IET Communications

Research Article

Distributed energy efficient algorithm for ensuring coverage of wireless sensor networks

ISSN 1751-8628
Received on 7th May 2018
Revised 14th October 2018
Accepted on 10th December 2018
E-First on 7th February 2019
doi: 10.1049/iet-com.2018.5329
www.ietdl.org

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Abstract: Energy consumption, network lifetime and coverage are the major challenges in wireless sensor networks. This study proposes a method that grids network area into square cells on a geographical basis. The node possessing the highest energy is selected as an aggregator in each cell. Given the cover area and remaining energy, the firefly algorithm functions to select and actively maintain the most suitable node in each cell while deactivating others. The uniqueness of the proposed evolutionary firefly algorithm is to ensure the desirable and effective network coverage. Omnet++ was applied for simulation study, the results of which were compared with those from both TCO and ACO-Greedy models. A significantly greater coverage was provided by the proposed method with fewer nodes and 30% decrement in energy demand. The added advantage was the elongation of network lifetime.

1 Introduction

Recent years has witnessed a rapid development and universal application of wireless communication system technology. The precise location of nodes, more often than not, is not pre-determined. This specific design characteristic makes it possible for the sensor nodes to be used in dangerous and remote places. A wireless sensor network consists of a number of nodes that have certain characteristics like sensing ability, establishment of communication, observation of relative incidents or specific phenomena within a certain operational environment and effective reaction against them. The aim is to collect process and transfer data for a base station [1]. Any physical limitation in the nodes is bound to result in corresponding limitations in energy, coverage and operational lifetime. The sensor nodes have low energy and cannot be recharged or changed after the initial instalment [2]. Therefore, as the time passes, its energy runs down, causing some nodes to deactivate. This in turn produces holes in the region under investigation. Each sensor has an in-built capability to sense a limited coverage area within the functional context with a limited radius of node in question. It is on such basis that in regions without node coverage, some holes are produced. The category or class of application that the proposed system is expected to select is the principal factor that dictates the specific nodes to perform the design function [3]. The system's military utility is a case in point where there would be a need for high network coverage. The latter necessitates simultaneous functioning of several sensors to ensure sufficient coverage for each sensor's catchment area.

A certain minimum coverage percentage is however required in different operational settings such as those that monitor sensitive domains such as eco-systems and wild life or monitoring temperature in huge residential and commercial complexes. Those networks with a greater coverage are, to certain extent, protected against performance deficiency in nodes. For these very reasons, it should be born in mind during the designing phase that various applications require a suitable network coverage [4] that might necessitate a specifically defined, tailor-made system having capability to overcome the coverage challenges.

One way of prolonging the lifetime of networks is to schedule the activity of network sensors to determine the activity and passivity of the nodes in the system [5]. Scheduling the activity of nodes makes it possible to decrease the number of active nodes at a given time, making it possible to decrease energy consumption and prolong their operational lifetime [6].

The network coverage is classified based on its specific application and certain other criteria [4]. The classification generally consists of three types, namely, regional coverage, point coverage and barrier coverage [7].

Several different methods can be used for an optimum network coverage, one of which is the evolutionary algorithm. This algorithm has a widespread application for optimisation [8]. The evolutionary firefly algorithm is one of the proposed methods for optimum network coverage, which is the major focus of this paper. The aim of the proposed algorithm is to enhance the coverage with least number of nodes. The paper is organised as follows: Section 2 covers the related works, followed by network modelling and the firefly algorithm in Section 3. Section 4 introduces the proposed algorithm, which is followed by the simulation model and the analysis of the results in Section 5, and conclusions are drawn in Section 6.

2 Related works

Coverage and energy-efficiency optimisation in wireless sensor networks have recently been the focus of research investigations. For more details on summaries of the related issues pertaining to the subject matter, refer to [1, 7]. The two aforementioned issues were initially considered separately and independently as a means to reducing the challenges involved in the designing of protocol. Those sensor nodes with a limited battery energy source have their energies gradually depleted render some nodes dysfunctional, which in turn produces holes in the region under monitoring. In regions without node coverage, holes are therefore produced that appear to compromise the coverage [9].

