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Energy-saving Distributed Monitoring based Firefly Algorithm in Wireless Sensors Networks

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Abstract Coverage control represents an important research challenge during the design of Wireless Sensor Networks (WSNs) in an energy-efficient way. It is an indicator used to assess network services performance. In order to provide network services quality guarantee, it is essential to ensure the network coverage with a minimum consumed energy to extend the lifespan of the network. In this paper, an Energy-saving Distributed Monitoring based Firefly Algorithm (EDiMoFA) Protocol in Wireless Sensor Networks is proposed to ensure the coverage and to enhance the lifetime of WSNs. In the first phase, the sensing field is divided into smaller virtual regions using the concept divide-and conquer. The EDiMoFA protocol is distributed on every node in the resulted small regions in the second phase. The EDiMoFA protocol mixes three powerful approaches to work efficiently: virtual network division, dynamic distributed virtual region head selection in every region, wireless nodes scheduling based Firefly Algorithm (FA) is performed by every chosen head of the virtual region. The EDiMoFA protocol is periodic. Every period is composed of two different phases: a steady-state phase and monitoring one. The network information exchange, virtual region head selection, and a wireless sensors scheduling optimization-based FA are achieved in the steady-state phase. In the monitoring phase, the best sensor devices schedule produced by the FA will take the responsibility for monitoring the sensing field in every virtual region. The produced sensors schedule ensures coverage at a low consumed energy cost. Simulation results, which are obtained using the OMNeT++ network simulator, prove that the EDiMoFA protocol can increase the wireless sensors' lifetime and produces enhanced coverage control performances in comparison with some recent existing works in the literature. The EDiMoFA protocol has respectively prolonged the network lifetime from 3.2% up to 21.8%, from 10.4% up to 86.4%, from 35.2% up to 68.4%, and from 1.6% up to 6.7% in comparison with the DiLCO, DESK,

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GAF, and PeCO protocols while maintaining the suitable level of coverage for the sensing field of interest.

Keywords Wireless Sensor Networks · Scheduling · Firefly Optimization Algorithm · Coverage · Network lifetime · Distributed Computation

1 Introduction

The advances in wireless networking and smart sensor technologies have led to the emergence of wireless sensor devices which constitute the Wireless Sensor Network (WSN) that represents the most implemented element in the Internet of Things (IoT)[1]. These IoT smart sensors devices can be used in several applications such as danger alarm, vehicle tracking, battlefield surveillance, habitat monitoring, healthcare, military, etc [2,3]. Wireless sensors devices can be used on a large scale of IoT applications. The smart devices are capable of sensing, communicating, and processing the collected sensed data before transmitting them across the Internet to the base station for further analysis [4,5]. The lifetime coverage maximization problem has received a lot of attention, focusing in particular on how the physical space could be well monitored after the deployment. Coverage is one of the Quality of Service (QoS) parameters in WSNs, which is highly concerned with power depletion [6]. In addition to the coverage, the energy consumption and the lifespan are QoS parameters. The lifetime coverage maximization refers to how well the sensing field of interest is monitored for a longer time by the deployed sensors devices with a minimum amount of energy whilst preserving a suitable level of coverage [7]. The mission of preserving the desired level of coverage with a minimum number of sensor devices of the whole WSN is extremely important and represents a big challenge due to the limited resources of sensor devices like power, processing, memory, and bandwidth. Sensor devices have limited lifetime batteries which are often quite difficult to change, especially in a harsh environment such as underwater, deep forests, and so on. Therefore, the sensing field of interest must be deployed with a large number of sensor devices to exploit the redundant sensor devices and to improve the WSN lifespan. It is not essential to turn on the all sensor devices simultaneously in this high-density network. If all the sensor devices are turned on at the same time, the energy consumption would be quickly reduced which would thus decrease the lifespan of the network. Therefore, it is required to implement a scheduling technique to provide the schedule for the sensor devices by turning on some of them to provide the sensing services while turning off the other devices to save the energy thus extending the network lifetime of the WSN. The basic idea is to benefit from the overlapping sensing regions of some sensor nodes by putting some of them into a sleep mode during the sensing phase. The main advantages behind the scheduling technique are to turn on a minimum number of sensor devices, to maximize the lifespan of the sensor device battery, to reduce the collision on the channel, and to improve the lifespan of the WSNs[8]. Several works have been proposed based on an integer program to optimize the coverage problem in WSNs. As the complexity of this problem increases, metaheuristics can be used to provide high-quality and fewer execution time solutions to difficult coverage optimization problems. This paper makes the following contributions:

i) An Energy-saving Distributed Monitoring based Firefly Algorithm (EDiMoFA) Protocol in WSNs is proposed to ensure the coverage and to enhance the lifetime of WSNs. The EDiMoFA protocol relies on the framework of the DiLCO protocol [9] to schedule sensor devices to be activated periodically so that the network lifespan is improved while maintaining a certain level of coverage. The sensing field is divided into smaller regions using the concept divide-and conquer. EDiMoFA protocol is operated inside every sensor device in every region and operates into periods. Every period is composed of two phases: a steady-state phase and a monitoring one. The network information exchange, region head selection, and wireless sensors scheduling optimization-based FA are achieved during the steady-state phase. In the monitoring phase, the best sensors schedule that will be produced by the FA will tackle the task of monitoring the sensing field in every region. The produced schedule of sensor devices ensures coverage at a low consumed energy cost.

ii) The EDiMoFA protocol uses FA instead of GLPK optimization solver to solve the lifetime coverage optimization model to periodically produce the schedule of sensor devices inside the virtual region. The problem of lifetime coverage formulation is slightly adjusted to use sensor devices centers rather than the concept of primary points of sensor devices in the optimization model. Besides, the EDiMoFA protocol employs an efficient distributed region head election approach to select the head device in each region which is responsible for executing the FA to produce a better schedule of sensor devices sensing the monitoring phase of the current period.

iii) The OMNeT++ network simulator has been used to conduct the results of several experiments to show the improved performance of the EDiMoFA. The achieved results of our EDiMoFA protocol are compared with some existing works in the literature such as PeCO, DiLCO, GAF, and DESK which are proposed in [10], [9], [11], and [12] respectively. EDiMoFA, PeCO, and DiLCO are based on the same network model and framework. PeCO and DiLCO are employed by GLPK optimization solver to solve the scheduling optimization model while the EDiMoFA protocol implements the firefly algorithm to produce the optimal or near optimal schedule of sensor devices per period.

The paper structure is arranged in the following way. The related works are reviewed in the next section. The scientific background of the Firefly Algorithm is presented in Section 3. The EDiMoFA protocol is explained in more details in Section 4. The simulation results are achieved using OMNeT++ [13] and they are discussed and analyzed in Section 5. Section 6 presents the conclusion and the future works.

