

A Strategic Sensor Placement for a Smart Farm Water Sprinkler System: A Computational Model

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Abstract—Internet of Things (IoT) networking has attracted research with many emerging applications requiring remote control and automation. Effective deployment of IoT sensors is a major concern since it primarily determines the performance of the IoT network. Since multiple mobile sensors are generally involved, it is possible that the sensors are randomly distributed in a remote region at the initial phase then later relocated to some pre-computed optimal location with their full autonomy enabled. In this paper, we propose a computation for the optimal location of water sprinkler sensors of an IoT smart farm network in terms of the relative physical distance between them. The resulting sensors locations ensure minimal overlap coverage area and no uncovered area exists in the candidate farming region. With the proposed strategic deployment of smart water sprinklers sensors, farmers can be assured of the right water distribution for any given area of their farm.

Keywords—smart farm, IoT, water sprinkler, deployment

I. INTRODUCTION

The smart farming industry is growing and will become more important than ever due to the increasing role of IoT technology in irrigation management. The technology sets the future of farming to the next level with more accurate analytics and greater production capability [1, 2].

An IoT-based smart farm network consists of a large number of Sensor Nodes (SNs) equipped with water sprinkler capability and a Base Station (BS) device working as a controlling station. The SNs are deployed on some remote candidate farming region. Each SN activates or deactivates its associated water sprinkler based on the request from the BS and transmits its status data to the BS. The data is analyzed at the BS to postulate the events or activities taking place in the remote farming region. As a result, the smart farm network provides an efficient extraction of status data while reliably monitoring the farming region over a variety of environments. With this advantage, smart farm networks are emerging as a promising technology in realizing the trending Internet of Things (IoT) applications, context-aware automated systems, and smart grid environments [3].

Since SNs are left unattended once deployed, their strategic deployment in the remote farming region is the major factor in determining the connectivity. In this paper we assume a SN having smart water sprinkler functionality to automatically spread water around its area in a circular fashion. Typically, such SNs are equipped with very limited power, computational capacities, and memory. For this reason, these SNs possess a limited range (r) that they can supply water to. It therefore requires other SNs to be

vertically and horizontally placed within a distance d ($d \leq r$) in order to cover the watering area around the SN.

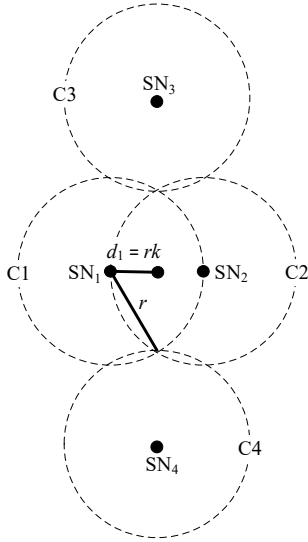
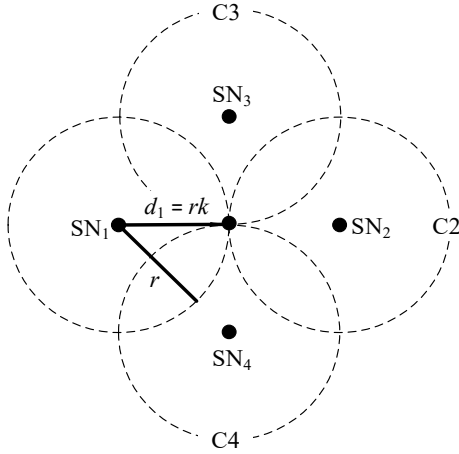
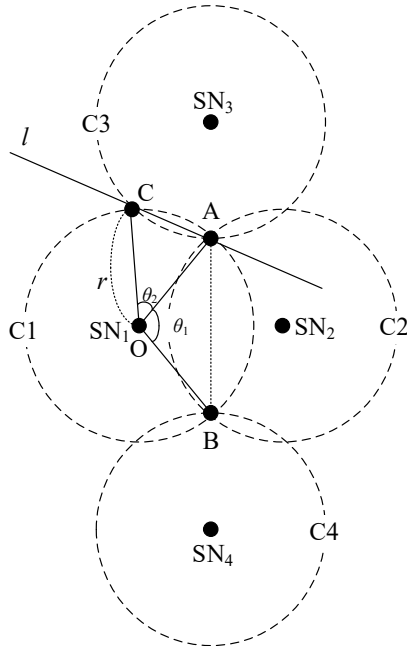
The current deployment technique models have adopted their ideas from some well-developed wireless sensor network technologies and can be broadly categorized into random scattering [4, 5] and deterministic strategy [6, 7]. The specific deployment techniques to apply are made based on the characteristics of the candidate region. For example, in a large-scale hostile battlefield, random scattering of SNs from an airplane would be a good strategy. In contrast, for a small scale smart farm, a point-to-point deterministic deployment of SNs can be adopted. Since many types of intelligent Mobile Sensor Nodes (MSNs) such as agricultural drones have been recently developed, a hybrid approach [8, 9] could also be considered. Here, the MSNs are randomly scattered initially at the candidate region and are left to relocate themselves to the most suitable positions.