Various techniques to enhance the wireless sensor network (WSN) coverage have been discussed in [10]. Node placement is one of the most significant factors that directly affect network coverage. Sensors can be deployed in the monitored area either randomly or deterministically. The selection of the deployment scheme of sensors depends largely on their type, application and the environmental setting within which they operate. The position of sensors strongly affects the network efficiency. Depending on the sensor, while it depends on the sensors deployment to achieve four primary objectives, deployment coverage can be increased, strong network connectivity can be achieved, network lifetime can be prolonged and data fidelity can be boosted. Random sensor deployment was unable to achieve the aforementioned objectives.

By contrast, the deterministic deployment achieved one or more of the deployment objectives.

In [11], the authors have classified deployment mechanisms into two main categories: deterministic and non-deterministic. Deterministic methods handle both regular and planned approaches. These methods use static deployment sensors to achieve full coverage. These methods also increase the sensing effectiveness of coverage with a lesser number of sensors. However, the deterministic strategy (point to point) for placement of WSNs may be used for small-scale deployments. Random and grid-based are among the strategies that are handled by non-deterministic techniques. In random deployment, sensors are usually scattered (e.g. by aircraft), resulting in a randomised distribution of sensors, although their density can be controlled to an extent. Random deployment can sometimes be the only feasible option in some applications where the region of interest (RoI) is inaccessible, such as in disaster areas and active war zones.

In [12], energy balanced node deployment algorithm (EBND) proposes as a novel algorithm. An optimisation problem is formulated as a means of determining the optimal node number in each layer. This makes it possible to maximise the network lifetime within the multiple constraints. The objective function and constraints in the EBND are estimated as a function of the node numbers in the layers. An algorithm is proposed to attain optimum node numbering in each layer on the basis of the total number of nodes. Results of the simulation point at the smaller node numbers demanded, by EBND, a comparatively lower energy than that is required by other schemes. Based on the findings, the EBND can ensure longer network lifetime than would be possible by other node deployment strategies while satisfying the constraints.

A physics-based heuristic for efficient placement of sensor nodes for the target coverage problem in wireless sensor networks has been presented [13]. The algorithm employed virtual sensors that move, merge, recombine and explode during a process in which merging and recombining virtual sensors reduce the number of actual sensors while maintaining full coverage. The rapidity and effectiveness of the proposed method were verified by the simulation results.

The grid-based coverage problem has been overcome with low cost and connectivity-guarantee (GCLC) in [14]. The objective was to avert energy hole, decrease deployment costmaries coverage speed and a more effective GCLC problem resolution. A novel deployment approach (ACO-Greedy) was proposed to settle this question. The approach relies on the ant colony optimisation with a greedy migration mechanism that can quickly complete the full coverage. It can achieve that with a markedly decreased deployment costs. Moreover, ACO-Greedy can dynamically adjust the sensing/communications radius to alleviate the energy hole issues and extend the network lifetime. Simulation results confirmed markedly decreasing deployment costs with a simultaneous balancing of power consumption among sensor nodes. The results further confirmed the elongation of network lifetime in greed-based WSNs.

A coverage hole detection and repair algorithm is proposed for solving the network disconnection problem [15]. The algorithm dynamically analyses the network topology based on maximum simple subnet and determines the boundary node of the empty area. The algorithm categorises the potential coverage holes in a network with the detection and repairing algorithm. A clustering strategy is proposed to detect and repair coverage holes by identifying the boundary holes around coverage holes. Comparison of the coverage hole area with the pre-set coverage hole area threshold makes it possible to determine the reasonable number of inactive nodes as cluster-head nodes. The simulation results show 10% higher hole-detection accuracy than those of other algorithms. Moreover, the comparative coverage was observed to be 40% higher than those of the other two methods.

In [16], a new algorithm for the detection and restoration of coverage holes in wireless sensor networks are proposed. Each sensor node finds out the crucial intersection points between neighbouring nodes and itself in order to detect coverage holes in the network. Those holes are restored by deploying new nodes over optimum locations. The bisection method for a straight line is used to detect the location of new nodes. The methodology involved drawing the line between two crucial interesting points situated at the maximum stored distance. Simulation results showed accurate detection of coverage holes, requiring a fewer patching nodes for restoring network holes.