2 Related Works

Recently, The lifetime coverage maximization problem represents a challenging issue in the WSN [14]. Some relevant works concerning the problem of coverage are reviewed in this section and then the disadvantages of the presented works are described. The authors in [11] have proposed a technique named GAF (geographical adaptive fidelity) to save energy in the ad hoc networks. GAF divides the network into grids based on the position information. One sensor device is activated in each grid to perform the mission of sensing and routing. The other sensor devices in the same grid will be either in sleep or listening mode. DESK is a

Distributed Energy-Efficient Scheduling Approach for K-Coverage in Sensor Networks that proposed by Vu et al. [12]. DESK works into rounds. It only needs the information of the one-hop neighbors. Each sensor device decides its status (Active or Sleep) based on the perimeter coverage model that was introduced by [15]. The work introduced in [16] has proposed an enhanced whale coverage optimization system in WSNs. First, they build a mathematical model that considers energy saving, node utilization, and coverage. Then, to improve the whale optimization method, they use the sine and cosine algorithm. The work in [17] proposed four algorithms to solve the problem of optimizing the coverage in WSN heuristically or approximately. This problem is defined as a set of targets that must be covered by a given set of mobile sensor nodes. The dispatch algorithm of a sensor is used to increase the covered targets and under the constraint of limiting the maximum moving distance for each node by threshold. The entire power minimization problem while the targets covering satisfies the requirement of the partial multi-cover is studied by[18]. It is named MinPowerPMC (minimum power partial multi-cover problem) in WSNs. In this problem, a fixed number of targets such that each target should be covered by a given number of nodes (named covering requirement). In [19], the authors proposed energy-aware heuristic to solve the k-coverage problem. The heuristic algorithm produces a set of various non-disjoint K-Covers to enhance the lifetime of WSNs. The work in [20] studies the Scheduling of Maximum Cover Sets in WSNs. The problem formulated as an integer program, and then a greedy approach is proposed to solve this problem. After that, the authors presented an approximation method to solve the formulated problem. The work in [21] presented a mathematical model to solve the weak coverage problem. The authors formulated it as an optimization algorithm based on perceived probability around nodes. The proposed algorithm can decrease the distance of nodes moving and increase the time of service in the network.

The authors in [22] have proposed two algorithms to solve sleep-scheduling which are named PSKGS (Pre-Scheduling-based K-coverage Group Scheduling) and SKS (Self-Organized K-coverage Scheduling). PSKGS improves the quality lifetime detection and the SKS approach decreases the cost of processing and communication of devices thus enhancing the network lifespan. The authors in [23] have proposed a clustering method based on the square division. The subdivision is based on the communication and sensing ranges as well as the secondary grouping. In every cluster, the scheduling algorithm is executed to ensure the coverage of the network. In [24], the deployment field is partitioned into concentric circles where the region of every annulus is equivalent. In each annulus, the probability density function is planned according to the density of the node. An algorithm for node distribution based on the probability density function is proposed. This scheme of distribution ensures coverage, energy-saving, and lifetime improvement in the network. The authors in [25] exhibited three heuristic methods to schedule the nodes' activity: cellular automata, fine and random-tuning, and hypergraph methods. These methods can not be optimal solutions and the produced schedules can be used as input to a strategy based local search with neighborhood functions. In [26], the authors presented a greedy algorithm to schedule the sensor nodes into cover sets to maximize the WSN lifespan. This method gives the nodes with the lowest power a higher priority and limits the number of nodes monitoring critical targets. The coverage and connectivity problem is well studied by [27]. The researchers proposed a hybrid approach which consists of the bee colony method and the free search method with pheromone sensitivity to achieve suitable coverage and connectivity to optimize the lifetime of the WSNs. In [28], The authors have studied the coverage problem with energy saving using Probability Density Function (PDF). They divided the field into circles where the annulus area is equal. The density of the nodes in each annulus is used to design the PDF.

Idrees et al. [9] introduced a protocol named Distributed Lifetime Coverage Optimization (DiLCO) to keep the coverage and enhance the network lifespan in WSNs. This protocol represents an ameliorated version of the protocol presented in [29]. The DiLCO protocol is based on partitioning the area of interest into subregions using a divide-and-conquer approach. After that, DiLCO is distributed on every sensor device in each subregion. The suggested DiLCO protocol is implemented in a periodic way, where each period consists of four phases: information exchange, leader election, decision, and sensing. The results of simulations show that DiLCO can improve the WSN lifetime and produces enhanced performances of coverage. In the PeCO protocol[10], a novel sensor devices perimeter-based optimization model is proposed. PeCO performs a centralized optimization to produce the sensor devices schedule inside the region while it is distributed on the sensor devices of the regions of the network. This schedule saves the energy while ensuring the required level of coverage for the region.

SHORTCOMINGS. Despite the introduction of various energy-saving protocols for coverage keeping and to enhance the lifespan of the network, no method could guarantee the coverage for the sensing field of interest with the optimal minimum number of sensor devices on the long-term. For instance, excellent solutions can be provided by the centralized approaches of optimization. Unfortunately this can lead to wasting large amount of energy due to the increased cost of the algorithm execution time and the sensor devices' communication in the network of the region. Hence, in dense networks, the centralized methods are not preferred. In the distributed approaches, the solutions are not optimal due to they depend on local information of the neighboring devices. These approaches can save energy because they decrease the communication and execution time costs in the sensor devices. Both distributed and centralized approaches would produce imperfect lifetime coverage in the WSNs.

OUR PROTOCOL. We propose an Energy-saving Distributed Monitoring based Firefly Algorithm (EDiMoFA) Protocol in WSNs to ensure a suitable level of coverage and to improve the lifetime of WSNs. The sensing field is divided into smaller regions using the concept divide-and-conquer in the first phase. In the second phase, the EDiMoFA protocol is distributed and executed on every node in each region. The EDiMoFA protocol works into periods. Each period is composed of two phases: steady-state and monitoring. The network information exchange, region head selection, and wireless sensors scheduling optimization-based FA are achieved in the steady-state phase. In the monitoring phase, the best sensors schedule that will be produced by the FA will take the responsibility of monitoring the sensing field in every virtual region. The produced sensors schedule ensures coverage at a low consumed energy cost and thus extends the network lifespan. The EDiMoFA protocol combines and employs the principal benefits of centralized and distributed strategies and gets rid of most of their disadvantages. In addition, the Firefly Algorithm is efficient, simple, light, and easy to implement and this is the main reason behind using the Firefly Algorithm by the proposed EDiMoFA protocol.

3 Firefly Algorithm

The Firefly algorithm is a nature-inspired metaheuristic optimization technique inspired by the real-world social life of the fireflies. The phrase Lightning bugs refers to the synonym of the Fireflies. In the world, the number of different firefly species is about 2000. The short and rhythmic flashes are produced by most of these firefly kinds. Each particular species has a personalized flashing pattern. The mating partners and potential preys are attracted by the signal of the flash of the firefly. Besides, the flashes can be used as an approach for secured warning. The firefly algorithm proposed by Yang can be explained as follows [30].

