Enhancing Heterogeneous Wireless Sensor Networks Using Swarm Intelligence –Based Routing Protocols

Original Scientific Paper

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Abstract *– The design of efficient communication protocols for wireless sensor networks has aroused great interest in the research community, especially in the face of the limited energy of sensor nodes and the frequent change in network topology. Routing remains a challenging problem in wireless communications, as deploying or replacing sensor nodes in hazardous environments is difficult. Many studies have been devoted to alleviate certain limitations, such as clustering to maintain network connectivity, injecting heterogeneity to avoid the rapid death of nodes, or incorporating evolution-based optimization methods to find the best network configuration. This work combined heterogeneity and swarm-based optimization to efficiently balance energy consumption between nodes to increase network reliability. Specifically, this work employed the binary particle swarm optimizer and the binary artificial bees colony optimizer to find approximately the optimal set of cluster heads (CHs) with their optimal number. Based on the probabilistic principle of the heterogeneous protocols: SEP, EDEEC, and BEENISH, a new refined formulation of CHs selection using swarm optimization is proposed. The swarm flight is guided towards the best CHs with an objective function representing a good balance between the initial and residual energy of nodes. Compared to the standard heterogeneous protocols SEP, EDEEC, and BEENISH, the developed protocols significantly perform better in terms of stability (FND), the round of half nodes' death (HND), the network lifetime (LND), and energy saving. Indeed, the BABC-SEP was found 31,66% better than SEP in terms of remaining energy percentage, and CHs selection in EDEEC and BEENISH using BABC improved them by more than 20% in the percentage of remaining energy.*

Keywords: *Wireless sensor networks, SEP, EDEEC, BEENISH, Binary PSO, Binary ABC, energy efficiency*

1. INTRODUCTION

Wireless sensor networks (WSNs) are an increasingly attractive area of research due to their simplicity, adaptability, scalability, fault tolerance, and ability to remotely monitor hostile environments. This new technology is now being investigated in various domains, such as medicine, industry, agriculture, ecology, military domain, etc. A communication protocol is a fundamental function of wireless communications, which aims to discover the best route that saves energy and ensures rapid data delivery. In ad-hoc networks, routing is performed by specific nodes, called routers, which are often physically protected. Whereas in a wireless network, the routing is performed by sensors themselves [1], this is why a sensor failure can generate a significant loss of information, and deteriorate dramatically the network reliability. Moreover, it is well-known that limited sensor power is the main cause of node failure, and has long imposed a great challenge on the research community [2]. Furthermore, maintaining network connectivity, self-reconfiguration, reliability, and latency are great challenges in designing wireless networks [3], [4].

The clustering-based protocols represent an effective solution to some of these problems. In clustering approaches, nodes are divided into groups, each joining the nearest cluster head based on its signal strength. Usually, the cluster head is a node with higher energy capacity and is responsible for processing and aggregating data collected from its member nodes to reduce data redundancy and hence the network latency [5]. Furthermore, multi-hop clustering approaches can help transmit data packets within the communication range of sensor nodes and thus maintain network connectivity and data reliability [6].

Most of the clustering-based protocols focus on extending the network lifetime without considering network stability or the first node death period, which is a fundamental factor for many real-world applications of WSNs. Heterogeneous networks have been introduced recently to extend the network lifetime and its stability period. In heterogeneous protocols, some nodes are powered with higher energy capacity to perform additional tasks. Typically, these nodes act as cluster heads for more data reliability and longer network stability.

Several heterogeneous communication protocols have been proposed, such as SEP, EDFCM, and ZREECR, which are more stable than energy-efficient, and the DEEC-based protocols, such as EDEEC, DDEEC, which are much more energy-efficient than stable [7].

Despite their variety, the proposed solutions remain limited since the CHs selection process is probabilistic in their setup phase. Finding the optimal set of cluster heads is a Non-deterministic Polynomial (NP)-hard problem, which involves searching in a vast space for potential solutions [8]. Swarm-based methods have been proven effective in solving NP-hard complex problems.

In this work, an effort is made to improve the standard heterogeneous routing protocols, namely, SEP, EDEEC, and BEENISH, based on swarm optimization in their setup phases to select the most powerful cluster heads (CHs). More specifically, the binary particle swarm optimizer (PSO) and the binary artificial bees colony optimizer (ABC) are used to select the best CHs in terms of their initial and remaining energy; the main purpose is to prevent the quick death of nodes to extend the network lifetime and to refine data reliability. Compared to SEP, EDEEC, and BEENISH the obtained results were improved in terms of stability (FND), the round of half-node death (HND), the network lifetime (LND), the number of packets delivered to the base station and energy saving.

The rest of the article is organized as follows:

In the second section, some of the closely related works are briefed. Section 3 describes the principle of the used heterogeneous protocols, namely, SEP, EDEEC, and BEENISH protocols. Section 4 presents the introduced optimization techniques in the mentioned communication protocols and their adaptation to select the best cluster heads (CHs). This work ends with a conclusion and some perspectives.

2. RELATED WORKS

Swarm intelligence optimization methods are robust and concurrent optimization techniques without centralized control, which mimic the natural collective behavior of animal groups to solve complex problems that have a vast search space for potential solutions [9].

Selecting the most powerful cluster heads, the shortest routes between nodes, or enhancing latency and reliability constitute the focus of swarm-based communication protocols. This section presents some of these broad swarm-based contributions.

