrt{3}}{3} r_c < l^T \le \frac{\sqrt{3}}{2} r_c & \text{at least 1 - } \textit{connectivity} \\ l^T \le \frac{\sqrt{3}}{3} r_c & \text{at least 3 - } \textit{connectivity} \end{cases} \tag{5}$$

Let l^T_{max} denote the maximum grid side length of the equilateral triangle pattern. Using (2) and (5), then

$$l^T_{\max} = \begin{cases} \sqrt{3}\min\left(r_s, \frac{1}{2} r_c \right) & \text{at least 1 - } \textit{connectivity} \\ \sqrt{3}\min\left(r_s, \frac{1}{3} r_c \right) & \text{at least 3 - } \textit{connectivity} \end{cases} \tag{6}$$

Similar calculation could be used for the other two patterns. Let l^S_{max}, l^H_{max} denote the maximum grid side length of the square and hexagon pattern respectively. Hence, we obtain

$$l^S_{\max} = \begin{cases} \min\left(r_s, \frac{\sqrt{10}}{5} r_c \right) & \text{at least 1 - } \textit{connectivity} \\ \min\left(r_s, \frac{\sqrt{5}}{5} r_c \right) & \text{at least 4 - } \textit{connectivity} \end{cases} \tag{7}$$

$$l^H_{\max} = \begin{cases} \min\left(\frac{\sqrt{3}}{3} r_s, \frac{\sqrt{7}}{7} r_c \right) & \text{at least 1 - } \textit{connectivity} \\ \frac{1}{3}\min\left(\sqrt{3} r_s, r_c\right) & \text{at least 3 - } \textit{connectivity} \\ \min\left(\frac{\sqrt{3}}{3} r_s, \frac{\sqrt{13}}{13} r_c \right) & \text{at least 6 - } \textit{connectivity} \end{cases} \tag{8}$$

4 Efficiency Comparison of Different Deployment Patterns

Which is the best pattern on the efficiency among these systematic random deployment patterns? For the same field, the number of sensor nodes could be calculated using the area of grid cell. The bigger the grid cell area, the fewer required nodes.

$A^T{}_{max,}$ $A^S{}_{max,}$ $A^H{}_{max}$ are denoted the maximum area of grid cell in equilateral triangle, square and hexagonal patterns respectively. Then

$$A^T_{\max} = \frac{\sqrt{3}}{4}\left(l^T_{\max}\right)^2 \tag{9}$$

$$A^S_{\max} = \left(l^S_{\max}\right)^2 \tag{10}$$

$$A^H_{\max} = \frac{3\sqrt{3}}{2}\left(l^H_{\max}\right)^2 \tag{11}$$

Using (6) and (9), then

$$A^T_{\max} = \begin{cases} \frac{3\sqrt{3}}{16}(r_s)^2\left[\min(2,\frac{r_c}{r_s})\right]^2 & \text{at least 1 - } connectivity \\ \frac{\sqrt{3}}{12}(r_s)^2\left[\min(3,\frac{r_c}{r_s})\right]^2 & \text{at least 3 - } connectivity \end{cases} \tag{12}$$

Similar calculation could be used for the other two patterns. Then, we obtain

$$A^S_{\max} = \begin{cases} \frac{2}{5}(r_s)^2\left[\min(\frac{\sqrt{10}}{2},\frac{r_c}{r_s})\right]^2 & \text{at least 1 - } connectivity \\ \frac{1}{5}(r_s)^2\left[\min(\sqrt{5},\frac{r_c}{r_s})\right]^2 & \text{at least 4 - } connectivity \end{cases} \tag{13}$$

$$A^H_{\max} = \begin{cases} \frac{3\sqrt{3}}{14}(r_s)^2\left[\min(\frac{\sqrt{21}}{3},\frac{r_c}{r_s})\right]^2 & \text{at least 1 - } connectivity \\ \frac{\sqrt{3}}{6}(r_s)^2\left[\min(\sqrt{3},\frac{r_c}{r_s})\right]^2 & \text{at least 3 - } connectivity \\ \frac{3\sqrt{3}}{26}(r_s)^2\left[\min(\frac{\sqrt{39}}{3},\frac{r_c}{r_s})\right]^2 & \text{at least 6 - } connectivity \end{cases} \tag{14}$$

Comparing (12), (13) and (14), the maximum area A_{max} of the corresponding patterns is computed for all values of r_c/r_s. Fig.2 shows the results from which we make the following observations.

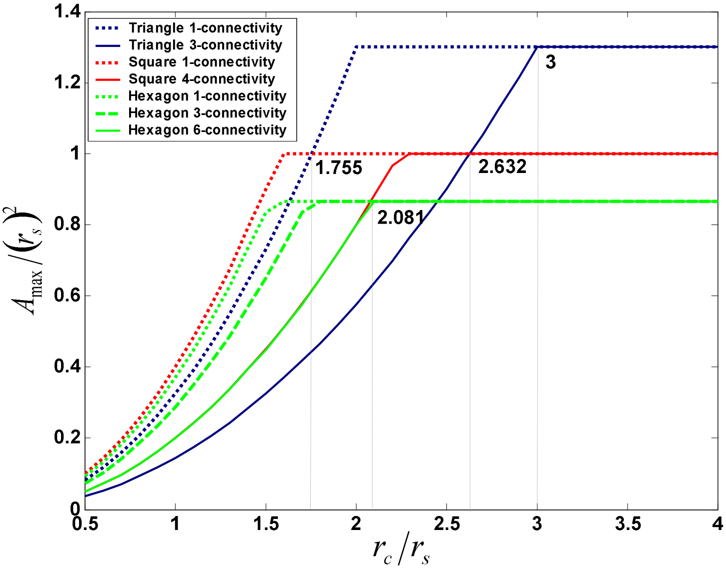


Fig. 2. Efficiency Comparison of different deployment patterns

1. When $r_c/r_s \le 1.755$, the square based pattern to achieve both coverage and 1-connectivity is optimal because it has the maximum grid area to ensure the best efficiency. While requiring more connectivity, the hexagon pattern which provides coverage and 3-connectivity should be chosen for this range of r_c/r_s.
2. When $1.755 \le r_c/r_s \le 2.081$, the triangle based pattern to achieve both coverage and 1-connectivity is optimal because it has the maximum grid area to ensure the best efficiency. If requiring more connectivity, the hexagon pattern which provides coverage and 3-connectivity should be chosen for this range of r_c/r_s.
3. When $2.081 \le r_c/r_s \le 2.632$, the triangle based pattern to achieve both coverage and 1-connectivity is optimal because it has the maximum grid area to ensure the best efficiency. If requiring more connectivity, the square pattern which provides coverage and 4-connectivity should be chosen for this range of r_c/r_s.
4. For $r_c/r_s \ge 3$, the triangle based pattern to achieve both coverage and 3-connectivity is optimal because it has the maximum grid area to ensure the best efficiency.

5 Conclusion

In this paper we discussed the problem on the sensor nodes deployment in agricultural sampling-interpolation applications. We proposed systematic random deployment approach to achieve coverage and k-connectivity based on three popular regular patterns-equilateral triangle, square and hexagon. We also compared the efficiency of different regular patterns of systematic random deployment, which enabling to make a better deployment decision for different values of r_c/r_s.

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