1. One firefly will be invited to join other fireflies without considering their sex where all fireflies are unisex.
2. Firefly Attractiveness is indicated by its light. The lower light firefly is moving toward the higher light one for any two flashing fireflies. The brightness is the measure of the attractiveness. When the distance of the of two fireflies grew, the attractiveness will be decreased. If the brightness of both fireflies is the same, one of them moves randomly.
3. The firefly brightness is calculated using an objective function. The brightness for the problem of the maximization is proportional to the objective function value. Algorithm 1 refers to the original firefly algorithm.

Algorithm 1 Firefly Technique

```
Goal function fun(y), $y = (y_1, ..., y_d)^T$
Create fireflies initial population $y_j, j = 1, ..., n$
Intensity of light $Intensity_j$ at $y_j$ is identified by fun($y_j$)
Set coefficient $\Upsilon(absorptionoflight)$
while stop condition true do
    for $j \longleftarrow 1$ to $n$ do
        for $k \longleftarrow 1$ to $n$ do
            if $Intensity_j < Intensity_k$ then
                Shift firefly j in the direction of firefly k
            end if
            Modify attractiveness with distance $dis$ by $exp(-\Upsilon * dis)$
             Assess new solutions and modify the Intensity of light
        end for
    end for
    Order the fireflies and locate the current global best gbest
end while
Process the output of the algorithm and transform it into a visual form
```

3.1 Attractiveness

The firefly attractiveness is fixed via its intensity of light. The following equation gives the attractiveness

$$B(dis) = B_0 * e^{-\Upsilon * dis^2} \tag{1}$$

Where B_0 is the attractiveness at distance $d = 0$, Υ is the coefficient of absorption.

3.2 Distance

The Cartesian distance is used to calculate the distance between firefly j and firefly k, at Y_j and Y_k respectively, as follows

$$dis_{jk} = \left||Y_j - Y_k\right|| = \sqrt{\sum_{j=1}^{d}(Y_{j,i} - Y_{k,i})^2} \tag{2}$$

3.3 Movement

The movement of a firefly j that is interested in another more winning firefly k is fixed via the following equation

$$Y_j = Y_j + B_0 * e^{-\Upsilon * dis^2_{j,k}} * (Y_k - Y_j) + \lambda(rand - 1/2) \tag{3}$$

Where λ is the randomization parameter and rand is the random generator function.

3.4 Discretization

If the firefly j shifts in the direction of firefly k, the firefly j position is adjusted from a value of the binary number to a real number value. Hence, it must replace this real value by a binary value. This will be done by using the following sigmoid function

$$S(Y_{j,k}) = \frac{1}{1 + exp(-Y_{j,k})} \tag{4}$$

4 EDiMoFA protocol

A randomly and uniformly deployed WSN composed of static homogeneous sensor devices is considered. The sensor devices have the same processing, communication, and sensing abilities. They have different initial energy levels. To guarantee initially a full coverage of the interesting sensing field, dense wireless sensor devices are deployed. Moreover, it is supposed that each sensor node knows its position by employing either a localization system or GPS. The sensing field is divided virtually using the concept divide and conquer concept, where each sensor device stores the information of the borders of each virtual region in the sensing field before the deployment process [9]. After the deployment, every sensor device will belong to a certain virtual region if its position is located inside the boundaries of that region. The sensors' devices are deployed uniformly over the virtual regions. Each sensor device includes the radio range R_s and the sensing range R_s. Therefore, if the distance length between any two devices less than or equal to $2R_s$, they are considered as neighbors. The sensor device can sense any event that occurs in its R_s. The disk model is supposed for every device where its radius is R_s. Every device can communicate within the disk radius of R_c. The multi-hop communication is used during the information exchange among the sensor devices inside the virtual region as well as when the sensor devices transmit their measurements to the cluster head of the region.

The EDiMoFA protocol is introduced in this section. Each sensor node in every virtual region of the sensing field includes the EDiMoFA protocol. Three energy-efficient techniques are integrated to implement the EDiMoFA protocol. These techniques are virtual WSN division, region head selection, and sensors schedule production based on FA to ensure the coverage of the sensing field with a minimum consumed energy. The EDiMoFA protocol is periodic and each period consists of two phases: steady-state and monitoring. The former is composed of three steps: Information exchange, Region Head Selection, and Sensors Scheduling Production based FA. Figure 1 shows proposed EDiMoFA protocol.

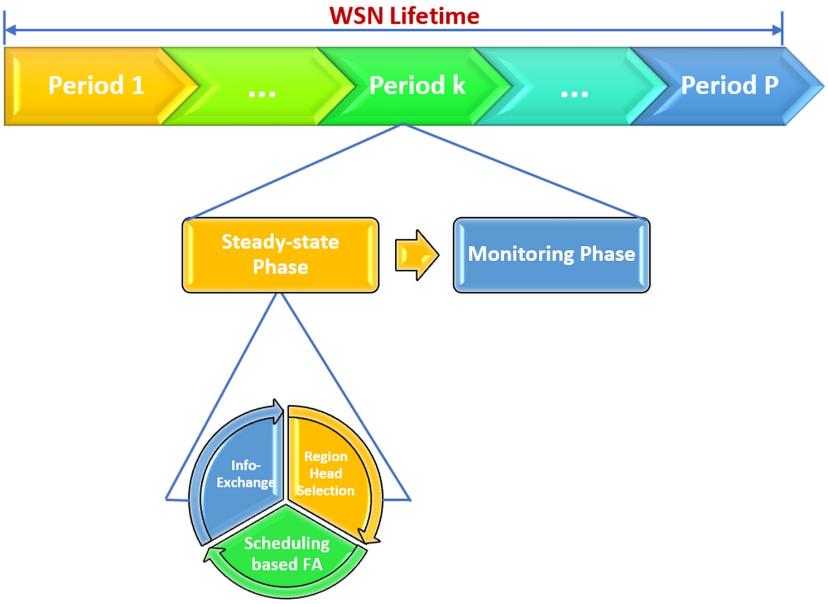


Fig. 1: EDiMoFA Protocol.

EDiMoFA protocol applies two types of packets throughout the execution:

I) INFO Message is employed to exchange information among sensor devices. INFO Message contains two components: header and payload data. The sensor ID is incorporated in the header, where the header size is 8 bits. The data section includes position coordinates (64 bits) and residual power (32 bits). Hence, the size of the INFO Message is 104 bits.

II) ActiveSleep Message is employed to notify sensor devices to remain Active or to go Sleep throughout the phase of monitoring. The ActiveSleep Message is 16 bits of length.

Moreover, every sensor device will have five possible states in the sensor network: Listening, Processing, Active, Sleep, and Communication (Message sending or receiving).

As exhibited in Figure 1, the suggested EDiMoFA protocol lifespan is broken into periods, where each period consists of two phases: steady-state and monitoring: in the former, information exchange, region head choice, and sensor activity scheduling based FA optimization. In the latter, the produced sensors schedule will monitor the sensing field during the current period. For every period, only one schedule of sensor devices is responsible for covering the sensing field of interest. The periodic implementation of the EDiMoFA protocol can enhance the robustness of the WSN against sensor failures [9]. Algorithm 2 refers to the EDiMoFA protocol implemented in every sensor device in each region.