The termite colony algorithm for optimising coverage in the wireless sensor network is used in [17]. Some parameters such as the size of network, the number of nodes and the number of termites are used to calculate the coverage area. The nodes or termites are initially distributed randomly throughout the network. The major function of the high-energy communication node (HECN) is the analysis of data within the network. The linkage, connection between other nodes with HECN, is in the form of hop-by-hop. Those nodes are considered useful in that these have the capability to establish effective linkage or communication with the base station. Those nodes without the aforementioned performance characteristics are not considered useful. The latter are not able to establish an effective link with the other nodes and are therefore swept away from the network routes. Under the circumstances where the designer has some limitations on the selection of the minimum number of nodes in the network, it is obvious that the quality of network service would be compromised due to the minimum network coverage. Therefore, the objective function in the termite colony optimisation algorithm should be designed in such a way that it can maximise the coverage of the network using the least number of sensor nodes.

The DEHCIC algorithm based on the clustering scheme has been presented in [18] to improve coverage. This algorithm covers the holes as much as possible by static sensor nodes. If that was not forthcoming, the nearest mobile node covers the coverage holes. This algorithm consequently maintains only those sensor nodes active that are essential to cover the interest points. It further puts some sensor nodes with overlapping areas into low-power sleep mode. The DEHCIC can achieve enhanced network coverage lifetime. The simulation results show a decreased dependency of the algorithm on the movement of mobile nodes. A much-improved coverage is achieved with the minimum number of active nodes and thus a markedly prolonging coverage lifetime.

A new energy-efficient heuristic is introduced to schedule the sensors in different non-disjoint networks aimed at prolonging network lifetime in [19]. The methodology involved first identifying all critical targets (those covered by the least number of sensors) and criminal sensors (those covering the critical targets). The algorithm maximises network lifetime by giving priority to sensors with more remaining energy, covering maximum number of uncovered targets and ensuring minimum critical sensors in each sensor cover. The proposed rules ensure the maintenance the critical sensors alive for a longer period and as such extend the lifetime of network. Simulation results show that the proposed heuristic outperforms various other approaches to overcome target coverage problems.

An optimised deployment scheme of the *N*-node coverage with an improved genetic algorithm (OPEN) is proposed in [20]. It proposes a new coverage problem in WSNs, named *N*-node coverage, for acquiring maximum information about monitored objects with *N* sensors. It is meant to enhance the efficiency of deployment, redeployment and the coverage scheduling of the WSNs. The *N*-node coverage model is established to represent the coverage capability of the WSNs as well as devising the corresponding deployment scheme. Establishing an optimal *N*-node coverage model involves a combinatorial optimisation, which is proved to be an NP-hard problem. Experimental results show a remarkable improvement in the coverage performance of the WSNs by the OPEN. It is also able to improve the practical guidelines for the deployment of WSNs with a limited number of nodes.

Energy conservation and connectivity requirements are achieved without any sensing and transmission range restrictions [3]. Maximum disjoint sets for maintaining coverage and connectivity (MDS-MCC) is proposed to prove an NP-complete problem. Furthermore, heuristic and network flow algorithms to solve NDS-MCC are proposed. The algorithm aims to find the *K* disjoint subset of the sensor node in such a manner that each subset can monitor whole targets and convey the data to end users. Any incident of a node failing its duties results inadvertently in the total network collapse. Such incidences are averted by the redundant subset of sensor nodes.

An exact method, disjoint set covers-boolean satisfiability (DSC-SAT), is proposed to find a maximum number of DSC of sensors for extending the lifetime of WSNs in [21]. The method is based on a polynomial time reduction of the DSC problem into a number of SAT problems. The DSC problem is reduced to an instance of the Boolean satisfiability (SAT) problem in polynomial time and subsequently solved through a SAT solver. The prime purpose is to divide the sensors into a maximum number of disjoint groups known as covers, each of which can cover all targets. This makes it possible for only one active cover at any time. The simulation results show a clear superiority of the proposed method over others.

The multi-objective optimisation coverage and topology control (MOOCTC) framework is proposed as a new optimisation approach to simultaneously optimise several conflicting issues [22]. It will deal with the number of active sensor nodes. Coverage rate of the monitoring area and balanced energy consumption considering the network connectivity. The approach makes it possible for the sensing and communication ranges of sensor nodes to be dynamically adjusted to conserve energy on the one hand and prolong the network lifetime on the other. The simulation results showed the superiority of the proposed method in terms of network lifespan, coverage catchment area and connectivity.