The idea explored in [10] is to use Refined Bacterial Foraging Optimization (RBFO) and Hybrid BFO-BSO (Bee swarm Optimization) to select the Cluster Heads in WSNs. The considered objective function is a weighted sum of the Packet Loss Ratio and the minimum remaining energy divided by the initial energy of a node. Results proved that RBFO and the Hybrid BFO-BSO provided better performance in terms of power conservation, the packet loss rate, and the end-to-end delay with respect to KBFO and LEACH.

In order to extend the network lifetime, D. Karaboga et al [11], introduced the ABC optimizer in the setup phase of LEACH to efficiently select the cluster head nodes. The considered objective function is the sum of the distances between nodes and their CHs and the distances between the CHs and the base station.

The work presented by M. A. Latiff et al is another centralized PSO-based protocol. The optimized objective function is a weighted sum of Euclidean distances between nodes and their CHs, and the network's remaining energy. Results were better than LEACH, LEACH-C, GA, and K-means [12].

An ACO and ABC-based approach for route construction is presented by J.C. Blandón et al [13], where node selection is relayed on their energy and their distances to the base station. Results were better in terms of energy conservation compared to a non-bio-Inspired algorithm.

Another route establishment approach based on a cooperative PSO to find the best path from a source node to the nearest mobile sink is developed by Y.F. Hu et al [14]. In this work, each node represents a particle, and the set of particles with the best Fitness is selected for data routing to the sink node. The optimized function is the sum of particles' remaining energy divided by a weighted function taking into account the distance, the consumed energy, and the communication delay between nodes. The obtained results were superior to IAR and TTDD protocols in terms of delay and energy.

In this paper [15], the selection of the best cluster heads is improved by the ABC optimization method. The work also used the polling control based on busy/idle nodes in the steady state phase to improve energy conservation.

Wang et al [16], used the CGTABC algorithm for cluster-head selection in the setup phase of LEACH and used an ACO-based routing algorithm to find the best routes between CHs and the base station.

A PSO-based approach for path discovery from sender nodes to the Sink is presented in [17]; the considered objective function is only based on the sum of distances between nodes building the path to the Sink. The PSO-based path discovery performs better than GA based algorithm in terms of energy efficiency.

In [18], an improved artificial bees colony algorithm is used to generate routing paths in a multi-hop clustering-based approach. The optimized function is based on the average energy of the routing path, its minimum energy, and the length of the shortest path. The cluster head selection is based on their remaining energy and the average energy of their member nodes. This approach extended the network lifetime compared to LEACH, EEUC, and MSDG protocols.

In [19], ABC and ALO optimization algorithms were used for CHs and their vicinity CHs (VCHs) selection in the setup phase of the LEACH protocol. The ALO-LEACH protocol outperformed ABC-LEACH in terms of energy consumption, throughput, and the number of alive nodes.

Despite the rich literature on swarm intelligence-based protocols to prolong the lifetime of WSNs, the quick death of some nodes cannot be avoided. To overcome this drawback, heterogeneous protocols have been introduced and improved based on swarm optimization. Examples of heterogeneous swarm-based protocols include the work presented in [20], in which a ring clustering-based approach whose cluster head selection is performed by the PSO method in heterogeneous sensor networks.

Another heterogeneous fault-tolerant and energy-efficient protocol to solve the hotspot problem is presented in [21]. This approach allowed better allocation of time transmission slots in the TDMA protocol using the PSO method and provided a longer network lifetime compared to other heterogeneous protocols such as CEEC and E-BEENISH. A PSO-based approach for the CHs selection in a three-level heterogeneous network is presented in [22]. This approach resulted in better performance in terms of network lifetime, stability period, throughput, and scalability compared to SEP and LEACH.

As exhibited above, most of the swarm intelligence-based protocols incorporate swarm optimization techniques in relatively old homogeneous protocols such as LEACH. The main drawback of LEACH-based protocols is the rapid death of CH nodes, which deteriorates the data reliability, and shortens the network lifetime. The focus of this paper is to study the effectiveness of swarm optimization in heterogeneous protocols. To this end, a new formulation of cluster head selection based on BPSO or BABC in two, three, and four-level heterogeneous networks is proposed. The achieved protocols enabled better results in terms of stability (FND), the round of half nodes' death (HND), and the network lifetime (LND) compared to SEP, EDEEC, and BEENISH protocols.

2.1 SEP PROTOCOL (STABLE ELECTION PROTOCOL)

SEP is a heterogeneous protocol designed for the routing of two energy level networks consisting of normal nodes with initial energy Eo and advanced nodes with more energy: Eo×(1+a); "a" is a positive real value. Being selected based on their initial energy; the advanced nodes are more likely to become CHs using the probabilistic equations below [23], [24]:

$$P_{norm} = \frac{P}{1+a.m} \tag{1}$$

$$P_{advan} = \frac{P}{1+a.m} * (1+a) \tag{2}$$

m: is the fraction of advanced nodes

In SEP, each node generates a random number between 0 and 1. If this number is less than a threshold that takes into account its initial energy and the number of rounds in which it is not elected as a CH, this node will take the role of a cluster head.