Algorithm 2 EDiMoFA(s_j)

```
if $E_j^R \geq E_{th}$ then
    $s_j.state$ = COMMUNICATION
    Broadcast $INFO()$ Message to other sensor devices in the same region
    Wait $INFO()$ Message from other sensor devices in the same region
    RegionHeadID = Region Head Selection()
    if $s_j.ID = RegionHeadID$ then
        $s_j.state$ = COMPUTATION
        $\{(Y_1, \dots, Y_s, \dots, Y_S)\} \longleftarrow$ Execute Firefly Algorithm($S$)
        $s_j.state$ = COMMUNICATION
        Transmit $ActiveSleep()$ Message to each sensor device $s$ in region
        Update $E_j^R$
    else
        $s_j.state$ = LISTENING
        Wait $ActiveSleep()$ Message from the Region Head
        Update $E_j^R$
    end if
else
    Exclude $s_j$ from joining in the current period
end if
```

4.1 Information exchange

As displayed in Algorithm 2, a sensor device s_j tests whether it has adequate power. i.e, the residual power of $s_j \geq E_{th}$. The E_{th} represents the minimum power required by the sensor device to remain active throughout one period. If the condition is satisfied, sensor device exchanges INFO Messages with the all sensor devices belonging to the same region. It gathers from every sensor device its location coordinates, remaining power(E_j^R), and sensor ID. These three parameters are exchanged only in the first period, while during the next periods, every sensor device will only send its E_j^R. If there is any change to its location, it can be sent with the remaining energy to update the information of the sensor devices in the region.

4.2 Region Head Selection

Once the first step in the steady-state phase is completed, each sensor device in the region implements the region head selection method to choose the region head of the current region. The region head selection method is executed in a distributed way in every sensor device. Each s_j in the virtual region employing Eq. 5 and for every sensor device s, $s \in S$, where $|S|$ is the number of sensor devices in the region. For each sensor device s in the region, the weight w_s will be calculated. Hence, the head of the virtual region during the current period in the current virtual region is the sensor device s which has the maximum weight of w_s. The same Eq. 5 will be applied by the all of the sensor devices in the same virtual region. Therefore, they will have the same maximum weight for the winning sensor device as the head of the virtual region. The parameter z in Eq. 5 is used to prevent the sensor devices from selecting more than one head of the virtual region at the same time in the case of equality between sensor devices.

$$w_s = \left(\sigma * \left(\frac{E_s^R}{E_{max}} \right) + \varsigma * \left(\sum_{i \in |S|} \left(1 - \frac{dis(s,i)}{2 * R_s} \right) \right) \right) + z \tag{5}$$

Where $z = \left(\frac{ID_s}{|S|} \right) * \delta$, $\sigma + \varsigma = 1$, $s \in |S|$, and $\delta = 0.005$.

$$dis(s,i) = \sqrt{(x_s - x_i)^2 + (y_s - y_i)^2} \tag{6}$$

The head of the virtual region is responsible for executing the Firefly Algorithm to provide the best sensor devices schedule for the current period (see Section 4.3.2. Every head of the virtual region will transmit an ActiveSleep message to the all sensor devices in the same region based on the produced schedule by the FA. This message will notify the sensor device either stay active or to go into sleep mode. Otherwise, if the sensor device is not the region head, it will listen for the ActiveSleep message to identify its status throughout the monitoring phase. The head of the virtual region will stay active during the current period and it will be responsible for receiving the measurements from the sensor devices inside the virtual cluster.

4.3 Sensors Scheduling based Firefly Algorithm

The main objective of sensor scheduling after choosing the region head is to select the minimum number of sensor devices to enhance the lifetime of WSN while achieving a suitable rate of covering and monitoring of the region with a lower consumed energy. In each period and each region of the sensing field, one new sensor devices schedule will be provided to tackle the mission of sensing inside every region of the current period. The coverage problem represents an optimization problem and it can be solved using the FA technique.

4.3.1 Coverage Problem Formulation

The mathematical model of the coverage problem is formulated in this section as an integer linear program. This model is inspired by the model proposed in [31] with some modifications and considers the center points of sensor nodes instead of the targets.

The problem of area coverage is declared as the monitor of a set of center points of the deployed sensors devices in the monitoring area. The set of center points of the deployed sensors devices is indicated by C and the set of alive sensors by S.

Definition 1 Boolean Parameter $\Phi_{c,s}$ describes the actual relation between the center point c of sensor device and the sensor device s.

$$\Phi_{c,s} = \begin{cases} 1 \text{ if center point } c \text{ is covered by sensor device } s; \forall c \in C, \forall s \in S \\ 0 \text{ otherwise.} \end{cases} \tag{7}$$

Definition 2 Boolean Parameter Y_s Indicating the activation (1 if yes) or not (0 if not) of the sensor s.

$$Y_s = \begin{cases} 1 \text{ if sensor device } s \text{ is Active,} \\ 0 \text{ otherwise.} \end{cases} \tag{8}$$

Definition 3 Active node number is denoted as the number of sensor devices that covers the sensor device center point as $\sum_{s \in S} \Phi_{c,s} * Y_s$.

Definition 4 Outside Coverage Out_c refers to the number of sensor devices that monitor the center point c minus one.

$$Out_c = \begin{cases} 0 & \text{if center point of sensor device is not covered,} \\ (\sum_{s \in S} \Phi_{c,s} * Y_s) - 1 & \text{otherwise.} \end{cases} \tag{9}$$

Definition 5 Inside Coverage In_c refers to the fact that if the center point c is covered (takes the value 0) or not (takes the value 1).

$$In_c = \begin{cases} 1 \text{ if center point of sensor device is not covered,} \\ 0 \text{ otherwise.} \end{cases} \tag{10}$$

Hence, the region coverage problem can then be mathematically formulated as follows

$$Minimize \sum_{c=1}^{C} (\alpha_{Out} \cdot Out_c + \alpha_{In} \cdot In_c) \tag{11}$$

Subject to

$$\sum_{s=1}^{S} (\Phi_{c,s} \cdot Y_s) = 1 + Out_c - In_c \qquad \forall c \in C \tag{12}$$

$$Y_s \in \{0, 1\}, \forall s \in S \tag{13}$$

$$Out_c \in \mathbb{N}, \forall c \in C \tag{14}$$

$$In_c \in \{0, 1\}, \forall c \in C \tag{15}$$

Furthermore, The constant parameters α_{Out} and α_{In} help to increase the importance for either Outside Coverage Out_c or Inside Coverage In_c in Eq. 11.