An improved GA-based approach for energy-efficient scheduling of the sensor nodes has been proposed [23]. This is meant to ensure a full coverage of target points and maintain connectivity among the activated sensor nodes and the base station. This makes it possible for the data to be forwarded. During the scheduling, those sensor nodes with higher energy levels are in the preference so that they can provide maximum rounds of service delivery. The chromosomes are efficiently represented, and it is also assured that even after crossover and mutation operations the offspring will be a valid chromosome. In contrast to the traditional GA, the approach has introduced a novel mutation operation for better performance and has a faster convergence of the proposed algorithm.

3 Preliminaries

This section introduces the network model and the optimisation of the firefly algorithm.

3.1 Network model

The sensor nodes are randomly distributed over the specific environmental domain. The assumption is that the nodes are incapable of moving after their initial placement. The network model consists of the following:

i. The network environment is assumed to have a dimension of $200 \times 200\ \text{m}^2$.
ii. From the geographical perspective, the network is divided into smaller sizes of equal dimension of $20 \times 20\ \text{m}^2$.
iii. The network is homogenous with the sensors having the initial energy, radial sensing, communication radius, memory and similar process capability.
iv. Sensing nodes are equipped with the GPS with the characteristic quality to have access to the data from the neighbouring cells.
v. The sensing radius (R_s) of each node and its communication radius (R_c) are equal ($R_s = R_c$).

3.2 Firefly algorithm

This is one of the evolutionary optimising algorithms modelled and designed on the basis of behavioural characteristics of a firefly that produces regular shining light to attract their mates [24]. The rhythmic lights, lightning rate and time intervals between light signals are principal factors to attract mates. Those fireflies that produce greater lights become more attractive to others. Three major assumptions are considered in this algorithm, listed as follows:

i. All fireflies are unisexual.
ii. Attraction rate depends on their brightness. The more brightness one firefly has, the greater would be the probability for those with a less brightness to move.
iii. The greater the increase in distance between two fireflies, the lesser would be the brightness intensity. Under the circumstances where two fireflies have similar brightness, their movement is bound to be random.

In order to solve the optimisation problem, the brightness intensity I for a particular firefly in a specific area X can be expressed by the following relation: $I(x) \propto F(x)$. Although the attractiveness β is somehow relative, it should nonetheless be considered from the perspectives of other fireflies. Due to the variation in the intervals r_{ij}, the attraction rates between the fireflies i and j is bound to vary [25].

Since the attractiveness rate of a firefly is proportional to the brightness intensity seen by the neighbourhood firefly, the following relation is used to define the attractiveness rate of firefly i from the viewpoint of firefly j:

$$\beta_{i,j} = \beta_0 \mathrm{e}^{-\gamma r_{ij}^2} \quad (1)$$

where β_0 represents the attractiveness rate of firefly i in $r = 0$ and γ represents the brightness absorption coefficient. γr can be substituted by other functions such as γr^m so that $m > 0$. The distance between two fireflies i and j at locations X_i and X_j can be considered as Euclidean or any other distances. The movement of the firefly i towards the firefly j having a greater attraction can be determined by the following equation:

$$x_i(t+1) = x_i(t) + \beta_{i,j}(x_j - x_i) + \alpha\,\varepsilon_i \quad (2)$$

where the second term is related to the attraction, while the third relates to randomisation α, which nominates the randomisation parameter, and ε represents a vector of random numbers drawn from a Gaussian distribution or uniform distribution at time t. In most implementations, $\beta_0 = 1$.

4 Proposed method

The provision of coverage is one of the major challenges for a wireless sensor network. The principal aim of the algorithms is to ensure sufficient coverage of the system with the minimum number of nodes. Various methods for coverage optimisation in a wireless sensor network are applied, with the evolutionary algorithm being the principal one. The latter helps to select the most appropriate nodes for coverage. With the use of an appropriate time scheduling programme, it is possible to deactivate other nodes. This makes the maintenance of sufficient coverage possible with the least energy demand, thus prolonging the operational lifetime of the network.