The threshold is defined for each type of node (normal S_n or advanced S_a) as per the equations below [24]:

$$T(S_n) = \begin{cases} \dfrac{P_n}{1 - P_n * \left(r \bmod \dfrac{1}{P_n}\right)}, & if\ S_n \in G' \\ 0 & , otherwise \end{cases} \tag{3}$$

$$T(S_a) = \begin{cases} \dfrac{P_a}{1 - P_a * \left(r \bmod \dfrac{1}{P_a}\right)}, & if\ S_a \in G'' \\ 0 & , otherwise \end{cases} \tag{4}$$

G' and G'' are, respectively, the set of normal nodes and the set of advanced nodes which have not been elected as CHs in the last $1/P_n$ and $1/P_a$ rounds.

After cluster head identification, each node joins the group of its closest cluster head, and the communication within each group is planned according to the TDMA protocol, where each cluster head establishes a transmission schedule between its member nodes to avoid cohesion and to conserve the node energy in its waiting or idle states. The cluster heads communicate with the base station according to CSMA protocol to verify the channel availability and ensure data delivery.

2.2. EDEEC PROTOCOL

EDEEC is designed for the routing of three-levels heterogeneous networks consisting of normal nodes, advanced nodes and super nodes according to their initial energy: E_0, ($E_0.a$) and ($E_0.b$) respectively, with a >1 and b>a. The selection of nodes as CHs is based on their types, their residual energy $E_i(r)$ and the r^th^ network average energy $\bar{E}_i(r)$ as formulated by the following equations [25]:

$$\begin{aligned} P_{i\,norm} &= \frac{P.E_i(r)}{(1+a+b).\bar{E}(r)} \\ P_{i\,advan} &= \frac{P.E_i(r).a}{(1+a+b).\bar{E}(r)} \\ P_{i\,super} &= \frac{P.E_i(r).b}{(1+a+b).\bar{E}(r)} \end{aligned} \tag{5}$$

$E_i(r)$ is the residual energy of node "I" in round "r" $\bar{E}_i(r)$ represents the r^{th} network average energy at round r, which is calculated as below:

$$\bar{E}(r) = \frac{1}{N}.E_{total}\left(1 - \frac{r}{R}\right) \quad (6)$$

R is the estimated network lifetime and is calculated as:

$$R = \frac{E_{total}}{E_{round}} \quad (7)$$

$$E_{round} = k\begin{pmatrix} 2NEelec + NEda \\ +S.Emp.d^4_{CH\ to\ BS} + N.Efsd^2_{N\ to\ CH}\end{pmatrix} \quad (8)$$

k is the packet size.

S is the optimal number of cluster heads and calculated as

$$S = \sqrt{\frac{N}{2\pi}}.\frac{xm}{d_{to\ BS}}.d_o$$

$d_{to\ CH}$ and $d_{to\ BS}$ Are respectively the average distance between CH and member nodes, and the average distance between a cluster head and the base station.

$$d_{to\ CH} = \frac{xm}{\sqrt{2\pi k}}, d_{to\ BS} = 0.765\frac{xm}{2},$$

In EDEEC, each node generates a random value between 0 and 1 if this value is lower than the threshold $T(S_i)$ calculated as below, then this node becomes a cluster head [25]:

$$\begin{cases} T(S_i) = \dfrac{p}{1 - p * r\ mod(\frac{1}{p})}, & S_i \in G \\ T(S_i) = 0\ , & otherwise \end{cases} \quad (9)$$

p is calculated by equation (5) and represents the related selection probability of a node type.

2.3. BEENISH PROTOCOL

BEENISH is designed for routing heterogeneous wireless networks constituted of four types of nodes, called respectively: normal, advanced, super, and ultra-super nodes, according to their initial energy: E_0, $(E_0.a)$,$(E_0.b)$ and $(E_0.u)$, with $u > b > a$. The nodes' selection as CHs is based on their types, their residual energy $E_i(r)$, and the rth network average energy $E(r)$ as formulated by equation (10) below [26]:

$$\begin{aligned} P_{i\ norm} &= \frac{P.E_i(r)}{\left(1+m.\left(a+m_0.(-a+b+m_1.(-b+u))\right)\right).\bar{E}(r)} \\ P_{i\ advan} &= \frac{P.(1+a).E_i(r)}{\left(1+m.\left(a+m_0.(-a+b+m_1.(-b+u))\right)\right).\bar{E}(r)} \\ P_{i\ super} &= \frac{P.(1+b).E_i(r)}{\left(1+m.\left(a+m_0.(-a+b+m_1.(-b+u))\right)\right).\bar{E}(r)} \\ P_{i\ ultra} &= \frac{P.(1+u).E_i(r)}{\left(1+m.\left(a+m_0.(-a+b+m_1.(-b+u))\right)\right).\bar{E}(r)} \end{aligned} \quad (10)$$

As in EDEEC protocol, each node generates a random value between 0 and 1, if this value is less than the threshold $T(S_i)$ calculated by equation (9) on the corresponding P_i of equation (10), then the node becomes a CH.

3. THE PROPOSED WORK

In order to save more energy and keep the network running as long as possible, BPSO and BABC have been introduced in the setup stage of SEP, EDEEC, and BEENISH protocols. The objective is to find the most powerful CHs of each round to prevent their rapid death and consequently improve network reliability. In SEP, the role of being a CH is alternated between nodes by probabilistic equations taking into account the type of nodes (advanced or normal), the desired percentage of cluster heads, the set of unelected nodes as CHs, and the number of completed rounds [27]. In EDEEC and BEENISH protocols, the CH role alternation between nodes is based on probabilistic equations considering the node types, their residual energy, the rth network average energy, and the set of unelected nodes as CHs for a number of rounds.