4.3.2 Firefly Algorithm for Lifetime Coverage optimization

Nature-Inspired Metaheuristics are generic search approaches to investigate search spaces and to solve complex problems. Nature-Inspired Metaheuristic consists of two main elements: intensification (exploitation) and diversification (exploration) [30]. The latter consists in producing various solutions to investigate the search space on a global scale, whereas the former concentrates the search in a local search space to find the adequate solution by exploiting the information of this space. These approaches balance between the intensification of the aggregated search experience and the diversification of the search space. This balance can offer regions in the search space with excellent solutions, while avoiding to lose too much time via randomization in regions of the search space which have either been previously investigated or do not produce better quality solutions (i.e., increasing solutions diversity). Hence, Nature-Inspired Metaheuristic offers an adequate solution to any optimization problem, such as inadequate information or insufficient processing capability [32].

The Firefly Algorithm (FA) is one of the nature-inspired metaheuristic methods which copies the social behavior of fireflies. The FA is a highly effective method to locate global optima with increased success ratios [33]. Xin-She Yang has proved that FA outperforms both PSO and GA in terms of success ratio and efficiency during the performance evaluation by simulation [33]. The authors in [34] investigated the FA to solve optimization problems and they have indicated the effectiveness of FA. Since integer linear programming is NP-hard [35,36] and many problem are complex, therefore the heuristic methods must be used instead. FA is a metaheuristic method suitable to solve NP-hard problems and produce approximate solutions. Compared to optimization solvers, FA gives a near-optimal solution with acceptable execution times. The FA also needs smaller amount of memory particularly for large size problems. Optimization solvers provide an optimal solution, but they need higher execution times and larger amounts of memory for large problems.

This section introduces a Nature-Inspired Metaheuristic based FA to solve the problem of coverage optimization. The suggested FA gives a near-optimal schedule of devices for sensing the interested monitoring field per period. The proposed FA depends on the model of optimization which is introduced in Section 4.3.1. The authors in [37] have explained that the Tanh function can improve the performance of the binary FA better than the Sigmoid function. Both Tanh and Sigmoid functions have scaled the values of the input vector in the [0,1] range. Therefore, the Tanh function is employed to enhance our binary firefly algorithm performances. Algorithm 3 exhibits the suggested FA to solve the coverage lifetime optimization problem.

The proposed protocol which is based on FA in the steady-state phase is named EDiMoFA. It aims to produce the optimal (or near-optimal) schedule of the sensor devices which takes the duty of monitoring the region of interest in the next phase. The individual (schedule) in FA is represented in binary values, where the 0 value refers to a sleep state and the 1 value refers to an active state. After generating the initial population in the FA, every individual is assessed and assigned a fitness value according to the fitness function illustrated in Eq. (17). It is computed based on both Eq. (11) and Eq.(12). In the suggested FA, the optimal (or near-optimal) candidate solution, is the one with the minimum value for the fitness function.

Algorithm 3 Firefly Algorithm(S)

```
Require: all the parameters that are related to both coverage model and the FA algorithm
Ensure: $Y^{Best}$ ( Sensors devices schedule)
Compute the parameter $\Phi_{c,s}$ using equation (7)
for $i \longleftarrow 1$ to $Firefly_{No}$ do
    Initialize $Y^i$ randomly by 1 if $Rand() > 0.5$ or 0 otherwise.
    Update Outside coverage $Out_c$,Inside coverage $In_c$, and Penalty $Pen_c$
    Compute the fitness value $Fitness(Y^i)$ using equation (17)
    $Intensity^i \leftarrow Fitness(Y^i)$
end for
Initialize $t \leftarrow 0$
while ($t \leqslant MAXG$) and (The $MaxMinFit$ condition is not met) do
    for $i \longleftarrow 1$ to $Firefly_{No}$ do
        for $j \longleftarrow 1$ to $Firefly_{No}$ do
            if $Intensity^i < Intensity^j$ then
                $dis_{i,j} \leftarrow Distance(Y^i, Y^j)$
                $Beta \leftarrow Attractiveness(Intensity_0, \Upsilon; dis_{i,j})$
                $Y^i \leftarrow (1 - Beta) \times Y^i + Beta \times Y^j$
                $Y^i \leftarrow Y^i + \lambda \times (Rand() - \frac{1}{2})$
            end if
            Update Outside coverage $Out_c$,Inside coverage $In_c$, and Penalty $Pen_c$
            Compute the fitness value $Fitness(Y^i)$ using equation (17)
            $Intensity^i \leftarrow Fitness(Y^i)$
        end for
    end for
    $minF \leftarrow \arg\min_{i \in 1,\cdots,Firefly_{No}} Fitness(Y^i)$
    for $j \longleftarrow 1$ to $S$ do
        $Y_j^B \leftarrow Y_j^{minF} + \lambda \times (Rand() - \frac{1}{2})$
        $Y_j^B \leftarrow \frac{exp(2 \times |Y_j^B|) - 1}{exp(2 \times |Y_j^B|) + 1}$
        if $Rand() < Y_j^B$ then
            $Y_j^{Best} \leftarrow 1.0$
        else
            $Y_j^{Best} \leftarrow 0.0$
        end if
    end for
    $t \leftarrow t + 1$
end while
return $Y^{Best}$
```

This function rewards the decrease in the sensor devices which covers the same center point and penalizes the decrease to zero in the sensor devices covering the center point.

$$Pen_c = \begin{cases} S & \sum_{s=1}^{S} (\Phi_{c,s} \cdot Y_s) = 0, \\ 0 & \text{otherwise.} \end{cases} \tag{16}$$

$$F^i = \sum_{c=1}^{C} ((\alpha_{Out} \cdot Out_c + \alpha_{In} \cdot In_c) + Pen_c) \tag{17}$$

The proposed FA is terminated as soon as one of the two stopping criteria is achieved. The first criterion refers to the maximum number of iterations performed by the FA. The second criterion is called MaxMinFit. It is met when the maximum fitness value in the population is equal to the minimum fitness value. The best solution will be chosen as a schedule of sensor devices for the monitoring phase in the current period. The time complexity of the proposed Firefly Algorithm(S) 3 can be given as $\Theta(MAXG \ . \ {Firefly_{No}}^2)$.

5 Performance Evaluation and Analysis

This section focuses on assessing the performance of the proposed protocol EDiMoFA by conducting several simulation experiments using the OMNeT++ network simulator [13]. Table 1 shows the parameters and their values which are used during the simulation. In this simulation, the sensor nodes in the network are deployed in a controlled way in order to guarantee the full coverage of the sensing field of interest of size $(50 \times 25)\ m^2$ by the deployed sensor devices. They are deployed randomly only within every region of the sensing field.

Table 1: simulation parameters and their values.

