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Network Lifetime and Coverage Fraction Analysis for Wireless Sensor Networks

Shilpa Das[1]*, Benudhar Sahu[2] and Ganapati Panda[3]

[1]Department of Computer Science and Engineering, ITER, S'O'A University, Bhubaneswar, Odisha, India
[2]Department of Electronics and Communication Engineering, ITER, S'O'A University, Bhubaneswar, Odisha, India
[3]Department of Electronics and Communication Engineering, C V Raman College of Engineering, Bhubaneswar, Odisha, India

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In Wireless Sensor Networks, two crucial parameters are lifetime of the network and optimal coverage for sensed region. This paper addresses the issues and challenges pertaining to these parameters for further investigation, and provides a method to approximate the energy utilization and optimal coverage inside the bottleneck zone for wireless sensor networks. The proposed analytical framework calculates correctly the network lifetime upper bound of wireless sensor networks. The derivation of the network lifetime upper bound is carried out using (i) network coding and (ii) network coding with duty cycle. Based on that, an approximate derivation is made and the corresponding results are obtained from the simulation study. The comparison of the results of the previous study and those obtained in this paper reveals that the actual network lifetime upper bound is lower in the present case. This is due to the assumption made by authors of previous work, on coder nodes' presence throughout the bottleneck zone instead of only one hop distance away from the sink. In addition, the effect of coverage fraction in case of node failure, on network lifetime upper bound is derived for the previously reported and present model. The simulated results obtained from new derivation show that the coverage fraction is lesser than that obtained by previous model.

Keywords: Energy Efficiency, Network Coding, Network lifetime, Coverage Fraction, Wireless Sensor Networks (WSNs)

Introduction

Wireless Sensor Network (WSN) is an area of interest to researchers for study of various aspects of WSN such as effective deployment, power optimization, secrecy and reliable communication for effective solution. Out of these issues, the optimization of energy is an interesting area, as minimization of energy usage limits network lifetime & functionality of WSN.[1] This current work focuses upon the determination of network lifetime upper bound with appropriate deployment of network coder nodes inside the bottleneck zone at only one hop distance away from the sink. It has also been found out that the probability of node failure with appropriate energy expenditure estimation, both in case of network coding and network coding along with the duty cycle. The determined node failure probability is then used, to find the coverage fraction in case of node failure, which was not addressed in earlier works. The organization of the paper proceeds as follows. In Section II, the detailed literature survey of the related work has been provided. The network lifetime analysis and the derived expressions are provided in Section III. Section IV depicts how the node failure and its effect on coverage fraction impacts lifetime upper bound of WSN. The simulated results of the derived lifetime expressions have been presented in V. Section VI deals with results and the discussions that have been obtained for this work. Finally, the concluding remarks for the paper is provided in the Section VII.

Network lifetime analysis

The network lifetime of the WSN is affected mostly by the nodes which are present near the sink. This is due to the fact that the maximum energy is spent by the nodes on transmission and relaying of data by the nodes. Therefore, these nodes are vulnerable to failure, due to constant involvement in the transmission and relaying of data, including its own data and from throughout the network. If these nodes tend to fail due to constant energy depletion, it would act as a bottleneck to the WSN. This as a result affects the lifetime of the entire network, and these nodes comprise of the bottleneck zone. Rout &

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*Author for Correspondence
E-mail: shilpadas.soajuly2013@gmail.com

Ghosh[2] have used the network coding and duty cycle to improve the achieved network lifetime upper bound by focusing on the energy consumption by the nodes inside the bottleneck zone, but, an inaccurate equation derivation and the assumption is made. The derived equation considers 50% of the nodes deployed to be network coder nodes and the rest 50% to be general relay nodes inside the bottleneck zone. These nodes are deployed throughout the bottleneck zone with their energy consumed for relaying data coming from outside it, using network coding and duty cycle along with network coding. The process of decoding takes place at the sink. However, if all the nodes present inside bottleneck zone are divided equally into coder and relay nodes, then, the sink wouldn't have the original packets of the data generated inside bottleneck zone by network coder nodes to decode the packets. In this work, the consumed energy of the nodes inside the bottleneck zone is derived, and improvement methods have been implemented.