In this work, the CHs selection is based on an optimization process guided by BPSO or BABC towards the best ones in terms of their number and energy. The objective is to find the approximate optimal set of CHs in terms of both their initial and residual energy, combining in such a way the principle of CHs selection in SEP, EDEEC, and BEENISH protocols.

The proposed approach is clustering-based, where each cluster head receives internal messages from its cluster members, aggregates similar packets, and acts as a gateway with the other cluster heads, which helps to reduce redundancy and therefore improves latency.

The clustering process is commonly performed in two main phases: the setup phase and the communication phase. In the setup phase, CHs identification and cluster formation are performed. While in the communication phase, the sensed data are forwarded from nodes to CHs via the TDMA protocol and then from CHs to the base station via the CSMA protocol. These steps are addressed in the next subsections

3.1. THE SETUP PHASE

In this phase, the cluster-head selection is performed centrally by the base station based on two powerful swarm intelligence-based methods. The list of found CHs is then broadcast to all nodes, where each of them joins the nearest cluster head (CH) according to the strength of its radio signal (RSSI). Then, each CH defines a transmission schedule with its member nodes based on the time division multiple access (TDMA) protocol.

To find an optimal network configuration, BPSO and BABC are suggested to solve the CHs selection problem. To do this, the structure of each solution, whether a particle or a bee, is a vector of binary values indicating whether the associated node is selected as a cluster head or not.

The trajectory of particles (bees) in the search space is guided by an objective function whose maximization favors the CHs with the greatest ratio of the sum of CHs' residual energies to the sum of their initial energies as formulated below:

$$F = \frac{\sum_{i=1}^{nb\ CHs} Er_i}{\sum_{i=1}^{nb\ CHs} Ei_i} \quad (11)$$

Er_i is the residual energy of node i

Ei_i is its initial energy

$nb\ CHs$ is the number of nodes elected as CH.

In another way, the preferred CHs are those with higher initial and higher residual energy.

3.1.1 THE BINARY ABC FOR CHS SELECTION

In ABC optimization, the artificial colony of bees is organized into three types of bees: Employed bees relating to food sources, Onlooker bees observing the dance of the employed bees to select a food source, and scout bees searching for random food sources [27].

The ABC steps

1. Bees initialization
2. For each iteration, do
3. Employed bees phase
4. Onlooker bees phase
5. Scout bees phase
6. **End for**

Updating Employed and Onlooker bees in binary ABC is based on the following steps [28], [29]:

- Produce a new bee (NewBee) in the neighborhood of the old "d" dimensional bee "B" by the equation below.

$$NewBee_d = Bee_{B,d} + \alpha.\varphi.\left(Bee_{B,d} - Bee_{K,d}\right)$$
$$\alpha = 1, \varphi\epsilon[-1,1], K \text{ is different from } B \quad (12)$$

- Normalize the newfound Bee to binary values based on the sigmoid function; that is, if the normalized position ($NewBee$) by the sigmoid function is less than 0.5, then the $NewBee$ is set to 1 otherwise to 0.

An onlooker bee selects an employed bee "G" using the roulette wheel on the bees probabilities "$P(B)$" as below [27]:

$$F(B) = e^{-\frac{F(B)}{mean\,(F)}} \quad (13)$$

F(B) is the Fitness of the employed bee "B"

mean (F): is the average Fitness of Employed Bees.

$$P(B) = \frac{F(B)}{\sum_{i=1}^{N} F(i)} \quad (14)$$

"N" is the number of employed bees

The BABC-based routing protocol

Input: A sink and a number of sensor nodes randomly positioned in the area of interest.

Output: Cluster heads identification and data routing.

Step 1: Network Initialization

1. Initialize fraction m of n nodes as advanced nodes with initial energy $E_0.(1+a)$ in the SEP-based protocols
2. Initialize fraction m of n nodes as intermediate nodes and fraction mo of m as super nodes with initial energy: (E_0*a) and(E_0*b) in the EDEEC-based protocol
3. Initialize a fraction m of n nodes as intermediate nodes, a fraction mo of m as super nodes and a fraction m_1 of mo as ultra-super nodes respectively with(E_0*a), (E_0*b) and (E_0*u) in the BEENISH- based protocol.
4. Initialize the rest of the normal nodes with E_0 energy capacity.
5. Initialize the Sink with unlimited energy power.

Step2: Bees initialization

6. Initialize a number of employed bees with random binary values and a size equal to the number of network nodes.
7. **For each** round, **do**

Step 3: The employed bees phase

8. For each employed bee B **do**
9. Produce a New Bee in the neighborhood of B using the equation (12).
10. Replace B with the New Bee if it is better in terms of Fitness (equation (11))
11. Otherwise, increase the bee B inefficiency counter
12. **End** for

Step 4: The onlooker Bees phase

13. **For** each onlooker bee, **do**
14. Select an employed bee "G" using the roulette wheel on the calculated probabilities by equations (13) & (14).
15. Produce a New Bee in the neighborhood of G by equation (12)
16. Normalize into binary the newfound Bee
17. Replace the bee G with the newfound Bee if it is better in terms of Fitness (equation (11))
18. Otherwise, increase the bee G inefficiency counter

19. **End** for

Step 5: The Scout bees phase

20. Randomly reset the ineffective solutions (their inefficiency counter is upper than a limit value)
21. Calculate the new Fitness of each employed Bee

Step 6: cluster heads identification

22. The nodes associated with value 1 in the best found employed Bee are the cluster heads of the current round.
23. The rest of the nodes join the closest cluster heads.