The aim of the proposed method is to use the firefly algorithm to schedule the sensors in such a manner to ensure maximum coverage with minimum energy consumption. In other words, the objective of using the proposed algorithm is to have the least number of active nodes from among those in the network and to inactivate the other nodes in order to provide the required cover. This is achieved by a much reduced energy requirement while extending the operational lifetime of the network. The first step in the proposed algorithm is to divide the geography of the network into equal-sized square cells. This simplifies the calculation processes. After gridding the network environment, the nodes in each cell communicate a hello packet to inform other nodes of the energy and position. The node with the greatest energy is selected as an aggregator, which announces the packet to other cells. The aggregator node runs the firefly algorithm for each cell in a parallel manner. The objective is to select the most appropriate nodes in such a manner to have the greatest rate of energy storage and maximum coverage area for each cell. Thus, a sensor from each cell is selected to ensure the following objectives:

i. The node has the highest energy level.
ii. There is maximum coverage area of the cell.

The energy of the node and coverage area of the cell by each node constitute the inputs of the firefly algorithm.

The processes of the proposed algorithm are as follows:

i. The network area is gridded in the form of square cells on the geographical basis.
ii. The nodes in each cell announce their precise location and the level of energy through a package known as hello. Therefore, each node knows its own precise location and the level of energy and those of others that are in the same cell.
iii. The node with the greatest energy in each cell waits for a random period, called back-off time, and then through a pre-packed programme announces its role as an aggregator node to others. If there is no back-off time, announcement packets of two nodes with the maximum and equal level of energy will collide and be wasted. The back-off time therefore prevents simultaneous transmission of announcement of nodes.
iv. The aggregator node selects the most appropriate node in each cell with the help of the firefly algorithm to maintain active state in the network as follows:

a. The whole sets of nodes in cell are considered as the initial population of the firefly algorithm.

b. The energies of each node and those parts of the cell that are covered by nodes are considered as the inputs of the firefly algorithm. The aggregator node here obtains the energy level and location of each node from stage ii.

c. The location of the sensor node plays a crucial role in defining the coverage area in each cell. In the proposed method, a and R_s denote the length of each side of cell and the sensing radius, respectively. Assuming a square with a side length of $a - 2R_s$ in the centre of the cell, a sensor node that is located inside the square provides the maximum coverage area (would have the maximum priority). In the proposed method, the priority of locating nodes within a cell is ranked from 1 to 10 and denoted by $\text{Priority}_{\text{Node}_i}$. So, when the sensor node is located in this central square area, its priority equals 10.

Under the circumstances where the sensor node is not located inside the square, its priority changes according to its location. The outside area of the central square is divided into nine concentric squares. Higher priorities belong to more internal squares. The priority model is depicted in Fig. 1.

d. The aggregator node estimates the fitness of each node from the fitness function. The fitness of each node is signified by the attractiveness of the firefly from the viewpoint of other fireflies. To select the node with the highest energy level and coverage area, the fitness function is defined as follows:

$$F(x) = \alpha \frac{E_{\text{current}}}{E_{\text{Max}}} + (1 - \alpha) \frac{\text{Priority}_{\text{Node}_i}}{10} \tag{3}$$

$$\text{Priority}_{\text{Cell}_i} = \{1.2.3.4.5.6.7.8.9.10\} \tag{4}$$

where E_{current} indicates the current energy and E_{Max} presents the energy of the node when the battery is fully charged. $\text{Priority}_{\text{cell}_i}$ is the priority of a sensor node, which is allocated to it on the basis of its location within each cell. α represents the impact factor of parameters in relation to fitness function.

e. The firefly algorithm runs until the terminus state and the latter runs for 100 turns. The most appropriate node with the greatest attraction for other fireflies is selected. The selected node remains active, whereas the others become inactive.

v. In the majority of scheduling methods, the duration of the inactive period is regulated randomly or on a fixed basis. When the energy of an active node is completely depleted while other nodes are inactive, a hole is emerged in the area in question. The period of inactiveness of the inactive nodes should be therefore determined in accordance to the remaining energy of the selected active node according to iv-d. The inactive period of inactive nodes is obtained from the remaining energy of active node according to the following equation:

$$T_{\text{Inactive}} = \frac{E_{\text{Current}}}{E_{\text{Max}}} \times T_{\text{Max}} \tag{5}$$

where T_{Inactive} is the estimate of the inactive period of the nodes that have become inactive, E_{Current} is the current energy of the active node, E_{Max} is the energy of the active node with fully charged battery and T_{Max} is the maximum lifetime of each sensor node with fully charged battery.
vi. The scheduling programme runs and the selected node in Stage iv remains active, while the others become inactive.
vii. Under the circumstances where the active period of the selected node reaches its end, it will then proceed to Stage ii.