Network Model

A network with an area, A, is set up with N_T number of nodes deployed, and sink, S, at the centre. The area near sink is called bottleneck zone, with an area, B_A, and a radius, R_B. The network coder nodes are deployed equally along with relay nodes only one-hop away from the sink. The rest of the bottleneck zone comprises of only relay nodes. The initial energy, E_{int} for the all the nodes are same.

Energy Consumption and Network Lifetime

The lifetime of network is found to be crucially dependent on the nodes inside bottleneck zone. Therefore, the energy consumed by the nodes inside bottleneck zone needs to be taken into consideration for finding the upper bound of the network lifetime. The network lifetime upper bound is analytically computed by correctly improving the network lifetime using network coding and network coding along with the duty cycle. A major portion of the energy consumed inside B_A, is due to the process of relaying data bits received from the nodes outside the bottleneck zone, sensing and relaying the data which are generated inside bottleneck zone. Therefore, the amount of energy utilized by the relay nodes which are present at more than one hop distance from the sink, for relaying one bit of data generated outside bottleneck zone, is given as,

$$E_{R1}(ij) \geq E_1 \frac{n}{n-1}\left(\frac{R_B}{C_d} - 1\right) \qquad \ldots (1)$$

where, E_1 is the amount of energy utilized in the transmission and receiving of a data bit, n is the path loss exponent and C_d is the characteristic distance. The amount of energy utilized by a relay node present at a distance of only one-hop from the sink, for relaying a data bit generated outside of the bottleneck zone, is,

$$E_{R2}(ij) \geq E_1 \frac{n}{n-1} \qquad \ldots (2)$$

The consumed energy of the network coder nodes, for relaying a bit of data, which is generated outside bottleneck zone, is given as,

$$E_C(ij) \geq E_1 \frac{n}{z(n-1)} \qquad \ldots (3)$$

where, z is total number of data packets which are being coded into single packet by the network coder nodes. The energy consumed by the nodes present inside the bottleneck zone for relaying all the data bits being generated outside of the bottleneck zone in time, t, is expressed as,

$$E_{ONC} \geq \sum_{i=1}^{\left\lfloor N_T \frac{A-B_A}{A} R_S t \right\rfloor} \sum_{j=1}^{\left\lfloor \frac{\gamma+1}{2} \right\rfloor} E_{R1}(ij) + \sum_{i=1}^{\left\lfloor N_T \frac{A-B_A}{cA} R_S t \right\rfloor} \sum_{j=1}^{\left\lfloor \frac{\gamma+1}{2} \right\rfloor} E_{R2}(ij) + \qquad \ldots (4)$$

where, A is total network area including the bottleneck zone, N is total number of sensor nodes, R_S is average sensing rate for all sensor nodes, $\left\lfloor \frac{\gamma+1}{2} \right\rfloor$ is the average number of the active neighbours which receive redundant data inside B_A, $\frac{1}{c}$ of the data received from outside bottleneck zone relayed by network coder nodes and $\left(1 - \frac{1}{c}\right)$ of the data by the relay codes, present at one – hop distance from the sink.

The amount of energy utilized by the bottleneck zone nodes to sense data inside the bottleneck zone with network coding, is given by,

$$E_{SNC} = N_T \frac{B_A}{A} R_S E_S t \qquad \ldots (5)$$

where, E_S is the amount of energy spent in sensing a bit of data. The energy spent in just receiving a bit of data is given by E_{12}. We, then calculate the amount of energy spent for relaying the data generated inside B, by the nodes inside bottleneck zone with network coding, can be computed as,

$$E_{INC} = \frac{N_T}{A} R_S t \iint_B l(y) dS$$

$$\Rightarrow E_{INC} \geq \frac{N_T}{A} R_S t \iint_B \left(E_1 \frac{n}{n-1} \frac{y}{C_d} - E_{12} \right) dS \qquad \ldots (6)$$

Therefore, the network lifetime upper bound using network coding from equations (4), (5) and (6), for the network is expressed as,

$$E_{TNC} = E_{ONC} + E_{SNC} + E_{INC} \leq \frac{N_T B_A}{A} E_{int} \qquad \ldots (7)$$

which is derived as,

$$t \leq \frac{C_d B_A E_{int}}{I_x} = T_{NC} \qquad \ldots (8)$$

where,

$$I_x = r_s \left[\alpha_1 \frac{n}{n-1} \left[(A - B_A) \frac{m+1}{2} \right] \left\{ (R_B - C_d) + \frac{C_d\left(1+k(h-1)\right)}{kh} \right\} + \iint_{B_A} x dS + B_A C_d (e_s - \alpha_{12}) \right] \qquad \ldots (9)$$