We propose an optimal sensor placement computation for a smart farm sprinkler system in terms of the physical distance between the deployed sensors that maximize the overall watering area leaving no uncovered areas. The contribution of our proposal to the growth of smart irrigation system is to promote water conservation through strategic deployment of smart SNs, which increases farm productivity. In addition, our proposed physical distance computational model can also be implemented in various hybrid deployment schemes to allow the MSNs to autonomously relocate themselves to some pre-computed locations.

The rest of this paper is organized as follows. Section 2 defines the computational model for the strategic deployment for smart water sprinklers expressed in sensor nodes. In Section 3 we show and discuss the results. We conclude the paper and suggest future work in Section 4.

II. OPTIMAL PHYSICAL DISTANCE

Let us consider four SNs having the same water spreading range r to cover the area of some target region. Since our interest is the relative physical distance between the locations of adjacent SNs in terms of radius r , the distance between $(0, 0)$ and the center of gravity point of the intersection area d_1 can be represented by rk . We restrict the range of k from half of the radius r to the full radius r . This is because if k is larger than r , it will result in some uncovered area being created. Likewise, if it is smaller than half of r , there will exist a large overlap area, which is counter intuitive in the effort to find the optimal physical distance. The two end ranges of k are depicted in Fig. 1, and 2, respectively.


 Fig. 1. Four sensor nodes deployment with $k = \frac{1}{2}$

 Fig. 2. Four sensor nodes deployment with $k = 1$

 Fig. 3. Generalized four sensor nodes deployment covering range r with some overlapped covering area

For generalization, the coordinates for the center point O of circle C1 are set to $(0, 0)$, which is the location of SN₁. As depicted in Fig. 3, C1 will therefore satisfy the circle equation (1).

$$C1: x^2 + y^2 - r^2 = 0 \quad (1)$$

The coordinates for the center point of circle C2 is $(2rk, 0)$, satisfying circle equation (2).

$$C2: x^2 + y^2 - 4rkx + 4r^2k^2 - r^2 = 0, \quad (\frac{1}{2} \leq k \leq 1) \quad (2)$$

Circles C1 and C2 have now two intersection points, A and B.

$$A(rk, \sqrt{r^2 - r^2k^2}), B(rk, -\sqrt{r^2 - r^2k^2})$$

Also, the center of C1 has center angle θ_1 with point A and B. Since $\cos(\frac{\theta_1}{2}) = k$, the size of θ_1 is given by

$$\theta_1 = 2\cos^{-1}(k). \quad (3)$$

The sector form area with θ_1 is $r^2\cos^{-1}(k)$. If we subtract the triangle ΔOAB area from sector form area, we can obtain the area of half intersection $S_{<C1, C2>}$ between C1 and C2.

$$S_{<C1, C2>}: r^2\cos^{-1}(k) - r^2k\sqrt{1 - k^2} \quad (4)$$

In order to avoid creating an uncovered area, the circle C3 has to pass through intersection point A. As such the coordinates for the center point of circle C3 are therefore $(rk, r + \sqrt{r^2 - r^2k^2})$, satisfying circle equation (5).

$$C3: x^2 + y^2 - 2rkx - 2r(1 + \sqrt{1 - k^2})y + r^2 + 2r^2\sqrt{1 - k^2} = 0 \quad (5)$$

C1 and C3 share two intersection points, A and C. The linear line l passing through the two points obeys the linear equation (6).

$$l: 2rkx + 2r(1 + \sqrt{1 - k^2})y - 2r^2(1 + \sqrt{1 - k^2}) = 0 \quad (6)$$

Therefore, the vertical distance d_2 from the point O to line l can be calculated as follows.