The general methodology of the proposed method is shown in Fig. 2.

5 Simulation and results

The proposed method is compared to the TCO algorithm [17] and ACO-Greedy [14] using Omnet++ simulation modelling software. The implementation parameters are presented in Table 1.

Fig. 3 shows the average area coverage percentage provided by the proposed algorithm in comparison with TCO and ACO-Greedy algorithms for 500 nodes. As can be seen from Fig. 3, 90% coverage is secured with 500 nodes under the similar conditions. Such is the case where the other two algorithms are able to cover only 75% of the network. This is because the proposed method systematically and intelligently selects the most appropriate nodes for activeness according to the required coverage of the network. The firefly algorithm is instrumental in achieving those nodes.

The coverage percentages of the network area at various times are shown in Fig. 4. As the nodes deteriorate with time, the coverage holes in the wireless sensor network emerge because of decreasing network coverage. Since a scheduling programme for maintaining nodes active and since one of the criteria for selecting the active nodes is their coverage area of the cell, a considerable decrease in energy consumption occurs with the passage of time. This leads to a greater number of nodes to remain active because of increasing coverage area. As shown in Fig. 4, the proposed algorithm maintains about 70% coverage in 500 s, while this is 40% in the TCO algorithm and less than 50% in the ACO-Greedy algorithm.