Parameter	Value
Network Field	$(50 \times 25)\ m^2$
No. of Devices	100, 150, 200, 250 and 300 nodes
Primary Energy	500-700 joules
Period of monitoring	60 Minutes
R_s	5 m
E_{thr}	36 Joules
R_c	10 m
$MaxIter$	1000
λ	0.5
Υ	1.0
S_{pop}	50
α_{Out}	1
α_{In}	$\lvert C^2 \rvert$
σ	0.9
ς	0.1
B_0	1.0

The conducted results are the average of 50 simulation runs. In our simulations, it is supposed that the concerned sensing field is partitioned into 16 regions in a similar way as explained in [9]. The consumed energy by the sensor devices is calculated according to the energy consumption model which is employed by [9]. This power model is described in Table 2 and the proposed protocol EDiMoFA takes into account all the sensor status when calculating the energy consumption inside each sensor device.

For simplicity's sake , the required amount of energy to change the sensor status from one state to another, to activate the radio, to start-up operation of the sensor device, etc are ignored. The proposed model of energy consumption in [9] is suggested to use 0.2575 mW as the cost of consumed energy for transmitting and receiving a one-bit message. Hence, the energy consumption for a message of length LM bits is equal to 0.2575 * LM.

Every sensor device initializes its energy randomly in the range $[500 - 700]$. The minimum required energy inside every device to stay alive during one period

Table 2: Power consumption values

Sensor status	MCU	Radio	Sensing	*Power (mW)*
COMPUTATION	ON	ON	ON	26.83
ACTIVE	ON	OFF	ON	9.72
LISTENING	ON	ON	ON	20.05
SLEEP	OFF	OFF	OFF	0.02
The required energy to transmit or receive a 2-bit message				0.515

is referred to as E_{th}= 36 Joules, where $E_{th} = CE \times TP$. The EC is the consumed energy during active state (9.72 mW) and TP is the time of one period (3600s). Therefore, in our simulation, if the residual energy of the sensor device is less than E_{th}, it cannot participate in the next period. The efficiency of EDiMoFA is evaluated using different performance metrics such as the coverage ratio, the active sensors ratio, the network lifespan, and the energy consumption. These metrics are used similarly in [9]. The execution time is used as an additional performance metric to evaluate the EDiMoFA protocol. In this simulation, the lifetime of the network is defined as the amount of time until the ratio of coverage is degraded below a certain threshold. The Lifetime95, Lifetime90, Lifetime85, and Lifetime50 are denoted by the amount of time in which the protocol can achieve a network coverage level greater than 95%, 90%, 85%, and 50% respectively. It is supposed that the network operates until the all sensor devices have died or have lost the connectivity of the network.

The EDiMoFA protocol was simulated with a laptop (DELL) with an Intel Core i3 2370 M (1.8 GHz) processor (2 cores) whose MIPS (Million Instructions Per Second) rate is equal to 35330. In the simulation, every deployed sensor device uses Atmel's AVR ATmega103L microcontroller (6 MHz) having a MIPS rate equal to 6. Therefore, in order to be consistent with the use of this device, the original run time on the DELL laptop is multiplied by 2944.2 $\left(\frac{35330}{2} \times \frac{1}{6}\right)$.

The effectiveness of EDiMoFA is tested and compared to four other techniques like DESK [12], GAF[11], DiLCO[9], PeCO[10]. The DESK is a distributed technique for solving coverage problems. The GAF technique partitions the sensing field into fixed cells. After that, only one sensor device will be activated inside each cell in the sensing field. The DiLCO protocol is the enhanced protocol of the protocol introduced in [9]. In the DiLCO protocol, the sensing field is virtually subdivided into small cells according to the divide and conquer method and then distributes the DiLCO protocol inside every small cell to optimize simultaneously both the coverage and lifespan in the cell. The PeCO protocol is also based on the virtual division of the sensing field. It performs the optimization inside each small cell in a distributed way based on the perimeter-coverage model and it also produces the optimal schedule of sensor devices inside each cell simultaneously.

In this paper, DiLCO, PeCO, and EDiMoFA protocols are based on the same framework of the network subdivision and they produce the optimal schedules of sensor devices based on solving the optimization model. The network subdivision consists of 16 subregions and this subdivision has given the best results as explained in [9]. The size of the network and the size of the interested area can play an important role in adapting the number of regions. The three protocols mentioned above can be distinguished from each other by their mathematical formulations and the coverage models to introduce the schedule of sensor devices in each period. For example, the DiLCO protocol has achieved the optimization to cover a set of primary points. The PeCO protocol has performed the optimization to reach the best level of coverage for each perimeter of the sensor device. Both the DiLCO and PeCO protocols are employed by the integer program to produce the optimal schedule of sensor devices. This integer program is solved and executed by using a GLPK optimization solver. In the EDiMoFA protocol, the mathematical optimization model is implemented to achieve the coverage of the sensors centers points. EDiMoFA protocol employs the Firefly Algorithm to optimize both the network lifetime and the coverage.

5.1 Coverage Ratio

The trade-off between network energy-saving and a suitable level of coverage for the sensing field of interest is an essential challenge in the WSNs. The coverage ratio for 200 sensor devices and the five protocols are presented in Figure 2. In the first 33^{rd} periods, it can be seen that DiLCO, DESK, GAF can introduce a light better coverage ratio with 99.02%, 99.99%, and 99.91% respectively in comparison with 98.76% and 98% provided by PeCO and EDiMoFA respectively. On the one hand, EDiMoFA, DiLCO, and PeCO protocols turn off a larger number of redundant sensor devices that led to minimizing the coverage ratio slightly due to implementing the optimization. On the other hand, the other two protocols provide a higher coverage ratio due to activating a larger number of sensor devices because they did not apply the optimization. After the 33^{rd} period, it is clear that the proposed EDiMoFA protocol introduces a better coverage ratio than the PeCO protocol and it preserves the ratio of coverage better than other protocols for longer periods. For example, for network topology of 200 sensor devices, the ratio of the coverage is kept greater than 85% for 65, 70, and 72 periods in the DiLCO, PeCO, and EDiMoFA protocols respectively. The DiLCO, PeCO, and EDiMoFA protocols produced a coverage ratio greater than 95% for 60, 57, and 63 periods respectively. The energy saved by the EDiMoFA protocol in the early periods allows later for a substantial increase in the lifetime coverage performance.

