Boundary Effect in Node Deployment: Coverage Fraction and Information Generation in Wireless Sensor Network

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Abstract—Network coverage is important in wireless sensor network. It depends on node deployment strategy. Boundary effect in node deployment plays an important role in network coverage. In this paper, we present the impact of boundary effect on node coverage success probability and coverage fraction. This result will be useful in studying information generation, collection and forwarding in a wireless sensor network. It has been found the boundary effect can be ignored when node sensing area of a node is much smaller than the area of interest.

Index Terms—Boundary effect, coverage fraction, information generation, wireless sensor network.

I. INTRODUCTION

A wireless sensor network (WSN) consists of a large number of energy-constrained sensor nodes that are deployed for the purpose of monitoring physical phenomena [1]. Sensor nodes produce measurable responses to the changes in physical and chemical conditions and transmit them towards the sink in the form of packet. Usually one data sink is deployed inside or outside the area of interest for collecting information. A sensor node has limited radio range. Usually, nodes use intermediate nodes as relay nodes for forwarding packets to the sink (multi-hop). Thus the relay nodes collect information and forward it towards the sink. Nodes dissipate energy for sensing, processing and radio communication. A general model of information generation, collection and routing has direct impact on network lifetime. An accepted definition of network lifetime is the time span from the instant of network deployment to the instant when the network becomes non-functional [2]. When a network becomes non-functional that depends on the application specifications. A network becomes non-functional even when a single node dies or a group of nodes die.

In WSN the data collection may be triggered by the internal clock of sensors, the event of interest, the demand from the end-user or both event and demand. Based on the data collection initiative, traffic in WSN is usually two types: Constant Bit Rate (CBR) traffic and Variable Bit Rate (VBR) traffic. Clock-driven or data gathering network generates CBR traffic while the rest of the networks produce VBR traffic. The traffic is usually transmitted in the form of packet over the wireless channel with path loss exponent varies between 2.0 and 4.0 [3]. Performance studies of WSN require realistic data traffic suitable for describing the physical phenomena. Thus the traffic generated from the periodic monitoring of a surveillance area can be modeled using CBR traffic while that for tracking a moving object requires VBR traffic. The event may be two types: static and moving. Typical examples of event include forest fire, intruder in a restricted area, movement of enemy soldiers etc.

The sensing information in a general wireless sensor network depends on the following factors:

1) Node coverage degree at the point of event occurrence. Usually a sensor node produces one packet per sampling interval to the response of detecting an event. Node density plays an important role for network coverage. Coverage also depends on the node deployment strategies viz. random, regular and planned deployment.

2) Event distribution over the area of interest. Event behavior is not known in a deterministic manner. However, a stochastic knowledge of an event for e.g. spatial probability density function (pdf) will be useful in modeling information generation. Number of events occurred in the area of interest may be greater than one. The speed of the event plays an important role in packet generation.

3) An event has finite region of observability. A circular observable event with radius of observation r_o implies that only those nodes less than r_o distance away from the event can observe it. Generally, r_o equals to sensing range, r of a node.

4) The distance between an event and data sink has also an important role in calculating generated traffic in the network. The more is the separation the more intermediate nodes will take part in data forwarding.

5) It also depends on sampling interval of sensor nodes. Sampling interval should be such that no important event misses without sensing it. Again the more is the sampling frequency the more energy will be spent. Thus there is a trade-off between energy savings and missing of events.

A sensor node has to transmit sensing information in the form of packet under the circumstances: (a) an event occurs within its sensing range, (b) a packet from neighbor node has been received which has to be routed towards the sink, and (c) both (a) and (b).

Nodes are randomly placed one by one. Any event is said to be detectable if at least one node lies within its observable range. Then the event is said to be covered by the node. A node will cover less area when it is placed near the boundary of the area of interest than when it is placed at the central zone. This is known as boundary or border effect. The reason is that some portion of its sensing area will lie outside the area of interest when it is placed near the border.

Demirkol *et al.* [4] have studied traffic generation in the form of packet in a WSN. The study highlights packet generation mechanism for a moving object and shows Markov dependencies on packet generation between two successive sensing intervals. The authors have not considered boundary effect while calculating probability of coverage success in Bernoulli experiment of node deployment. Also, no attention has been paid about information collection and routing.

Liu *et al.* [5] have considered coverage of static event by deploying nodes over a circular area of interest. This study considers the boundary effect while calculating probability of coverage success in Bernoulli trials. A similar study has been made by Yen *et al.* in [6] for a rectangular area. Liu *et al.* [7] have also studied the coverage of a wireless sensor network. However, the mechanism of information generation and collection has not been considered. Also the impact of boundary effect on node coverage and coverage fraction has not been considered.