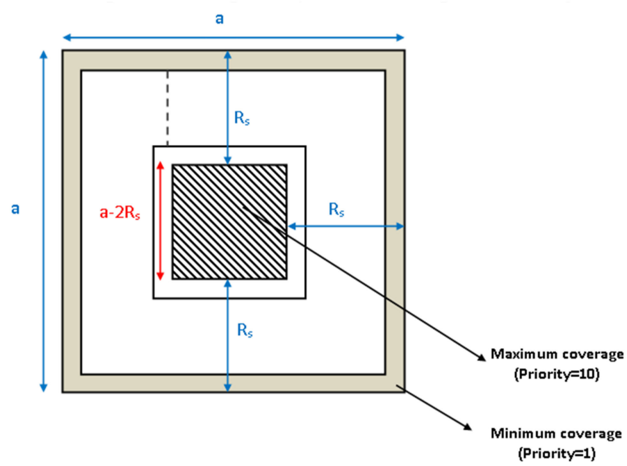

Fig. 1 *Prioritising coverage model based on node location*

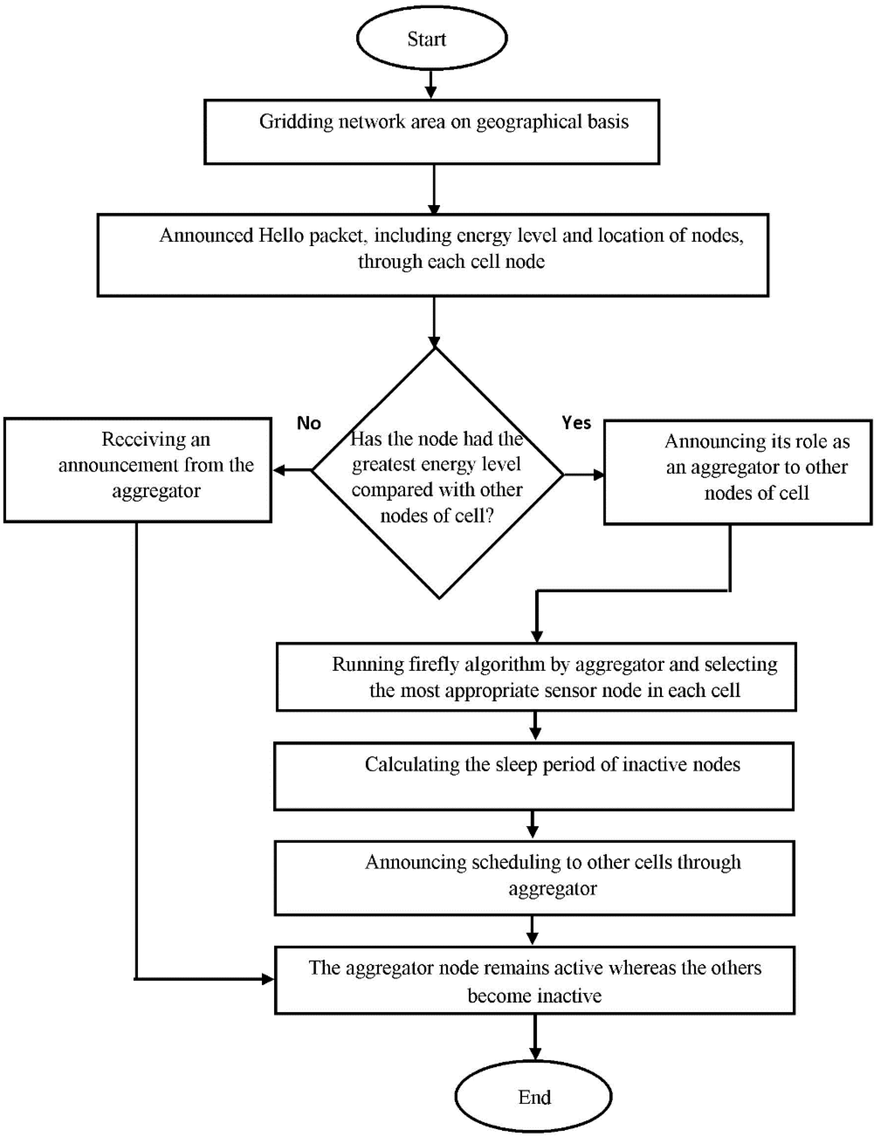

Fig. 2 *General methodology of the proposed method*

Fig. 5 shows the average energy consumption for each node in comparison with TCO and ACO-Greedy algorithms during 500 s. Given an effective scheduling method and minimisation of the number of nodes in the network, it can be deduced from Fig. 5 that the proposed method consumes a significantly less average energy over times relative to the other two methods.

Table 2 presents the overall results of comparison between the proposed method and the other two algorithms. It is noticeable that the network coverage has improved compared to that of the other two methods and that the energy consumption of the network has also decreased.

Table 1 Simulation parameters

Parameters	Values
network size	200 × 200 m^2
size of each cell	20 × 20 m^2
number of nodes	500
initial energy of each node	5 J
sensing radius	30 m
communication radius	30 m
node deployment method	random

6 Conclusion

The evolutionary firefly algorithm was the basis of the model used in this paper to optimise coverage in wireless sensor networks. The methodology is based on a gridding network on a geographical basis. Moreover, a node with the highest remaining energy in each cell is selected as an aggregator. The objective is to pick the nodes with the highest level of remaining energy and coverage area in each cell to stay active, while others to become inactive. The evolutionary firefly algorithm is used to select the most appropriate node. This makes it possible for the proposed technique to ensure considerably a must greater coverage area. The latter makes it possible to ensure the establishment of simultaneous minimal active nodes and maximal network coverage area. The energy consumption is decreased and the lifetime of the network is enhanced as a result. The results of simulation modelling show that increasing the number of active nodes increases an average of 30% network coverage compared with that of the other two methods. A much greater coverage area is therefore provided by the proposed method. The proposed algorithm was simulated with the Omnet++ software, the results of which were compared with those of the TCO and ACO-Greedy algorithms to validate the results.