$$\begin{aligned} d_2 &= \frac{|-2r^2(1 + \sqrt{1 - k^2})|}{\sqrt{4r^2k^2 + 4r^2(1 + \sqrt{1 - k^2})^2}} = \frac{2r^2(1 + \sqrt{1 - k^2})}{\sqrt{8r^2(1 + \sqrt{1 - k^2})}} \\ &= \frac{2r^2(1 + \sqrt{1 - k^2})\sqrt{8r^2(1 + \sqrt{1 - k^2})}}{8r^2(1 + \sqrt{1 - k^2})} = \frac{2r\sqrt{2 + 2\sqrt{1 - k^2}}}{4} \\ &= \frac{\sqrt{1 + k} + \sqrt{1 - k}}{2} r. \end{aligned} \quad (7)$$

The center of C1 has center angle θ_2 , with points, A and C. The size of θ_2 is given by

$$\theta_2 = 2\cos^{-1}\left(\frac{\sqrt{1 + k} + \sqrt{1 - k}}{2}\right). \quad (8)$$

The area of sector form with θ_2 is $r^2 \cos^{-1}(\frac{\sqrt{1+k}+\sqrt{1-k}}{2})$. We can now obtain the area of the triangle ΔOAC as follows.

$$\begin{aligned} \Delta OAC &: \sqrt{r^2 - \left(\frac{\sqrt{1+k}+\sqrt{1-k}}{2}r\right)^2} \left(\frac{\sqrt{1+k}+\sqrt{1-k}}{2}r\right) \\ &= r \sqrt{1 - \left(\frac{2+2\sqrt{1-k^2}}{4}\right) \frac{\sqrt{1+k}+\sqrt{1-k}}{2}} r \\ &= \frac{r}{2} \sqrt{2 - 2\sqrt{1-k^2}} \frac{\sqrt{1+k}+\sqrt{1-k}}{2} r \\ &= \frac{\sqrt{1+k}-\sqrt{1-k}}{2} r \frac{\sqrt{1+k}+\sqrt{1-k}}{2} = \frac{r^2}{2} k \end{aligned} \quad (9)$$

Therefore, the half intersection area $S_{<c1, c3>}$ between C1 and C3 is given by

$$S_{<c1, c3>}: r^2 \cos^{-1}\left(\frac{\sqrt{1+k}+\sqrt{1-k}}{2}\right) - \frac{r^2}{2} k \quad (10)$$

When we narrow down the remote region surrounded by SN_1, SN_2, SN_3 , and SN_4 , the total intersection area S among the four SNs results in two of $S_{<c1, c2>}$ plus eight of $S_{<c1, c3>}$, resulting in

$$\begin{aligned} S &= 2r^2 \cos^{-1}(k) - 2r^2 k \sqrt{1-k^2} + 8r^2 \cos^{-1}\left(\frac{\sqrt{1+k}+\sqrt{1-k}}{2}\right) - 4r^2 k \\ &= 2r^2 [\cos^{-1}(k) + 4\cos^{-1}\left(\frac{\sqrt{1+k}+\sqrt{1-k}}{2}\right) - k(\sqrt{1-k^2} + 2)] \end{aligned} \quad (11)$$

The remote area covered by the four SNs is therefore $4\pi r^2 - S$. As such, the optimal value k minimizing the overlapped area S will guarantee maximum coverage area for the given remote region for any fixed number of SNs.

III. RESULTS AND DISCUSSIONS

We evaluate the size of the overlapped area S among the four sensor nodes with different r values. Fig. 4 shows the result of equation (11) with r set to 10 meters.

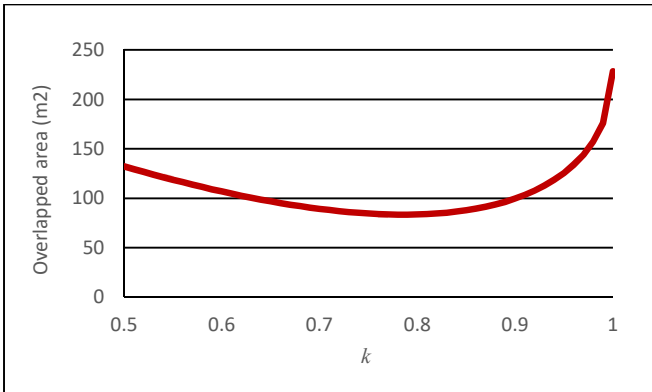


Fig. 4. Overlapped area in terms of k when r is set to 10 meters.

