Effective Coverage Analysis for Wireless Multihop Sensor Network Incorporate Overlapping

Bhawna Kankane, Rajesh Mishra, and Sandeep Sharma

Abstract Wireless multihop sensor network (WMSN) has a wide range of applications in various fields, especially with Internet of Things (IoT) and other smart devices that may include weather forecasting, health monitoring, military surveillance, etc. This paper proposes an analytical model for effective coverage estimation that incorporate a redundant area for a defined region of interest with uniform random distribution for sensor node. Proper coverage is one of the major concerns for WMSN. The model is proposed in two steps. First, the effective coverage area is evaluated with redundant possibility using Euclidean distance between two neighboring nodes and excluding the overlap area to reduce redundancy. Finally, the coverage is estimated with detection probability for a known effective coverage area. The simulation result shows that the proposed model gives better coverage than previous work. It extends the detection probability significantly for a wireless multihop sensor network.

Keywords Effective coverage · Overlap area · Wireless multihop sensor network · Euclidean distance · Detection probability · Boolean sensing model · Sensor nodes

1 Introduction

With emerging technology, miniaturization of the devices has developed an interest in the design of tiny sensors that have a wide range of applications in various field such as military surveillance, industrial application and health monitoring system [1]. Sensors are the basic building block for any wireless network and primarily comprised a sensing unit, transceiver, memory and power unit. In most applications, coverage efficiency reflects the system's performance, especially in IoT-based applications or in other smart devices; thus, it becomes necessary to enhance coverage of such wireless networks. In literature, different approaches with different sensing

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models have been used to analyze coverage. Sensor nodes' deployment is the key step for a network design, and various deployment strategies have been used to achieve maximum coverage. The wireless sensor network is highly applicable for the hostile region, so random deployment is widely used. Nowadays, coverage has become a major concern of research for researchers. The area of coverage sensed by a sensor is determined by the fraction of sensed area to the total area of the region. In 2016, Katti and Lobiyal [2] studied and discussed different ways to enhance the coverage efficiency using a deterministic model. Jin et al. [3] developed a model for coverage and connectivity analysis under border effect in a circular region. The assumption has taken that the sensor is equipped with an omni-directional antenna with uniform sensing range. Cai et al. [4] have proposed an approach for energy conservation for wireless sensor networks where the sensor nodes are defined in three different modes, i.e., low power, sleep and active modes for a disk sensing model. Sensors in different modes prolong the network lifetime. Similarly, in 2020, Suparna et al. [5] have presented a Monte Carlo simulation approach for area coverage with sensors in three different states, viz, sleep, active and relay. The proposed model establishes connectivity for mobile sink based on the state of the sensors and defined coverage for every established connection. In this article, the node position is predetermined and is not applicable for random distribution. Sensor nodes collect and process sensed data which are further forwarded to the sink node. In literature, various coverage and connectivity-based reliability models have been proposed. In 2013, Liu et al. [6] have done coverage analysis using percolation theory. In 2020, S. Chakraborty et al. [7] proposed an area coverage-based model for multi-state sensor nodes where Voronoi cells are used for sensor nodes' representation. The connectivity between the sensor nodes is shown using Euclidean distance and energy matrix. Author has also applied a sum of disjoint approach to determine area coverage. In 2019, Amutha et al. [8] reviewed different strategies of wireless sensor network to improve coverage and energy efficiency. In 2017, Al-Karaki and Gawanmeh [9] have done a performance evaluation and maximize network endurance with the mentioned parameters like nodes' availability, connectivity and coverage. In 2021 [10], Nagar et al. have formulated an approach to define connectivity in a multihop scenario using node degree distribution and node isolation probability. The author has also considered the border effect. Most of the work has been done for coverage analysis for wireless sensor networks considering different sensing models and different performance parameters. However, none of the researchers has considered a redundant area for coverage. In the proposed model, the effective coverage is estimated by considering the overlap area. The formulating result shows the redundancy is reduced to the greater extent and required coverage estimation is highly improved.