5.2 Active Sensors Ratio

The energy of the sensor device represents the most critical factor that affects the performance of the network. Therefore, it is essential to cover the interesting sensing field by using the minimum number of sensor devices as possible to save energy and extend the lifetime of the network. The ratio of the active sensor devices for 200 sensor devices is illustrated in Figure 3. In the first 14 periods, DESK and GAF are activated closely 30.36 % and 34.96 % respectively of sensor devices, whilst DiLCO, PeCO, and EDiMoFA protocols are turned on 17.92%, 20.16%, and 19.44% of sensor devices during the same first fourteen periods. The reason behind activating a lower number of sensor devices with DiLCO, PeCO, and EDiMoFA protocols is that they have implemented an optimization model to produce the optimal (or near-optimal) schedule of sensor devices to optimize both the coverage and the lifespan of the network. DESK and GAF did not implement the optimization model to schedule the sensor devices in every period. As can be

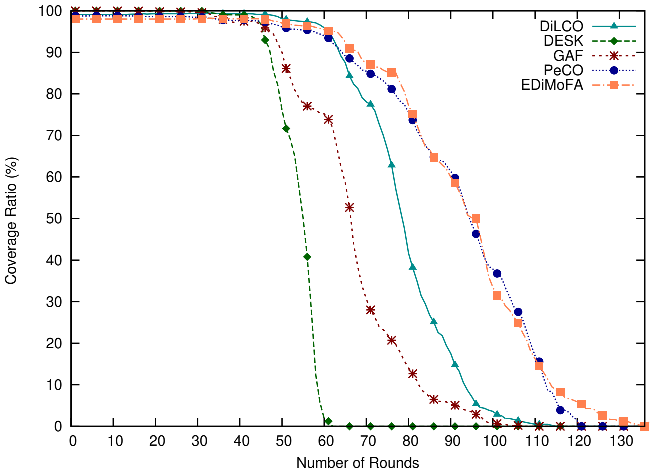


Fig. 2: Coverage ratio for 200 deployed nodes.

seen from Figure 2, the EDiMoFA protocol activated a large number of sensor devices after the 40^{th} period compared with other protocols to introduce a higher ratio of coverage for the sensing field.

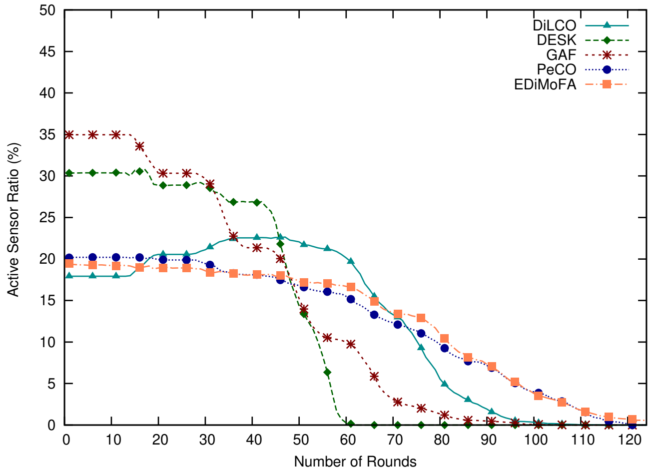
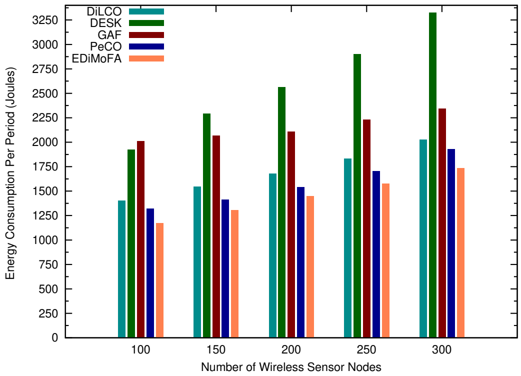


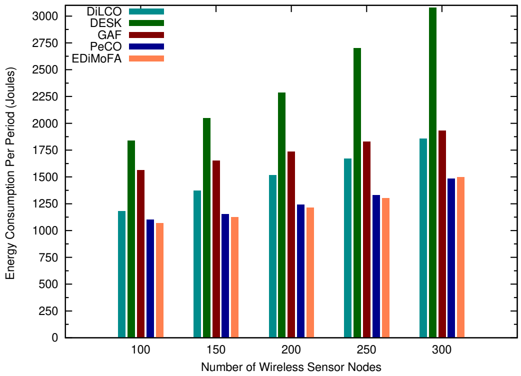
Fig. 3: Active sensors ratio for 200 deployed nodes.

5.3 Energy Consumption

The energy consumption is an essential resource that must taken into account during designing energy-efficient WSN protocols due to the limited power of the sensor device batteries. Since replacing the sensor device battery is impractical in large networks or may even be impossible in hostile environments. Hence, it is essential to save the power of sensor batteries to improve the lifetime of the network. Energy consumption optimization has a direct impact on the network's lifetime. This experiment studies the impact of the consumed energy on the performance of the network. Different states of the energy consumption model implemented by the sensor devices are considered such as: active, sleep, transmitting, receiving, processing, and listening. The results of the five protocols are conducted and compared using different network densities. The energy consumption for different network densities and for both $Lifetime_{95}$ and $Lifetime_{50}$ is shown in Figures 4. As shown in both (a) and (b) of Figures 4, EDiMoFA protocol conserves the energy of the sensor device from 9.4% up to 14.5%, from 41.8% up to 47.9%, from 25.9% up to 31.6%, and from 2.7% up to 10% in comparison with DiLCO, DESK, GAF, and PeCO respectively. It can be seen that the EDiMoFA protocol efficiently saves energy due to producing the most suitable set of active sensor devices per period using the Firefly optimization algorithm and puts the redundant sensor devices in sleep mode. The results have been shown the superiority of the EDiMoFA protocol from an energy-saving point of view. It consumes less energy than the other protocols which can lead to an extension of the network lifespan.



(a) $Lifetime_{95}$.

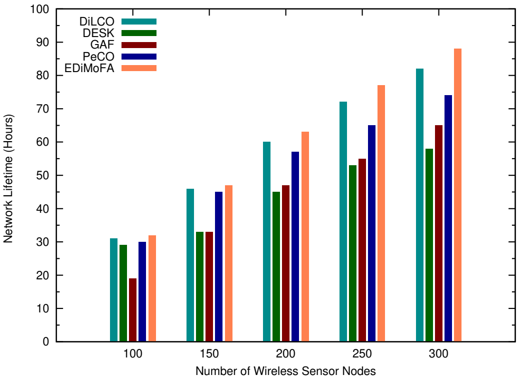


(b) $Lifetime_{50}$.

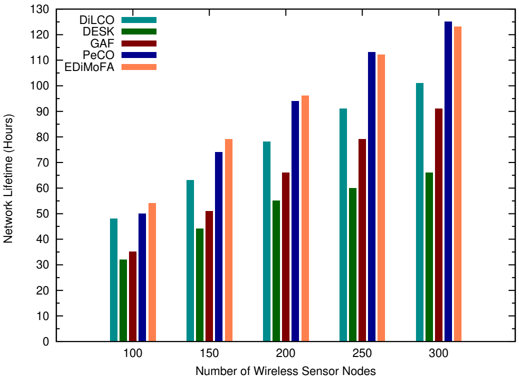
Fig. 4: Energy consumption per period.

5.4 Network Lifespan

One of the most important factors that must be taken into account when designing the WSN is the network lifetime while preserving a suitable level of coverage for the sensing field. Figure 5 presents the network lifespan for different network sizes and for both (a) $Lifetime_{95}$ and (b) $Lifetime_{50}$. The comparison results have proved that the EDiMoFA protocol has prolonged the network lifetime from 3.2% up to 21.8%, from 10.4% up to 86.4%, from 35.2% up to 68.4%, and from 1.6% up to 6.7% in comparison with the DiLCO, DESK, GAF, and PeCO protocols respectively. The results have shown the superiority of EDiMoFA protocol from the network lifetime point of view for $Lifetime_{95}$, while the EDiMoFA and PeCO protocols have introduced the best network lifetime for $Lifetime_{50}$. It is clear that the lifetime increases when the network density increases.