As we intuitively measured in Fig. 2, when k is equal to 1, which means the distance from the center point of C1 to the intersection point with C2 is equal to radius r , it produces the largest overlapped area. On the other hand, with k set to 0.5, the computed overlap area is 132.27m². This value gets smaller as the k value increases. The minimum overlap area of 83.43m² is reached when k is 0.785. Thereafter, we observe that the size of the overlap area increases almost

exponentially reaching the maximum of 228.31m² when $k = 1$. Of course, this variation gets larger with increase in r .

From our analysis and experiment we can conclude that for four sensor nodes, the optimal distance that results in the minimum overlap area without any blind spots is achieved when k is equal to $\pi/4$. Following this conclusion, distance d between C1 and C2 is therefore equal to $(\pi/2)r$. In adherence to this conclusion, once the sensor nodes are distributed in random scattered method, they need to be autonomously relocated by satisfying the following parameter values with $k = \pi/4$.

$$\begin{aligned} d_{<C1, C2>} &= \frac{\pi}{2} r \approx 1.57r \\ d_{<C1, C3>} &= d_{<C1, C4>} = d_{<C2, C3>} = d_{<C2, C4>} \\ &= \sqrt{r^2 k^2 + (r + \sqrt{r^2 - r^2 k^2})^2} = r\sqrt{2 + 2\sqrt{1-k^2}} \\ &= r(\sqrt{1+k} + \sqrt{1-k}) \approx 1.80r \\ \theta_1 &= 2\cos^{-1}(k) \approx 1.334 \text{ rad.} \approx 76.48^\circ. \\ \theta_2 &= 2\cos^{-1}\left(\frac{\sqrt{1+k}+\sqrt{1-k}}{2}\right) \approx 0.903 \text{ rad.} \approx 51.73^\circ. \end{aligned}$$

With the optimized parameter values, we now evaluate the minimum number of sensors required to cover the area of the given circular target of radius R and compare the results to those from a well-aligned but not optimized sensor deployment. To achieve this, we first divide the target farming area into grids and designate each sensor to cover a grid. Since the area of each grid should be fully covered by a sensor, its area should intuitively be less than the total area covered by the sensor. Considering a circular spreading fashion of each sensor, the well-aligned shape can be obtained by deploying the sensor at the center of the grid while its covering area is touching the four vertices of the grid as shown in Figure 5.

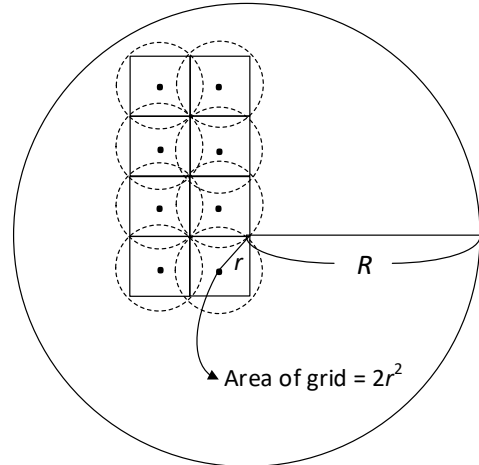


Fig. 5. Well-aligned sensor deployment

Since one side of a grid is $\sqrt{2}r$ in length, the area of a grid is $2r^2$. Therefore, the number of sensors that can be deployed is the same as the number of $2r^2$ size grids that can be circumscribed in a πR^2 size circle without losing their square shape; and can be calculated as follows:

$$\frac{\text{area of target}}{\text{area of grid}} - \frac{\text{circumference of target}}{\text{diagonal of grid}} = \frac{\pi R^2}{2r^2} - \frac{2\pi R}{2r} \quad (12)$$

As such, the most important factor in deciding the number of sensors required to fully cover a given target area is the grid size. For our optimized sensor deployment, the shape of the grid is not square but rectangular as shown in Figure 6. The grid width is given by $2rk$.