2 System Model

This paper presents a mathematical model for the analysis of effective coverage area without redundancy. The proposed model considers a random square region of area $\left(A = a^2\right)$ with dimension 100 x 100 m^2. We first assume that two random nodes 'A' and 'B' as shown in Fig. 1 with equal and uniform sensing range 'R_S' are randomly deployed. Due to random distribution of sensor nodes, some of the regions of ROI are covered by both sensors and considered as redundant area. The redundancy for coverage area depends on the distance between the neighboring nodes which is given by Euclidean distance between the nodes. The redundancy occurs if the distance between the nodes is less than or equal to twice the sensing range. The distance 'D' in Eq. (1) between the two neighboring sensor nodes with coordinates $\left(A_i, A_j\right)$ and $\left(B_i, B_j\right)$ is determined by the Euclidean distance [11]. The expression for 'D' is given by:

$$D = \sqrt{(B_i - A_i)^2 + \left(B_j - A_j\right)^2}. \tag{1}$$

The coverage area by the sensor nodes is estimated by the ratio of the effective area sensed by the sensor to the total area of RoI. In the presence of overlap area, the effective coverage area A_{eff} is evaluated as in Eq. (2).

$$A_{eff} = A_{2S} - A_O, \tag{2}$$

where A_{2S} is sensing area covered by two sensor nodes for uniform sensing range as sensors are representing with a disk sensing model. If the sensing range of a sensor is R_S, then the area covered by each sensor is πRs^2; similarly, for n number of sensors, it will be $\left(n \times \pi R^2\right)$. The sensing area for two sensor nodes will be $\left(2 \times \pi R^2\right)$, and A_O is defining the overlapping area or common area between the sensors.

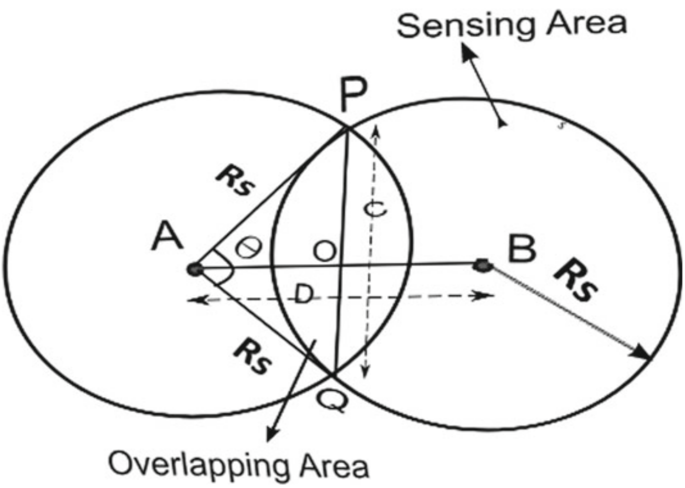

Fig. 1 Sensor node coverage with overlapping area

2.1 The Mathematical Expression for Overlap Area

The overlapping area is decided by the Euclidean distance 'D' and can be mathematically expressed by considering three conditions as discussed below:

$$A_O = \begin{cases} \pi R_S^2 & \text{for} \quad D = 0 \\ 0 & \text{for} \quad D \geq 2R_S \\ A_O & \text{for} \quad D \leq 2R_S \end{cases} \tag{3}$$

Overlapping area can be evaluated if the value of D lies between $0 < D < 2Rs$ and is given by the equation.

$$A_O = \{\text{Area of sector} - \text{Area of triangle}\}, \tag{4}$$

$$A_O = \left\{\widehat{APQ} - \Delta(APQ)\right\} \tag{5}$$

The area of sector is given by $\frac{1}{2}\theta R_S^2$, where the value of θ is evaluated by using cosine rule. Similarly, the area of triangle in the overlap region is evaluated by Heron's formula [12].

$$\Delta APQ = \sqrt{s(s - R_S)^2(s - C)}, \tag{6}$$

where 'C' is the chord length which is estimated as $C = \sqrt{2R_S^2(1 - \cos\theta)}$ and 's' is given by $\frac{2R_S+C}{2}$. By using Eq. (2), the effective coverage area is estimated as

$$\begin{aligned} A_{eff} &= 2 \times \pi R^2 \\ &- \frac{1}{2}\left\{\cos^{-1}\left(\frac{2R_S^2 - C^2}{2R_S^2}\right)R_S^2 - \sqrt{s(s - R_S)^2\left(s - \sqrt{2R_S^2(1 - \cos\theta)}\right)}\right\}. \end{aligned} \tag{7}$$