In this paper we study the impact of boundary effect on node deployment. This study also focuses on information generation and dissemination in a wireless sensor network. The rest of the paper is organized as follows. Section II presents the system model. Section III presents the analysis of coverage fraction and information generation. Numerical results are presented in Section IV. Finally, Section V concludes the paper.

II. SYSTEM MODEL

We consider a general sensor network where N energy-constrained nodes are deployed one by one. Let E_0 be the initial energy of each node. A sink node is situated inside the network for collecting the monitoring information. We assume that the sink node is not energy constrained.

The energy dissipation model for radio communication is assumed similar to [8]–[9], following which the energy consumed by a node for transmitting a packet over a distance h is $E_t = e_t + e_d h^n$. Here e_t is the amount of energy spent per packet in the transmitter electronics circuitry and $e_d h^n$ is the amount of energy necessary for transmitting a packet satisfactorily over the distance h. n is the path loss exponent. On the receiving end, the amount of energy spent to capture an incoming packet is e_r units. The idle state energy is equal to $e_{id} T_{id} P$, where T_{id} is the idle time and $e_{id} = c.e_r$ is the idle state energy spent per packet duration, where $0 < c \leq 1.0$. We assume that each node can deal with P packets/second.

III. ANALYSIS OF COVERAGE FRACTION AND INFORMATION GENERATION

Let N be the number of nodes deployed randomly and independently over an area of interest. The shape of the area of interest may be circular, rectangular or any shape. We assume that each node has sensing radius, r. Boolean sensing model has been assumed. The probability of any arbitrary node to be within the neighboring area of any arbitrary point can be modeled as a Bernoulli experiment with success probability, p. The calculation of p has been done in [6] and

[5] for the rectangular and circular area, respectively.
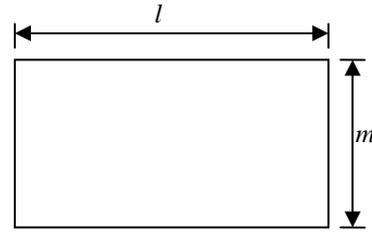
Fig. 1. Rectangular area of interest with length and width l and m, respectively where N nodes are deployed randomly.

Considering the boundary effect the success probability, p for a rectangular area (Fig. 1) is given by [6]

$$p = \frac{\frac{1}{2}r^4 - \frac{4}{3}lr^3 - \frac{4}{3}mr^3 + \pi r^2 ml}{m^2 l^2} \tag{1}$$

where l and m are the length and width of the rectangular area. The sensing radius, r satisfied the condition $r \leq \min(l, m)/2$.
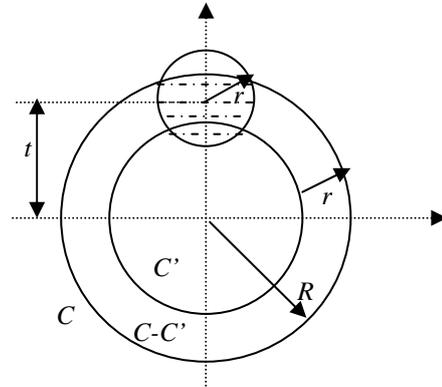
Fig. 2. Circular area of interest with radius R where N nodes are deployed randomly.

Similarly, considering the boundary effect, the probability p for a circular area (Fig. 2) is given by [5]

$$p = \frac{A_1}{\pi R^2} \tag{2}$$

where A_1 is the average neighboring area and is given by [5]

$$A_1 = [2\int_{R-r}^{R} tA(x_1, y_1)_{c-c'} dt + \pi r^2 (R-r)^2]/R^2 \tag{3}$$

where $A(x_1, y_1)_{C-C'}$ is the neighboring area of a point (x_1, y_1) lies in the annular disk (C-C') with inner and outer radii $(R-r)$ and R, respectively.

If the boundary effect is not considered then the probability, p becomes equal to $\frac{\pi r^2}{lm}$ and $\frac{r^2}{R^2}$ for the rectangular and circular area, respectively.

The coverage fraction (f_a) which is defined as the ratio of covered area to the total area of interest and is given by [5], [6]

$$f_a = 1 - (1-p)^N \tag{4}$$

where N is the number of nodes deployed over the area of interest.