Similarly, the expression for the energy consumption in relaying the data coming from outside the bottleneck zone, considering network coding along with duty cycle is obtained as,

$$E_{ONCD} \geq \sum_{i=1}^{\left\lfloor N_T p_{DC} \frac{A-B_A}{A} R_S t \right\rfloor} \sum_{j=1}^{\left\lfloor \frac{\gamma+1}{2} \right\rfloor} E_{R1}(ij) + \sum_{i=1}^{\left\lfloor N_T p_{DC} \frac{A-B_A}{cA} R_S t \right\rfloor} \sum_{j=1}^{\left\lfloor \frac{\gamma+1}{2} \right\rfloor} E_{R2}(ij) + \sum_{i=1}^{\left\lfloor N_T p_{DC} \frac{A-B_A(c-1)}{cA} R_S t \right\rfloor} \sum_{j=1}^{\left\lfloor \frac{\gamma+1}{2} \right\rfloor} E_C(ij) \qquad \ldots (10)$$

where, p_{DC} is the probability of a node of staying active till time, t. The amount of energy utilized by bottleneck zone nodes to sense data inside bottleneck zone for network coding with duty cycle is,

$$E_{SNCD} = N_T \frac{B_A}{A} p_{DC} R_S E_S t \qquad \ldots (11)$$

The amount of energy spent for relaying the data generated inside B, by the nodes inside bottleneck zone for duty cycle along with network coding is found to be,

$$E_{INCD} = \frac{N_T}{A} p_{DC} R_S t \iint_B l(y) dS$$

$$\Rightarrow E_{INC} \geq \frac{N_T}{A} p_{DC} R_S t \iint_B \left(E_1 \frac{n}{n-1} \frac{y}{C_d} - E_{12} \right) dS \qquad \ldots (12)$$

The amount of energy spent by nodes inside bottleneck zone during the inactive period of the duty cycle is given by,

$$E_{SLNCD} = (1 - p_{DC}) t N_T \frac{B_A}{A} E_{ID} \qquad \ldots (13)$$

Therefore, the network lifetime upper bound utilizing duty cycle along with network coding from equation (10), (11), (12) and (13), for the network is given as,

$$E_{TNCD} = E_{ONCD} + E_{SNCD} + E_{INCD} + E_{SLNCD} \leq \frac{N_T B_A}{A} E_{int} \qquad \ldots (12)$$

which is derived as,

$$t \leq \frac{C_d B_A E_{int}}{I_x} = T_{NCD} \qquad \ldots (15)$$

where,

$$I_y = p_{DC} r_s \left[E_1 \frac{n}{n-1} \left[(A - B_A) \frac{\gamma+1}{2} \left\{ (R_B - C_d) + \frac{C_d\left(1+k(h-1)\right)}{kh} \right\} + \iint_{B_A} x dS \right] + B_A C_d \left(p r_s (e_s - \alpha_{12}) + (1-p) E_{sleep} \right) \right] \qquad \ldots (16)$$

Coverage fraction and Node failure

The network coverage can be defined by the particular sensing model which is used for the network, shows how well the target area is being covered by the nodes present in the area. Coverage Fraction explains the actual network coverage, and can be defined as ratio of the area covered by the WSN to the target area being sensed. The probability of an event not being detected, by the nodes present in the area, can be due to two main factors - the event occurs beyond the covered area, or due to the node failure in that particular region. Coverage is another factor which is affected by the energy loss by the sensor nodes, in case of node failure. This, thereby, decreases the coverage fraction of the network. Hossain *et al.*[3] have also studied on how the coverage fraction of the WSN is affected by the sensing model used in the network. The coverage area not only affects the network lifetime but, also, quality of monitoring as shown in earlier works.[4] It is also observed that network lifetime with deployment models based on various coverage mechanisms is affected similarly as studied in detail.[5] There have been methods which look into improving network lifetime through mobile sink node and coverage through clustering the network.[6] The concept of cover sets has also been used for enhancing coverage along with network lifetime by Singh *et al.*[7] Coverage fraction of a particular area is greatly affected by node failure, which generally occurs due to the depletion of energy. The maximum depletion of energy by a node occurs due to transmission and relay of data, and a very minimum amount of energy is lost due to the sensing. The energy lost by nodes inside bottleneck zone area and the possible effect of node failure due to lost energy on the coverage fraction inside the bottleneck zone are focused in this paper. Coverage fraction can be calculated by the following equation,

$$C_f = 1 - (1 - P_C)^N \quad \dots (17)$$

where, P_C is the probability that the event being detected is by a random sensor node and N is the total number of nodes deployed. In order to find P_C, two models are considered in this work for the coverage fraction of the bottleneck zone.