2.2 Coverage Estimation Using Boolean Sensing Model

In this model, the sensing area for each sensor is defined by $A_S = \pi R_S^2$. A sensor in the given area can sensed the target if the target exists under the sensing range of a sensor node. The detection probability of a sensor node for a particular target is given as $p_d = \frac{A_S}{A}$, where 'A' is the total area of square region of interest [13]. If incorporating the overlap area between two sensor nodes [14], the detection probability for the system model will be expressed as $p_d = \frac{A_{eff}}{A}$, and hence, the equation will become

$$P_d = \frac{2 \times \pi R^2 - \frac{1}{2}\left\{\cos^{-1}\left(\frac{2R_S^2 - C^2}{2R_S^2}\right)R_S^2 - \left\{\sqrt{\left\{\frac{2R_S + C}{2}\right\}\left\{\frac{2R_S + C}{2} - R_S\right\}^2\left\{\frac{2R_S + C}{2} - \sqrt{2R_S^2(1 - COS\theta)}\right\}}\right\}\right\}}{A}. \quad (8)$$

The coverage probability p_c by at least one sensor node among the 'k' set of sensor nodes can be expressed as

$$P_C = 1 - (1 - P_d)^K. \quad (9)$$

As the value of 'N' is very large, so taking approximation of Eq. (9) and the equation is approximated as shown below in (10):

$$P_C = 1 - \exp\left[\frac{-K\left(2\pi R_S^2 - A_O\right)}{A}\right]. \quad (10)$$

The coverage probability is estimated using the above Eq. (10), where it shows that as the overlap area increases, the redundancy increases and reduces the effective coverage area. Thus, the detection probability is reduced significantly.

3 Simulation Result and Discussion

This section describes performance evaluation for coverage analysis of a wireless multihop sensor network in a square region with $100 \times 100\ \text{m}^2$ dimensions as shown in Fig. 2. Here, we have randomly deployed 20, 30 and 40 active sensor nodes with a maximum sensing range of 10 m in a square region. The performance is estimated in an effective coverage area over several sensor nodes and sensing ranges. It has been observed that the effective coverage area is being reduced with an increase in the number of nodes as shown in Fig. 3. Another important parameter is the detection probability. The detection probability increases with the increase in number of nodes and sensing range. The analytical result is formulated using Eqs. (2), (3) and (10). Finally, the performance analysis for coverage is done in MATLAB R2015a simulation environment.

4 Conclusion

In this paper, we have estimated the effective coverage area under different performance parameters. The proposed model eliminates the overlap area and thus reduces the redundancy in the coverage analysis. The analytical formulation is done using a

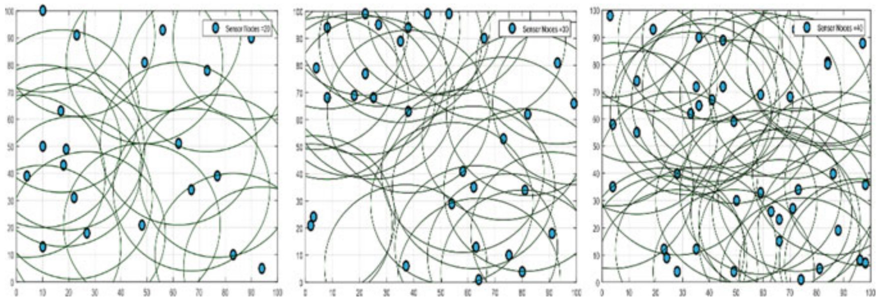

Fig. 2 Random node deployment in $100 \times 100\ \text{m}^2$ with $K = 20, 30, 40$

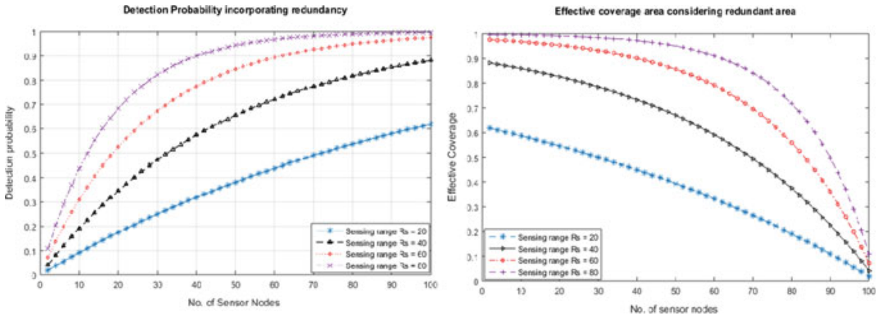

Fig. 3 Detection probability and effective coverage area incorporating redundancy with respect to number of sensor node for different sensing ranges

mathematical model and simulated under MATLAB environment. In future, the work can be extended using different sensing models together with considering boundary effects.

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