Step 7: The steady-state phase

24. Forward data from nodes to CHs based on TDMA protocol and from CHs to BS based on CSMA protocol.
25. **Until** a maximum number of rounds

3.1.2 The binary PSO for CH selection

PSO is an optimization method, which attempts to imitate the collective flight of birds. In the basic PSO method, each solution called particle has a position (Pos) in the search space, a random speed (Velocity), a personal best solution (Pbest), and a global or swarm best solution (Gbest) [30].

The BPSO steps

1. Particles initialization
2. For each iteration, do
3. Update Pbest
4. Update Gbest
5. Update velocity
6. Update positions
7. **End**

The $Pbest$ is the personal best-found solution of the particle, and $Gbest$ is the best-found solution by the group of particles [31].

Particle velocity update in PSO is based on the equation below [18]:

$$V_{pd} = w.V_{pd} + c_1.r_1.\left(Pbest_{pd} - Pos_{pd}\right) + c_2.r_2.\left(Gbest \quad - Pos_{pd}\right) \tag{15}$$

c_1, c_2 are respectively the cognitive and social factors, r_1 and $r_2 \in]0, 1[$, w is the inertia weight.

In binary optimization, the velocity of each particle is normalized between [0, 1] using the sigmoid function as per the equation below [32]:

$$V_{pd} = \frac{1}{\left(1+e^{-V_{pd}}\right)} \tag{16}$$

Then a random value between 0 and 1 is generated, if the V_{pd} value is upper than the random value, then the normalized position is set to 1, otherwise to 0.

Below is the BPSO-based solution to CHs selection:

The BPSO-based routing protocol

Input: A sink, a number of nodes randomly deployed in the area of interest

Output: Cluster heads identification & packets routing

1. **Step 1**: Network Initialization
2. **Step2:** Particles initialization
3. **For** each round, do
4. **Step 3:** Particles evaluation using equation (11)
5. **Step 4:** Update Pbest and Gbest
6. **Step 5:** Update particles' velocity using eq (15)
7. **Step 6:** Normalize velocity and update particles' positions
8. **Step 7: cluster heads identification**

The nodes associated with value 1 in the Gbest particle are the cluster heads of the current round

9. **Step 8**: **The communication phase**

Forward data from nodes to CHs and from CHs to BS based on TDMA & CSMA protocols. Update the network energy based on the first-order energy model.

10. **Until** the maximum number of rounds.

3.2. THE COMMUNICATION PHASE

In the communication phase (Steady-state phase), which is the same as in SEP, EDEEC, and BEENISH protocols, the CHs receive data from their member nodes and perform their aggregation according to TDMA protocol, and then send the compressed signals to the base station according to the CSMA protocol.

In order to simulate the energy expenditure by the electronic circuits of sensor nodes, the first-order radio energy model is implemented for better comparison as it is the most widely used model in clustering-based protocols [24].

Let E_{Tx} and E_{Rx} be respectively the consumed energy by the transmitter and the receiver circuits of a sensor node.

There are two channel models to transmit a k-bit packet to a receiver M meters away:

The free-space channel model is used when the distance between a source node and the destination node is less than a predefined threshold as formulated below [33]:

$$E_{Tx}(k,M) = k \times Eelec + k \times efs \times M^2 \ , \ if \ M < d_0 \quad (17)$$

$Eelec$ is the required energy by the electronic circuit of the transmitter.

efs is the required energy by the amplifier circuit in free space

$d_0 = \sqrt{efs/emp}$, is a distance threshold.

The multipath fading channel model is used to amplify the signal thus avoiding its degradation when the distance between the source and destination nodes is greater than the predefined threshold [33].

$$E_{Tx}(k,M) = k \times Eelec + k \times emp \times M^4 \ , if \ M > d_0 \quad (18)$$

emp : is the required energy by the amplifier circuit in multipath fading space.

The consumed energy by a CH node to receive a k-bit packet is [33]:

$$E_{Rx}(k) = k\,(Eelec + \mathrm{EDA}) \quad (19)$$

EDA: is the required energy for data aggregation.

4. RESULTS & DISCUSSION

Experiments were run in Matlab 2018, under Windows 10 with an Intel(R) Core(TM) i5-5300U, 2.30 GHz, and 4GB RAM. Sensors are powered with an initial energy of 0.5 Joules and the Sink is powered with unlimited energy.

Table 1. Parameters setting

The network parameters	
The size of the detection area	250×250 m^2
Number of nodes	100
Initial Energy of each Node	0.5 Joules
Eelec	50 nano joules
Emp (the amplifier energy)	100 Pico joules
EDA (Data Aggregation Energy)	5 nano joules
K(Size of a data packet)	4000 bits
BPSO parameters	
Number of particles	20
C_1=C_2	1.49
W(inertia weight)	0.78
Velocity constriction	[-5, 5]
BABC parameters	
Number of employed bees	20
Number of Onlooker Bees	20
Abandonment Limit	20
α (Acceleration Coefficient)	1
Upper & Lower bounds	5 & -5

Heterogeneity is injected into each network type according to these percentages: the fraction of ultra-super nodes, super nodes, advanced or intermediate nodes is respectively: m1=0.2, mo=0.3, m=0.5, and their corresponding energy factors are respectively: u=2.75, b=2.5, and a=2.12.

Table 2 presents the related data to residual and dead-node curves of figures 1, 2 and 3.