Boolean Sensing Model

The simplest model is the binary sensing model, where the sensor node is capable to sense the events occurring within its sensing range with a probability of 1, and cannot sense beyond its sensing range. So, in this model the sensing range is a circular area with a radius r, called the sensing radius. This model ignores the effect of the possible environmental conditions like obstacles due to building, foliage, etc. and the emitted signal strength on sensing. The probability that an event is detected using the Boolean sensing model is given by,

$$P_C = \frac{\pi S_r^2}{A} \quad \dots (18)$$

where, S_r is the node's sensing range, and A is the total area of deployment.

Elfes Sensing Model

The Elfes' sensing model is probabilistic in nature, where it provides an actual perception of sensor detection. This model defines, that the probability of an event being sensed, that it occurs at the distance, d, from a sensor node is shown by,

$$P_C(x) = \begin{cases} 1, & 0 \le x \le R_{un} \\ e^{-\lambda(d-R_1)\beta}, & R_{un} < x < R_{max} \\ 0, x \gg R_{max} & \end{cases} \quad \dots (19)$$

where R_{un} defines onset of unreliability of the sensor detection and R_{max} is maximum sensing range of the node. Here, λ and β are the parameters which are adjusted on the basis of the physical properties of the sensor node.

Node Failure

Node failure can occur due to several factors in WSN. It may result due to energy depletion due to communication, software or harware problems, etc. In the current study, the energy spent in transmission is considered to be a factor responsible for node failure. The node failure directly affects the coverage fraction of the WSN. So, the coverage fraction for node failure can be given as,

$$C_f = 1 - \left(1 - P_C\left(1 - P_{nf}\right)\right)^N \quad \dots (20)$$

where, P_C is the probability of the detection of an event by a random sensor node, which is determined using either boolean or elfes' sensing model, N is total number of nodes present, and P_{nf} is probability of node failure for WSN using network coding, is given by,

$$P_{nf} = \frac{E_{1NC} + E_{2NC} + E_{3NC}}{E_{int}} \quad \dots (21)$$

The probability of node failure for duty-cycled WSN using network coding is obtained as,

$$P_{nf}{}^{*} = \frac{E_{1NCD} + E_{2NCD} + E_{3NCD}}{E_{int}} \quad \dots (22)$$

In the next section, the obtained expressions are used to determine the network lifetime upper bound under different situations is carried out for simulation based experiments.

Simulation study

The following Table – 1, enlists all the parameters used for the simulation of effect of uneven deployment on the network lifetime. The comparison between the network lifetime upper bound obtained by our expression and network lifetime upper bound presented in[2], using network coding along with duty cycle, for m=3. It is seen that our network lifetime upper bound obtained in the present case is less than the upper bound reported in[2], and from eqn. (8) and (9), due to the original packets being sent along with coded packets for decoding with correct calculation of network lifetime. The information sensed and forwarded by sensors would hold no meaning for data generated inside bottleneck zone, without the correction as it could not be decoded. The network lifetime upper bound for our work is shown in Fig. 2 by using duty cycle with network coding, with increase in the number of neighbours, m = 1, 3, 5, 7, 9. It is found that even with increase in number of neighbours, network lifetime upper bound decreases, in contrast to the results obtained in[2] compared to eqn. (15) and (16), for all the cases. The probability of node failure is determined by calculating the total energy consumption by the sensor nodes with respect to the total initial energy present inside the bottleneck zone for the current and previous work. The actual probability of node failure with increase in time is more as derived from eqn. (21) as shown in Fig. 3. As, the actual energy consumption is more; hence, the probability of the node failure is more. coverage fraction considering the probability of node failure with increase in time is given in Fig. 3. The coverage fraction has been calculated using both Boolean and Elfes' Sensing model in case of node failure. It is observed that under ideal scenario, the coverage fraction in the present case would actually be lesser than the obtained result for work in[3] from eqn. (22). It would eventually be lesser over time due to energy loss during transmission of both original & coded packets, both in case of Boolean and Elfes' Sensing model.