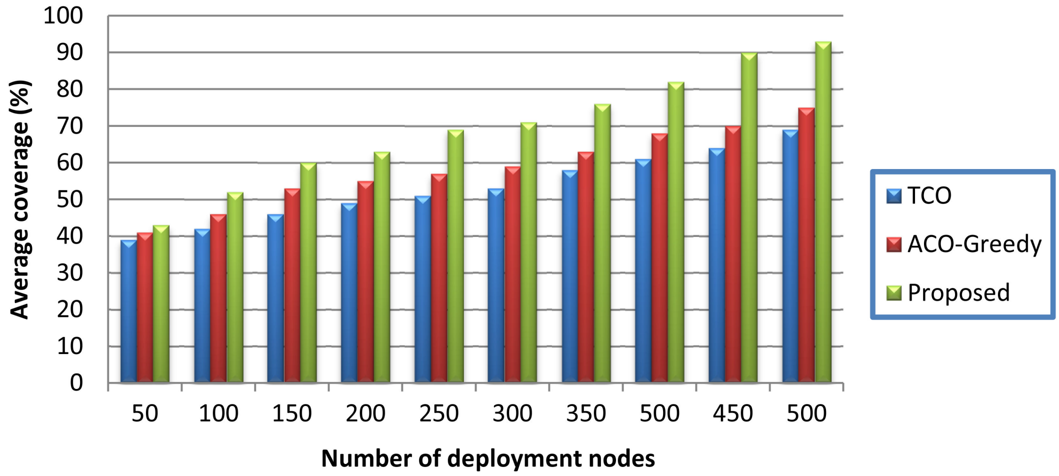

Fig. 3 *Average coverage percentage of network with various numbers of nodes*

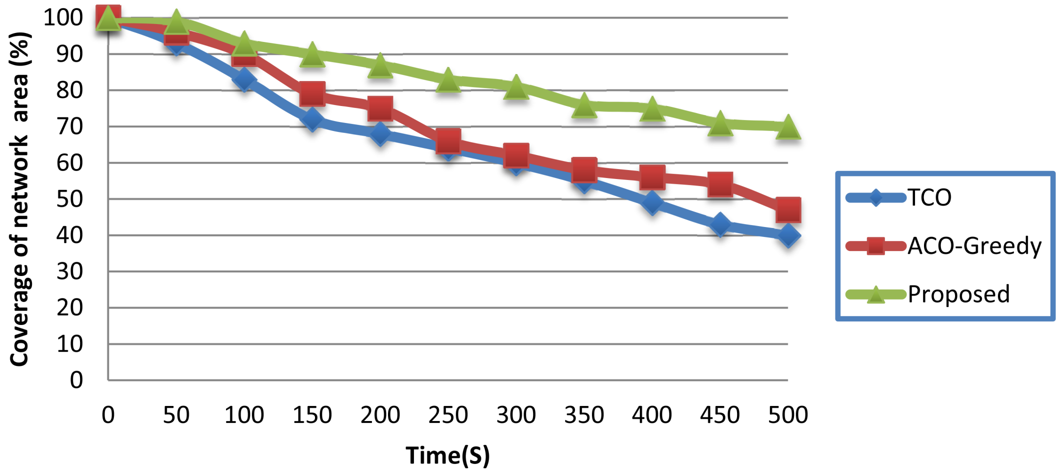

Fig. 4 *Coverage percentage of network area at various times*

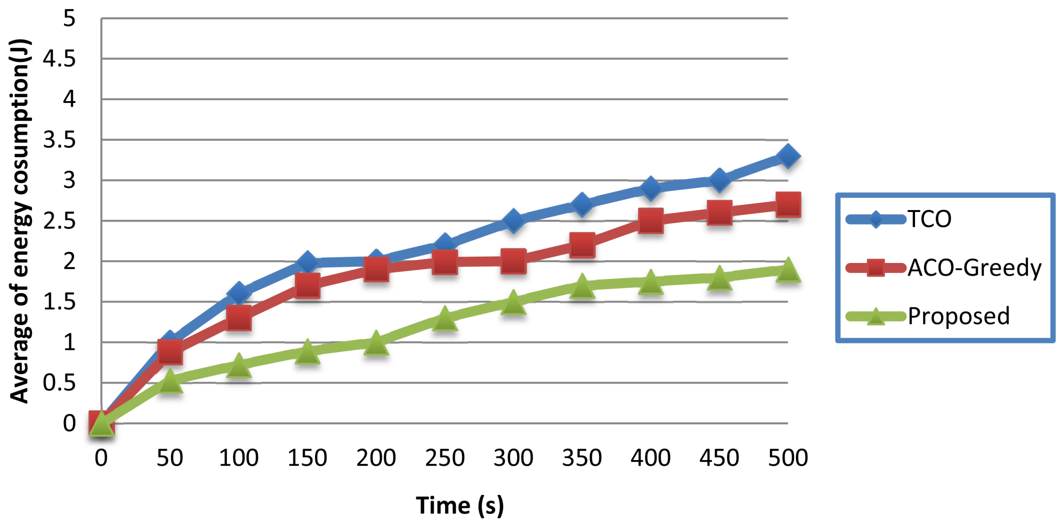

Fig. 5 *Average of energy consumption for each node at various times*

Table 2 Comparison of the proposed method with the other two algorithms

Parameters	TCO	ACO-Greedy	Proposed method
coverage with various number of nodes, %	69	75	93
coverage at various times, %	40	47	70
energy consumption at various times, J	3/3	2/7	1/9

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