Table 2. Comparison in terms of FND, HND, and LND

	FND	HND	LND	RES %	Time
BABC-SEP	640	2471	7646	36,5	0,031
BPSO-SEP	217	1921	7493	22,21	0,047
SEP	444	1619	4883	4,84	0
BABC-BEENISH	815	2469	8604	34,2	0,032
BPSO-BEENISH	264	1929	8975	23,60	0,046
BEENISH	143	1234	7981	12,05	0,003
BABC-EDEEC	588	2468	8353	33,19	0,032
BPSO-EDEEC	173	1473	8315	18,34	0,031
EDEEC	140	1105	7844	11,47	0

Figures 1, 2, and 3 show the behavior of the proposed protocols in terms of energy saving, the number of dead nodes, and the number of packets delivered to BS.

A comparison between the studied protocols, in terms of the Round of First Node Dies (FND), the Round of Half Node Dies (HND), the Round of Last Node Dies (LND), and the percentage of remaining energy in the network is shown in the table 2.

The percentage of residual energy in the network is calculated as below [34]:

$$Res = 100 \times \frac{\sum_{i=1}^{n} Er_i(r)}{\sum_{i=1}^{n} Eo_i} \quad (20)$$

$Er_i(r)$ is the residual energy of node "I" in round "r"

Eo_i is the initial energy of node "I"

Analysis of table 2, shows that the BABC-based protocols perform significantly better than SEP, EDEEC, and BEENISH protocols in terms of FND, HND, LND, and energy saving percentage.

The first death is observed with the EDEEC protocol (in round 140) with slow sensors' death until the total death of the network's in 7844 rounds.

The BPSO-EDEEC protocol delays the first death of nodes until round 173 with a slower sensor death rate than EDEEC (from round 173 until round 8315) because the selection of CHs is based on an optimized process by the binary PSO algorithm.

The BABC-based protocols seem to be the best way to delay sensor death. Indeed, the BABC-SEP, BABC-EDEEC, and BABC-BEENISH protocols record their first death in rounds 640, 588, and 815, respectively; their half nodes death is recorded in 2471, 2468, and 2469, and their total network nodes death (LND) is recorded in 7646, 8353, 8604 rounds respectively.

Moreover, the BABC-based approaches outperform the other algorithms in terms of HND and percent improvement in power saving compared to SEP, EDEEC, and BEENISH protocols. Especially the BABC-SEP approach that has a superior HND with more than 1000 rounds and an energy-saving percentage of more than 31 % compared to SEP protocol. The BABC-BEENISH and the BABC-EDEEC have also a higher HND with more than 1000 rounds compared to BEENISH and EDEEC and saved their power by more than 21%.

The BABC-SEP protocol delays the first network death until round 640 with a slower increase in dead sensors compared to BPSO-SEP (its first death at round 217) and the rest of the protocols. In addition, the BABC-SEP protocol extends the lifetime of the network up to 7646 rounds thanks to its efficient strategy of searching for powerful CHs.

Additionally, the BPSO-based approaches perform slightly better than SEP, EDEEC and BEENISH protocols in terms of HND, LND, and energy-saving percentage. Indeed, the BPSO-based approaches offer a higher HND with more than 300 rounds and save the energy of SEP, and BEENISH protocols by more than 11 %.