Table 1 — Parameters usede

Parameters	Values
Total Area of Deployment, A	$200 * 200m^2$
Bottleneck Zone Radius, R_B	60 m
Bottleneck Zone Area, B_A	$\pi R_B^2 m^2$
Total No. of Nodes, N	1000
Initial Node Energy, E_{int}	25 KJ
Path Loss Exponent, n	2
Characteristic Distance, C_d	10 m
Duty Cycle Probability, P_{DC}	0.01 - 0.1
Sensing Rate, R_s (H = 960 bits)	$\frac{H}{(A-B)\frac{N_T}{A}}$ bits/sec
Energy loss in transmitting along with start-up energy loss, E_{11}	0.937 μjoule/bit
Energy loss in receiving, E_{12}	0.787 μjoule/bit
Total energy in transmitting and receiving, E_1	$E_{11} + E_{12}$
Energy loss in amplifying, E_2	0.0172μjoule /bit
Energy loss during sleep state, E_S	30 μjoule/bit
Energy loss in sensing a bit, E_{SB}	0.0001 J
Idle State Energy, E_{id}	$c * E_{12}$ (c = 0.9)
Total no. of nodes in radial array, N_r	6
Sensing radius, S_R	4
Total no. of active neighbors, $\frac{m+1}{2}$	(m=1, 3, 5)

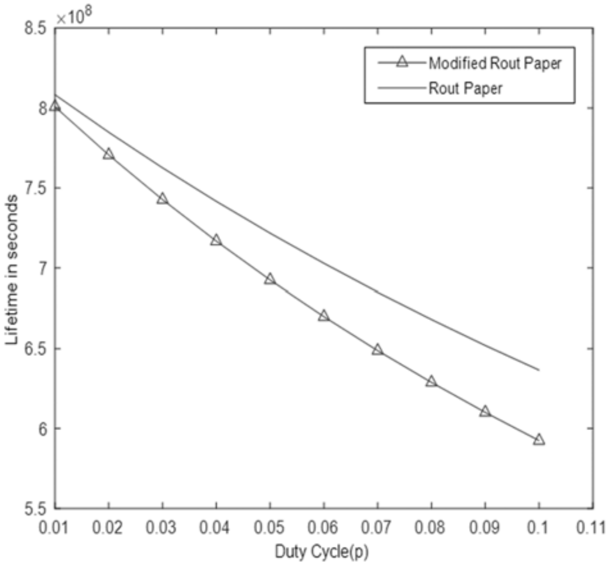

Fig. 1 — Lifetime upper bound comparison by using the network coding and duty cycle (m=3)

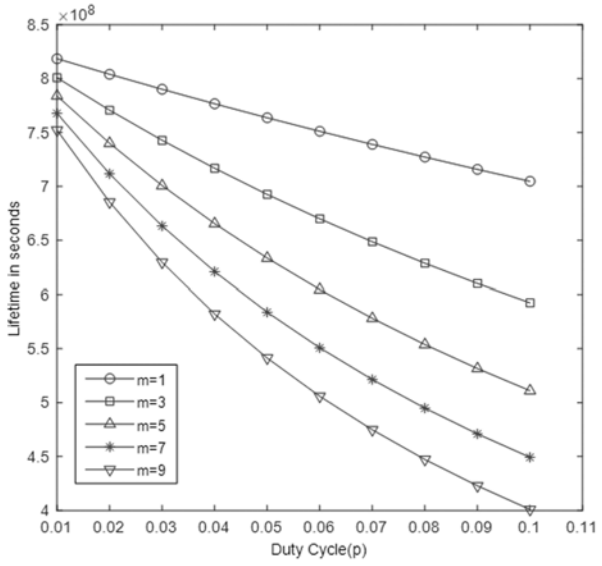

Fig. 2 — Upper bound of network lifetime by combining duty cycle and network coding