(a)

(b)
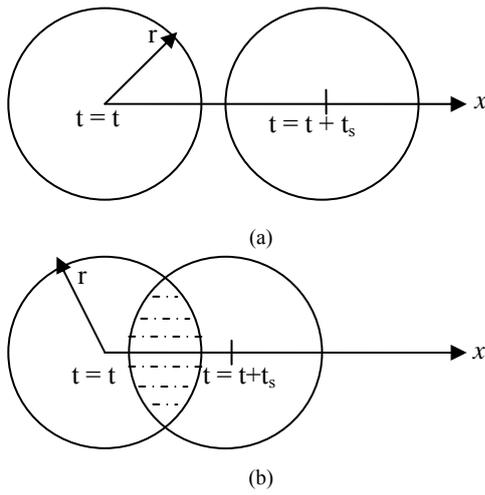
Fig. 3. Tracking of an object moving along the direction of x-axis. Two sampling instants (t and $t + t_s$ are shown by circle with radius r: (a) $v_T t_s \geq 2r$, no overlapping between the successive coverage area, (b) $v_T t_s < 2r$, overlapping between the successive coverage area.

Let us consider a situation of tracking a moving object. Let v_T be the speed of the object. We also assume that nodes are programmed to sense the ambient conditions periodically with interval t_s. If the speed of the object and sampling interval of the sensor node satisfy the condition $v_T t_s \geq 2r$ then the coverage degree probabilities of two nearby surveillance area points can be considered as independent as they are not intersected to each other (Fig. 3a).

For large N and small p the above problem can be modeled as Poisson distribution with average density of node coverage, $\lambda = Np$. The probability that node coverage at any sampling time can be expressed as

$$P(k) = \frac{e^{-\lambda}\,\lambda^k}{k!} \quad k = 0,\ 1,\ 2\ etc. \tag{5}$$

When $v_T t_s < 2r$, the coverage probability of two nearby surveillance points are dependent of each other (Fig. 3b) and can not be modeled as Poisson distribution. Demirkol *et al.* in [4] have shown Markov dependencies of packet generation between two successive sampling points. In the next section we present some numerical examples to show the impact of boundary effect on node coverage.

Packets are generated inside the network and forwarded to the sink using the intermediate nodes between the source node and the sink. Thus a node has two types of traffic: own packet generated by the node itself and the packet has been received that to be relayed to the neighbour node towards the sink. Let $\lambda_{org,i}$ and $\lambda_{rel,i}$ be the number of packets (per unit time) generated and has to be relayed by the ith node. These two parameters explicitly depend on the data collection mechanism and network architecture. For a data gathering network it is constant for a particular node. However, in event-driven and query-driven network it depends on the probability of occurrence of the event or query. Now, according to the node energy dissipation model, the energy dissipated by the ith node per unit time can be expressed as

$$E(i) = (e_t + e_d h_i^n)(\lambda_{org,i} + \lambda_{rel,i}) +$$
$$e_r \lambda_{rel,i} + e_{id}(P - \lambda_{org,i} - \lambda_{rel,i}) \tag{6}$$

The node lifetime can be expressed as

$$t_i = \frac{E_0}{E(i)} \tag{7}$$

The network lifetime can be expressed as

$$T = \min\ (t_i),\ \text{for all}\ i \tag{8}$$

where, we assume the definition of network lifetime is limited by the first node failure.

IV. NUMERICAL EXAMPLES

In this section we present the dependencies of node coverage on boundary effect using some numerical examples. The results obtained by considering the boundary effect are compared with that obtained without considering the boundary effect.

Figs. 4 and 5 show the variation of p with sensing radius for a rectangular area of interest. The probability p increases with the increase of sensing radius. It is clear that p gets reduced by incorporating the boundary effect. The boundary effect has no impact on p when the area of interest is much higher than the sensing area of a node as shown in Fig. 5.
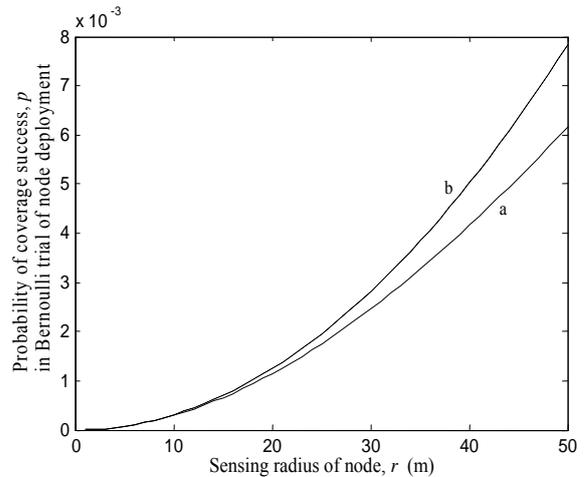
Fig. 4. Variation of p with sensing radius of node for a rectangular area with l=10km, m=100m: (a) for boundary effect, (b) without boundary effect.
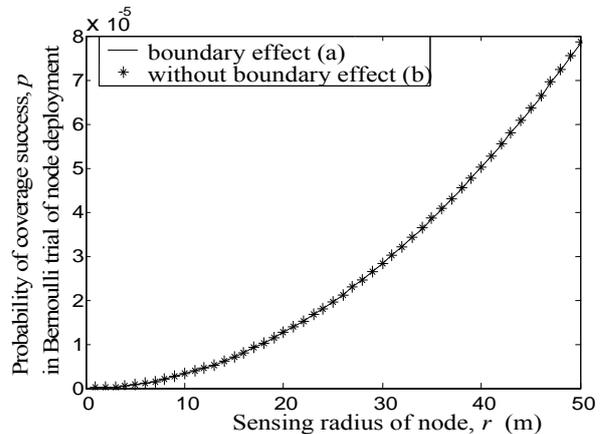
Fig. 5. Variation of p with sensing radius of node for a rectangular area with l = 10 km, m = 10 km: (a) for boundary effect, (b) without boundary effect.