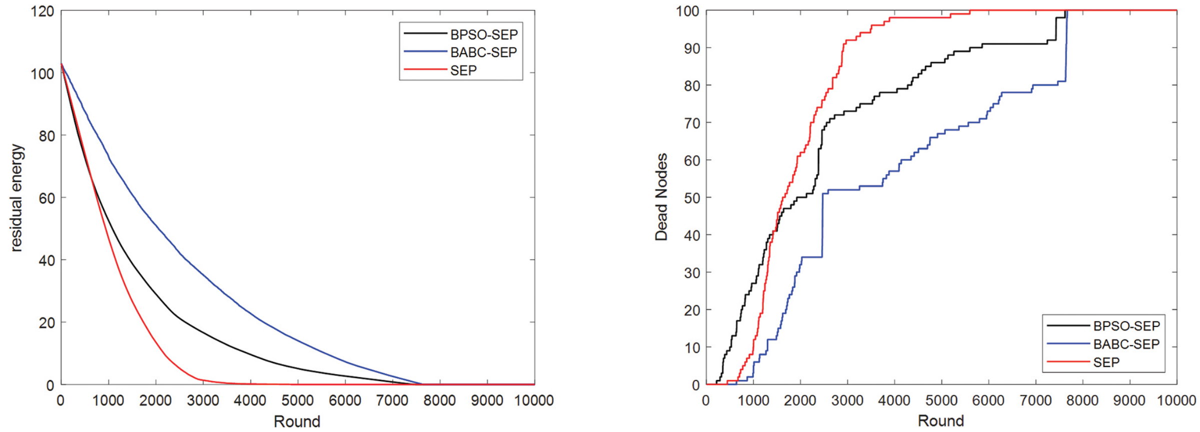

Fig. 1. The behavior of SEP-based protocols

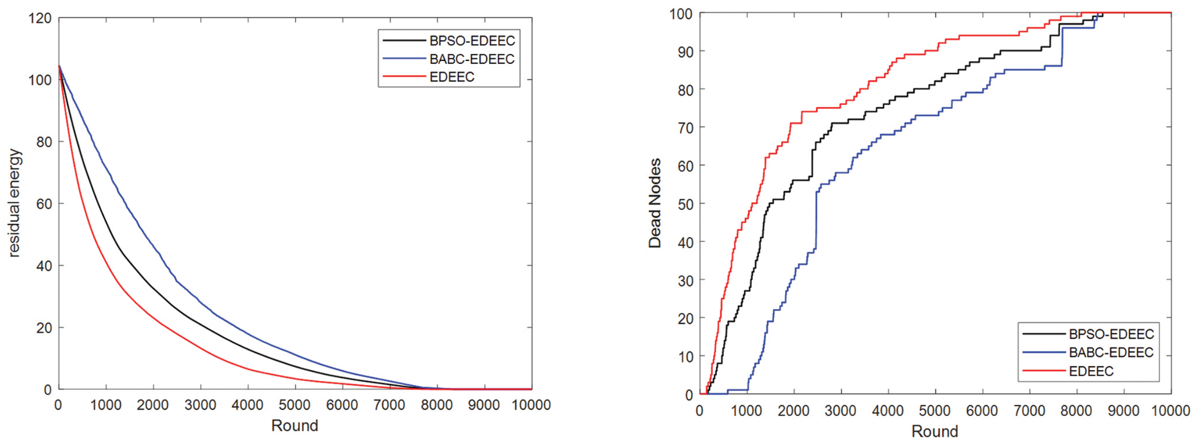

Fig. 2. The behavior of EDEEC-based protocols

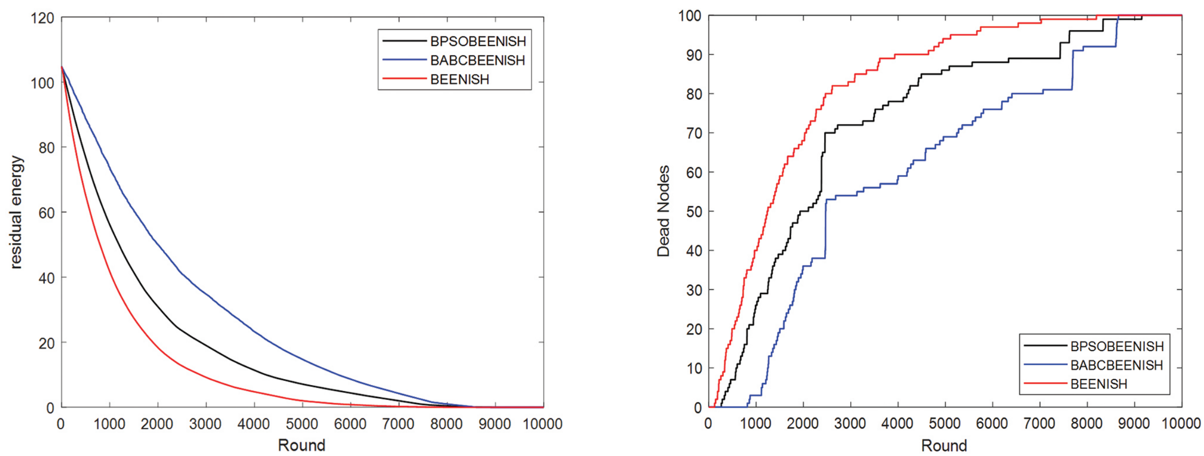

Fig. 3. The behavior of BEENISH-based protocols

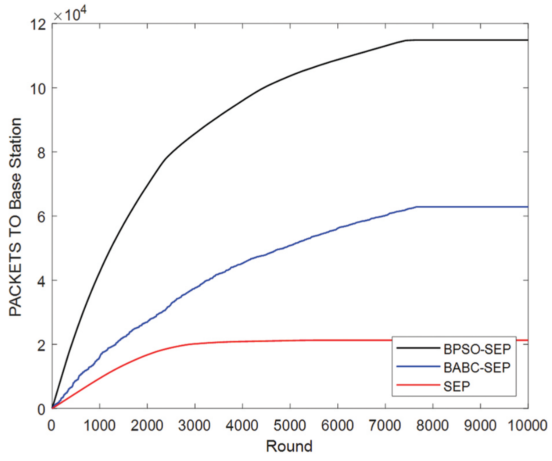

Fig. 4. Packets to BS of SEP-based protocols

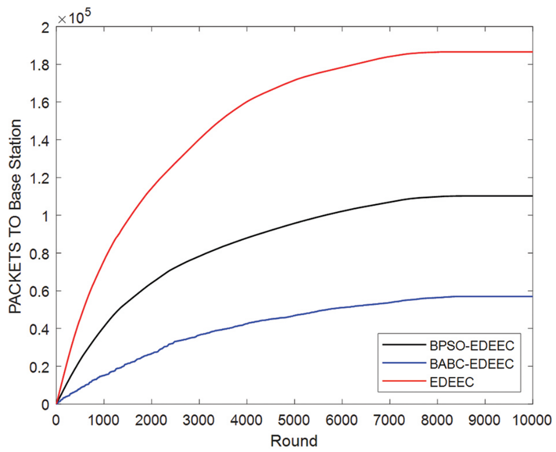

Fig. 5. Packets to BS of EDEEC-based protocols

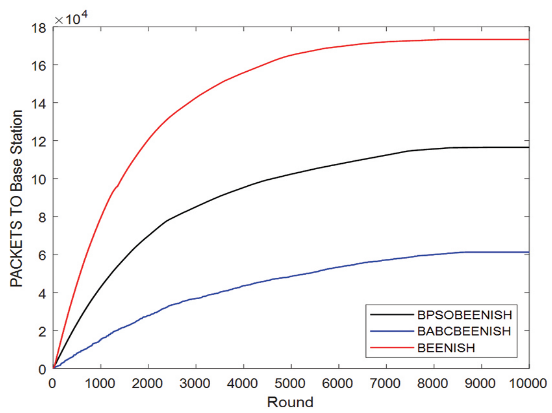

Fig. 6. Packets to BS of BEENISH-based protocols

4.1. FINDING

BABC-based Approaches, namely: BABC-BEENISH, BABC-EDEEC, and BABC-SEP, are the best in terms of FND, HND, and LND. In particular, the BABC-BEENISH protocol that provided the longest stability period and the maximum network lifetime.