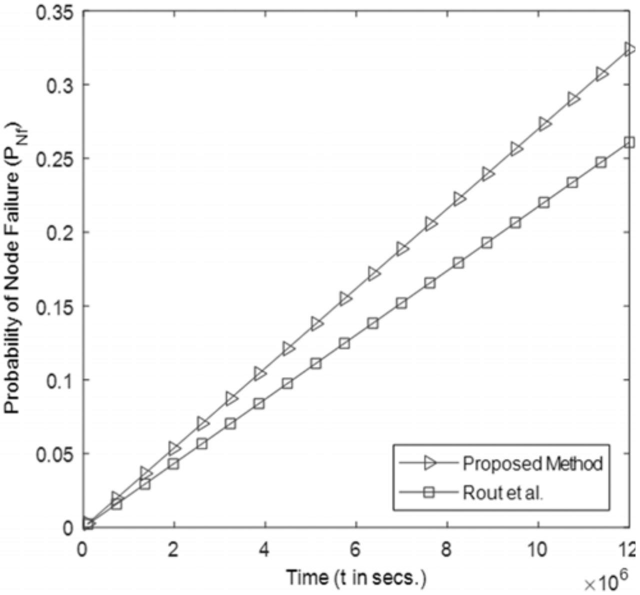

Fig. 3 — Probability of Node failure with increase in time

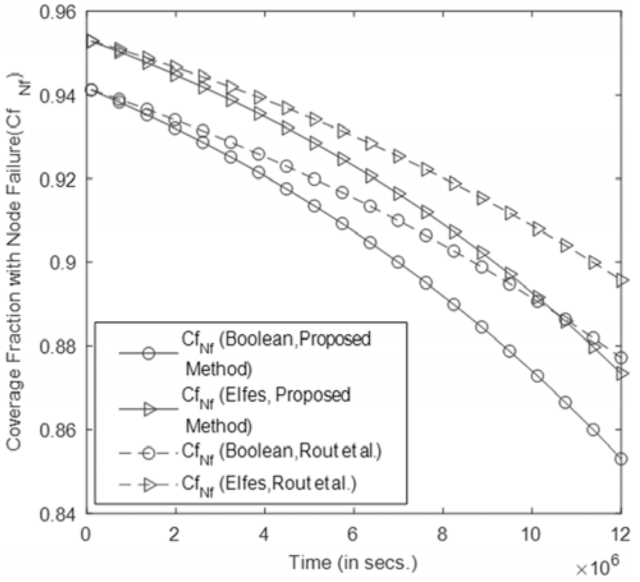

Fig. 4 — Coverage Fraction with probability of node failure with increase in time

Result and Discussions

By considering the actual deployment of network coder nodes in [2], the approximate expressions of the energy consumed by the nodes inside bottleneck zone have been derived. The major contributions of the paper are considered.

-The expression of energy consumption for relaying data that are generated outside bottleneck zone is provided. It considers network coder nodes to be 50% of the nodes, present only a single hop away from sink, while other are relay nodes.

The probability of node failure is derived for our expression, and Rout & Ghosh[2] is done, both using duty cycle and without using duty cycle.

The coverage fraction in case of node failure is derived, using Boolean and Elfes' Sensing Model, and is compared with the coverage fraction derived for Rout & Ghosh[2].

Conclusion

In this work, the actual network lifetime upper bound is determined by the appropriate deployment of network coder nodes inside the bottleneck zone. In the current work, 50% of the network coder nodes are present only one-hop away from the sink, while the rest are relay nodes inside bottleneck zone. This deployment is considered for derivation of lifetime upper bound with only network coding, and other along with duty cycle. This paper has investigated on the amount of energy expenditure inside the bottleneck zone for relaying data coming from outside. The network lifetime bound is observed to be lesser in comparison to that obtained by the previous work. This work also has analyzed the effect of energy expenditure inside the bottleneck zone on the coverage fraction of WSN. The probability of node failure is obtained, both in case of network coding and duty cycle along with network coding. This is achieved using the amount of energy expenditure by the sensor nodes inside the bottleneck zone. Using Boolean and Elfes' sensing model, the coverage fraction for the network in case of node failure is also found out. This concept used in this work can also be applied to other existing model such as dynamic sensing model and the results obtained can be analyzed. This work can be further improved by considering network clustering, energy harvesting techniques along with multi-objective parameters like bandwidth allocation, other data collection schemes, etc. along with intelligent methods with clustering of nodes as that of implemented by Gopinath *et al.*[8].

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