In order to compute the height of the grid, which is represented by $\overline{AB} + \overline{AD}$ in Figure 6, we consider $\triangle CDSN_3$.

$$\overline{DSN_3} = r \sin(90 - \theta_2) = r \cos(\theta_2)$$

$$\overline{AD} = \overline{ASN_3} - \overline{DSN_3} = r - r \cos(\theta_2)$$

Then, $\overline{AB} + \overline{AD}$ can be represented by

$$\overline{AB} + \overline{AD} = 2\sqrt{r^2 - r^2 k^2} + r - r \cos(\theta_2) \quad (13)$$

Therefore, the area and the diagonal of the grid are computed as follows:

$$\begin{aligned} \text{Area of grid} &= 2rk(2\sqrt{r^2 - r^2k^2} + r - r\cos(\theta_2)) \\ \text{Diagonal of grid} &= \sqrt{4r^2k^2 + r^2(2\sqrt{1 - k^2} + 1 - \cos(\theta_2))^2} \end{aligned}$$

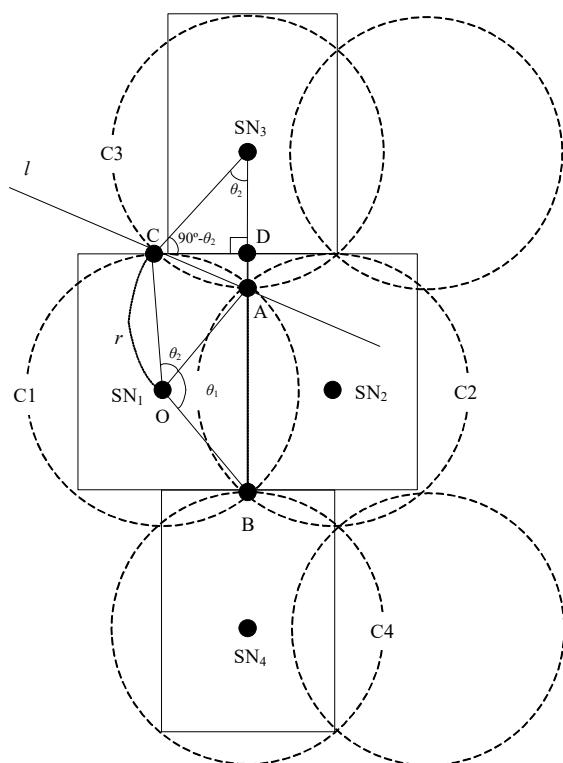


Fig. 6. Optimized sensor deployment with rectangle-shaped grids

Figure 7 shows the results when we evaluated the number of sensors required for deployment in different size target areas in terms of R . We set the value of r to 10. Since the grid size of the optimized method is maximized by minimizing the overlapped covering area among the sensors, our proposed method requires only 76% of the number of sensors needed in the well-aligned method for the same target area. This difference increases as the target area increases.

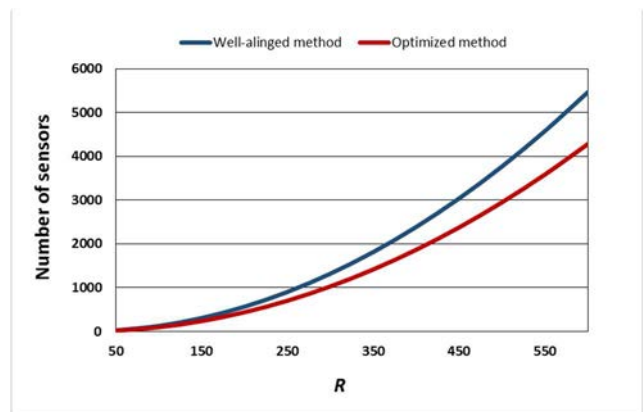


Fig. 7. The number of required sensors as a function of target area size

IV. CONCLUSION AND FUTURE WORK

We have proposed an optimal relative physical distance location computation for sensor nodes in a smart farm network. The proposed sprinkler sensors positioning based on our computational model ensures minimum overlap coverage area while at the same time ensuring that no area in the target zone is left uncovered. The result of this is a more efficient water usage and a more productive smart farm. The limitation of our current proposal lies in the fact that it assumes a flat, even, and unobstructed region. The proposal would therefore be applicable only in limited small-sized and controlled farming areas. It would not be effectively applicable in cases of uneven or areas with physical obstructions. To overcome this, our future work will be to extend the current approach to a more robust 3-dimensional framework applicable in the real world with physical man-made obstructions and natural undulating topologies.

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