Fig. 6 shows the variation of node coverage probability for a rectangular area where 1000 nodes are deployed randomly and independently. The result shows that boundary effect reduces the average degree of node coverage. It shows that less traffic (packet) will be generated from the network if the boundary effect is taken into account.

Fig. 7 shows the variation of coverage fraction (f_a) with sensing radius (r). It shows that by incorporating boundary effect, the coverage fraction gets reduced. Fig. 8 shows the variation of coverage fraction with number of sensor nodes deployed over the area of interest.
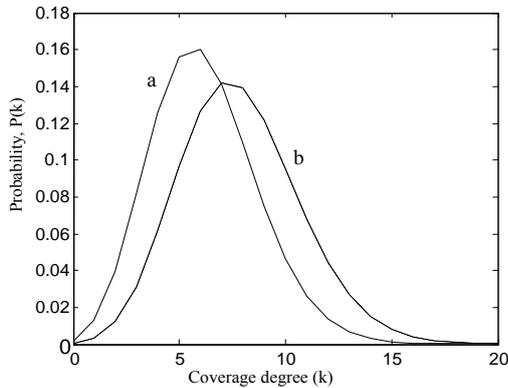
Fig. 6. Probability of node coverage using Poisson process for $N = 1000$, $l = 10$ km, $m = 100$ m, $r = 50$ m: (a) for boundary effect, (b) without boundary effect.
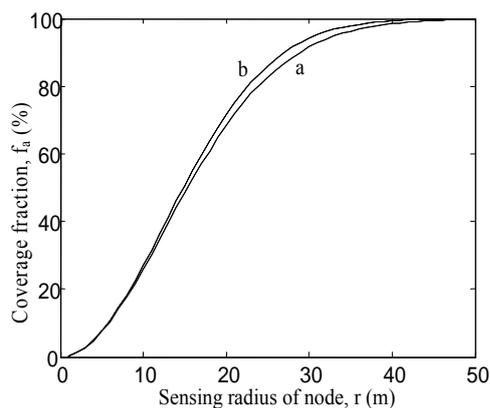
Fig. 7. Variation of coverage fraction with sensing radius for a rectangular area with $l = 10$ km, $m = 100$ m and $N = 1000$: (a) for boundary effect; (b) without boundary effect.
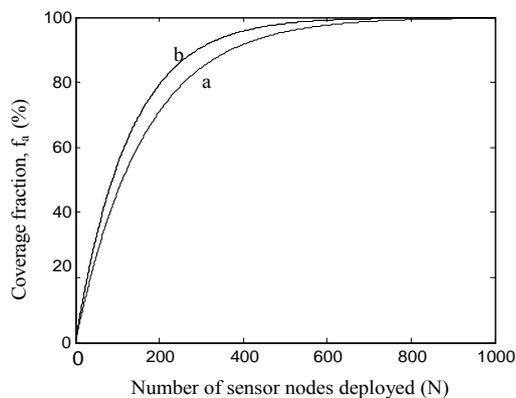
Fig. 8. Variation of coverage fraction with number of sensor nodes for a rectangular area with $l = 10$ km, $m = 100$ m and $r = 50$ m: (a) for boundary effect; (b) without boundary effect.

V. CONCLUSION

This study gives the insight how boundary effect affects coverage fraction, node coverage probability etc. It is clear from this study that boundary effect should be taken into account for studying the information generation in a wireless sensor network. However, the effect can be ignored when node sensing area is much smaller than the area of interest.

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