(a) $Lifetime_{95}$.



(b) $Lifetime_{50}$.

Fig. 5: Network Lifetime.

The lifetime of the coverage for the EDiMoFA, DiLCO, and PeCO protocols are compared and shown in Figure 6. In this experiment, Protocol/85, Protocol/90, and Protocol/95 denote the amount of time during which the coverage protocol can respectively preserve the level of coverage ratio greater than 85%, 90%, and 95% . Hence, the term Protocol refers to EDiMoFA, DiLCO, or PeCO. It can be seen from the results that the EDiMoFA protocol outperforms PeCO and DiLCO for all coverage ratios. Moreover, the improvements in the network lifetime increase when the network size increases. Some WSNs applications do not need full coverage for the sensing field. For instance, forest fire applications should provide full coverage in the summer seasons, while in the rainy seasons, they only need 80% of coverage for the sensing field [38].

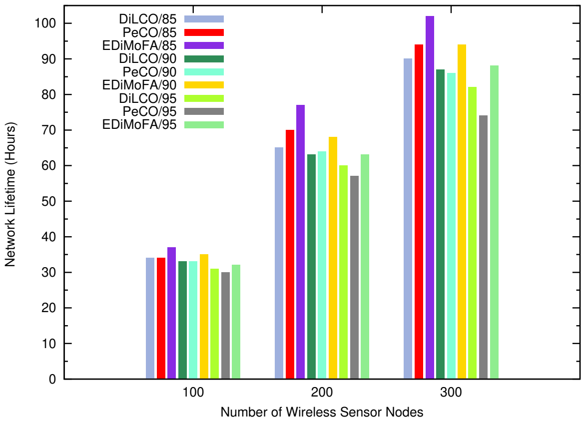


Fig. 6: Network lifetime for different coverage ratios.

5.5 Execution Time

In this experiment, the impact of the execution time on the performance of the network is investigated. Figure 7 presents the execution time in seconds which is required to solve the lifetime coverage optimization problem by EDiMoFA, PeCO, and DiLCO for different network densities. The PeCO and DiLCO protocols are employed in the optimization solver GLPK (GNU Linear Programming Kit) which applies the Branch-and-Bound technique to solve the lifetime coverage optimization problem. The EDiMoFA protocol applies the Firefly Algorithm to solve the same lifetime coverage optimization problem. As previously explained in this section, to be consistent with the use of a sensor device, the original execution time calculated on the DELL laptop is multiplied by 2944.2. As illustrated in the results, the Branch-and-Bound technique consumes a lot of time to solve the lifetime coverage optimization in the PeCO and DiLCO protocols. This has led to losing a large amount of energy by the region head to solve the lifetime coverage optimization problem. Notice that the EDiMoFA protocol always outperforms the PeCO and DiLCO protocols from the execution time point of view. This has a great impact on the increase of the network performance by reducing the energy consumption and thus improving the lifetime of the network while maintaining a suitable level of coverage for the sensing field.

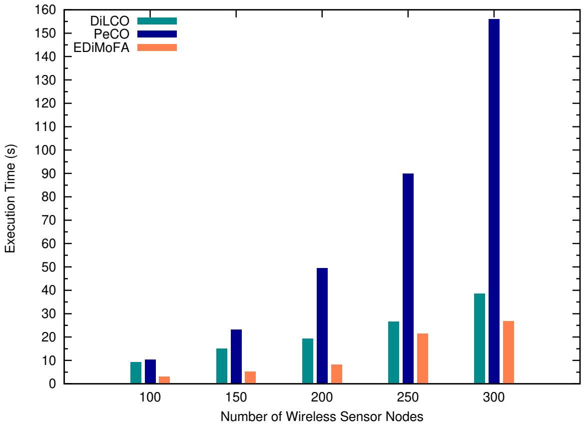


Fig. 7: Execution Time (s).

5.6 The t-test metric

To show the significant difference between the results of the proposed EDiMoFA protocol with previous methods, the statistical analysis using t-test is used to explain that the conducted results of the proposed EDiMoFA protocol are significant. Hence, the t-test is implemented on the result of the comparison of energy consumption between EDiMoFA protocol and other methods like DiLCO, DESK, GAF, and PeCO for both $Lifetime_{95}$ and $Lifetime_{50}$. For the case of $Lifetime_{95}$, the t-test (with p-value) between EDiMoFA and DiLCO, EDiMoFA and DESK, EDiMoFA and GAF, EDiMoFA and PeCO are 1.54972E-05, 0.000649791, 3.76788E-05, and 0.001009918 respectively. While for the case of the $Lifetime_{50}$, the t-test (with p-value) between EDiMoFA and DiLCO, EDiMoFA and DESK, EDiMoFA and GAF, EDiMoFA and PeCO are 0.00204484, 0.00078877, 4.5961E-06, and 0.02568722 respectively. Hence, the t-test (with p-value < 0.05) shows that our results are significant in terms of energy consumption compared with other methods and the energy consumption is significantly reduced.

6 Conclusion and Perspectives

This paper has studied the lifetime coverage optimization problem in WSNs. In this paper, an Energy-saving Distributed Monitoring based Firefly Algorithm (EDiMoFA) Protocol in WSNs is proposed to ensure the coverage and to enhance the lifetime of WSNs of IoTs. The main challenges consist in selecting the region head efficiently in the regions of the sensing field as well as optimizing the lifetime coverage to produce the best schedule of sensor devices and to extend the network lifetime while maintaining an acceptable coverage level. The sensing field is partitioned into smaller regions using the concept divide-and conquer. EDiMoFA protocol is distributed on every node in the resulted regions. EDiMoFA protocol operates into periods. Each period consists of two phases: steady-state and monitoring. The network information exchange, region head selection, and wireless sensors scheduling optimization-based FA are achieved in the steady-state phase.

In the monitoring phase, the best sensors schedule that will be produced by the FA will undertake to monitor every region in the sensing field. The produced sensors schedule ensures coverage at a low consumed energy cost. To evaluate the EDiMoFA protocol performances, several simulations experiments are achieved using the OMNeT++ network simulator. The results prove that the EDiMoFA protocol outperforms some of the other existing protocols in terms of network lifetime, coverage ratio, active sensors ratio, processing time, and energy consumption. In the future, the proposed Firefly Algorithm will be extended to introduce schedules of sensor devices for several periods instead of executing it every period to give a new schedule. This can contribute to reducing energy consumption and maximize the lifetime of the network. Besides, the lifetime coverage optimization model will be improved to take into account the heterogeneous sensor devices.

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