BPSO-based approaches, namely: BPSO-SEP, BPSO-EDEEC, and BPSO-BEENISH, contributed respectively to improving the SEP, EDEEC and BEENISH protocols in terms of HND and LND, and improved EDEEC and BEENISH in terms of FND while the SEP protocol remains better than BPSO-SEP in terms of stability (FND).

From the obtained results, it can be seen that the BABC algorithm has perfectly contributed to improving the three protocols SEP, EDEEC, and BEENISH in terms of FND, HND, LND, and energy-saving percentage.

From Table 2 and figures (1 to 3), the proposed approaches compete with the heterogeneous protocols SEP, EDEEC, and BEENISH in terms of delay and the number of packets delivered to the base station.

From the obtained curves, we observed that EDEEC and BEENISH provided the highest rate of packets delivered to the base station, followed by BPSO-based approaches, then BABC-based approaches, and the SEP protocol comes last, providing the lowest rate of packets delivered to the BS.

BEENISH is better than EDDEC in terms of stability (FND) and network lifetime extension (LND). Whereas, the SEP protocol is better in terms of stability.

4.2 DISCUSSION

There is a difference between the initial energy levels of the three protocols: SEP, EDEEC, and BEENISH, since the EDEEC protocol, has a fraction of super nodes with more energy than the advanced nodes of the SEP protocol, and BEENISH has a fraction of ultra-super nodes with more energy than EDEEC-protocol' super nodes. This is why EDEEC provides better results than SEP, and BEENISH provides better results than EDEEC. We can say that these solutions are hardware based rather than software, as it is explained below:

In SEP-based protocols, the number of normal nodes is $m \times n$. Thus, the total network energy=number of normal nodes $\times Eo$+ number of advanced nodes $\times Eo \times (1+a)$ $=(1-m) \times n \times Eo + m \times n \times Eo \times (1+a) = 103$.

In EDEEC-based protocols, the number of normal nodes is $n \times (1-m)$, the number of intermediate nodes is $n \times m \times (1-mo)$, and the number of super-nodes is $n \times m \times mo$.

Thus, the total energy $= n \times (1-m) \times Eo + n \times m \times (1-mo) \times Eo \times (1+a) + n \times m \times mo \times Eo \times (1+b) = 107{,}91$.

In BEENISH-based protocols, the number of normal nodes is $n \times (1-m)$, the number of intermediate nodes is $n \times m \times (1-mo)$, the number of super nodes is $n \times m \times mo \times (1-m1)$, and the number of ultra-super nodes is $n \times m \times mo \times m1$.

Thus, the network energy $= n \times (1-m) \times Eo + n \times m \times (1-mo) \times Eo \times (1+a) + n \times m \times mo \times (1-m1) \times Eo \times (1+b) + n \times m \times mo \times m1 \times Eo \times (1+u) = 110{,} 035$.

The proposed BABC or BPSO-based approaches have contributed to improving the three types of protocols based on the principle of finding the most powerful CHs thus avoiding the rapid exhaustion of nodes' energy and the loss of data packets.

The binary ABC algorithm has solved the routing problem more efficiently than the binary PSO. However, the number of delivered packets to the BS by the EDEEC and BEENISH protocols are the highest, due to their distributed strategy, where neighboring nodes to the BS send their packets directly to the BS without aggregation.

The BPSO optimizer converges faster than the BABC optimizer to the approximate optimal solution without maintaining diversity. Therefore, the selected CHs by BPSO are always the most powerful and can ensure sending the received packets from their member nodes.

5. CONCLUSION

The main objective of this work was to improve energy efficiency and lifetime extension in heterogeneous WSNs using swarm optimization methods. To this end, two communication protocols for WSNs have been developed using swarm optimization methods. The first is based on binary PSO, while the second is based on the binary ABC that have been employed to improve the performances of the standard heterogeneous protocols SEP, EDEEC & BEENISH. The proposed protocols were significantly better in terms of energy saving and lifetime extension, especially those based on binary ABC, which displayed an energy-saving percentage of more than 30% compared to the protocols of basis: SEP, EDEEC, and BEENISH. This was made possible through better load balancing and, therefore, a better alternation of the CH's role between the network nodes using the swarm optimization methods.

In future works, the following perspectives can be addressed:

- Implementation of these algorithms in real-world applications, such as environmental monitoring and irrigation systems in agriculture.
- Consider the packet loss rate, the link quality, delay, and reliability to refine the quality of results through multi-objective optimization.
- Explore other more recent swarm intelligence methods, such as the comprehensive learning particle swarm optimization (CLPSO). Salp swarm algorithm, the Rao algorithm, etc.

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